SAS® Optimization Mathematical Optimization Procedures

2024.02*

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SAS® Documentation
February 15, 2024

The correct bibliographic citation for this manual is as follows: SAS Institute Inc. 2024. *SAS® Optimization: Mathematical Optimization Procedures*. Cary, NC: SAS Institute Inc.

SAS® Optimization: Mathematical Optimization Procedures

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February 2024

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Chapter 1
Introduction

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Overview of SAS Optimization

SAS Optimization includes both general optimization (OPTLP, OPTMILP, OPTQP, and CLP) and network optimization (OPTNETWORK) procedures that take advantage of the distributed, cloud-based computational environment that SAS Viya provides. Optimization solvers are provided for linear (LP), mixed integer linear (MILP), quadratic (QP), nonlinear (NLP), network, and black-box optimization problems. Constraint logic programming (CLP) is also supported. A decomposition algorithm can exploit several different types of structures in LP and MILP problems to decrease solution time. The network solver includes algorithms that solve optimization problems such as shortest path and minimum cost network flow, and also provide algorithms that analyze network structure, including connected components and cycle detection. The OPTMODEL procedure builds optimization models and calls the various solvers.

Optimization models are built in SAS, and solvers execute in CAS. The specialized procedures accept input CAS tables that specify a problem (LP, MILP, QP, network, and CLP) and invoke the corresponding solver.

NOTE: When you license SAS Optimization, you also have access to SAS/OR software. For more information about SAS/OR procedures, see the SAS/OR documentation.

About This Book

This book assumes that you are familiar with Base SAS software and with the books *SAS Programmers Guide: Essentials* and *Base SAS Procedures Guide*. It also assumes that you are familiar with basic SAS System concepts, such as using the DATA step to create SAS data sets and using Base SAS procedures (such as the PRINT and SORT procedures) to manipulate SAS data sets.

Chapter Organization

This book contains the following chapters:

- Chapter 1, this chapter, provides an overview of SAS Optimization and summarizes related information, products, and services.
- Chapter 2 provides an overview of the operations research tools that SAS Optimization provides and shows which procedures you can use to tackle various programming problems and to build models.
- Chapter 3 provides information about topics that are common to multiple procedures. Topics include how to use SAS Cloud Analytic Services (CAS) sessions, how to load a SAS data set onto a CAS server, and information about multithreaded parallel computing, memory limits, and numerical difficulties.
- The remaining chapters describe the SAS Optimization procedures and solvers, in addition to the MPS-format data table and the decomposition algorithm. These chapters are organized as follows:
  - The “Overview” section briefly describes the analysis provided by the procedure, solver, or algorithm.
  - The “Getting Started” section provides a quick introduction through a simple example.
  - The “Syntax” section describes the SAS statements and options that control the procedure, solver, or algorithm.
  - The “Details” section discusses methodology and other topics, such as ODS tables.
  - The “Examples” section contains examples.
  - The “References” section contains references for the methodology.

Typographical Conventions

This book uses several type styles for presenting information. The following list explains the meaning of the typographical conventions used in this book:

roman	is the standard type style used for most text.
UPPERCASE ROMAN	is used for SAS statements, options, and other SAS language elements when they appear in text. However, you can enter these elements in your own SAS programs in lowercase, uppercase, or a mixture of the two.
UPPERCASE BOLD	is used in the "Syntax" sections' initial lists of SAS statements and options.
oblique	is used in the syntax definitions and in text to represent arguments for which you supply a value.
VariableName	is used for the names of variables and data sets when they appear in text.
bold	is used for matrices and vectors.
italic	is used for terms that are defined in text, for emphasis, and for references to publications.
`monospace bold`	is used for example code. In most cases, this book uses lowercase type for SAS code.

Options Used in Examples

The HTMLBLUE style is used to create the graphs and the HTML tables that appear in the online documentation. The PEARLJ style is used to create the PDF tables that appear in the documentation. A style template controls stylistic elements such as colors, fonts, and presentation attributes. You can specify a style template for an HTML ODS destination as follows:

```
ods html style=HTMLBlue;
```

You can also specify a style template for a PDF ODS destination as follows:

```
ods pdf style=PearlJ;
```

Most of the PDF tables are produced by using the following SAS System option:

```
options papersize=(6.5in 9in);
```

If you run the examples, you might get slightly different output. This is a function of the SAS System options that are used and the precision that your computer uses for floating-point calculations.

Where to Turn for More Information

Online Documentation

You can access the documentation by going to http://support.sas.com/documentation.

SAS Technical Support Services

The SAS Technical Support staff is available to respond to problems and answer technical questions regarding the use of procedures in this book. Go to http://support.sas.com/techsup for more information.

Chapter 2
Introduction to Optimization

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Overview

Operations research tools are directed toward the solution of resource management and planning problems. Models in operations research are representations of the structure of a physical object or a conceptual or business process. Using the tools of operations research involves the following:

- defining a structural model of the system under investigation
- collecting the data for the model
- solving the model
- interpreting the results

SAS Optimization includes a set of procedures for exploring models of distribution networks, production systems, resource allocation problems, and scheduling problems using the tools of operations research.

The following list suggests some of the application areas in which optimization-based decision support systems have been used. In practice, models often contain elements of several applications listed here.

- **Product-mix problems** find the mix of products that generates the largest return when several products compete for limited resources.
- **Blending problems** find the mix of ingredients to be used in a product so that it meets minimum standards at minimum cost.
- **Time-staged problems** are models whose structure repeats as a function of time. Production and inventory models are classic examples of time-staged problems. In each period, production plus inventory minus current demand equals inventory carried to the next period.
- **Scheduling problems** assign people to times, places, or tasks so as to optimize people's preferences or performance while satisfying the demands of the schedule.
- **Multiple objective problems** have multiple, possibly conflicting, objectives. Typically, the objectives are prioritized, and the problems are solved sequentially in a priority order.
- **Capital budgeting and project selection problems** ask for the project or set of projects that yield the greatest return.
- **Location problems** seek the set of locations that meets the distribution needs at minimum cost.
- **Cutting stock problems** find the partition of raw material that minimizes waste and fulfills demand.

The basic optimization problem is that of minimizing or maximizing an objective function subject to constraints imposed on the variables of that function. The objective function and constraints can be linear or nonlinear; the constraints can be bound constraints, equality or inequality constraints, or integer constraints. Traditionally, optimization problems are divided into various types depending on the sets of values that the variables are restricted to (real, integer, or binary, or a combination) and the nature of functional form of the constraints and objectives (linear, quadratic, or general nonlinear). An expression of an optimization problem in mathematical form is called a mathematical program.

When the complete description of a mathematical program is supplied to an appropriate algorithm (such as one of the solvers described in this book), the algorithm determines the optimal values for the decision variables so the objective is either maximized or minimized, the optimal values that are assigned to decision variables are on or between allowable bounds, and the constraints are obeyed. This process of solving mathematical programs is called mathematical programming, mathematical optimization, or just optimization.

When the constraints in an optimization problem are linear and the objective is either linear or quadratic, the optimization problem can be encapsulated in SAS data tables and then solved using the appropriate SAS Optimization procedure: the OPTLP, OPTMILP, or OPTQP procedure.

Often optimization problems, and especially those with nonlinear elements, are formalized in an algebraic model that represents the problem. When formulated in its most abstract form, such an algebraic model is independent of problem data. A specific optimization problem instance (including the original problem) is then just an instantiation of the algebraic model with the specific data associated with that instance. An optimization modeling language (also called an algebraic modeling language) is a programming environment that has syntax, structures, and operations that enable you to express a mathematical program in a form that corresponds in a natural and transparent way to its algebraic model. The syntax, structures, and operations also enable you to populate an algebraic model with a specific data instance and then solve the resulting optimization problem instance with an appropriate solver. The OPTMODEL procedure is such an algebraic modeling language in SAS Optimization software and can be viewed as a single, unified environment to formulate and solve mathematical programming problems of many different types.

Whether mathematical programs are represented in SAS data tables or in an algebraic model in PROC OPTMODEL, they can be saved, easily changed, and solved again. The SAS Optimization procedures also output SAS data tables that contain the solutions. These data tables can then be used to produce customized reports or as input to other SAS procedures. This structure enables you to use the tools of operations research and other SAS tools as building blocks to build decision support systems.

This chapter describes how to use SAS Optimization to solve a wide variety of optimization problems. It describes various types of optimization problems, indicates which SAS Optimization procedures you can use, and shows how you provide data, run the procedure, and obtain optimal solutions. For additional examples that demonstrate the features of the OPTMODEL procedure, see *SAS/OR User's Guide: Mathematical Programming Examples*.

The following sections broadly classify the SAS Optimization procedures based on the types of mathematical programming problems that they can solve.

Linear Programming Problems

The OPTLP Procedure

The OPTLP procedure solves linear programming problems that are submitted in a SAS data table that uses a mathematical programming system (MPS) format.

The MPS file format is a format commonly used for describing linear programming (LP) and integer programming (IP) problems (Murtagh 1981; IBM 1988). MPS-format files are in text format and have specific conventions for the order in which the different pieces of the mathematical model are specified. The MPS-format SAS data table corresponds closely to the MPS file format and is used to describe linear programming problems for PROC OPTLP. For more information, see Chapter 8, "The MPS-Format Data Table."

PROC OPTLP provides four algorithms to solve general LPs: primal simplex, dual simplex, network simplex, and interior point. For more information about solving LPs with PROC OPTLP, see Chapter 5, "The OPTLP Procedure." The OPTLP procedure also provides a decomposition algorithm for solving LPs. For more information about the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm."

The OPTMODEL Procedure

The OPTMODEL procedure, a general purpose optimization modeling language, can also be used for concisely modeling linear programming problems. If an LP has special network structure, the structure is typically natural and evident in a well-formulated model of the problem in PROC OPTMODEL.

Within PROC OPTMODEL you can declare a model, pass it directly to various solvers, and review the solver result. You can also save an instance of a linear model in data table form for use by the OPTLP procedure. For more information, see Chapter 9, "The OPTMODEL Procedure."

Mixed Integer Linear Programming Problems

The OPTMILP Procedure

The OPTMILP procedure solves general mixed integer linear programs (MILPs)—linear programs in which a subset of the decision variables are constrained to be integers. The OPTMILP procedure solves MILPs by using an LP-based branch-and-bound algorithm augmented by advanced techniques such as cutting planes and primal heuristics. For more information about the OPTMILP procedure, see Chapter 6, "The OPTMILP Procedure." The OPTMILP procedure also provides a decomposition algorithm for solving MILPs. For more information about the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm."

The OPTMILP procedure requires a MILP to be specified by a SAS data table that adheres to the MPS format. For more information about the MPS-format data set, see Chapter 8, "The MPS-Format Data Table."

The OPTMODEL Procedure

The OPTMODEL procedure, a general purpose optimization modeling language, can also be used for concisely modeling mixed integer linear programming problems. In fact, except for the declaration of some subset of variables to be integer or binary, modeling these problems is quite analogous to modeling LPs. Within OPTMODEL you can declare a model, pass it directly to various solvers, and review the solver result. You can also save an instance of a mixed integer linear model in data table form for use by PROC OPTMILP. For more details, see Chapter 9, "The OPTMODEL Procedure."

Quadratic Programming Problems

The OPTQP Procedure

The OPTQP procedure uses the interior point algorithm to solve quadratic programs—problems that have a quadratic objective function and a collection of linear constraints, including general linear constraints along with lower or upper bounds (or both) on the decision variables.

You can specify the problem input data in one SAS data table that uses a quadratic programming system (QPS) format. For details about the QPS-format data specification, see Chapter 8, "The MPS-Format Data Table." For more details about the OPTQP procedure, see Chapter 7, "The OPTQP Procedure."

The OPTMODEL Procedure

The OPTMODEL procedure, a general-purpose optimization modeling language, can also be used for concisely modeling quadratic programming problems. Within OPTMODEL you can declare a model, pass it directly to various solvers, and review the solver result. You can also save an instance of a quadratic model in data table form for use by PROC OPTQP. For more details, see Chapter 9, "The OPTMODEL Procedure."

Nonlinear Programming Problems

The OPTMODEL Procedure

The OPTMODEL procedure, a general-purpose optimization modeling language, can also be used for concisely modeling nonlinear programming (NLP) problems. Within OPTMODEL you can declare a nonlinear optimization model, pass it directly to various solvers, and review the solver result. For more details, see Chapter 9, "The OPTMODEL Procedure."

You can solve many different types of NLP problems by using the nonlinear solver functionality of PROC OPTMODEL. The NLP solver implements two primal-dual based algorithms—interior point trust region line search and active-set trust region linear search—for finding a local minimum. For more information about the nonlinear programming solver, see Chapter 16, "The Nonlinear Programming Solver."

Model Building with PROC OPTMODEL

Model generation and maintenance are often difficult and expensive aspects of applying mathematical programming techniques. The richly expressive syntax and features of PROC OPTMODEL, in addition to the flexible data input and output capabilities, simplify this task considerably. Although PROC OPTMODEL offers almost unlimited latitude in how a particular optimization problem is formulated, the most effective use of OPTMODEL is achieved when the model is abstracted away from the data. This aspect makes PROC OPTMODEL somewhat unusual among SAS procedures and is important enough to illustrate with a simple example.

A small product-mix problem serves as a starting point for a discussion of two different ways of modeling with PROC OPTMODEL.

A candy manufacturer makes two products: chocolate and toffee. What combination of chocolate and toffee should be produced in a day in order to maximize the company's profit? Chocolate contributes $0.25 per pound to profit, and toffee contributes $0.75 per pound. The decision variables are *chocolate* and *toffee*.

Four processes are used to manufacture the candy:

1. Process 1 combines and cooks the basic ingredients for both chocolate and toffee.
2. Process 2 adds colors and flavors to the toffee, then cools and shapes the confection.

3. Process 3 chops and mixes nuts and raisins, adds them to the chocolate, and then cools and cuts the bars.

4. Process 4 is packaging: chocolate is placed in individual paper shells; toffee is wrapped in cellophane packages.

During the day, there are 7.5 hours (27,000 seconds) available for each process.

Firm time standards have been established for each process. For Process 1, mixing and cooking take 15 seconds for each pound of chocolate, and 40 seconds for each pound of toffee. Process 2 takes 56.25 seconds per pound of toffee. For Process 3, each pound of chocolate requires 18.75 seconds of processing. In packaging, a pound of chocolate can be wrapped in 12 seconds, whereas a pound of toffee requires 50 seconds. These data are summarized as follows:

	Process	Available Time (sec)	Required per Pound chocolate (sec)	Required per Pound toffee (sec)
1	Cooking	27,000	15	40
2	Color/Flavor	27,000		56.25
3	Condiments	27,000	18.75	
4	Packaging	27,000	12	50

The objective is to maximize the company's total profit, which is represented as

Maximize: $0.25(\textit{chocolate}) + 0.75(\textit{toffee})$

The production of the candy is limited by the time available for each process. The limits placed on production by Process 1 are expressed by the following inequality:

Process 1: $15(\textit{chocolate}) + 40(\textit{toffee}) \leq 27{,}000$

Process 1 can handle any combination of chocolate and toffee that satisfies this inequality.

The limits on production by other processes generate constraints described by the following inequalities:

Process 2: $56.25(\textit{toffee}) \leq 27{,}000$

Process 3: $18.75(\textit{chocolate}) \leq 27{,}000$

Process 4: $12(\textit{chocolate}) + 50(\textit{toffee}) \leq 27{,}000$

This linear program illustrates an example of a product mix problem. The mix of products that maximizes the objective without violating the constraints is the solution.

First, the following statements demonstrate a way of representing the optimization model in PROC OPTMODEL that is almost a verbatim translation of the mathematical model:

```
proc optmodel;
   /* declare variables */
   var choco >= 0, toffee >= 0;

   /* maximize objective function (profit) */
   maximize profit = 0.25*choco + 0.75*toffee;

   /* subject to constraints */
```

```
   con process1:    15*choco +    40*toffee <= 27000;
   con process2:               56.25*toffee <= 27000;
   con process3: 18.75*choco                <= 27000;
   con process4:    12*choco +    50*toffee <= 27000;

   /* solve LP using primal simplex algorithm */
   solve with lp / algorithm = primal_spx;

   /* display solution */
   print choco toffee;
quit;
```

The optimal objective value and the optimal solution are displayed in Figure 2.1:

Figure 2.1 Solution Summary

The OPTMODEL Procedure

Solution Summary	
Solver	LP
Algorithm	Primal Simplex
Objective Function	profit
Solution Status	Optimal
Objective Value	475
Primal Infeasibility	0
Dual Infeasibility	3.172066E-17
Bound Infeasibility	0
Iterations	4
Presolve Time	0.01
Solution Time	0.02

choco	toffee
1000	300

You can observe from the preceding example that PROC OPTMODEL provides an easy and very direct way of modeling and solving mathematical programming models. Although this way of modeling, where the data are intertwined heavily with model elements, is correct, has significant practical limitations. The model is not easy to explain, it is hard to generalize, and clearly this approach does not scale to large problems of the same type. To overcome these issues, you need to separate the data from the essential algebraic structure of the model. Along those lines, you can make the reasonable assumption that you have the following two data sets (one for the products and one for processes that capture the parameters and data elements of this product mix problem):

```
data ProductData;
   length Name $10.;
   input Name $ Profit;
   datalines;
Chocolate  0.25
Toffee     0.75
;
```

```
data ProcessData;
   length Name $15.;
   input Name $ Available_time Chocolate Toffee;
   datalines;
Cooking            27000          15          40
Color/Flavor       27000           0          56.25
Condiments         27000         18.75         0
Packaging          27000          12          50
;
```

The following alternative model in PROC OPTMODEL can solve the same problem by taking these data sets as input:

```
proc optmodel;
   /* declare sets and data indexed by sets */
   set <string> PRODUCTS;
   set <string> PROCESSES;
   num Profit{PRODUCTS};
   num AvailableTime{PROCESSES};
   num RequiredTime{PRODUCTS,PROCESSES};

   /* declare the variable */
   var Amount{PRODUCTS};

   /* maximize objective function (profit) */
   maximize TotalProfit = sum{p in PRODUCTS} Profit[p]*Amount[p];

   /* subject to constraints */
   con Availability{r in PROCESSES}:
      sum{p in PRODUCTS} RequiredTime[p,r]*Amount[p] <= AvailableTime[r];

   /* abstract algebraic model that captures the structure of the */
   /*    optimization problem has been defined without referring  */
   /*    to a single data constant                                */

   /* populate model by reading in the specific data instance */
   read data ProductData into PRODUCTS=[name] Profit;
   read data ProcessData into PROCESSES=[name] AvailableTime=Available_time
      {p in PRODUCTS} <RequiredTime[p,name]= col(p)>;

   /* solve LP using primal simplex algorithm */
   solve with lp / algorithm = primal_spx;

   /* display solution */
   print Amount;
quit;
```

The details of the syntax and elements of the PROC OPTMODEL language are discussed in Chapter 9, "The OPTMODEL Procedure." The key observation here is that the preceding version of the PROC OPTMODEL statements capture the essence of the optimization model concisely, but completely, and the model can be explained, modified, and maintained easily. It also achieves total separation of the data from the model in that the same PROC OPTMODEL statements can be applied to any other specific problem of this type (and of any size) by simply changing the data sets appropriately and rerunning the same PROC OPTMODEL statements.

Also, because of PROC OPTMODEL's ability to read data very flexibly and from any number of data sets, the problem data can be in its most natural form, making the model easier to explain and understand.

References

IBM (1988). *Mathematical Programming System Extended/370 (MPSX/370) Version 2 Program Reference Manual.* Vol. SH19-6553-0. Armonk, NY: IBM.

Murtagh, B. A. (1981). *Advanced Linear Programming: Computation and Practice*. New York: McGraw-Hill.

Rosenbrock, H. H. (1960). "An Automatic Method for Finding the Greatest or Least Value of a Function." *Computer Journal* 3:175–184.

Chapter 3
Shared Concepts

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Introduction to CAS

SAS Optimization procedures run on SAS Viya. One component of SAS Viya is SAS Cloud Analytic Services (CAS), which is the analytic server and associated cloud services. The following subsections describe how to set up and use CAS sessions. The sections after that then provide details on the concepts that are common to most of the procedures.

Using CAS Sessions and CAS Engine Librefs

SAS Cloud Analytic Services (CAS) is the analytic server and associated cloud services in SAS Viya. This section describes how to create a CAS session and set up a CAS engine libref that you can use to connect to the CAS session. It assumes that you have a CAS server already available; contact your system administrator if you need help starting and terminating a server. This CAS server is identified by specifying the host on which it runs and the port on which it listens for communications. To simplify your interactions with this CAS server, the host information and port information for the server are stored as SAS option values that are retrieved automatically whenever this CAS server needs to be accessed. You can examine the host and port values for the server at your site by using the following statements:

```
proc options option=(CASHOST CASPORT);
run;
```

In addition to starting a CAS server, your system administrator might also have created a CAS session and a CAS engine libref for your use. You can define your own sessions and CAS engine librefs that connect to the CAS server as shown in the following statements:

```
cas mysess;
libname mycas cas sessref=mysess;
```

The CAS statement creates the CAS session named mysess, and the LIBNAME statement creates the mycas CAS engine libref that you use to connect to this session. It is not necessary to explicitly name the CASHOST and CASPORT of the CAS server in the CAS statement, because these values are retrieved from the corresponding SAS option values.

If you have created the mysess session, you can terminate it by using the TERMINATE option in the CAS statement as follows:

```
cas mysess terminate;
```

For more information about the CAS statement and the LIBNAME statement, see *SAS Cloud Analytic Services: User's Guide*. For general information about CAS and CAS sessions, see *SAS Cloud Analytic Services: Fundamentals*.

Loading a SAS Data Set onto a CAS Server

Procedures in this book require the input data to reside on a CAS server. To work with a SAS data set, you must first load the data set onto the CAS server. Data loaded on the CAS server are called *data tables*. This section lists three methods of loading a SAS data set onto a CAS server. In this section, mycas is the name of the caslib that is connected to the mysess CAS session.

- You can use a single DATA step to create a data table on the CAS server as follows:

  ```
  data mycas.Sample;
     input y x @@;
     datalines;
  .46 1 .47 2 .57 3 .61 4 .62 5 .68 6 .69 7
  ;
  ```

  Note that DATA step operations might not work as intended when you perform them on the CAS server instead of the SAS client.

- You can create a SAS data set first, and when it contains exactly what you want, you can use another DATA step to load it onto the CAS server as follows:

  ```
  data Sample;
     input y x @@;
     datalines;
  .46 1 .47 2 .57 3 .61 4 .62 5 .68 6 .69 7 .78 8
  ;
  data mycas.Sample;
     set Sample;
  run;
  ```

- You can use the CASUTIL procedure as follows:

```
proc casutil sessref=mysess;
   load data=Sample casout="Sample";
quit;
```

The CASUTIL procedure can load data onto a CAS server more efficiently than the DATA step. For more information about the CASUTIL procedure, see *SAS Cloud Analytic Services: User's Guide*.

The mycas caslib stores the Sample data table, which can be distributed across many machine nodes. You must use a caslib reference in procedures in this book to enable the SAS client machine to communicate with the CAS session. For example, the following OPTLP procedure statements use a data table that resides in the mycas caslib:

```
proc optlp data = mycas.Sample;
  ...statements...;
run;
```

You can delete your data table by using the DELETE procedure as follows:

```
proc delete data = mycas.Sample;
run;
```

The Sample data table is accessible only in the mysess session. When you terminate the mysess session, the Sample data table is no longer accessible from the CAS server. If you want your Sample data table to be available to other CAS sessions, then you must *promote* your data table. For more information about data tables, see *SAS Cloud Analytic Services: User's Guide*.

Parallel Computing

Although the speed of a single-core processor has increased considerably over the decades, further gains in computing power are possible through the use of multiple cores or processors. This practice is called *parallel computing*, in which certain computations are partitioned into independent smaller subcomputations. Each subcomputation is then processed on separate cores or processors simultaneously. Consumer-grade PCs and servers are often equipped with multicore processors; multiprocessor configurations are becoming relatively common and inexpensive. As a result, parallel computing is becoming increasingly important. One type of parallel computing is multithreaded computing, in which several threads use the processors of a single server to work concurrently on subtasks. These threads share the random access memory (RAM) of that server. In another type of parallel computing, distributed computing, computation is parallelized over several processors (possibly multithreaded), each of which owns an independent memory allocation. Most optimization algorithms use sparse computation, which is not easy to parallelize well. Some algorithms (such as branch and cut) can be parallelized, but the computation can become highly unbalanced. For these reasons, a very high speedup is not usually possible even when the number of threads is increased.

Memory Limit

The system option MEMSIZE sets a limit on the amount of memory that the SAS System uses. If you do not specify a value for this option, then the SAS System sets a default memory limit. Your operating environment determines the actual size of the default memory limit set by the SAS System, which is sufficient for many applications. However, the solution of many realistic optimization problems can require more memory than the default. It is therefore recommended that the memory limit be increased above the default when you are solving optimization problems. This reduces the chance of a procedure failing because of an out-of-memory error.

NOTE: The MEMSIZE system option is not available in some operating environments. See the documentation for your operating environment for more information.

You can specify -MEMSIZE 0 to indicate that all available memory can be used, but use this setting with caution. In most operating environments, it is better to specify an adequate amount of memory than to specify -MEMSIZE 0. For example, if you are running PROC OPTLP to solve LP problems with only a few hundred thousand variables and constraints, -MEMSIZE 500M might be sufficient to enable the procedure to run without an out-of-memory error. When a problem has millions of variables, -MEMSIZE 2G or higher might be needed. These are rules of thumb; problems with atypical structure, density, or other characteristics can increase the optimizer's memory requirements.

No matter how much memory is installed, 32-bit Windows operating systems permit the SAS System to use at most 4 gigabytes of memory. This memory limit might be lower, depending on which version of Windows you are running. The limit is enforced by the Windows operating system, not the SAS System.

You can specify the MEMSIZE option at system invocation, on the SAS command line, or in a configuration file. The syntax is described in the *SAS Companion* book for your operating environment.

To report a procedure's memory consumption, you can use the FULLSTIMER option. The syntax is described in the *SAS Companion* book for your operating environment.

Numerical Difficulties

Extremely large or extremely small numerical values might cause computational difficulties (singularities, stalled solution progress, false infeasibilities, and so on) for optimization solvers, but the occurrence of such difficulties is hard to predict. For this reason, solvers issue a data error message when they detect model data that exceed a specific threshold number. The value of the threshold number depends on your operating environment and is printed in the log as part of the data error message.

The following conditions produce a data error:

- The absolute value of an objective coefficient, constraint coefficient, or range (difference between the upper and lower bounds on a constraint) is greater than the threshold number.
- A variable's lower bound, a $\geq$ or = constraint's right-hand side, or a range constraint's lower bound is greater than the threshold number.

- A variable's upper bound, a $\leq$ or = constraint's right-hand side, or a range constraint's upper bound is smaller than the negative threshold number.

If a variable's upper bound is greater than 1E20, then all solvers treat the bound as ∞. Similarly, if a variable's lower bound is less than –1E20, then the LP solver treats the bound as $-\infty$.

If a solver fails or experiences numerical difficulties when solving a problem, try one of the following remedies:

- Improve the input data: Rescale very large and very small numbers in constraints, objectives, right-hand sides, and variable bounds. It is recommended that the magnitudes of the largest and smallest constraint coefficients not exceed 1E6.
- Specify different algorithms or options (or both): For example, to solve a linear program, you can choose from the primal simplex, dual simplex, interior point, and network simplex algorithms. Using available options, you can tighten or relax feasibility or optimality tolerances.

Problem Size

The maximum number of allowed variables, constraints, nonzero constraint coefficients, branching variables, or nonzero quadratic coefficients in the data input files is $2^{31} - 1$.

References

Andrews, G. R. (1999). *Foundations of Multithreaded, Parallel, and Distributed Programming*. Reading, MA: Addison-Wesley.

Chapter 4
The CLP Procedure

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Overview: CLP Procedure

The CLP procedure is a finite-domain constraint programming solver for constraint satisfaction problems (CSPs) with linear, logical, and global constraints. In addition to having an expressive syntax for representing CSPs, the CLP procedure features powerful built-in consistency routines and constraint propagation algorithms, a choice of nondeterministic search strategies, and controls for guiding the search mechanism that enable you to solve a diverse array of combinatorial problems.

You can also solve standard constraint satisfaction problems via the constraint programming solver in PROC OPTMODEL. For more information, see the constraint programming solver chapter in *SAS Optimization: Mathematical Optimization Procedures*.

The Constraint Satisfaction Problem

Many important problems in areas such as artificial intelligence (AI) and operations research (OR) can be formulated as constraint satisfaction problems. A CSP is defined by a finite set of variables that take values from finite domains and by a finite set of constraints that restrict the values that the variables can simultaneously take.

More formally, a CSP can be defined as a triple $\langle X, D, C \rangle$:

- $X = \{x_1, \ldots, x_n\}$ is a finite set of *variables*.
- $D = \{D_1, \ldots, D_n\}$ is a finite set of *domains*, where D_i is a finite set of possible values that the variable x_i can take. D_i is known as the *domain* of variable x_i.
- $C = \{c_1, \ldots, c_m\}$ is a finite set of *constraints* that restrict the values that the variables can simultaneously take.

The domains need not represent consecutive integers. For example, the domain of a variable could be the set of all *even* numbers in the interval [0, 100]. A domain does not even need to be totally numeric. In fact, in a scheduling problem with resources, the values are typically multidimensional. For example, an activity can be considered as a variable, and each element of the domain would be an *n-tuple* that represents a start time for the activity and one or more resources that must be assigned to the activity that corresponds to the start time.

A solution to a CSP is an assignment of values to the variables in order to satisfy all the constraints. The problem amounts to finding one or more solutions, or possibly determining that a solution does not exist.

The CLP procedure can be used to find one or more (and in some instances, all) solutions to a CSP with linear, logical, and global constraints. The numeric components of all variable domains are assumed to be integers.

Techniques for Solving CSPs

Several techniques for solving CSPs are available. Kumar (1992) and Tsang (1993) present a good overview of these techniques. It should be noted that the satisfiability problem (SAT) (Garey and Johnson 1979) can be regarded as a CSP. Consequently, most problems in this class are nondeterministic polynomial-time complete (NP-complete) problems, and a backtracking search mechanism is an important technique for solving them (Floyd 1967).

One of the most popular tree search mechanisms is chronological backtracking. However, a chronological backtracking approach is not very efficient because conflicts are detected late; that is, it is oriented toward *recovering* from failures rather than *avoiding* them to begin with. The search space is reduced only after detection of a failure, and the performance of this technique is drastically reduced with increasing problem size. Another drawback of using chronological backtracking, for the same reason, is encountering repeated failures, sometimes called "thrashing." The presence of late detection and "thrashing" has led researchers to develop consistency techniques that can achieve superior pruning of the search tree. This strategy uses constraints actively, rather than passively.

Constraint Propagation

A more efficient technique than backtracking is constraint propagation, which uses consistency techniques to effectively prune the domains of variables. Consistency techniques are based on the idea of *a priori* pruning, which uses the constraint to reduce the domains of the variables. Consistency techniques are also known as relaxation algorithms (Tsang 1993), and the process is also called problem reduction, domain filtering, or pruning.

One of the earliest applications of consistency techniques was in the AI field in solving the scene labeling problem, which required recognizing objects in three-dimensional space by interpreting two-dimensional line drawings of the object. The Waltz filtering algorithm (Waltz 1975) analyzes line drawings by systematically labeling the edges and junctions while maintaining consistency between the labels.

An effective consistency technique for handling resource capacity constraints is edge finding (Applegate and Cook 1991). Edge-finding techniques reason about the processing order of a set of activities that require a given resource or set of resources. Some of the earliest work related to edge finding can be attributed to Carlier and Pinson (1989), who successfully solved MT10, a well-known 10×10 job shop problem that had remain unsolved for over 20 years (Muth and Thompson 1963).

Constraint propagation is characterized by the extent of propagation (also referred to as the level of consistency) and whether domain propagation or interval propagation is the domain pruning scheme that is followed. In practice, interval propagation is preferred over domain propagation because of its lower computational costs. This mechanism is discussed in detail in Van Hentenryck (1989). However, constraint propagation is not a complete solution technique and needs to be complemented by a search technique in order to ensure success (Kumar 1992).

Finite-Domain Constraint Programming

Finite-domain constraint programming is an effective and complete solution technique that embeds incomplete constraint propagation techniques into a nondeterministic backtracking search mechanism, implemented as follows. Whenever a node is visited, constraint propagation is carried out to attain a desired level of consistency. If the domain of each variable reduces to a singleton set, the node represents a solution to the CSP. If the domain of a variable becomes empty, the node is pruned. Otherwise a variable is selected, its domain is distributed, and a new set of CSPs is generated, each of which is a child node of the current node. Several factors play a role in determining the outcome of this mechanism, such as the extent of propagation (or level of consistency enforced), the variable selection strategy, and the variable assignment or domain distribution strategy.

For example, the lack of any propagation reduces this technique to a simple generate-and-test, whereas performing consistency on variables already selected reduces this to chronological backtracking, one of the systematic search techniques. These are also known as look-back schemas, because they share the disadvantage of late conflict detection. Look-ahead schemas, on the other hand, work to prevent future conflicts. Some popular examples of look-ahead strategies, in increasing degree of consistency level, are forward checking (FC), partial look ahead (PLA), and full look ahead (LA) (Kumar 1992). Forward checking enforces consistency between the current variable and future variables; PLA and LA extend this even further to pairs of not yet instantiated variables.

Two important consequences of this technique are that inconsistencies are discovered early and that the current set of alternatives that are coherent with the existing partial solution is dynamically maintained. These consequences are powerful enough to prune large parts of the search tree, thereby reducing the "combinatorial explosion" of the search process. However, although constraint propagation at each node results in fewer nodes in the search tree, the processing at each node is more expensive. The ideal scenario is to strike a balance between the extent of propagation and the subsequent computation cost.

Variable selection is another strategy that can affect the solution process. The order in which variables are chosen for instantiation can have a substantial impact on the complexity of the backtrack search. Several heuristics have been developed and analyzed for selecting variable ordering. One of the more common ones is a dynamic heuristic based on the *fail first* principle (Haralick and Elliott 1980), which selects the variable whose domain has minimal size. Subsequent analysis of this heuristic by several researchers has validated this technique as providing substantial improvement for a significant class of problems. Another popular technique is to instantiate the most constrained variable first. Both these strategies are based on the principle of selecting the variable most likely to fail and to detect such failures as early as possible.

The domain distribution strategy for a selected variable is yet another area that can influence the performance of a backtracking search. However, good value-ordering heuristics are expected to be very problem-specific (Kumar 1992).

The CLP Procedure

The CLP procedure is a finite-domain constraint programming solver for CSPs. In the context of the CLP procedure, CSPs can be classified into the following two types:

- A *standard CSP* is characterized by integer variables, linear constraints, array-type constraints, global constraints, and reified constraints. In other words, X is a finite set of integer variables, and C can contain linear, array, global, or logical constraints.
- A *scheduling CSP* is characterized by activities, temporal constraints, and resource requirement constraints. In other words, X is a finite set of activities, and C is a set of temporal constraints and resource requirement constraints. This capability requires a SAS/OR license to run. For more information, see *SAS/OR User's Guide: Constraint Programming*.

In order to solve a standard CSP, the CLP procedure requires a Solution data table for storing the solution(s) to the CSP; to specify this data table, you use the OUT= option in the PROC CLP statement. For more information about the format and layout of the Solution data table, see the section "Solution Data Table" on page 47. In addition, the procedure expects only ALLDIFF, ARRAY, CUMULATIVE, ELEMENT, FOREACH, GCC, LEXICO, LINCON, PACK, REIFY, and VARIABLE statements. You can also specify a Constraint data table by using the CONDATA= option in the PROC CLP statement instead of, or in combination with, VARIABLE and LINCON statements.

Consistency Techniques

The CLP procedure features a full look-ahead algorithm for standard CSPs that follows a strategy of maintaining a version of generalized arc consistency that is based on the AC-3 consistency routine (Mackworth 1977). This strategy maintains consistency between the selected variables and the unassigned variables and also maintains consistency between unassigned variables.

Selection Strategy

A search algorithm for CSPs searches systematically through the possible assignments of values to variables. The order in which a variable is selected can be based on a *static* ordering, which is determined before the search begins, or on a *dynamic* ordering, in which the choice of the next variable depends on the current state of the search. The VARSELECT= option in the PROC CLP statement defines the variable selection strategy for a standard CSP. The default strategy is the dynamic MINR strategy, which selects the variable with the smallest range.

Assignment Strategy

After a variable has been selected, the assignment strategy dictates the value that is assigned to it. The assignment strategy is specified with the VARASSIGN= option in the PROC CLP statement. The default assignment strategy selects the minimum value from the domain of the selected variable.

Getting Started: CLP Procedure

The following examples illustrate the use of the CLP procedure in the formulation and solution of two well-known logical puzzles in the constraint programming community.

Send More Money

The Send More Money problem consists of finding unique digits for the letters D, E, M, N, O, R, S, and Y such that S and M are different from zero (no leading zeros) and the following equation is satisfied:

$$\begin{array}{r} \text{S E N D} \\ +\text{M O R E} \\ \hline \text{M O N E Y} \end{array}$$

You can use the CLP procedure to formulate this problem as a CSP by representing each of the letters in the expression with an integer variable. The domain of each variable is the set of digits 0 through 9. The VARIABLE statement identifies the variables in the problem. The DOM= option defines the default domain for all the variables to be [0,9]. The OUT= option defines the Solution data table. The LINCON statement defines the linear constraint SEND + MORE = MONEY, and the restrictions that S and M cannot take the value zero. (Alternatively, you can simply specify the domain for S and M as [1,9] in the VARIABLE statement.) Finally, the ALLDIFF statement is specified to enforce the condition that the assignment of digits should be unique. The complete representation, using the CLP procedure, is as follows:

```
proc clp dom=[0,9]                  /* Define the default domain    */
         out=mycas.out;             /* Name the Solution data table */
   var S E N D M O R E M O N E Y;   /* Declare the variables        */
   lincon                           /* Linear constraints           */
                                    /* SEND + MORE = MONEY          */
      1000*S + 100*E + 10*N + D + 1000*M + 100*O + 10*R + E
      =
      10000*M + 1000*O + 100*N  + 10*E + Y,
      S<>0,                         /* No leading zeros          */
      M<>0;
   alldiff();      /* All variables have pairwise distinct values*/
run;
```

The Solution data table that is produced by the CLP procedure is shown in Output 4.1.

Output 4.1 Solution to SEND + MORE = MONEY

S	E	N	D	M	O	R	Y
9	5	6	7	1	0	8	2

The unique solution to the problem that the CLP procedure finds is as follows:

$$\begin{array}{r} 9\,5\,6\,7 \\ +\,1\,0\,8\,5 \\ \hline 1\,0\,6\,5\,2 \end{array}$$

Eight Queens

The Eight Queens problem is a special instance of the N-Queens problem, where the objective is to position N queens on an $N \times N$ chessboard such that no two queens attack each other. The CLP procedure provides an expressive constraint for variable arrays that can be used for solving this problem very efficiently.

You can model this problem by using a variable array A of dimension N, where $A[i]$ is the row number of the queen in column i. Since no two queens can be in the same row, it follows that all the $A[i]$'s must be pairwise distinct.

In order to ensure that no two queens can be on the same diagonal, the following should be true for all i and j:

$$A[j] - A[i] <> j - i$$

and

$$A[j] - A[i] <> i - j$$

In other words,

$$A[i] - i <> A[j] - j$$

and

$$A[i] + i <> A[j] + j$$

Hence, the $(A[i] + i)$'s are pairwise distinct, and the $(A[i] - i)$'s are pairwise distinct.

These two conditions, in addition to the one requiring that the $A[i]$'s be pairwise distinct, can be formulated using the FOREACH statement.

One possible such CLP formulation is presented as follows:

```
proc clp out=mycas.out
         varselect=fifo; /* Variable Selection Strategy               */
   array A[8] (A1-A8);   /* Define the array A                        */
   var (A1-A8)=[1,8];    /* Define each of the variables in the array */
                         /* Initialize domains                        */
```

```
   /* A[i] is the row number of the queen in column i*/
   foreach(A, DIFF,  0); /* A[i] 's are pairwise distinct */
   foreach(A, DIFF, -1); /* A[i] - i 's are pairwise distinct */
   foreach(A, DIFF,  1); /* A[i] + i 's are pairwise distinct */
run;
```

The ARRAY statement is required when you are using a FOREACH statement, and it defines the array A in terms of the eight variables A1–A8. The domain of each of these variables is explicitly specified in the VARIABLE statement to be the digits 1 through 8 since they represent the row number on an 8×8 board. FOREACH(A, DIFF, 0) represents the constraint that the $A[i]$'s are different. FOREACH(A, DIFF, –1) represents the constraint that the $(A[i] - i)$'s are different, and FOREACH(A, DIFF, 1) represents the constraint that the $(A[i] + i)$'s are different. The VARSELECT= option specifies the variable selection strategy to be first-in-first-out, the order in which the variables are encountered by the CLP procedure.

The following statements display the Solution data table shown in Output 4.2:

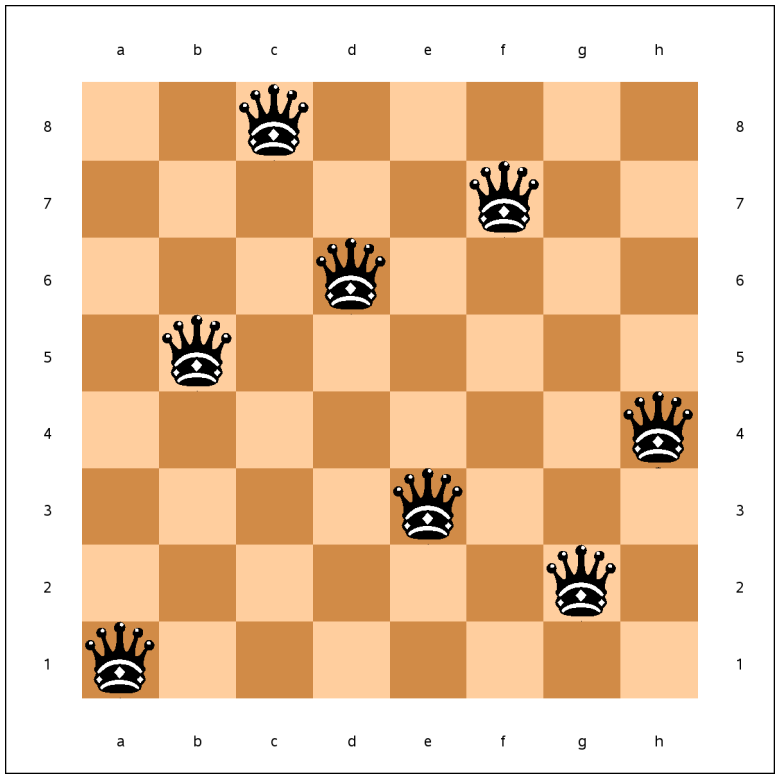
```
proc print data=mycas.out noobs label;
   label A1=a A2=b A3=c A4=d
         A5=e A6=f A7=g A8=h;
run;
```

Output 4.2 A Solution to the Eight Queens Problem

a	b	c	d	e	f	g	h
1	5	8	6	3	7	2	4

The corresponding solution to the Eight Queens problem is displayed in Figure 4.1.

Figure 4.1 A Solution to the Eight Queens Problem



Syntax: CLP Procedure

The following statements are used in PROC CLP:

PROC CLP *options* **;**
  ALLDIFF *alldiff constraints* **;**
  ARRAY *array specifications* **;**
  CUMULATIVE *cumulative constraints* **;**
  ELEMENT *element constraints* **;**
  FOREACH *foreach constraints* **;**
  GCC *global cardinality constraints* **;**
  LEXICO *lexicographic ordering constraints* **;**
  LINCON *linear constraints* **;**
  OBJ *objective function options* **;**
  PACK *bin packing constraints* **;**
  REIFY *reified constraints* **;**
  VARIABLE *variable specifications* **;**

Functional Summary

The statements and options available in PROC CLP are summarized by purpose in Table 4.1.

Table 4.1 Functional Summary

Description	Statement	Option
Assignment Strategy Options		
Specifies the variable assignment strategy	PROC CLP	VARASSIGN=
Data Table Options		
Specifies the Constraint input data table	PROC CLP	CONDATA=
Specifies the Solution output data table	PROC CLP	OUT=
Domain Options		
Specifies the global domain of all variables	PROC CLP	DOMAIN=
Specifies the domain for selected variables	VARIABLE	
General Options		
Specifies the upper bound on time (seconds)	PROC CLP	MAXTIME=
Suppresses preprocessing	PROC CLP	NOPREPROCESS
Permits preprocessing	PROC CLP	PREPROCESS
Specifies the units of MAXTIME	PROC CLP	TIMETYPE=
Implicitly defines Constraint data table variables	PROC CLP	USECONDATAVARS=
Objective Function Options		
Specifies the lower bound for the objective	OBJ	LB=
Specifies the tolerance for the search	OBJ	TOL=

Table 4.1 *continued*

Description	Statement	Option
Specifies the upper bound for the objective	OBJ	UB=
Output Control Options		
Finds all possible solutions	PROC CLP	FINDALLSOLNS
Specifies the number of solution attempts	PROC CLP	MAXSOLNS=
Indicates progress in log	PROC CLP	SHOWPROGRESS
Selection Strategy Options		
Specifies the variable selection strategy	PROC CLP	VARSELECT=
Specifies variable selection strategies for evaluation	PROC CLP	EVALVARSEL=
Enables time limit updating for strategy evaluation	PROC CLP	DECRMAXTIME
Standard CSP Statements		
Specifies the alldifferent constraints	ALLDIFF	
Specifies the array specifications	ARRAY	
Specifies the cumulative constraints	CUMULATIVE	
Specifies the element constraints	ELEMENT	
Specifies the foreach constraints	FOREACH	
Specifies the global cardinality constraints	GCC	
Specifies the lexicographic ordering constraints	LEXICO	
Specifies the linear constraints	LINCON	
Specifies the bin packing constraints	PACK	
Specifies the reified constraints	REIFY	
Defines the variable specifications	VARIABLE	

PROC CLP Statement

PROC CLP *options* **;**

The PROC CLP statement invokes the CLP procedure. You can specify options to control a variety of search parameters that include selection strategies, assignment strategies, maximum running time, and number of solution attempts. You can specify the following options:

CONDATA=*CAS-libref.data-table*

identifies the input data table that defines the constraints, variable types, and variable bounds and an objective function. The CONDATA= data table provides support for linear constraints only. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

You can also specify the linear constraints in-line by using the LINCON statement. The CLP procedure enables you to define constraints by using a combination of the two specifications. When defining

constraints, you must define the variables by using a VARIABLE statement or implicitly define them by specifying the USECONDATAVARS= option when using the CONDATA= data table. You can define variable bounds by using the VARIABLE statement, and any such definitions override the implicit definitions of variables in the CONDATA= data table.

DECRMAXTIME

dynamically decreases the maximum solution time in effect during evaluation of the variable selection strategy. The DECRMAXTIME option is effective only when the EVALVARSEL= option is specified. Initially, the maximum solution time is the value specified by the MAXTIME= option. Whenever a solution is found with the current variable selection strategy, the value of MAXTIME for future attempts is reduced to the current solution time. The DECRMAXTIME option thus provides a sense of which strategy is the fastest for a given problem. However, you must use caution when comparing the strategies, because the individual strategy results might pertain to different time limits.

By default, the DECRMAXTIME option is disabled; each variable selection strategy is given the amount of time specified by the MAXTIME= option.

DOMAIN=*[lb, ub]*

DOM=*[lb, ub]*

specifies the global domain of all variables to be the closed interval [*lb*, *ub*]. You can override the global domain for a variable with a VARIABLE statement or the CONDATA= data table. The default domain is [0,∞].

EVALVARSEL*<=(keyword(s))>*

evaluates specified variable selection strategies by attempting to find a solution with each strategy. You can specify any combination of valid variable selection strategies in a space-delimited list enclosed in parentheses. If you do not specify a list, all available strategies are evaluated in alphabetical order, except that the default strategy is evaluated first. Descriptions of the available selection strategies are provided in the discussion of the VARSELECT= option.

When the EVALVARSEL= option is in effect, the MAXTIME= option must also be specified. By default, the value specified for the MAXTIME= option is used as the maximum solution time for each variable selection strategy. When the DECRMAXTIME option is specified and a solution has been found, the value of the MAXTIME= option is set to the solution time of the current solution.

After the CLP procedure has attempted to find a solution with a particular strategy, it proceeds to the next strategy in the list. For this reason, the VARSELECT=, ALLSOLNS, and MAXSOLNS= options are ignored when the EVALVARSEL= option is in effect. All solutions that are found during the evaluation process are saved in the output data table that you specify in the OUT= option.

The macro variable _ORCLPEVS_ provides more information that is related to the evaluation of each variable selection strategy. The fastest variable selection strategy is indicated in the macro variable _ORCLP_, provided that either at least one solution is found or the problem is found to be infeasible. See "Macro Variable _ORCLP_" on page 50 for more information about the _ORCLP_ macro variable; see "Macro Variable _ORCLPEVS_" on page 51 for more information about the _ORCLPEVS_ macro variable.

The EVALVARSEL= option enables you to evaluate strategies concurrently under certain conditions in a distributed environment. For more information, see the section "Parallel Processing" on page 47.

FINDALLSOLNS
ALLSOLNS
FINDALL
attempts to find all possible solutions to the CSP.

MAXSOLNS=*n*
specifies the maximum number of solutions to attempt to find. The default value is 1. It is important to note that the specified number of solutions might not be attainable in the time allotted; therefore the total number of solutions found might be fewer than the number given by the MAXSOLNS= parameter.

MAXTIME=*n*
specifies an upper bound on the number of seconds that are allocated for solving the problem. The type of time, either CPU time or real time, is determined by the value of the TIMETYPE= option. The default type is CPU time. The time specified by the MAXTIME= option is checked only once at the end of each iteration. Therefore, the actual running time can be longer than that specified by the MAXTIME= option. The difference depends on how long the last iteration takes. The default value of MAXTIME= is ∞. If you do not specify this option, the procedure does not stop based on the amount of time elapsed.

NOPREPROCESS
suppresses any preprocessing that would typically be performed for the problem.

OUT=*CAS-libref.data-table*
identifies the output data table that contains one or more solutions to a standard CSP, if one exists. This option is required in order to run the CLP procedure. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts." Each observation in the OUT= data table corresponds to a solution of the CSP. You can control the number of solutions that are generated by specifying the MAXSOLNS= option in the PROC CLP statement.

PREPROCESS
permits any preprocessing that would typically be performed for the problem.

SHOWPROGRESS
prints a message to the log whenever a solution has been found.

TIMETYPE=CPU | REAL
specifies whether CPU time or real time is used for evaluation of the MAXTIME= option and the reporting of timing values in the ODS tables and macro variables. The default value of this option is CPU.

USECONDATAVARS=0 | 1
specifies whether the numeric variables in the CONDATA= data table, with the exception of any reserved variables, are implicitly defined or not. A value of 1 indicates they are implicitly defined, in which case a VARIABLE statement is not necessary to define the variables specified in the data table. The default value is 0. Currently, _RHS_ is the only reserved numeric variable.

VARASSIGN=MAX | MIN

specifies the value selection strategy. Currently, there are two strategies:

- MAX, which selects the maximum value from the domain of the selected variable
- MIN, which selects the minimum value from the domain of the selected variable

The default value selection strategy is MIN.

VARSELECT=*keyword*

specifies the variable selection strategy. The strategy can be static, dynamic or conflict-directed. Typically, static strategies exploit information about the initial state of the search, whereas dynamic strategies exploit information about the current state of the search process. Conflict-directed strategies are strategies which exploit information from previous states of the search process as well as the current state (Boussemart et al. 2004)

Static strategies are as follows:

- FIFO, which uses the first-in-first-out ordering of the variables as encountered by the procedure
- MAXCS, which selects the variable with the maximum number of constraints (degree)

Dynamic strategies are as follows:

- DOMDDEG, which selects the variable with the smallest ratio of domain size by dynamic degree
- DOMDEG, which selects the variable with the smallest ratio of domain size by degree
- MAXC, which selects the variable with the largest number of active constraints (dynamic degree)
- MINR, which selects the variable with the smallest range (that is, the minimum value of upper bound minus lower bound)
- MINRMAXC, which selects the variable with the smallest range, breaking ties by selecting one with the largest number of active constraints

Conflict-directed strategies are as follows:

- DOMWDEG, which selects the variable with the smallest ratio of domain size by weighted degree
- WDEG, which selects the variable with the largest weighted degree

The dynamic strategies embody the "fail first principle" (FFP) of Haralick and Elliott (1980), which suggests that "To succeed, try first where you are most likely to fail." The degree of a variable is the number of constraints in which the variable appears. The dynamic degree of a variable is the degree of the variable with respect to the current set of active constraints. Boussemart et al. (2004) introduced the concept of weighted degree, which takes into account dead ends during searches. Weights are associated with constraints and variables. The weight of a constraint is initially set to 1 and incremented each time the constraint is responsible for a dead end. The weight of a variable is equal to the sum of the weights of the active constraints that it is associated with. The default variable selection strategy is MINR.

ALLDIFF Statement

ALLDIFF *(variable_list-1)* < . . . *(variable_list-n)* > **;**

ALLDIFFERENT *(variable_list-1)* < . . . *(variable_list-n)* > **;**

The ALLDIFF statement can have multiple specifications. Each specification defines a unique global constraint on a set of variables, requiring all of them to be different from each other. A global constraint is equivalent to a conjunction of elementary constraints.

For example, the statements

```
var (X1-X3) A B;
alldiff (X1-X3) (A B);
```

are equivalent to

$$\begin{array}{rcl} X1 & \neq & X2 \text{ AND} \\ X2 & \neq & X3 \text{ AND} \\ X1 & \neq & X3 \text{ AND} \\ A & \neq & B \end{array}$$

If the variable list is empty, the ALLDIFF constraint applies to all the variables.

ARRAY Statement

ARRAY *specification-1* < . . . *specification-n* > **;**

An ARRAY *specification* is in a form as follows:

name[dimension](variables)

The ARRAY statement is used to associate a *name* with a list of *variables*. Each of the *variables* in the variable list must be defined using a VARIABLE statement or implicitly defined using the CONDATA= data table. The ARRAY statement is required when you are specifying a constraint by using the FOREACH statement.

CUMULATIVE Statement

CUMULATIVE *cumulative_constraint-1* < . . . *cumulative_constraint-n* > **;**

Each *cumulative_constraint* is specified in the following form, where the options can be specified in any order and are subject to the restrictions that follow:

(< **START=(***list***)** > < **DURATION=(***list***)** > < **END=(***list***)** > < **DEMAND=(***list***)** > < **CAPACITY=***capacity* > **)**

- You must specify at least two of the START=, DURATION=, and END= options.
- At least one of the START=, DURATION=, and END= options must specify a list of numeric variables.

- The number of values in the *lists* that are specified in the START=, DURATION=, END=, and DEMAND= options must be the same.

The CUMULATIVE statement specifies one or more cumulative (scheduling) constraints. A cumulative constraint conveys that a collection of tasks (activities) is to be executed on a resource that has limited capacity. Each task is defined by its start time, duration (processing time), end time (finish time), and demand (resource usage). A task i is said to overlap a time point t if and only if its start time is less than or equal to t and its end time is strictly greater than t. The cumulative constraint enforces that at each point in time, the accumulated demand (resource usage) of the tasks that overlap the time point does not exceed the specified capacity of the resource.

A cumulative constraint also enforces the following equation for all tasks i:

$$\text{start_time}[i] + \text{duration}[i] = \text{end_time}[i]$$

You can specify the following options (you must specify at least two of the START=, END=, and DURATION= options):

START=(*variables* | *integers* **)**
specifies a list of task starting times. If you specify this option, the number of *variables* or *integers* must match the number of *variables* or *integers* that are specified in each of the specified END=, DURATION=, and DEMAND= options.

DURATION=(*variables* | *nonnegative-integers* **)**
DUR=(*variables* | *nonnegative-integers* **)**
specifies a list of task processing durations. If you specify this option, the number of *variables* or *nonnegative-integers* must match the number of *variables* or *integers* that are specified in each of the specified START=, END=, and DEMAND= options.

END=(*variables* | *integers* **)**
specifies a list of task ending times. If you specify this option, the number of *variables* or *integers* must match the number of *variables* or *integers* that are specified in each of the specified START=, DURATION=, and DEMAND= options.

DEMAND=(*variables* | *nonnegative-integers* **)**
HEIGHT=(*variables* | *nonnegative-integers* **)**
specifies a list of task demands. If you specify this option, the number of *variables* or *nonnegative-integers* must match the number of *variables* or *integers* that are specified in each of the specified START=, END=, and DURATION= options. If you omit this option, the demand of each corresponding task is 1.

CAPACITY=*variable* | *nonnegative-integer*
LIMIT=*variable* | *nonnegative-integer*
specifies the capacity limit of the corresponding resource. If you omit this option, the capacity of each corresponding resource is 1.

ELEMENT Statement

ELEMENT *element_constraint-1* < . . . *element_constraint-n* > **;**

An *element_constraint* is specified in the following form:

(index variable, (integer list), variable)

The ELEMENT statement specifies one or more element constraints. An element constraint enables you to define dependencies, not necessarily functional, between variables. The statement

ELEMENT$(I, (L), V)$

sets the variable V to be equal to the Ith element in the list L. The list of integers $L = (v_1, \ldots, v_n)$ is a list of values that are potentially assigned to the variable V and are not necessarily distinct. The variable I is the index variable, and its domain is considered to be $[1, n]$. Each time the domain of I is modified, the domain of V is updated and vice versa.

An element constraint enforces the following propagation rules:

$$V = v \Leftrightarrow I \in \{i_1, \ldots, i_m\}$$

where v is a value in the list L and $i_1, \ldots, i_m$ are all the indices in L whose value is v.

The following statements use the element constraint to implement the quadratic function $y = x^2$:

```
proc clp out=mycas.clpout;
   var x=[1,5] y=[1,25];
   element (x,(1, 4, 9, 16, 25), y);
run;
```

An element constraint is equivalent to a conjunction of reified and linear constraints. For example, the preceding statements are equivalent to:

```
proc clp out=mycas.clpout;
        var x=[1,5] y=[1,25] (R1-R5)=[0,1];
        reify R1: (x=1);
        reify R1: (y=1);
        reify R2: (x=2);
        reify R2: (y=4);
        reify R3: (x=3);
        reify R3: (y=9);
        reify R4: (x=4);
        reify R4: (y=16);
        reify R5: (x=5);
        reify R5: (y=25);
        lincon R1 + R2 + R3 + R4 + R5 = 1;
run;
```

Element constraints can also be used to define positional mappings between two variables. For example, suppose the function $y = x^2$ is defined on only odd numbers in the interval $[-5, 5]$. You can model this by using two element constraints and an artificial index variable:

```
element (i, ( -5, -3, -1, 1, 3,  5), x)
        (i, ( 25,  9,  1, 1, 9, 25), y);
```

The list of values L can also be specified by using a convenient syntax of the form *start* TO *end* or *start* TO *end* BY *increment*. For example, the previous element specification is equivalent to:

```
element (i, ( -5 to 5 by 2), x)
        (i, ( 25,  9,  1, 1, 9, 25), y);
```

FOREACH Statement

FOREACH *(array, type, < offset >)* **;**

where *array* must be defined by using an ARRAY statement, *type* is a keyword that determines the type of the constraint, and *offset* is an integer.

The FOREACH statement iteratively applies a constraint over an array of variables. The type of the constraint is determined by *type*. Currently, the only valid *type* keyword is DIFF. The optional *offset* parameter is an integer and is interpreted in the context of the constraint type. The default value of *offset* is zero.

The FOREACH statement that corresponds to the DIFF keyword iteratively applies the following constraint to each pair of variables in the array:

$$variable_i + offset \times i \neq variable_j + offset \times j \quad \forall\, i \neq j,\ i, j = 1, \ldots, array_dimension$$

For example, the constraint that all $(A[i] - i)$'s are pairwise distinct for an array A is expressed as

```
foreach (A, diff, -1);
```

GCC Statement

GCC *global_cardinality_constraint-1 < . . . global_cardinality_constraint-n >* **;**

where *global_cardinality_constraint* is specified in the following form:

(*variables***) = (** (v_1, l_1, u_1) < . . . (v_n, l_n, u_n) > < **DL=** *dl* > < **DU=** *du* > **)**

v_i is a value in the domain of one of the variables, and l_i and u_i are the lower and upper bounds on the number of variables assigned to v_i. The values of *dl* and *du* are the lower and upper bounds on the number of variables assigned to values outside of $\{v_1, \ldots, v_n\}$.

The GCC statement specifies one or more global cardinality constraints. A *global cardinality constraint* (GCC) is a constraint that consists of a set of variables $\{x_1, \ldots, x_n\}$ and for each value v in $D = \bigcup_{i=1,\ldots,n} Dom(x_i)$, a pair of numbers l_v and u_v. A GCC is satisfied if and only if the number of times that a value v in D is assigned to the variables $x_1, \ldots, x_n$ is at least l_v and at most u_v.

For example, the constraint that is specified with the statements

```
var (x1-x6) = [1, 4];
gcc(x1-x6) = ((1, 1, 2) (2, 1, 3) (3, 1, 3) (4, 2, 3));
```

expresses that at least one but no more than two variables in $x_1, \ldots, x_6$ can have value 1, at least one and no more than three variables can have value 2 (or value 3), and at least two and no more than three variables can have value 4. For example, an assignment $x_1 = 1, x_2 = 1, x_3 = 2, x_4 = 3, x_5 = 4$, and $x_6 = 4$ satisfies the constraint.

If a global cardinality constraint has common lower or upper bounds for many of the values in D, the DL= and DU= options can be used to specify the common lower and upper bounds.

For example, the previous specification could also be written as

```
gcc(x1-x6) = ((1, 1, 2) (4, 2, 3) DL=1 DU=3);
```

You can also specify missing values for the lower and upper bounds. The values of *dl* and *du* are substituted as appropriate. The previous example can also be expressed as

```
gcc(x1-x6) = ((1, ., 2) (4, 2, .) DL=1 DU=3);
```

The following statements specify that each of the values in $\{1, \ldots, 9\}$ can be assigned to at most one of the variables $x_1, \ldots, x_9$:

```
var (x1-x9) = [1, 9];
gcc(x1-x9) = (DL=0 DU=1);
```

Note that the preceding global cardinality constraint is equivalent to the alldifferent constraint that is expressed as:

```
var (x1-x9) = [1, 9];
alldiff(x1-x9);
```

If you do not specify the DL= and DU= options, the default lower and upper bound for any value in D that does not appear in the (v, l, u) format is 0 and the number of variables in the constraint, respectively.

The global cardinality constraint also provides a convenient way to define disjoint domains for a set of variables. For example, the following syntax limits assignment of the variables $x_1, \ldots, x_9$ to even numbers between 0 and 10:

```
var (x1-x9) = [0, 10];
gcc(x1-x9) = ((1, 0, 0) (3, 0, 0) (5, 0, 0) (7, 0, 0) (9, 0, 0));
```

If the variable list is empty, the GCC constraint applies to all the variables.

LEXICO Statement

LEXICO *lexicographic_ordering_constraint-1* <. . . *lexicographic_ordering_constraint-n*> **;**

LEXORDER *lexicographic_ordering_constraint-1* <. . . *lexicographic_ordering_constraint-n*> **;**

where *lexicographic_ordering_constraint* is specified in the form

((*variable-list-1***)** *order_type* **(***variable-list-2***))**

where *variable-list-1* and *variable-list-2* are variable lists of equal length. The keyword *order_type* signifies the type of ordering and can be one of two values: LEX_LE, which indicates lexicographically less than or equal to ($\leq_{\text{lex}}$), or LEX_LT, which indicates lexicographically less than ($<_{\text{lex}}$).

The LEXICO statement specifies one or more lexicographic constraints. The lexicographic constraint $\leq_{\text{lex}}$ and the strict lexicographic constraint $<_{\text{lex}}$ are defined as follows. Given two n-tuples $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$, the n-tuple x is *lexicographically less than or equal to* y ($x \leq_{\text{lex}} y$) if and only if

$$\big(x_i = y_i \ \forall i = 1, \ldots, n\big) \vee \big(\exists j \text{ with } 1 \leq j \leq n \text{ such that } x_i = y_i \ \forall i = 1, \ldots, j-1 \text{ and } x_j < y_j\big)$$

The n-tuple x is *lexicographically less than* y ($x <_{\text{lex}} y$) if and only if $x \leq_{\text{lex}} y$ and $x \neq y$. Equivalently, $x <_{\text{lex}} y$ if and only if

$$\exists j \text{ with } 1 \leq j \leq n \text{ such that } x_i = y_i \ \forall i = 1, \ldots, j-1 \text{ and } x_j < y_j$$

Frisch et al. (2002) introduced an optimal algorithm to establish generalized arc consistency (GAC) for the $\leq_{\text{lex}}$ constraint between two vectors of variables. Informally you can think of the lexicographic constraint $\leq_{\text{lex}}$ as sorting the n-tuples in alphabetical order. Mathematically, $\leq_{\text{lex}}$ is a partial order on a given subset of n-tuples, and $<_{\text{lex}}$ is a strict partial order on a given subset of n-tuples (Brualdi 2010).

For example, you can express the lexicographic constraint $(x_1, \ldots, x_6) \leq_{\text{lex}} (y_1, \ldots, y_6)$ by using a LEXICO statement as follows:

```
lexico( (x1-x6) lex_le (y1-y6) );
```

The assignment $x_1 = 1$, $x_2 = 2$, $x_3 = 2$, $x_4 = 1$, $x_5 = 2$, $x_6 = 5$, $y_1 = 1$, $y_2 = 2$, $y_3 = 2$, $y_4 = 1$, $y_5 = 4$, and $y_6 = 3$ satisfies this constraint because $x_i = y_i$ for $i = 1, \ldots, 4$ and $x_5 < y_5$. The fact that $x_6 > y_6$ is irrelevant in this ordering.

Lexicographic ordering constraints can be useful for breaking a certain kind of symmetry that arises in CSPs with matrices of decision variables.

LINCON Statement

LINCON *linear_constraint-1* < . . . ,*linear_constraint-n*> **;**

LINEAR *linear_constraint-1* < . . . ,*linear_constraint-n*> **;**

where *linear_constraint* has the form

linear_expression-l type linear_expression-r

where *linear_expression* has the form

< **+|-** >*linear_term-1* < . . . , **(+|-)** *linear_term-n*>

where *linear_term* has the form

(*variable* | *number*< * *variable*>**)**

The keyword *type* can be one of the following:

<, <=, =, >=, >, <>, LT, LE, EQ, GE, GT, NE

The LINCON statement allows for a very general specification of linear constraints. In particular, it allows for specification of the following types of equality or inequality constraints:

$$\sum_{j=1}^{n} a_{ij} x_j \ \{\leq \mid < \mid = \mid \geq \mid > \mid \neq\} \ b_i \quad \text{for } i = 1, \ldots, m$$

For example, the constraint $4x_1 - 3x_2 = 5$ can be expressed as

```
var x1 x2;
lincon 4 * x1 - 3 * x2 = 5;
```

and the constraints

$$\begin{aligned} 10x_1 - x_2 &\geq 10 \\ x_1 + 5x_2 &\neq 15 \end{aligned}$$

can be expressed as

```
var x1 x2;
lincon 10 <= 10 * x1 - x2,
       x1 + 5 * x2 <> 15;
```

Note that variables can be specified on either side of an equality or inequality in a LINCON statement. Linear constraints can also be specified by using the CONDATA= data table.

Regardless of the specification, you must define the variables by using a VARIABLE statement or implicitly by specifying the USECONDATAVARS= option.

User-specified scalar values are subject to rounding based upon a platform-dependent tolerance.

OBJ Statement

OBJ *options* **;**

The OBJ statement enables you to set upper and lower bounds on the value of an objective function that is specified in the Constraint data table. You can also use the OBJ statement to specify the tolerance used for finding a locally optimal objective value.

If upper and lower bounds for the objective value are not specified, the CLP procedure tries to derive bounds from the domains of the variables that appear in the objective function. The procedure terminates with an error message if the objective is unbounded.

You can specify the following options in the OBJ statement:

LB=*m*
specifies the lower bound of the objective value.

TOL=*m*
specifies the tolerance of the objective value. The tolerance must not be less than 1E–6, which is the default.

UB=*m*
specifies the upper bound of the objective value.

For more information about using an objective function, see the section "Objective Function" on page 46.

PACK Statement

PACK *bin_packing_constraint-1* < . . . *bin_packing_constraint-n* > **;**

where *bin_packing_constraint* is specified by the form

((b_1 < . . . b_k >) **(** s_1 < . . . s_k >) **(** l_1 < . . . l_m > **))**

The PACK constraint is used to assign k items to m bins, subject to the sizes of the items and the capacities of the bins. The item variable b_i assigns a bin to the ith item so that the domain for the item variables is 1 to m. Optionally, the domain for the item variables can be any contiguous set up to size m, where the smallest member represents the first bin, the second-smallest member represents the second bin, and so on. The constant s_i gives the size or weight of the ith item. The value of load variable l_j is determined by the total size of the contents of the corresponding bin.

For example, suppose there are three bins with capacities 3, 4, and 5. There are five items with sizes 4, 3, 2, 2, and 1 to be assigned to these three bins. The following statements formulate the problem and find all solutions:

```
proc clp out=mycas.out findallsolns;
   var bin1 = [0,3];
   var bin2 = [0,4];
   var bin3 = [0,5];
   var (item1-item5) = [1,3];
   pack ((item1-item5) (4,3,2,2,1) (bin1-bin3));
```

```
run;
```

Each row of Table 4.2 represents a solution to the problem. The number in each item column is the number of the bin to which the corresponding item is assigned.

Table 4.2 Bin Packing Solutions

	Item Variable				
	item1	**item2**	**item3**	**item4**	**item5**
	2	3	3	1	1
	2	3	1	3	1
	2	1	3	3	3
	3	1	2	2	3

NOTE: In specifying a PACK constraint, it can be more efficient to list the item variables in order by nonincreasing size and to specify VARSELECT=FIFO in the PROC CLP statement so that load variables are selected last.

REIFY Statement

REIFY *reify_constraint-1* < . . . *reify_constraint-n* > **;**

where *reify_constraint* is specified in the following form:

variable : constraint

The REIFY statement associates a binary variable with a constraint. The value of the binary variable is 1 or 0 depending on whether the constraint is satisfied or not, respectively. The constraint is said to be *reified*, and the binary variable is referred to as the *control variable*. Currently, the only type of constraint that can be reified is the linear constraint, which should have the same form as *linear_constraint* defined in the LINCON statement. As with the other variables, the control variable must also be defined in a VARIABLE statement or in the CONDATA= data table.

The REIFY statement provides a convenient mechanism for expressing logical constraints, such as disjunctive and implicative constraints. For example, the disjunctive constraint

$$(3x + 4y < 20) \vee (5x - 2y > 50)$$

can be expressed with the following statements:

```
var x y p q;
reify p: (3 * x + 4 * y < 20) q: (5 * x - 2 * y > 50);
lincon p + q >= 1;
```

The binary variables p and q reify the linear constraints

$$3x + 4y < 20$$

and

$$5x - 2y > 50$$

respectively. The following linear constraint enforces the desired disjunction:

$$p + q \geq 1$$

The implication constraint

$$(3x + 4y < 20) \Rightarrow (5x - 2y > 50)$$

can be enforced with the linear constraint

$$q - p \geq 0$$

The REIFY constraint can also be used to express a constraint that involves the absolute value of a variable. For example, the constraint

$$|X| = 5$$

can be expressed with the following statements:

```
var x p q;
reify p: (x = 5) q: (x = -5);
lincon p + q = 1;
```

VARIABLE Statement

VARIABLE *var_specification-1* < . . . *var_specification-n* > **;**

VAR *var_specification-1* < . . . *var_specification-n* > **;**

A *var_specification* can be one of the following types:

variable < =[*lower-bound* < , *upper-bound* >]>

(variables) < =[*lower-bound* < , *upper-bound* >]>

The VARIABLE statement declares all variables that are to be considered in the CSP and, optionally, defines their domains. Any variable domains defined in a VARIABLE statement override the global variable domains that are defined by using the DOMAIN= option in the PROC CLP statement in addition to any bounds that are defined by using the CONDATA= data table. The values of *lower-bound* and *upper-bound* can also be specified as missing, in which case the appropriate values from the DOMAIN= specification are substituted.

Details: CLP Procedure

Type of Solvers

The CLP procedure features two different solvers. The choice of which one to use is determined by the nature of the CSP that you are attempting to solve.

- The *standard solver* is used to solve CSPs that are defined by alldifferent constraints, cumulative constraints, element constraints, GCC constraints, lexicographic constraints, linear constraints, pack constraints, reified constraints, ARRAY statements, and FOREACH statements. When you invoke the standard solver, the decision variables are one-dimensional; a variable is assigned an integer in a solution.
- The *scheduling solver* is used to solve CSPs that are defined by scheduling-specific constraints, such as temporal constraints (precedence and time) and resource constraints. When you use the scheduling solver, the variables are typically multidimensional; a variable is assigned a start time and possibly a set of resources in a solution. Furthermore, the variables are referred to as activities, and the solution is referred to as a schedule.

The scheduling solver runs only on the SAS client and requires a SAS/OR license.

Constraint Data Table

The Constraint data table defines linear constraints, variable types, bounds on variable domains, and an objective function. You can use a Constraint data table in lieu of, or in combination with, a LINCON or a VARIABLE statement (or both) in order to define linear constraints, variable types, and variable bounds. You can use the Constraint data table in lieu of, or in combination with, the OBJ statement to specify an objective function. The Constraint data table is specified by using the CONDATA= option in the PROC CLP statement.

The Constraint data table must be in dense input format. In this format, a model's columns appear as variables in the input data table and the data table must contain the _TYPE_ variable, at least one numeric variable, and any reserved variables. Currently, the only reserved variable is the _RHS_ variable. If this requirement is not met, the CLP procedure terminates. The _TYPE_ variable is a character variable that tells the CLP procedure how to interpret each observation. The CLP procedure recognizes the following keywords as valid values for the _TYPE_ variable: EQ, LE, GE, NE, LT, GT, LOWERBD, UPPERBD, BINARY, FIXED, MAX, and MIN. An optional character variable, _ID_, can be used to name each row in the Constraint data table.

Linear Constraints

For the _TYPE_ values EQ, LE, GE, NE, LT, and GT, the corresponding observation is interpreted as a linear constraint. The _RHS_ variable is a numeric variable that contains the right-hand-side coefficient of the linear constraint. Any numeric variable other than _RHS_ that appears in a VARIABLE statement is interpreted as a structural variable for the linear constraint.

The _TYPE_ values are defined as follows:

EQ (=) defines a linear equality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;=\; b_i$$

LE (<=) defines a linear inequality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;\leq\; b_i$$

GE (>=) defines a linear inequality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;\geq\; b_i$$

NE (<>) defines a linear inequality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;\neq\; b_i$$

LT (<) defines a linear inequality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;<\; b_i$$

GT (>) defines a linear inequality of the form

$$\sum_{j=1}^{n} a_{ij} x_j \;>\; b_i$$

Domain Bounds

The keywords LOWERBD and UPPERBD specify additional lower bounds and upper bounds, respectively, on the variable domains. In an observation where the _TYPE_ variable is equal to LOWERBD, a non-missing value for a decision variable is considered to be a lower bound for that variable. Similarly, in an observation where the _TYPE_ variable is equal to UPPERBD, a non-missing value for a decision variable is considered to be an upper bound for that variable. Note that lower and upper bounds defined in the Constraint data table are overridden by lower and upper bounds that are defined by using a VARIABLE statement.

Variable Types

The keywords BINARY and FIXED specify numeric variable types. If the value of _TYPE_ is BINARY for an observation, then any decision variable with a non-missing entry for the observation is interpreted as being a binary variable with domain $\{0,1\}$. If the value of _TYPE_ is FIXED for an observation, then any decision variable with a non-missing entry for the observation is interpreted as being assigned to that non-missing value. In other words, if the value of the variable X is c in an observation for which _TYPE_ is FIXED, then the domain of X is considered to be the singleton $\{c\}$. The value c should belong to the domain of X, or the problem is deemed infeasible.

Objective Function

The keywords MAX and MIN specify the objective function of a maximization or a minimization problem, respectively. In an observation where the _TYPE_ variable is equal to MAX or MIN, a non-missing value for a decision variable is the coefficient of this variable in the objective function. The value specified for _RHS_ is ignored in this case.

The bisection method is used to find the optimal objective value within the specified or derived lower and upper bounds. A solution is considered optimal if the difference between consecutive objective values is less than or equal to the tolerance. You can use the OBJ statement to specify the tolerance in addition to upper and lower bounds on the objective value. The minimum objective tolerance is 1E–6, which is the default.

When an optimal solution is found, the solution is stored in the output data table and the resulting objective value is stored in the macro variable _ORCLP_. The objective value is not necessarily optimal when it is computed within a time limit specified by the MAXTIME= option. In this case, the last valid solution computed within the time limit appears in the output data table. See the macro variable _ORCLP_ for more information about solution status.

The MAX and MIN functions are defined as follows:

MAX defines an objective function of the form

$$\max \sum_{j=1}^{n} c_j x_j$$

MIN defines an objective function of the form

$$\min \sum_{j=1}^{n} c_j x_j$$

Variables in the CONDATA= Data Table

Table 4.3 lists all the variables that are associated with the Constraint data table and their interpretations by the CLP procedure. For each variable, the table also lists its type (C for character, N for numeric), the possible values it can assume, and its default value.

Table 4.3 Constraint Data Table Variables

Name	Type	Description	Allowed Values	Default
TYPE	C	Observation type	EQ, LE, GE, NE, LT, GT, LOWERBD, UPPERBD, BINARY, FIXED, MAX, MIN	
RHS	N	Right-hand-side coefficient		0
_ID_	C	Observation name (optional)		
Any numeric variable other than _RHS_	N	Structural variable		

Solution Data Table

In order to solve a standard CSP, you need to specify a Solution data table by using the OUT= option in the PROC CLP statement. The Solution data table contains all the solutions that have been determined by the CLP procedure. You can specify an upper bound on the number of solutions by using the MAXSOLNS= option in the PROC CLP statement. If you prefer that PROC CLP determine all possible solutions instead, you can specify the FINDALL option in the PROC CLP statement.

The Solution data table contains as many decision variables as have been defined in the CLP procedure invocation. Every observation in the Solution data table corresponds to a solution to the CSP. If a Constraint data table has been specified, then any variable formats and variable labels from the Constraint data table carry over to the Solution data table.

Parallel Processing

You can solve a CSP in single-machine mode or distributed mode. In single-machine mode, the computation is executed on a single computer.

In distributed mode, the CSP is statically decomposed into a set of mutually exclusive and exhaustive CSPs, in that the union of their solution sets represents the solution set to the original CSP. Each of the subproblem CSPs is solved on one of the computing nodes in a distributed computing environment by using the same variable selection and variable assignment strategies that were specified for the original problem. Because of the nature of distributed computing, the order in which the solutions are found will not necessarily be the same as when you are solving the original problem on a single node.

CSPs that have an objective function will run only in single-machine mode.

In addition, the EVALVARSEL= option enables you to take advantage of a distributed system to run concurrently, provided that there are at least as many computing nodes as there are strategies for evaluation. The original problem is executed on grid nodes by using a different node for each variable selection strategy. The DECRMAXTIME option causes the procedure to terminate when a solution is found or the problem

is determined to be infeasible. If the number of computing nodes is less than the number of strategies for evaluation, the problem will run in single-machine mode.

ODS Tables

PROC CLP creates three Output Delivery System (ODS) tables by default. The first table, ProblemSummary, is a summary of the input CSP. The second table, SolutionSummary, is a brief summary of the solution status. The third table, OutputCasTables, is a summary of output CAS table information. You can use the ODS OUTPUT statement with table names to select tables and create output data sets. For more information about ODS, see *SAS Output Delivery System: User's Guide*.

Output 4.2 shows an example of a ProblemSummary table.

Figure 4.2 PROC CLP Output: Problem Summary

The CLP Procedure

Problem Summary	
Number of Variables	3
Number of Constraints	2
ALLDIFF	1
CUMULATIVE	0
ELEMENT	0
FOREACH	0
GCC	0
LEXICO	0
LINCON	1
PACK	0
REIFY	0

Output 4.3 shows an example of a SolutionSummary table.

Figure 4.3 PROC CLP Output: Solution Summary

The CLP Procedure

Solution Summary	
Solution Status	All Solutions
Variable Selection	MINR
Value Selection	MIN
Solutions Found	360
Solution Time	0

Output 4.4 shows an example of an OutputCasTables table.

Figure 4.4 PROC CLP Output: Output CAS Tables

The CLP Procedure

Output CAS Tables			
CAS Library	Name	Number of Rows	Number of Columns
CASUSER(tiarno)	ODSOUT	360	3

When you specify the EVALVARSEL= option, an EvalInfo ODS table is created. The EvalInfo table provides information that is related to the evaluation of each variable selection strategy. It contains four columns, which identify the selection strategy, evaluation time, solution index, and number of variables selected.

Output 4.3 shows an example of an EvalInfo table.

Output 4.3 PROC CLP Output: Strategy Evaluation

The CLP Procedure

Variable Selection Strategy Evaluation			
Selection Strategy	Evaluation Time	Solution Index	Variables Selected
MINR	1	NOT FOUND	127
FIFO	0.55	1	144
MAXC	0.56	2	144
MAXCS	0.55	3	144
MINRMAXC	1	NOT FOUND	127
WDEG	0.03	4	144
DOMDDEG	1	NOT FOUND	125
DOMWDEG	1	NOT FOUND	113
DOMDEG	1	NOT FOUND	127

Table 4.4 summarizes all the ODS tables that the CLP procedure can produce, along with the statement and option specifications that are required in order to produce each table.

Table 4.4 ODS Tables Produced by PROC CLP

ODS Table Name	Description	Statement	Option
ProblemSummary	Summary of the input CSP	PROC CLP	Default
SolutionSummary	Summary of the solution status	PROC CLP	Default
OutputCasTables	A special ODS table that has information about all the CAS tables that are created during a CAS action execution	PROC CLP	Default
EvalInfo	Detailed EVALVARSEL= option statistics	PROC CLP	EVALVARSEL=

Macro Variable _ORCLP_

The CLP procedure defines a macro variable named _ORCLP_. This variable contains a character string that indicates the status of the CLP procedure upon termination. The various terms of the macro variable are interpreted as follows.

STATUS

indicates the procedure status at termination. It can take one of the following values:

OK	The procedure terminated successfully.
DATA_ERROR	An input data error occurred.
IO_ERROR	A problem in reading or writing data occurred.
MEMORY_ERROR	Insufficient memory is allocated to the procedure.
SEMANTIC_ERROR	The use of semantic action is incorrect.
SYNTAX_ERROR	The use of syntax is incorrect.
ERROR	The status cannot be classified into any of the preceding categories.

If PROC CLP terminates normally or if an I/O error is detected while the procedure is closing a data table, the following terms are added to the macro variable.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

ALL_SOLUTIONS	All solutions are found.
INFEASIBLE	The problem is infeasible.
OPTIMAL	The solution is optimal.
SOLN_LIMIT_REACHED	The required number of solutions specified with the MAXSOLNS= option is reached.
TIME_LIMIT_REACHED	The execution time limit specified with the MAXTIME= option is reached.
EVALUATION_COMPLETE	The evaluation process is finished. This solution status appears only when the EVALVARSEL= option is specified.
ABORT	The procedure is stopped by the user before any other stopping criterion is reached.

SOLUTIONS_FOUND

indicates the number of solutions that are found. This term is not applicable if SOLUTION_STATUS=INFEASIBLE.

SOLUTION_TIME
indicates the time taken to solve the problem. By default, the time reported is CPU time; see the TIMETYPE= option for more information.

VARSELTYPE
indicates the fastest variable selection strategy. This term appears only when the EVALVARSEL= option is active and either at least one solution is found or the problem is found to be infeasible.

OBJECTIVE
indicates the objective value. This term appears only when an objective function is specified and at least one solution is found.

Macro Variable _ORCLPEVS_

When you specify the EVALVARSEL= option to evaluate variable selection strategies for a standard CSP, the CLP procedure defines a macro variable named _ORCLPEVS_. This variable contains a character string that describes the solution attempt made with each selection strategy. The macro variable contains four terms for each selection strategy that is evaluated as follows:

VARSELTYPE
indicates the variable selection strategy being evaluated.

EVAL_TIME
indicates the amount of time taken to evaluate the variable selection strategy. By default, the time reported is CPU time; see the TIMETYPE= option for more information.

SOLUTION
indicates the index of the solution if a solution is found. Otherwise, SOLUTION=INFEASIBLE if the problem is found to be infeasible, or SOLUTION=NOT_FOUND.

MAX_VARSEL
indicates the maximum number of variables selected within the evaluation time.

Examples: CLP Procedure

This section contains several examples that illustrate the capabilities of the different logical constraints and showcase a variety of problems that the CLP procedure can solve. The following examples feature a standard constraint satisfaction problem (CSP):

- "Example 4.1: Logic-Based Puzzles" illustrates the capabilities of the alldifferent constraint in solving a popular logical puzzle, the sudoku. This example also contains a variant of sudoku that illustrates the capabilities of the GCC constraint and demonstrates the use of the EVALVARSEL= option.
- "Example 4.2: Car Painting Problem" involves limited sequencing of cars in an assembly process in order to minimize the number of paint purgings; it features the reified constraint.
- "Example 4.3: Scene Allocation Problem" illustrates how to schedule the shooting of different movie scenes in order to minimize production costs. This problem uses the GCC and linear constraints.
- "Example 4.4: Car Sequencing Problem" relates to sequencing the cars on an assembly line with workstations for installing specific options subject to the demand constraints for each set of options and the capacity constraints of each workstation.
- "Example 4.5: Scheduling a Major Basketball Conference" illustrates modeling the problem of scheduling a major basketball conference. The element constraint plays a key role in this particular example.
- "Example 4.6: Balanced Incomplete Block Design" illustrates how to use the lexicographic constraint to break symmetries in generating a balanced incomplete block design (BIBD), a standard combinatorial problem from design theory.
- "Example 4.7: Progressive Party Problem" illustrates how to use the pack constraint to solve the progressive party problem, a well-known constraint programming problem in which crews of various sizes must be assigned to boats of various capacities for several rounds of parties.
- "Example 4.8: Radio Link Frequency Assignment Problem" illustrates how to use the element and reified constraints to solve a radio link frequency assignment problem.
- "Example 4.9: Resource-Constrained Project Scheduling Problem with Time Windows" illustrates how to use the cumulative constraint to solve a resource-constrained project scheduling problem with time windows.
- "Example 4.10: Resource-Constrained Scheduling Problem with Nonstandard Temporal Constraints" illustrates how to use the cumulative constraint to solve a resource-constrained scheduling problem that has nonstandard temporal constraints.

Example 4.1: Logic-Based Puzzles

Many logic-based puzzles can be formulated as CSPs. Several such instances are shown in this example.

Sudoku

A sudoku is a logic-based, combinatorial number-placement puzzle that uses a partially filled 9×9 grid. The objective is to fill the grid with the digits 1 to 9, so that each column, each row, and each of the nine 3×3 blocks contain only one of each digit. Output 4.1.1 shows an example of a sudoku grid.

Output 4.1.1 An Example of an Unsolved Sudoku Grid

		5			7			1
	7			9			3	
			6					
		3			1			5
	9			8			2	
1			2			4		
		2			6			9
				4			8	
8			1			5		

This example illustrates the use of the ALLDIFFERENT constraint to solve the preceding sudoku problem.

The data set indata contains the partially filled values for the grid and is used to create the set of macro variables C_{ij} $(i = 1 \ldots 9, j = 1 \ldots 9)$, where C_{ij} is the value of cell (i, j) in the grid when specified, and missing otherwise.

```
data indata;
   input C1-C9;
   datalines;
. . 5 . . 7 . . 1
. 7 . . 9 . . 3 .
. . . 6 . . . . .
. . 3 . . 1 . . 5
. 9 . . 8 . . 2 .
1 . . 2 . . 4 . .
. . 2 . . 6 . . 9
. . . . 4 . . 8 .
8 . . 1 . . 5 . .
;
```

```
%macro store_initial_values;
   /* store initial values into macro variable C_i_j */
   data _null_;
      set indata;
      array C{9};
      do j = 1 to 9;
         i = _N_;
         call symput(compress('C_'||put(i,best.)||'_'||put(j,best.)),
            put(C[j],best.));
      end;
   run;
%mend store_initial_values;

%store_initial_values;
```

Let the variable X_{ij} ($i = 1 \ldots 9, j = 1 \ldots 9$) represent the value of cell (i, j) in the grid. The domain of each of these variables is $[1, 9]$. Three sets of alldifferent constraints are used to set the required rules for each row, each column, and each of the 3×3 blocks. The constraint ALLDIFF($X_{i1} - X_{i9}$) forces all values in row i to be different, the constraint ALLDIFF($X_{1j} - X_{9j}$) forces all values in column j to be different, and the constraint ALLDIFF(X_{ij}) $((i = 1, 2, 3; j = 1, 2, 3), (i = 1, 2, 3; j = 4, 5, 6), \ldots, (i = 7, 8, 9; j = 7, 8, 9))$ forces all values in each block to be different.

The following statements solve the sudoku puzzle:

```
%macro solve;
   proc clp out=mycas.outdata;

      /* Declare variables    */
      /* Nine row constraints */
      %do i = 1 %to 9;
         var (X_&i._1-X_&i._9) = [1,9];
         alldiff(X_&i._1-X_&i._9);
      %end;

      /* Nine column constraints */
      %do j = 1 %to 9;
         alldiff(
         %do i = 1 %to 9;
            X_&i._&j
         %end;
         );
      %end;

      /* Nine 3x3 block constraints */
      %do s = 0 %to 2;
         %do t = 0 %to 2;
            alldiff(
            %do i = 3*&s + 1 %to 3*&s + 3;
               %do j = 3*&t + 1 %to 3*&t + 3;
                  X_&i._&j
               %end;
            %end;
            );
```

```
         %end;
      %end;

      /* Initialize variables to cell values   */
      /* X_i_j = C_i_j if C_i_j is non-missing */
      %do i = 1 %to 9;
         %do j = 1 %to 9;
            %if &&C_&i._&j ne . %then %do;
               lincon X_&i._&j = &&C_&i._&j;
            %end;
         %end;
      %end;

   run;
   %put &_ORCLP_;
%mend solve;

%solve
```

Output 4.1.2 shows the solution.

Output 4.1.2 Solution of the Sudoku Grid

9	8	5	3	2	7	6	4	1
6	7	1	5	9	4	2	3	8
3	2	4	6	1	8	9	5	7
2	4	3	7	6	1	8	9	5
5	9	7	4	8	3	1	2	6
1	6	8	2	5	9	4	7	3
4	5	2	8	3	6	7	1	9
7	1	6	9	4	5	3	8	2
8	3	9	1	7	2	5	6	4

Finally, substituting the following PROC CLP statement and invoking the CLP procedure finds all 5,299,405 solutions to the partially filled sudoku grid shown in Output 4.1.3:

```
proc clp out=mycas.outdata findall timetype=real;
```

Output 4.1.3 An Example of an Unsolved Sudoku Grid

	7						3	
			6					
					1			5
	9						2	
1			2			4		
		2			6			9
				4			8	
8			1			5		

The solution summaries shown in Output 4.1.4 and Output 4.1.5 correspond to solutions of the CSP in two different modes. The first solution summary corresponds to solving the CSP in single-machine mode, and the second solution summary corresponds to solving the CSP in distributed mode by using a grid that contains 142 nodes.

Output 4.1.4 Single-Machine Mode

The CLP Procedure

Solution Summary	
Solution Status	All Solutions
Variable Selection	MINR
Value Selection	MIN
Solutions Found	5299405
Solution Time	692.554515

Output 4.1.5 Distributed Mode

The CLP Procedure

Solution Summary	
Solution Status	All Solutions
Variable Selection	MINR
Value Selection	MIN
Solutions Found	5299405
Solution Time	47.57219

Pi Day Sudoku

The basic structure of the classical sudoku problem can easily be extended to formulate more complex puzzles. One such example is the Pi Day sudoku puzzle. Pi Day is a celebration of the number π that occurs every March 14. In honor of Pi Day, Brainfreeze Puzzles (Riley and Taalman 2008) celebrated this day with a special 12×12 grid sudoku puzzle. The 2008 Pi Day sudoku puzzle is shown in Output 4.1.6.

Output 4.1.6 Pi Day Sudoku 2008

3			1	5	4			1		9	5
	1			3					1	3	6
		4			3		8			2	
5			1			9	2	5			1
	9			5			5				
5	8	1			9			3		6	
	5		8			2			5	5	3
				5			6			1	
2			5	1	5			5			9
	6			4		1			3		
1	5	1					5			5	
5	5		4			3	1	6			8

The rules for this puzzle are a little different from the rules for standard sudoku:

1. Rather than using regular 3×3 blocks, this puzzle uses jigsaw regions such that highlighted regions in the middle resemble the Greek letter π. Each jigsaw region consists of 12 contiguous cells.

2. The first 12 digits of π are used instead of the digits 1–9. Each row, column, and jigsaw region contains the first 12 digits of π (314159265358) in some order. In other words, there are no 7s; one each of 2, 4, 6, 8, and 9; two each of 1 and 3; and three 5s.

The data set raw contains the partially filled values for the grid and, similar to the sudoku problem, is used to create the set of macro variables C_{ij} $(i = 1, \ldots, 12, j = 1, \ldots, 12)$ where C_{ij} is the value of cell (i, j) in the grid when specified, and missing otherwise.

```
data raw;
   input C1-C12;
   datalines;
3  .  .  1  5  4  .  .  1  .  9  5
.  1  .  .  3  .  .  .  .  1  3  6
.  .  4  .  .  3  .  8  .  .  2  .
5  .  .  1  .  .  9  2  5  .  .  1
.  9  .  .  5  .  .  5  .  .  .  .
5  8  1  .  .  9  .  .  3  .  6  .
.  5  .  8  .  .  2  .  .  5  5  3
.  .  .  .  5  .  .  6  .  .  1  .
```

```
2  .  .  5  1  5  .  .  5  .  .  9
.  6  .  .  4  .  1  .  .  3  .  .
1  5  1  .  .  .  .  5  .  .  5  .
5  5  .  4  .  .  3  1  6  .  .  8
;

%macro cdata;
   /* store each pre-filled value into macro variable C_i_j */
   data _null_;
      set raw;
      array C{12};
      do j = 1 to 12;
         i = _N_;
         call symput(compress('C_'||put(i,best.)||'_'||put(j,best.)),
            put(C[j],best.));
      end;
   run;
%mend cdata;
%cdata;
```

As in the sudoku problem, let the variable X_{ij} represent the value of the cell that corresponds to row i and column j. The domain of each of these variables is $[1, 9]$.

For each row, column, and jigsaw region, a GCC statement is specified to enforce the condition that it contain exactly the first twelve digits of π.

In particular, the variables in row r, $r = 1, \ldots, 12$ are $X_{r1}, \ldots, X_{r12}$. The SAS macro %CONS_ROW(R) enforces the GCC constraint that row r contain exactly two 1s, two 3s, three 5s, no 7s, and one of each of the other values:

```
%macro cons_row(r);
   /* Row r must contain two 1's, two 3's, three 5's, no 7's, */
   /* and one for each of other values from 1 to 9.           */
   gcc(X_&r._1-X_&r._12) =
      ( (1, 2, 2) (3, 2, 2) (5, 3, 3) (7, 0, 0) DL=1 DU=1 );
%mend cons_row;
```

The variables in column c are $X_{1c}, \ldots, X_{12c}$. The SAS macro %CONS_COL(C) enforces a similar GCC constraint for each column c.

```
%macro cons_col(c);
   /* Column c must contain two 1's, two 3's, three 5's,    */
   /* no 7's, and one for each of other values from 1 to 9. */
   gcc( %do r = 1 %to 12;
      X_&r._&c.
      %end;
      ) = ((1, 2, 2) (3, 2, 2) (5, 3, 3) (7, 0, 0) DL=1 DU=1);
%mend cons_col;
```

Generalizing this concept further, the SAS macro %CONS_REGION(VARS) enforces the GCC constraint for the jigsaw region that is defined by the macro variable VARS.

```
%macro cons_region(vars);
   /* Jigsaw region that contains &vars must contain two 1's, */
   /* two 3's, three 5's, no 7's, and one for each of other   */
   /* values from 1 to 9.                                     */
   gcc(&vars.) = ((1, 2, 2) (3, 2, 2) (5, 3, 3) (7, 0, 0) DL=1 DU=1);
%mend cons_region;
```

The following SAS statements incorporate the preceding macros to define the GCC constraints in order to find all solutions of the Pi Day sudoku 2008 puzzle:

```
%macro pds(fn=mycas.pdsout,solns=allsolns,varsel=MINR,maxtime=900);

   proc clp out=&fn &solns
      varselect=&varsel /* Variable selection strategy */
      maxtime=&maxtime; /* Time limit                  */

      /* Variable X_i_j represents the grid of ith row and jth column. */
      var (
         %do i = 1 %to 12;
            X_&i._1 - X_&i._12
         %end;
         ) = [1,9];

      /* X_i_j = C_i_j if C_i_j is non-missing */
      %do i = 1 %to 12;
         %do j = 1 %to 12;
            %if &&C_&i._&j ne . %then %do;
               lincon X_&i._&j = &&C_&i._&j;
            %end;
         %end;
      %end;

      /* 12 Row constraints: */
      %do r = 1 %to 12;
         %cons_row(&r);
      %end;

      /* 12 Column constraints: */
      %do c = 1 %to 12;
         %cons_col(&c);
      %end;

      /* 12 Jigsaw region constraints: */
      /* Each jigsaw region is defined by the macro variable &vars. */

      /* Region 1: */
      %let vars = X_1_1 - X_1_3 X_2_1 - X_2_3
                  X_3_1 X_3_2 X_4_1 X_4_2 X_5_1 X_5_2;
      %cons_region(&vars.);

      /* Region 2: */
      %let vars = X_1_4 - X_1_9 X_2_4 - X_2_9;
      %cons_region(&vars.);
```

```
      /* Region 3: */
      %let vars = X_1_10 - X_1_12 X_2_10 - X_2_12
                  X_3_11 X_3_12 X_4_11 X_4_12 X_5_11 X_5_12;
      %cons_region(&vars.);

      /* Region 4: */
      %let vars = X_3_3 - X_3_6 X_4_3 - X_4_6 X_5_3 - X_5_6;
      %cons_region(&vars.);

      /* Region 5: */
      %let vars = X_3_7 - X_3_10 X_4_7 - X_4_10 X_5_7 - X_5_10;
      %cons_region(&vars.);

      /* Region 6: */
      %let vars = X_6_1 - X_6_3 X_7_1 - X_7_3
                  X_8_1 - X_8_3 X_9_1 - X_9_3;
      %cons_region(&vars.);

      /* Region 7: */
      %let vars = X_6_4 X_6_5 X_7_4 X_7_5 X_8_4 X_8_5
                  X_9_4 X_9_5 X_10_4 X_10_5 X_11_4 X_11_5;
      %cons_region(&vars.);

      /* Region 8: */
      %let vars = X_6_6 X_6_7 X_7_6 X_7_7 X_8_6 X_8_7
                  X_9_6 X_9_7 X_10_6 X_10_7 X_11_6 X_11_7;
      %cons_region(&vars.);

      /* Region 9: */
      %let vars = X_6_8 X_6_9 X_7_8 X_7_9 X_8_8 X_8_9
                  X_9_8 X_9_9 X_10_8 X_10_9 X_11_8 X_11_9;
      %cons_region(&vars.);

      /* Region 10: */
      %let vars = X_6_10 - X_6_12 X_7_10 - X_7_12
                  X_8_10 - X_8_12 X_9_10 - X_9_12;
      %cons_region(&vars.);

      /* Region 11: */
      %let vars = X_10_1 - X_10_3 X_11_1 - X_11_3 X_12_1 - X_12_6;
      %cons_region(&vars.);

      /* Region 12: */
      %let vars = X_10_10 - X_10_12 X_11_10 - X_11_12 X_12_7 - X_12_12;
      %cons_region(&vars.);


   run;

   %put &_ORCLP_;

%mend pds;
```

```
%pds;
```

The only solution of the 2008 Pi Day sudoku puzzle is shown in Output 4.1.7.

Output 4.1.7 Solution to Pi Day Sudoku 2008

Pi Day Sudoku 2008

Obs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
1	3	2	5	1	5	4	6	3	1	8	9	5
2	4	1	5	2	3	8	5	9	5	1	3	6
3	6	1	4	5	9	3	5	8	3	1	2	5
4	5	3	3	1	8	5	9	2	5	6	4	1
5	8	9	2	6	5	1	1	5	4	3	3	5
6	5	8	1	5	2	9	4	3	3	5	6	1
7	1	5	3	8	1	6	2	4	9	5	5	3
8	9	4	5	3	5	1	5	6	8	2	1	3
9	2	3	6	5	1	5	3	1	5	4	8	9
10	3	6	8	9	4	5	1	5	1	3	5	2
11	1	5	1	3	6	3	8	5	2	9	5	4
12	5	5	9	4	3	2	3	1	6	5	1	8

The corresponding completed grid is shown in Output 4.1.8.

Output 4.1.8 Solution to Pi Day Sudoku 2008

3	2	5	1	5	4	6	3	1	8	9	5
4	1	5	2	3	8	5	9	5	1	3	6
6	1	4	5	9	3	5	8	3	1	2	5
5	3	3	1	8	5	9	2	5	6	4	1
8	9	2	6	5	1	1	5	4	3	3	5
5	8	1	5	2	9	4	3	3	5	6	1
1	5	3	8	1	6	2	4	9	5	5	3
9	4	5	3	5	1	5	6	8	2	1	3
2	3	6	5	1	5	3	1	5	4	8	9
3	6	8	9	4	5	1	5	1	3	5	2
1	5	1	3	6	3	8	5	2	9	5	4
5	5	9	4	3	2	3	1	6	5	1	8

Next, a variation of this problem illustrates the use of the EVALVARSEL= option to help determine an appropriate selection strategy. Consider the same Pi Day sudoku puzzle with a few more missing cells, as shown in Output 4.1.9. The objective is to find all the possible solutions, subject to the same constraints as before.

Output 4.1.9 Pi Day Sudoku 2008

			1	5	4			1			
	1			3					1	3	6
		4			3		8			2	
5			1			9	2	5			1
	9			5			5				
5	8	1						3		6	
	5		8			2			5	5	3
				5			6			1	
2			5	1	5			5			9
	6			4		1			3		
1	5	1					5			5	
	5		4			3	1	6			

When you specify the EVALVARSEL= option without including a keyword list, the CLP procedure evaluates each available variable selection strategy for the amount of time that you specify in the MAXTIME= option. When you are running in distributed mode, in which there are at least as many machines as strategies, the CSPs are solved concurrently, with each selection strategy being evaluated on a different machine. The EvalInfo ODS table, which is shown in Output 4.1.10, identifies the variable selection strategies that find a solution within a second in distributed mode on a 10-machine network. This information can also be found in the _ORCLPEVS_ macro variable.

Output 4.1.10 EvalInfo ODS Table

The CLP Procedure

Variable Selection Strategy Evaluation			
Selection Strategy	**Evaluation Time**	**Solution Index**	**Variables Selected**
MINR	1.01	NOT FOUND	127
FIFO	0.36	1	144
MAXC	0.35	2	144
MAXCS	0.58	3	144
MINRMAXC	1.01	NOT FOUND	125
WDEG	0.03	4	144
DOMDDEG	1.01	NOT FOUND	125
DOMWDEG	1.01	NOT FOUND	113
DOMDEG	1.01	NOT FOUND	127

Finally, the CLP procedure is invoked in distributed mode by using the FINDALL option and the WDEG selection strategy. The resulting solution summary, which is shown in Output 4.1.11, indicates that all 5,361 solutions have been found, along with the solution time.

Output 4.1.11 WDEG Selection Strategy

The CLP Procedure

Solution Summary	
Solution Status	All Solutions
Variable Selection	WDEG
Value Selection	MIN
Solutions Found	5361
Solution Time	26.65

Example 4.2: Car Painting Problem

The car painting process is an important part of the automobile manufacturing industry. Purging (the act of changing colors during assembly) is expensive because of the added cost of wasted paint and solvents from each color change and the extra time that the purging process requires. The objective of the car painting problem is to sequence the cars in the assembly line in order to minimize the number of paint color changes (Sokol 2002; Trick 2004).

Suppose an assembly line contains 10 cars, which are ordered 1, 2, . . . , 10. A car must be painted within three positions of its assembly order. For example, car 5 can be painted in positions 2 through 8. Cars 1, 5, and 9 are red; 2, 6, and 10 are blue; 3 and 7 green; and 4 and 8 are yellow. The initial sequence 1, 2, . . . , 10 corresponds to the color pattern RBGYRBGYRB and has nine purgings. The objective is to find a solution that minimizes the number of purgings.

This problem can be formulated as a CSP as follows:

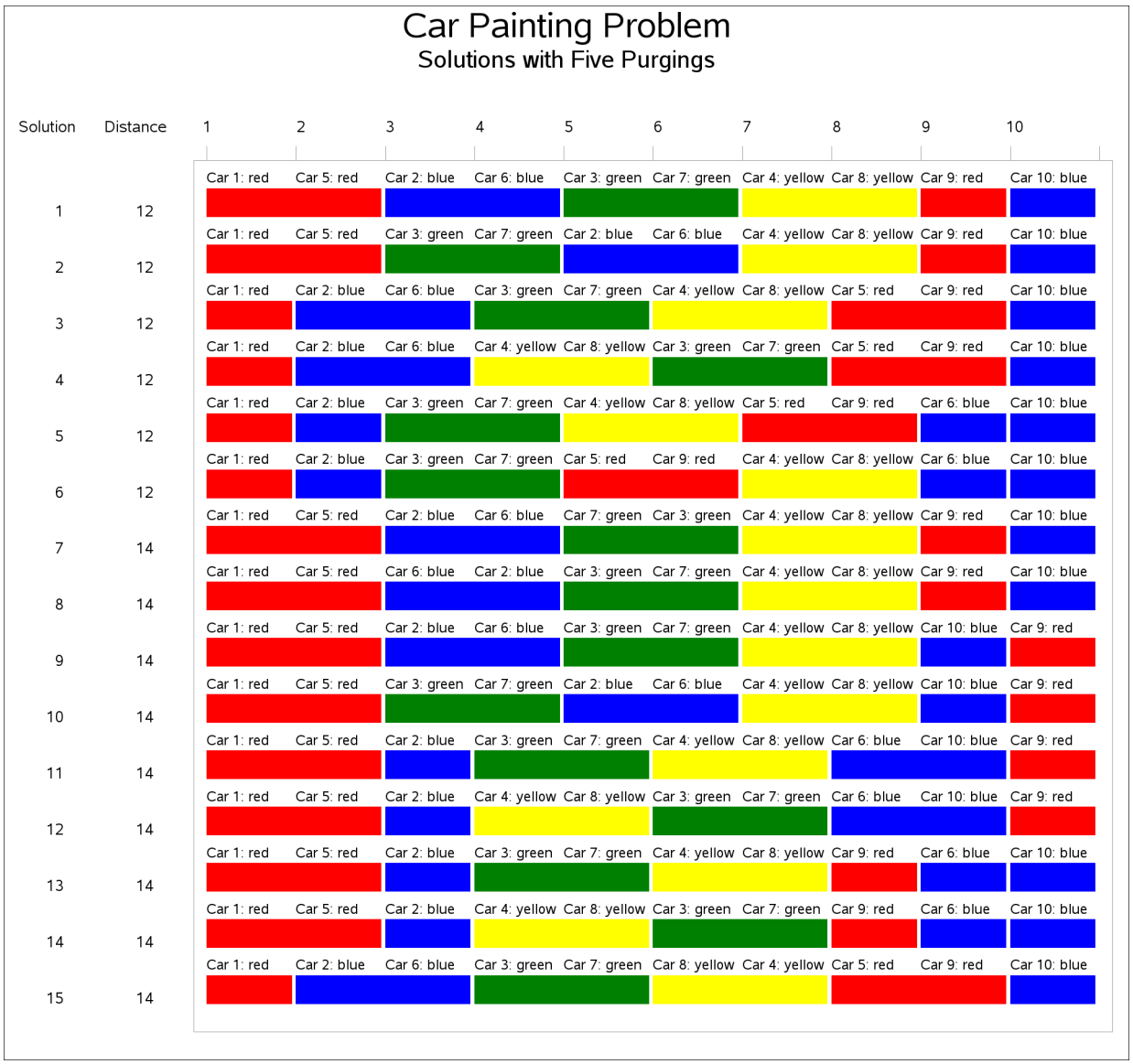
- The variables S_i and C_i represent the ID and color, respectively, of the car in slot i.
- An element constraint relates the car ID to its color.
- An alldifferent constraint ensures that every slot is associated with a unique car ID.
- Two linear constraints represent the constraint that a car must be painted within three positions of its assembly order.
- The binary variable P_i indicates whether a paint purge takes place after the car in slot i is painted.
- A linear constraint is used to limit the total number of purgings to the required number.

The following %CAR_PAINTING macro determines all feasible solutions for a particular number of purgings, which is specified as a parameter to the macro:

```
%macro car_painting(purgings);

    proc clp out=mycas.car_ds findall;

       %do i = 1 %to 10;
          var S&i = [1, 10]; /* which car is in slot &i.*/
          var C&i = [1, 4]; /* which color the car in slot &i is.*/
          /* Red=1; Blue=2; Green=3; Yellow=4 */
          element (S&i, (1, 2, 3, 4, 1, 2, 3, 4, 1, 2), C&i);
       %end;

       /* A car can be painted only once. */
       alldiff (S1-S10);

       /* A car must be painted within 3 positions of its assembly order. */
       %do i = 1 %to 10;
          lincon S&i-&i>=-3;
          lincon S&i-&i<=3;
       %end;

       %do i = 1 %to 9;
          var P&i = [0, 1]; /* Whether there is a purge after slot &i*/
          reify P&i: (C&i <> C%eval(&i+1));
       %end;

       /* Calculate the number of purgings. */
       lincon 0
       %do i = 1 %to 9;
          + P&i
       %end;
       <=&purgings ;
    run;

%mend;
%car_painting(5)
```

The problem is infeasible for four purgings. The CLP procedure finds 87 possible solutions for the five-purgings problem. The solutions are sorted by the total distance all cars are moved in the sequencing, which ranges from 12 to 22 slots. The first 15 solutions are displayed in the Gantt chart in Output 4.2.1. Each row represents a solution, and each color transition represents a paint purging.

Output 4.2.1 Car Painting Schedule with Five Purgings



Example 4.3: Scene Allocation Problem

The scene allocation problem consists of deciding when to shoot each scene of a movie in order to minimize the total production cost (Van Hentenryck 2002). Each scene involves a number of actors, and at most five scenes a day can be shot. All actors who appear in a scene must be present in the studio on the day the scene is shot. Each actor earns a daily rate for each day spent in the studio, regardless of the number of scenes in which he or she appears on that day. The goal is to shoot the movie for the lowest possible production cost.

The actors' names, their daily fees, and the scenes in which they appear are contained in the SCENE data set, which is shown in Output 4.3.1. The data table variables S_Var1, . . . , S_Var9 indicate the scenes in which the actor appears. For example, the first observation indicates that Patt's daily fee is 26,481 and that Patt appears in scenes 2, 5, 7, 10, 11, 13, 15, and 17.

Output 4.3.1 The Scene Data Set

Obs	Number	Actor	DailyFee	S_Var1	S_Var2	S_Var3	S_Var4	S_Var5	S_Var6	S_Var7	S_Var8	S_Var9
1	1	Patt	26481	2	5	7	10	11	13	15	17	.
2	2	Casta	25043	4	7	9	10	13	16	19	.	.
3	3	Scolaro	30310	3	6	9	10	14	16	17	18	.
4	4	Murphy	4085	2	8	12	13	15	.	.	.	.
5	5	Brown	7562	2	3	12	17	.	.	.	.	.
6	6	Hacket	9381	1	2	12	13	18	.	.	.	.
7	7	Anderson	8770	5	6	14	.	.	.	.	.	.
8	8	McDougal	5788	3	5	6	9	10	12	15	16	18
9	9	Mercer	7423	3	4	5	8	9	16	.	.	.
10	10	Spring	3303	5	6	.	.	.	.	.	.	.
11	11	Thompson	9593	6	9	12	15	18	.	.	.	.

There are 19 scenes. At most five scenes can be filmed in one day, so at least four days are needed to schedule all the scenes ($\lceil \frac{19}{5} \rceil = 4$). Let $\mathrm{S}j_k$ be a binary variable that equals 1 if scene j is shot on day k. Let $\mathrm{A}i_k$ be another binary variable that equals 1 if actor i is present on day k. The variable $\mathrm{Name}i$ is the name of the ith actor; $\mathrm{Cost}i$ is the daily cost of the ith actor. $\mathrm{A}i_\mathrm{S}j = 1$ if actor i appears in scene j, and 0 otherwise.

The objective function representing the total production cost is given by

$$\min \sum_{i=1}^{11} \sum_{k=1}^{4} \mathrm{Cost}i \times Ai_k$$

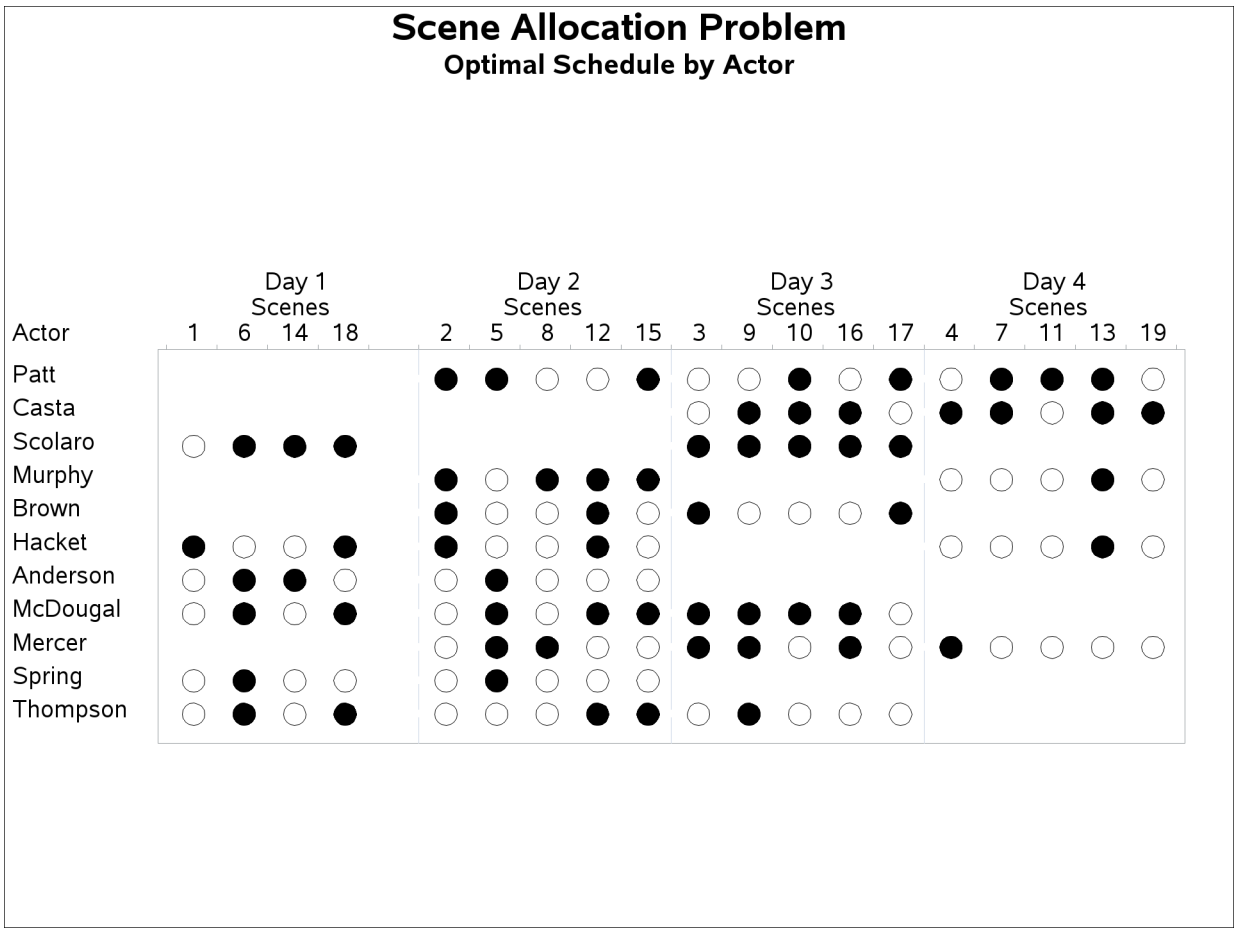
The %SCENE macro first reads the data set scene and produces three sets of macro variables: $\mathrm{Name}i$, $\mathrm{Cost}i$, and $\mathrm{A}i_\mathrm{S}j$. The data set cost is created next to specify the objective function. Finally, the CLP procedure is invoked. There are two sets of GCC constraints in the CLP call: one to make sure each scene is shot exactly once, and one to limit the number of scenes shot per day to be at least four and at most five. There are two sets of LINCON constraints: one to indicate that an actor must be present if any of his or her scenes are shot that day, and one for breaking symmetries to improve efficiency. Additionally, an OBJ statement specifies upper and lower bounds on the objective function to be minimized.

```
%macro scene;
   /* Ai_Sj=1 if actor i appears in scene j    */
   /* Ai_Sj=0 otherwise                        */
   /* Initialize to 0                          */
   %do i=1 %to 11; /* 11 actors */
      %do j=1 %to 19; /* 19 scenes */
         %let A&i._S&j=0;
      %end;
   %end;

   data scene_cost;
      set scene;
      keep DailyFee A;
      retain DailyFee A;
      do day=1 to 4;
         A='A'||left(strip(_N_))||'_'||left(strip(day));
         output;
      end;
      call symput("Name"||strip(_n_), Actor); /* read actor name */
      call symput("Cost"||strip(_n_), DailyFee); /* read actor cost */
      /* read whether an actor appears in a scene */
      %do i=1 %to 9; /* 9 scene variables in the data set */
         if S_Var&i > 0 then
            call symput("A"||strip(_n_)||"_S"||strip(S_Var&i), 1);
      %end;
   run;
   /* Create constraint data table which defines the objective function */
   proc transpose data=scene_cost out=cost(drop=_name_);
      var DailyFee;
      id A;
   run;
   data mycas.cost;
      set cost;
      _TYPE_='MIN';
      _RHS_=.;
   run;

   /* Find the minimum objective value.                    */
   proc clp condata=mycas.cost out=mycas.out varselect=maxc;
      /* Set lower and upper bounds for the objective value   */
      /* Lower bound: every actor appears on one day.         */
      /* Upper bound: every actor appears on all four days.   */
      obj lb=137739 ub=550956;

      /* Declare variables. */
      %do k=1 %to 4; /* 4 days */
      %do j=1 %to 19; /* 19 scenes */
         var S&j._&k=[0,1]; /* Indicates if scene j is shot on day k.   */
      %end;
      %do i=1 %to 11; /* 11 actors */
         var A&i._&k=[0,1]; /* Indicates if actor i is present on day k.*/
      %end;
      %end;
```

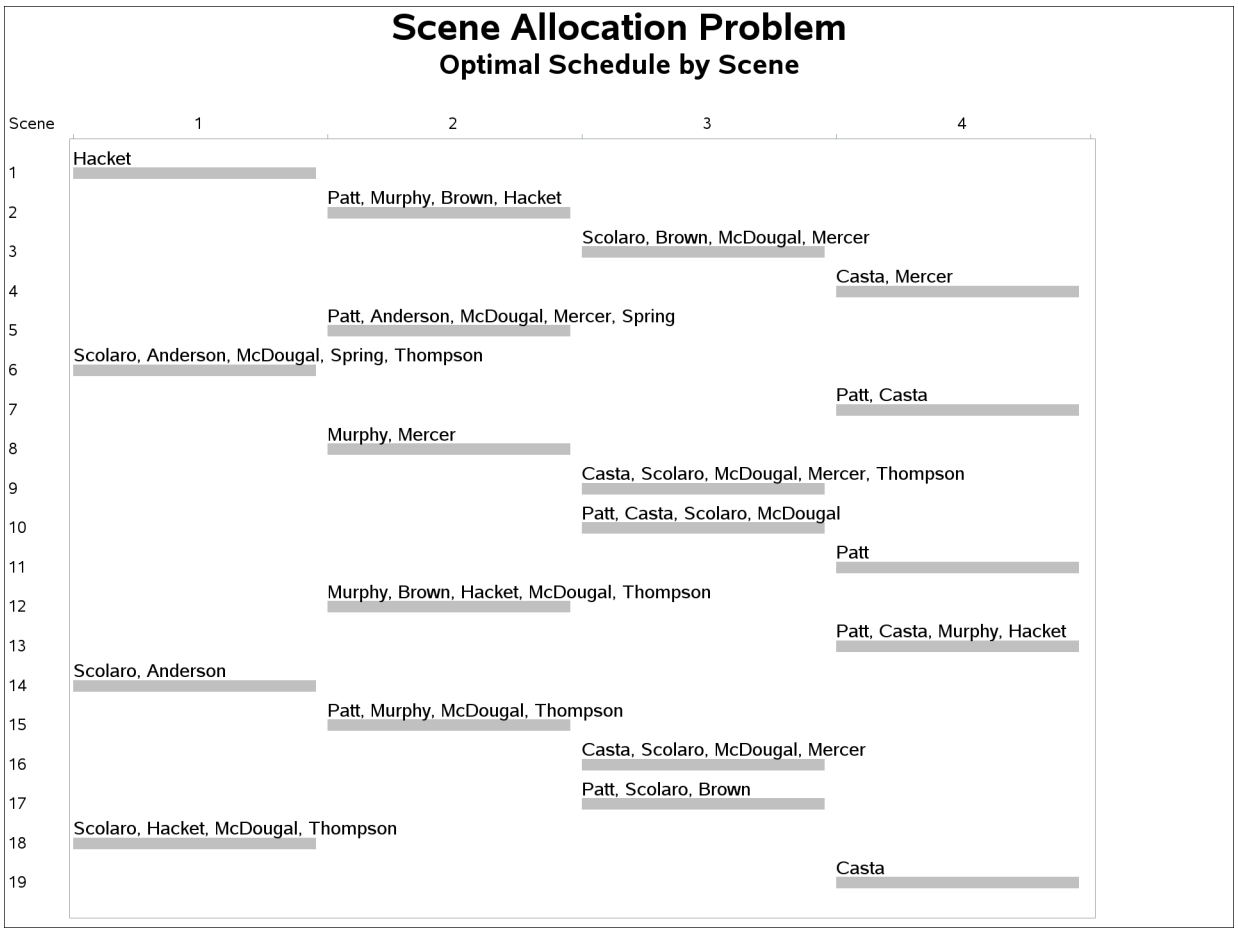
```
      /* Every scene is shot exactly once.*/
      %do j=1 %to 19;
         gcc (
            %do k=1 %to 4;
               S&j._&k
            %end;
            )=( (1, 1, 1) );
      %end;

      /* At least 4 and at most 5 scenes are shot per day. */
      %do k=1 %to 4;
         gcc (
            %do j=1 %to 19;
               S&j._&k
            %end;
            )=( (1, 4, 5) );
      %end;

      /* Actors for a scene must be present on day of shooting.*/
      %do k=1 %to 4;
         %do j=1 %to 19;
            %do i=1 %to 11;
               %if (&&A&i._S&j>0) %then %do;
                  lincon S&j._&k <= A&i._&k;
               %end;
            %end;
         %end;
      %end;

      /* Symmetry breaking constraints. Without loss of any generality, we */
      /* can assume Scene1 to be shot on day 1, Scene2 to be shot on day 1 */
      /* or day 2, and Scene3 to be shot on either day 1, day 2 or day 3.  */
      lincon S1_1 = 1, S1_2 = 0, S1_3 = 0, S1_4 = 0,
         S2_3 = 0, S2_4 = 0, S3_4 = 0;

      /* If Scene2 is shot on day 1,                */
      /* then Scene3 can be shot on day 1 or day 2. */
      lincon S2_1 + S3_3 <= 1;

   run;
   %put &_ORCLP_;

%mend scene;
```

The optimal production cost is 334,144, as reported in the _ORCLP_ macro variable. The corresponding actor schedules and scene schedules are displayed in Output 4.3.2 and Output 4.3.3, respectively.

Output 4.3.2 Scene Allocation Problem: Actor Schedules



Output 4.3.3 Scene Allocation Problem: Scene Schedules



Example 4.4: Car Sequencing Problem

This example is an instance of a category of problems known as the car sequencing problem. There is a considerable amount of literature related to this problem (Dincbas, Simonis, and Van Hentenryck 1988; Gravel, Gagne, and Price 2005; Solnon et al. 2008).

A number of cars are to be produced on an assembly line. Each car is customized to include a specific set of options, such as air conditioning, a sunroof, a navigation system, and so on. The assembly line moves through several workstations for installation of these options. The cars cannot be positioned randomly, because each workstation has limited capacity and needs time to set itself up to install the options as the car moves in front of the station. These capacity constraints are formalized using constraints of the form m out of N, which indicates that the workstation can install the option on m out of every sequence of N cars. The car sequencing problem is to determine a sequencing of the cars on the assembly line that satisfies the demand constraints for each set of car options and the capacity constraints for each workstation.

This example comes from Dincbas, Simonis, and Van Hentenryck (1988). Ten cars need to be customized with five possible options. A class of car is defined by a specific set of options; there are six classes of cars.

The instance data are presented in Table 4.5.

Table 4.5 The Instance Data

Option		Capacity	Car Class					
Name	**Type**	**m/N**	**1**	**2**	**3**	**4**	**5**	**6**
Option 1	1	1/2	1	0	0	0	1	1
Option 2	2	2/3	0	0	1	1	0	1
Option 3	3	1/3	1	0	0	0	1	0
Option 4	4	2/5	1	1	0	1	0	0
Option 5	5	1/5	0	0	1	0	0	0
Number of Cars			**1**	**1**	**2**	**2**	**2**	**2**

For example, car class 4 requires installation of option 2 and option 4, and two cars of this class are required. The workstation for option 2 can process only two out of every sequence of three cars. The workstation for option 4 has even less capacity—two out of every five cars.

The data for this problem are used to create a SAS data set, which in turn is processed to generate the SAS macro variables shown in Table 4.6 that are used in the CLP procedure. The assembly line is treated as a sequence of slots, and each car must be allocated to a single slot.

Table 4.6 SAS Macro Variables

Macro Variable	**Description**	**Value**
Ncars	Number of cars (slots)	10
Nops	Number of options	5
Nclss	Number of classes	6
Max_1–Max_5	For each option, the maximum number of cars with that option in a block	1 2 1 2 1
Blsz_1–Blsz_5	For each option, the block size to which the maximum number refers	2 3 3 5 5
class_1–class_6	Index number of each class	1 2 3 4 5 6
cars_cls_1–cars_cls_6	Number of cars in each class	1 1 2 2 2 2
list_1–list_5	Class indicator list for each option; for example, classes 1, 5, and 6 that require option 1 (*list_1*)	list_1=1,0,0,0,1,1 list_2=0,0,1,1,0,1 list_3=1,0,0,0,1,0 list_4=1,1,0,1,0,0 list_5=0,0,1,0,0,0
cars_opts_1–cars_opts_5	Number of cars for each option (cars_opts_1 represents the number of cars that require option 1)	5 6 3 4 2

The decision variables for this problem are shown in Table 4.7.

Table 4.7 The Decision Variables

Variable Definition	Description
S_1–S_10=[1,6]	S_*i* is the class of cars assigned to slot *i*.
O_1_1–O_1_5=[0,1] … O_10_1–O_10_5=[0,1]	O_*i*_*j*=1 if the class assigned to slot *i* needs option *j*.

The following SAS statements express the workstation capacity constraints by using a set of linear constraints for each workstation. A single GCC constraint expresses the demand constraints for each car class. An element constraint for each option variable expresses the relationships between slot variables and option variables.

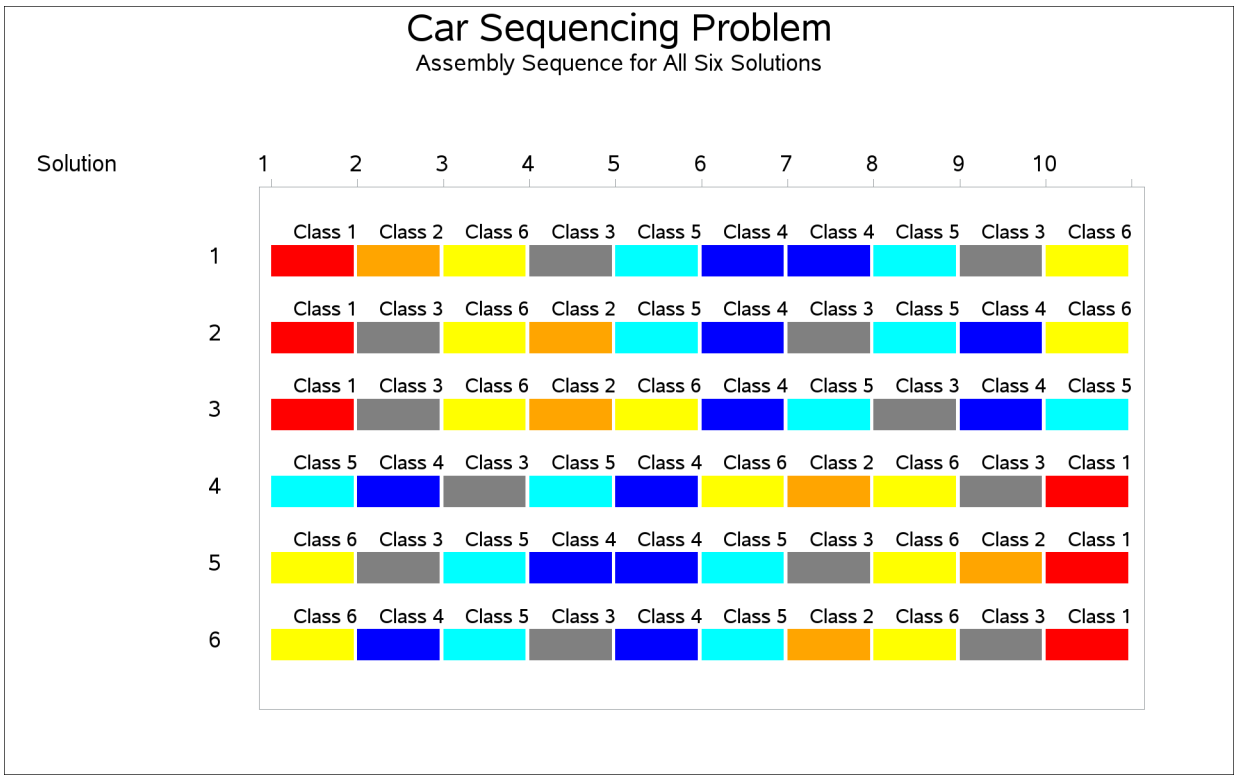
Finally, a set of redundant constraints are introduced to improve the efficiency of propagation. The idea behind the redundant constraint in this model is the following realization: if the workstation for option j has capacity r out of s, then at most r cars in the sequence $(n - s + 1), \ldots, n$ can have option j, where n is the total number of cars. Consequently, at least $n_j - r$ cars in the sequence $1, \ldots, n - s$ must have option j, where n_j is the number of cars that have option j. Generalizing this further, at least $n_j - k \times r$ cars in the sequence $1, \ldots, (n - k \times s)$ must have option j, $k = 1, \ldots, \lfloor n/s \rfloor$.

```
%macro car_sequencing(outdata);

proc clp out=&outdata varselect=minrmaxc findall;

   /* Declare Variables */
   var
      /* Slot variables: Si - class of car assigned to Slot i */
      %do i = 1 %to &Ncars;
          S_&i = [1, &Nclss]
      %end;

      /* Option variables: Oij
         - indicates if class assigned to Sloti needs Option j */
      %do i = 1 %to &Ncars;
          %do j = 1 %to &Nops;
              O_&i._&j = [0, 1]
          %end;
      %end;
      ;

   /* Capacity Constraints: for each option j */
   /* Installed in at most Max_j cars out of every sequence of BlSz_j cars */
   %do j = 1 %to &Nops;
      %do i = 0 %to %eval(&Ncars-&&BlSz_&j);
         lincon 0
         %do k=1 %to &&BlSz_&j;
            + O_%eval(&i+&k)_&j
         %end;
         <=&&Max_&j;
```

```
      %end;
   %end;

   /* Demand Constraints: for each class i */
   /* Exactly cars_cls_i cars */
   gcc (S_1-S_&Ncars) = (
      %do i = 1 %to &Nclss;
         (&&class_&i, &&cars_cls_&i, &&cars_cls_&i)
      %end;
      );

   /* Element Constraints: For each slot i and each option j */
   /* relate the slot variable to the option variables.      */
   /*  O_i_j is the S_i th element in list_j.                */
   %do i = 1 %to &Ncars;
      %do j = 1 %to &Nops;
         element (S_&i, (&&list_&j), O_&i._&j);
      %end;
   %end;


   /* Redundant Constraints to improve efficiency - for every  */
   /*    option j.                                             */
   /* At most &&Max_&j out of every sequence of &&BlSz_&j cars */
   /*    requires option j.                                    */
   /* All the other slots contain at least cars_opt_j - Max_j  */
   /*    cars with option j                                    */
   %do j = 1 %to &Nops;
      %do i = 1 %to %eval(&Ncars/&&BlSz_&j);
         lincon 0
         %do k=1 %to %eval(&Ncars-&i*&&BlSz_&j);
            + O_&k._&j
         %end;
         >= %eval(&&cars_opts_&j-&i*&&Max_&j);
      %end;
   %end;
run;

%mend;
%car_sequencing(mycas.sequence_out);
```

This problem has six solutions, as shown in Output 4.4.1.

Output 4.4.1 Car Sequencing



Although constraints can usually help performance, this is not necessarily always the case. Consider the instance shown in Table 4.8 with 100 cars, 5 options, and 18 classes from Dincbas, Simonis, and Van Hentenryck (1988).

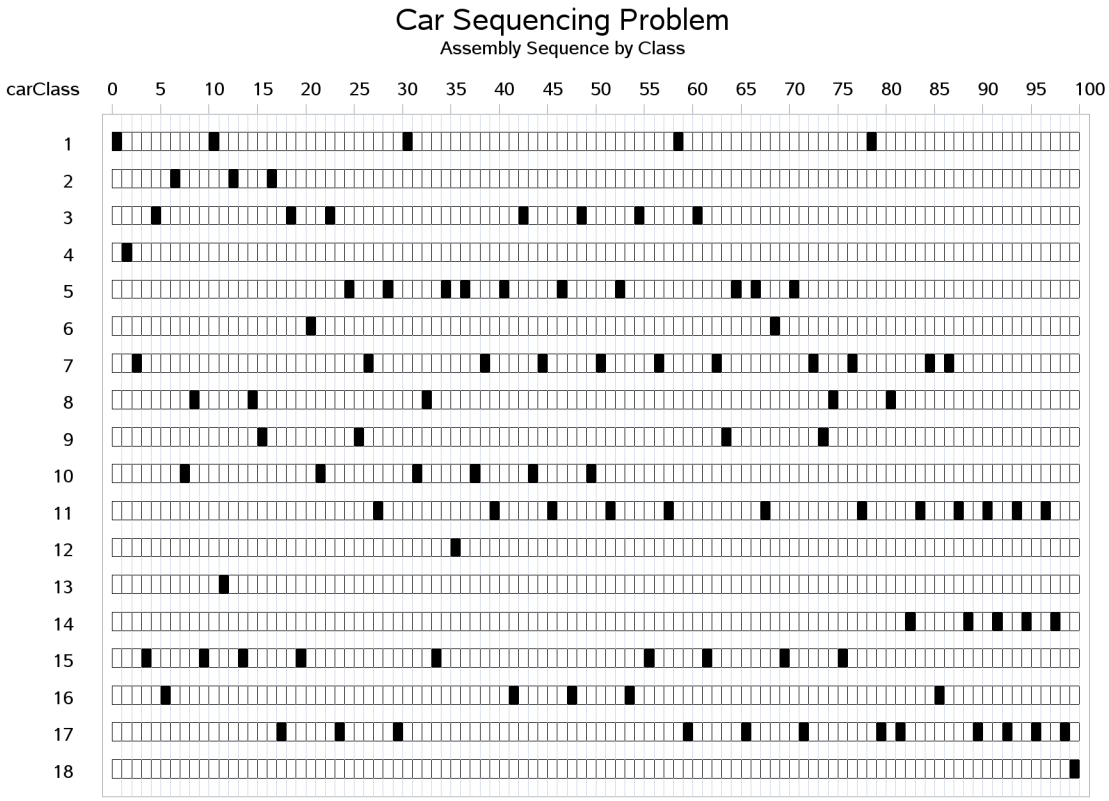
Table 4.8 Instance Data for 100 Cars, 5 Options, 18 Classes

Option		Capacity	Car Class																	
Name	**Type**	**m/N**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Option 1	1	1/2	1	1	1	0	1	1	1	1	0	0	0	0	0	1	0	0	0	0
Option 2	2	2/3	1	1	1	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0
Option 3	3	1/3	0	0	1	1	0	0	0	1	0	0	1	1	1	0	0	0	0	1
Option 4	4	2/5	0	1	0	1	0	0	1	0	0	1	0	0	1	0	0	0	1	0
Option 5	5	1/5	1	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0
Number of Cars			**5**	**3**	**7**	**1**	**10**	**2**	**11**	**5**	**4**	**6**	**12**	**1**	**1**	**5**	**9**	**5**	**12**	**1**

Using the same formulation as before, the CLP procedure was unable to find a solution in 10 seconds. However, removing the redundant constraints resulted in a solution being found almost immediately.

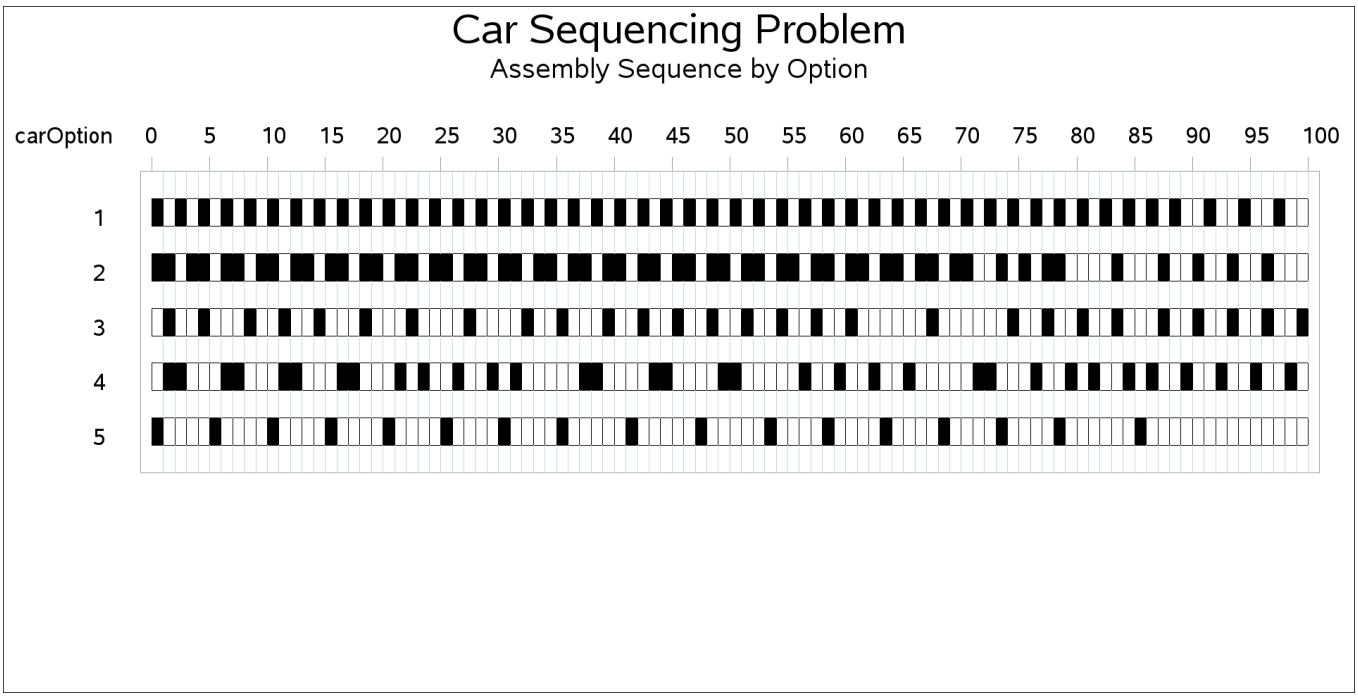
Two different views of the solution that was found are shown in Output 4.4.2 and Output 4.4.3. The horizontal axis in each chart represents the assembly sequence. The assembly sequence by class is shown in Output 4.4.2.

Output 4.4.2 Car Sequencing by Class



The assembly sequence by option is shown in Output 4.4.3. You can use this chart to quickly verify that the capacity constraints are satisfied. For example, from the corresponding block patterns in each row, it is evident that option 1 is never processed on consecutive cars, option 2 is never processed on three consecutive cars, and so on.

Output 4.4.3 Car Sequencing by Option



Finally, the two solution summaries shown in Output 4.4.4 and Output 4.4.5 contrast the number of solutions that are found in two different modes in the same time period, using the FINDALL option.

Output 4.4.4 Single-Machine Mode

Car Sequencing Problem
Single-Machine Mode

The CLP Procedure

Solution Summary	
Solution Status	Time Limit Reached
Variable Selection	WDEG
Value Selection	MIN
Solutions Found	1309
Solution Time	10.000704

Output 4.4.5 Distributed Mode (10 Machines)

Car Sequencing Problem
Distributed Mode

The CLP Procedure

Solution Summary	
Solution Status	Time Limit Reached
Variable Selection	WDEG
Value Selection	MIN
Solutions Found	14249
Solution Time	10.000133

Example 4.5: Scheduling a Major Basketball Conference

This example illustrates modeling and solving a well-known double round-robin problem using the CLP procedure. Round-robin tournaments (and variations of them) are a popular format in the scheduling of many sports league tournaments. In a single round-robin tournament, each team plays every other team just once. In a double round-robin (DRR) tournament, each team plays every other team twice: once at home and once away.

This example is based on the work of Nemhauser and Trick (1998) and deals with scheduling the Atlantic Coast Conference (ACC) Men's Basketball games for the 1997–1998 season.

A temporally dense double round-robin (DDRR) for n teams is a double round-robin in which the $n(n-1)$ games are played over a minimal number of dates or time slots. If n is even, the number of slots is $2(n-1)$ and each team plays in every time slot. If n is odd, the number of slots is $2n$ and $(n-1)$ teams play in each time slot. In the latter case, each time slot has a team with a bye, and each team has two byes for the season.

The Atlantic Coast Conference (ACC) 1997–1998 men's basketball scheduling problem as described in Nemhauser and Trick (1998) and Henz (2001) is a DDRR that consists of the following nine teams with their abbreviated team name and team number shown in parentheses: Clemson (Clem 1), Duke (Duke 2), Florida State (FSU 3), Georgia Tech (GT 4), Maryland (UMD 5), University of North Carolina (UNC 6), NC State (NCSU 7), Virginia (UVA 8), and Wake Forest (Wake 9).

The general objective is to schedule the DDRR to span the months of January and February and possibly include a game in December or March or both. In general, each team plays twice a week—typically Wednesday and Saturday. Although the actual day might differ, these two time slots are referred to as the "weekday slot" and the "weekend slot." Since there are an odd number of teams, there is a team with a bye in each slot and four games in each slot, resulting in a schedule that requires 18 time slots or nine weeks. The last time slot must be a weekend slot, which implies the first slot is a weekday slot. The first slot, denoted slot 1, corresponds to the last weekday slot of December 1997, and the final slot, slot 18, corresponds to the first weekend slot of March 1998. Each team plays eight home games and eight away games, and has two byes.

In addition several other constraints must be satisfied. This example uses the following criteria employed by Nemhauser and Trick (1998) as presented by Henz (2001).

1. **Mirroring:** The dates are grouped into pairs $(r1, r2)$, such that each team gets to play against the same team in dates $r1$ and $r2$. Such a grouping is called a mirroring scheme. A separation of nine slots can be achieved by mirroring a round-robin schedule; although this separation is desirable, it is not possible for this problem.

   Nemhauser and Trick fix the mirroring scheme to

   $$m = (1, 8), (2, 9), (3, 12), (4, 13), (5, 14), (6, 15), (7, 16), (10, 17), (11, 18)$$

   in order to satisfy the constraints that UNC and Duke play in time slots 11 and 18. (See criterion 9.)

2. **Initial and final home and away games:** Every team must play at home on at least one of the first three dates. Every team must play at home on at least one of the last three dates. No team can play away on both of the last two dates.

3. **Home/away/bye pattern:** No team can have more than two away games in a row. No team can have more than two home games in a row. No team can have more than three away games or byes in a row. No team can have more than four home games or byes in a row.

4. **Weekend pattern:** Of the nine weekends, each team plays four at home, four away, and has one bye.

5. **First weekends:** Each team must have home games or byes on at least two of the first five weekends.

6. **Rival matches:** Every team except FSU has a traditional rival. The rival pairs are Clem-GT, Duke-UNC, UMD-UVA, and NCSU-Wake. In the last date, every team except FSU plays against its rival, unless it plays against FSU or has a bye.

7. **Popular matches in February:** The following pairings must occur at least once in dates 11 to 18: Duke-GT, Duke-Wake, GT-UNC, UNC-Wake.

8. **Opponent sequence:** No team plays in two consecutive away dates against Duke and UNC. No team plays in three consecutive dates against Duke, UNC, and Wake (independent of the home or away status).

9. **Idiosyncrasies:** UNC plays its rival Duke in the last date and in date 11. UNC plays Clem in the second date. Duke has a bye in date 16. Wake does not play home in date 17. Wake has a bye in the first date. Clem, Duke, UMD and Wake do not play away in the last date. Clem, FSU, and GT do not play away in the first date. Neither FSU nor NCSU has a bye in last date. UNC does not have a bye in the first date.

Previous work for solving round-robin problems, including that of Nemhauser and Trick (1998) and Henz (2001), have used a general three-phase framework for finding good schedules.

1. pattern generation
2. pattern set generation
3. timetable generation

A pattern is a valid sequence of home, away, and bye games for a given team for the entire season. For example, the following is a valid pattern:

A H B A H H A H A A H B H A A H H A

For this example, patterns that satisfy criterion 1 through criterion 5 and some constraints in criterion 9 are generated using the CLP procedure with the SAS macro %PATTERNS.

```
/*****************************************************************/
/* First, find all possible patterns. Consider only time        */
/* constraints at this point. A pattern should be suitable      */
/* for any team. Do not consider individual teams yet.          */
/*****************************************************************/
%macro patterns();

proc clp out=mycas.all_patterns findall;
   /* For date 1 to 18. */
   %do j = 1 %to 18;
      var h&j = [0, 1]; /* home */
      var a&j = [0, 1]; /* away */
      var b&j = [0, 1]; /* bye */

      /* A team is either home, away, or bye. */
      lincon h&j + a&j + b&j=1;
   %end;

   /*---------------------------------------------------------------*/
   /* Criterion 1 - Mirroring Scheme                                */
   /*---------------------------------------------------------------*/
   /* The dates are grouped into pairs (j, j1), such that each   */
   /* team plays the same opponent on dates j and j1.            */
   /* A home game on date j will be an away game on date j1      */
   %do j = 1 %to 18;
      %do j1 = %eval(&j+1) %to 18;
         %if ( &j=1 and &j1=8 ) or ( &j=2 and &j1=9 ) or
             ( &j=3 and &j1=12 ) or ( &j=4 and &j1=13 ) or
             ( &j=5 and &j1=14 ) or ( &j=6 and &j1=15 ) or
             ( &j=7 and &j1=16 ) or ( &j=10 and &j1=17 ) or
             ( &j=11 and &j1=18 ) %then
            lincon h&j = a&j1, a&j = h&j1, b&j = b&j1;;
      %end;
   %end;

   /*---------------------------------------------------------------*/
   /* Criterion 2 - Initial and Final Home and Away Games        */
   /*---------------------------------------------------------------*/
   /* Every team must play home on at least one of the first three dates. */
   lincon h1 + h2 + h3 >= 1;

   /* Every team must play home on at least one of the last three dates. */
   lincon h16 + h17 + h18 >= 1;

   /* No team can play away on both last two dates. */
   lincon a17 + a18 < 2;
```

```
   /*-------------------------------------------------------------*/
   /* Criterion 3 - Home/Away/Bye Pattern                         */
   /*-------------------------------------------------------------*/
   %do j = 1 %to 16;
      /* No team can have more than two away matches in a row.*/
      lincon a&j + a%eval(&j+1) + a%eval(&j+2) < 3;
      /* No team can have more than two home matches in a row.*/
      lincon h&j + h%eval(&j+1) + h%eval(&j+2) < 3;
   %end;

   /* No team can have more than three away matches or byes in a row.*/
   %do j = 1 %to 15;
      lincon a&j + b&j + a%eval(&j+1) + b%eval(&j+1) + a%eval(&j+2)
             + b%eval(&j+2) + a%eval(&j+3) + b%eval(&j+3) < 4;
   %end;

   /* No team can have more than four home matches or byes in a row.*/
   %do j = 1 %to 14;
       lincon h&j + b&j + h%eval(&j+1) + b%eval(&j+1) + h%eval(&j+2)
              + b%eval(&j+2) + h%eval(&j+3) + b%eval(&j+3) + h%eval(&j+4)
              + b%eval(&j+4) < 5;
   %end;

   /*-------------------------------------------------------------*/
   /* Criterion 4 - Weekend Pattern                               */
   /*-------------------------------------------------------------*/
   /* Each team plays four weekends at home. */
   lincon 0 %do j = 2 %to 18 %by 2; +h&j %end; =4;
   /* Each team plays four weekends away. */
   lincon 0 %do j = 2 %to 18 %by 2; +a&j %end; =4;
   /* Each team has 1 weekend with a bye  */
   lincon 0 %do j = 2 %to 18 %by 2; +b&j %end; =1;

   /*-------------------------------------------------------------*/
   /* Criterion 5 - First Weekends                                */
   /*-------------------------------------------------------------*/
   /* Each team must have home games or byes on at least two     */
   /* of the first five weekends.                                 */
   lincon 0 %do j = 2 %to 10 %by 2; + h&j + b&j %end; >=2;

   /*-------------------------------------------------------------*/
   /* Criterion 9 - (Partial)                                     */
   /*-------------------------------------------------------------*/
   /* The team with a bye in date 1 does not play away on the    */
   /*    last date or home in date 17 (Wake)                      */
   /* The team with a bye in date 16 does not play away in       */
   /*    date 18 (Duke)                                           */
   lincon b1 + a18 < 2, b1 + h17 < 2, b16 + a18 < 2;

run;

%mend;
```

```
%patterns;
```

The %PATTERNS macro generates 38 patterns. The next step is to find a subset of patterns with cardinality equal to the number of teams that would collectively support a potential assignment to all of the teams. For example, each of the 18 time slots must correspond to four home games, four away games, and one bye. Furthermore, pairs of patterns that do not support a potential meeting date between the two corresponding teams are excluded. The following %PATTERN_SETS macro uses the CLP procedure with the preceding constraints to generate all possible pattern sets.

```
/*****************************************************************/
/* Determine all possible "pattern sets" considering only time   */
/* constraints.                                                  */
/* Individual teams are not considered at this stage.            */
/* xi - binary variable indicates pattern i is in pattern set    */
/*****************************************************************/

%macro pattern_sets();

data all_patterns;
   set mycas.all_patterns;
   %do i=1 %to 38;
      if _n_=&i then do;
         %do j=1 %to 18;
            call symput("h&i._&j", put(h&j,best.));
            call symput("a&i._&j", put(a&j,best.));
            call symput("b&i._&j", put(b&j,best.));
         %end;
      end;
   %end;
run;

proc clp out=mycas.pattern_sets findall;
   /* xi=1 if pattern i belongs to pattern set */
   var (x1-x38)= [0, 1];

   /* Exactly nine patterns per patterns set */
   lincon 0 %do i = 1 %to 38; + x&i %end;=9;

   /* time slot constraints */
   %do j = 1 %to 18;
      /* Four home games per time slot */
      lincon 0 %do i = 1 %to 38; + &&h&i._&j*x&i %end; =4;
      /* Four away games per time slot */
      lincon 0 %do i = 1 %to 38; + &&a&i._&j*x&i %end; =4;
      /* One bye per time slot */
      lincon 0 %do i = 1 %to 38; + &&b&i._&j*x&i %end; =1;
   %end;

   /* Exclude pattern pairs that do not support a meeting date */
   %do i = 1 %to 38;
      %do i1 = %eval(&i+1) %to 38;
         %let count=0;
         %do j=1 %to 18;
```

```
            %if ( (&&h&i._&j=0 or &&a&i1._&j=0) and
                  (&&a&i._&j=0 or &&h&i1._&j=0)) %then %do;
               %let count=%eval(&count+1);
            %end;
         %end;
         %if (&count=18) %then %do;
            lincon x&i+x&i1<=1;
         %end;
      %end;
   %end;
run;

%mend;

%pattern_sets;
```

The %PATTERN_SETS macro generates 17 pattern sets. The final step is to add the individual team constraints and match up teams to the pattern sets in order to come up with a schedule for each team. The schedule for each team indicates the opponent for each time slot (0 for a bye) and whether it corresponds to a home game, away game, or a bye.

The %FIND_SCHEDULES macro determines the team schedules by using the CLP procedure to match teams to pattern sets while satisfying the individual team constraints.

```
/*************************************************************/
/* Try all possible pattern sets to find all valid schedules. */
/*************************************************************/

%macro find_schedules;

proc transpose data=mycas.pattern_sets out=trans_good; run;

data _temp;
   set trans_good;
   set all_patterns;
run;

proc sql noprint;
   %do k = 1 %to 17; /* For each pattern */
      %do j=1 %to 18; /* For each date */
         select h&j into :col&k._h_&j
            separated by ',' from _temp where col&k=1;
         select a&j into :col&k._a_&j
            separated by ',' from _temp where col&k=1;
         select b&j into :col&k._b_&j
            separated by ',' from _temp where col&k=1;
      %end;
   %end;
run;

/*******************************************************************/
/* Assign individual teams to pattern sets                         */
/* Teams: 1 Clem, 2 Duke, 3 FSU, 4 GT, 5 UMD, 6 UNC, 7 NCSU, 8 UVA,  */
```

```
/*        9 Wake                                                        */
/*********************************************************************/
proc clp out=mycas.ACC_ds varselect=maxcs findall;

   var k = [1,17]; /* pattern set index */

   %do j = 1 %to 18;
      /*  alpha(i,j): Team i's opponent on date j ( 0 = bye ). */
      %do i = 1 %to 9;
         var alpha&i._&j = [0, 9];
      %end;

      /* Timetable constraint 1 */
      /* Opponents in a time slot must be distinct */
      alldiff ( %do i = 1 %to 9; alpha&i._&j %end; );

      /* Timetable constraint 2 */
      %do i = 1 %to 9;
         %do i1 = 1 %to 9;
            /* indicates if teams i and i1 play in time slot j */
            var X&i._&i1._&j = [0, 1];
            reify X&i._&i1._&j: (alpha&i._&j = &i1);

            /* team i plays i1 iff team i1 plays i */
            %if (&i1 > &i ) %then %do;
               lincon X&i._&i1._&j = X&i1._&i._&j;
            %end;
         %end;
      %end;
   %end;


   /* Mirroring Scheme at team level.                          */
   /* The dates are grouped into pairs (j, j1) such that each */
   /* team plays the same opponent in dates j and j1.         */
   /* One of these should be a home game for each team.       */
   %do i = 1 %to 9;
      %do j = 1 %to 18;
         %do j1 = %eval(&j+1) %to 18;
            %if ( &j=1 and &j1=8 ) or ( &j=2 and &j1=9 ) or
                ( &j=3 and &j1=12 ) or ( &j=4 and &j1=13 ) or
                ( &j=5 and &j1=14 ) or ( &j=6 and &j1=15 ) or
                ( &j=7 and &j1=16 ) or ( &j=10 and &j1=17 ) or
                ( &j=11 and &j1=18 ) %then %do;
               lincon alpha&i._&j=alpha&i._&j1,
               /* H and A are matrices that indicate home */
               /* and away games                          */
               H&i._&j=A&i._&j1,
               H&i._&j1=A&i._&j;
            %end;
         %end;
      %end;
   %end;
```

```
/* Timetable constraint 3 */
/* Each team plays every other team twice */
%do i = 1 %to 9;
   %do i1 = 1 %to 9;
      %if &i1 ne &i %then %do;
         lincon 0 %do j = 1 %to 18; + X&i._&i1._&j %end; = 2;
      %end;
   %end;
%end;

/* Timetable constraint 4 */
/* Teams do not play against themselves */
%do j = 1 %to 18;
   %do i = 1 %to 9;
      lincon alpha&i._&j<>&i;
      lincon X&i._&i._&j = 0;  /* redundant */
   %end;
%end;

/* Timetable constraint 5 */
/* Setup Bye Matrix */
/* alpha&i._&j=0 means team &i has a bye on date &j. */
%do j = 1 %to 18;
   %do i = 1 %to 9;
      var B&i._&j = [0, 1]; /*Bye matrix*/
      reify B&i._&j: ( alpha&i._&j = 0 );
   %end;
%end;

/* Timetable constraint 6 */
/* alpha&i._&j=&i1 implies teams &i and &i1 play on date &j */
/* It must be a home game for one, away game for the other  */
%do j = 1 %to 18;
   %do i = 1 %to 9;
      %do i1 = 1 %to 9;
         /* reify control variables.*/
         var U&i._&i1._&j = [0, 1] V&i._&i1._&j = [0, 1];

         /* if &i is home and &i1 is away. */
         reify U&i._&i1._&j: ( H&i._&j + A&i1._&j = 2);
         /* if &i1 is home and &i is away. */
         reify V&i._&i1._&j: ( A&i._&j + H&i1._&j = 2);

         /* Necessary condition if &i plays &i1 on date j  */
         lincon X&i._&i1._&j <= U&i._&i1._&j + V&i._&i1._&j;
      %end;
   %end;
%end;

/* Timetable constraint 7 */
/* Each team must be home, away or have a bye on a given date */
%do j = 1 %to 18;
   %do i = 1 %to 9;
      /* Team &i is home (away) at date &j. */
```

```
      var H&i._&j = [0, 1] A&i._&j = [0, 1];
      lincon H&i._&j + A&i._&j + B&i._&j = 1;
   %end;
%end;

%do i = 1 %to 9;
   %do i1 = %eval(&i+1) %to 9;

      /* Timetable constraint 8 */
      /*-------------------------------------------------------*/
      /* Criterion 6 - Rival Matches                           */
      /*-------------------------------------------------------*/
      /* The final weekend is reserved for 'rival games' */
      /* unless the team plays FSU or has a bye          */
      %if ( &i=1 and &i1=4 ) or ( &i=2 and &i1=6 ) or
          ( &i=5 and &i1=8 ) or ( &i=7 and &i1=9 ) %then %do;
         lincon X&i._&i1._18 + B&i._18 + X&i._3_18 = 1;

         /* redundant */
         lincon X&i1._&i._18 + B&i1._18 + X&i1._3_18 = 1;
      %end;

      /* Timetable constraint 9 */
      /*-------------------------------------------------------*/
      /* Criterion 7 - Popular Matches                         */
      /*-------------------------------------------------------*/
      /* The following pairings are specified to occur at      */
      /* least once in February.                               */
      %if ( &i=2 and &i1=4 ) or ( &i=2 and &i1=9 ) or
          ( &i=4 and &i1=6 ) or ( &i=6 and &i1=9 ) %then %do;
         lincon 0 %do j = 11 %to 18; + X&i._&i1._&j  %end; >= 1;

         /* redundant */
         lincon 0 %do j = 11 %to 18; + X&i1._&i._&j %end; >= 1;
      %end;
   %end;
%end;

/* Timetable constraint 10 */
/*-------------------------------------------------------*/
/* Criterion 8 - Opponent Sequence                       */
/*-------------------------------------------------------*/
%do i = 1 %to 9;
   /* No team plays two consecutive away dates against   */
   /* Duke (2) and UNC (6)                               */
   %do j = 1 %to 17;
      var Q&i._26_&j = [0, 1] P&i._26_&j = [0, 1];
      reify Q&i._26_&j: ( X&i._2_&j +  X&i._6_&j = 1 );
      reify P&i._26_&j: ( X&i._2_%eval(&j+1) +  X&i._6_%eval(&j+1) =1 );
      lincon Q&i._26_&j + A&i._&j + P&i._26_&j + A&i._%eval(&j+1) < 4;
   %end;

   /* No team plays three consecutive dates against      */
   /* Duke(2), UNC(6) and Wake(9).                       */
```

```
      %do j = 1 %to 16;
         var L&i._269_&j = [0, 1] M&i._269_&j = [0, 1]
             N&i._269_&j = [0, 1];
         reify L&i._269_&j: ( X&i._2_&j +  X&i._6_&j +  X&i._9_&j = 1 );
         reify M&i._269_&j: ( X&i._2_%eval(&j+1) + X&i._6_%eval(&j+1) +
                              X&i._9_%eval(&j+1) =1 );
         reify N&i._269_&j: ( X&i._2_%eval(&j+2) + X&i._6_%eval(&j+2) +
                              X&i._9_%eval(&j+2) =1 );
         lincon L&i._269_&j + M&i._269_&j + N&i._269_&j  < 3;
      %end;
   %end;


   /* Timetable constraint 11 */
   /*-------------------------------------------------------*/
   /* Criterion 9 - Idiosyncratic Constraints               */
   /*-------------------------------------------------------*/
   /* UNC plays Duke in date 11 and 18 */
   lincon alpha6_11 = 2 ;
   lincon alpha6_18 = 2 ;
   /* UNC plays Clem in the second date. */
   lincon alpha6_2 = 1 ;
   /* Duke has a bye in date 16. */
   lincon B2_16 = 1 ;
   /* Wake does not play home in date 17. */
   lincon H9_17 = 0 ;
   /* Wake has a bye in the first date. */
   lincon B9_1 = 1 ;
   /* Clem, Duke, UMD and Wake do not play away in the last date. */
   lincon A1_18 = 0 ;
   lincon A2_18 = 0 ;
   lincon A5_18 = 0 ;
   lincon A9_18 = 0 ;
   /* Clem, FSU, and GT do not play away in the first date. */
   lincon A1_1 = 0 ;
   lincon A3_1 = 0 ;
   lincon A4_1 = 0 ;
   /* FSU and NCSU do not have a bye in the last date. */
   lincon B3_18 = 0 ;
   lincon B7_18 = 0 ;
   /* UNC does not have a bye in the first date. */
   lincon B6_1 = 0 ;


/* Timetable constraint 12 */
/*-------------------------------------------------------*/
/* Match teams with patterns.                            */
/*-------------------------------------------------------*/
%do i = 1 %to 9; /* For each team */
   var p&i=[1,9];
   var pp&i = [1,153];
   lincon pp&i = 9 * k - 9 + p&i;
   %do j=1 %to 18; /* For each date */
      element ( pp&i, (
```

```
            %do k = 1 %to 17;
            &&col&k._h_&j
            %end;
            ), H&i._&j );
         element ( pp&i, (
            %do k = 1 %to 17;
            &&col&k._a_&j
            %end;
            ), A&i._&j );
         element ( pp&i, (
            %do k = 1 %to 17;
            &&col&k._b_&j
            %end;
            ), B&i._&j );
      %end;
   %end;
   run;

   data all;
      set mycas.ACC_ds;
   run;

   %mend;

   %find_schedules;
```

The %FIND_SCHEDULES macro generates 179 possible schedules including the one that was eventually used by the ACC, which is displayed in Output 4.5.1.

Output 4.5.1 ACC Basketball Tournament Schedule

ACC Basketball Tournament Scheduling

Team	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Clem	UMD	UNC	@Wake		FSU	@Duke	UVA	@UMD	@UNC	NCSU	@GT	Wake		@FSU	Duke	@UVA	@NCSU	GT
Duke	UVA	@UMD	NCSU	@FSU	@Wake	Clem		@UVA	UMD	GT	@UNC	@NCSU	FSU	Wake	@Clem		@GT	UNC
FSU	UNC	@NCSU	@UMD	Duke	@Clem	@GT	Wake	@UNC	NCSU		@UVA	UMD	@Duke	Clem	GT	@Wake		UVA
GT	NCSU		@UNC	Wake	@UVA	FSU	UMD	@NCSU		@Duke	Clem	UNC	@Wake	UVA	@FSU	@UMD	Duke	@Clem
UMD	@Clem	Duke	FSU	@NCSU	UNC	@Wake	@GT	Clem	@Duke	UVA		@FSU	NCSU	@UNC	Wake	GT	@UVA	
UNC	@FSU	@Clem	GT	UVA	@UMD		@NCSU	FSU	Clem	@Wake	Duke	@GT	@UVA	UMD		NCSU	Wake	@Duke
NCSU	@GT	FSU	@Duke	UMD		@UVA	UNC	GT	@FSU	@Clem	Wake	Duke	@UMD		UVA	@UNC	Clem	@Wake
UVA	@Duke	Wake		@UNC	GT	NCSU	@Clem	Duke	@Wake	@UMD	FSU		UNC	@GT	@NCSU	Clem	UMD	@FSU
Wake		@UVA	Clem	@GT	Duke	UMD	@FSU		UVA	UNC	@NCSU	@Clem	GT	@Duke	@UMD	FSU	@UNC	NCSU

Example 4.6: Balanced Incomplete Block Design

Balanced incomplete block design (BIBD) generation is a standard combinatorial problem from design theory. The concept was originally developed in the design of statistical experiments; applications have expanded to other fields, such as coding theory, network reliability, and cryptography. A BIBD is an arrangement of v distinct objects into b blocks such that the following conditions are met:

- Each block contains exactly k distinct objects.
- Each object occurs in exactly r different blocks.
- Every two distinct objects occur together in exactly λ blocks.

A BIBD is therefore specified by its parameters (v, b, r, k, λ). It can be proved that when a BIBD exists, its parameters must satisfy the following conditions:

- $rv = bk$
- $\lambda(v-1) = r(k-1)$

- $b \geq v$

The preceding conditions are not sufficient to guarantee the existence of a BIBD (Prestwich 2001). For example, the parameters $(15, 21, 7, 5, 2)$ satisfy the preceding conditions, but a BIBD that has these parameters does not exist. Computational methods of BIBD generation usually suffer from combinatorial explosion, in part because of the large number of symmetries: for any solution, any two objects or blocks can be exchanged to obtain another solution.

This example demonstrates how to express a BIBD problem as a CSP and how to use lexicographic ordering constraints to break symmetries. (Note that this example is for illustration only. SAS provides an autocall macro, MKTBIBD, for solving BIBD problems.) The most direct CSP model for BIBD, as described in Meseguer and Torras (2001), represents a BIBD as a $v \times b$ matrix X. Each matrix entry is a Boolean decision variable $X_{i,c}$ that satisfies $X_{i,c} = 1$ if and only if block c contains object i. The condition that each object occurs in exactly r blocks (or, equivalently, that there are r 1s per row) can be expressed as v linear constraints:

$$\sum_{c=1}^{b} X_{i,c} = r \quad \text{for } i = 1, \ldots, v$$

Alternatively, you can use global cardinality constraints to ensure that there are exactly $b - r$ 0s and r 1s in $X_{i,1}, \ldots, X_{i,b}$ for each object i:

$$\text{gcc}(X_{i,1}, \ldots, X_{i,b}) = ((0, 0, b - r)(1, 0, r)) \quad \text{for } i = 1, \ldots, v$$

Similarly, the condition that each block contains exactly k objects (there are k 1s per column) can be specified by the following constraints:

$$\text{gcc}(X_{1,c}, \ldots, X_{v,c}) = ((0, 0, v - k)(1, 0, k)) \quad \text{for } c = 1, \ldots, b$$

To enforce the final condition that every two distinct objects occur together in exactly λ blocks (equivalently, that the scalar product of every pair of rows equal λ), you can introduce the auxiliary variables $P_{i,j,c}$ for every $i < j$, which indicate whether objects i and j both occur in block c. The following reified constraint ensures that $P_{i,j,c} = 1$ if and only if block c contains both objects i and j:

$$\text{reify } P_{i,j,c} : (X_{i,c} + X_{j,c} = 2)$$

The following constraints ensure that the final condition holds:

$$\text{gcc}(P_{i,j,1}, \ldots, P_{i,j,b}) = ((0, 0, b - \lambda)(1, 0, \lambda)) \quad \text{for } i = 1, \ldots, v - 1 \text{ and } j = i + 1, \ldots, v$$

The objects and the blocks are interchangeable, so the matrix X has total row symmetry and total column symmetry. Because of the constraints on the rows, no pair of rows can be equal unless $r = \lambda$. To break the row symmetry, you can impose strict lexicographical ordering on the rows of X as follows:

$$(X_{i,1}, \ldots, X_{i,b}) <_{\text{lex}} (X_{i-1,1}, \ldots, X_{i-1,b}) \quad \text{for } i = 2, \ldots, v$$

To break the column symmetry, you can impose lexicographical ordering on the columns of X as follows:

$$(X_{1,c}, \ldots, X_{v,c}) \leq_{\text{lex}} (X_{1,c-1}, \ldots, X_{v,c-1}) \quad \text{for } c = 2, \ldots, b$$

The following SAS macro incorporates all the preceding constraints. For the specified parameters (v, b, r, k, λ), the macro either finds BIBDs or proves that a BIBD does not exist.

```
%macro bibd(v, b, r, k, lambda, out=bibdout, soln=);
   /* Arrange v objects into b blocks such that:
         (i) each object occurs in exactly r blocks,
         (ii) each block contains exactly k objects,
         (iii) every pair of objects occur together in exactly lambda blocks.

      Equivalently, create a binary matrix with v rows and b columns,
      with r 1s per row, k 1s per column,
      and scalar product lambda between any pair of distinct rows.
   */

   /* Check necessary conditions */
   %if (%eval(&r * &v) ne %eval(&b * &k)) or
      (%eval(&lambda * (&v - 1)) ne %eval(&r * (&k - 1))) or
      (&v > &b) %then %do;
      %put BIBD necessary conditions are not met.;
      %goto EXIT;
   %end;

   proc clp out=&out domain=[0,1] varselect=FIFO varassign=MAX &soln;
      /* Decision variables: */
      /* Decision variable Xi_c = 1 iff object i occurs in block c. */
      var (
           %do i=1 %to &v;
              x&i._1-x&i._&b.
           %end;
          ) = [0,1];

      /* Mandatory constraints: */
      /* (i) Each object occurs in exactly r blocks. */
      %let q = %eval(&b.-&r.);  /* each row has &q 0s and &r 1s */
      %do i=1 %to &v;
         gcc( x&i._1-x&i._&b. ) = ((0,0,&q.) (1,0,&r.));
      %end;

      /* (ii) Each block contains exactly k objects. */
      %let h = %eval(&v.-&k.);  /* each column has &h 0s and &k 1s */
      %do c=1 %to &b;
         gcc(
             %do i=1 %to &v;
                x&i._&c.
             %end;
            ) = ((0,0,&h.) (1,0,&k.));
      %end;

      /* (iii) Every pair of objects occurs in exactly lambda blocks. */
      %let t = %eval(&b.-&lambda.);
      %do i=1 %to %eval(&v.-1);
         %do j=%eval(&i.+1) %to &v;
            /* auxiliary variable p_i_j_c =1 iff both i and j occur in c */
            var ( p&i._&j._1-p&i._&j._&b. ) = [0,1];
            %do c=1 %to &b;
               reify p&i._&j._&c.: (x&i._&c. + x&j._&c. = 2);
```

```
            %end;

            gcc(p&i._&j._1-p&i._&j._&b.) = ((0,0,&t.) (1,0,&lambda.));
         %end;
      %end;

      /* Symmetry breaking constraints: */
      /* Break row symmetry via lexicographic ordering constraints. */
      %do i = 2 %to &v.;
         %let i1 = %eval(&i.-1);
         lexico( (x&i._1-x&i._&b.) LEX_LT (x&i1._1-x&i1._&b.) );
      %end;

      /* Break column symmetry via lexicographic ordering constraints. */
      %do c = 2 %to &b.;
         %let c1 = %eval(&c.-1);
         lexico( ( %do i = 1 %to &v.;
                      x&i._&c.
                   %end; )
                 LEX_LE
                 ( %do i = 1 %to &v.;
                      x&i._&c1.
                   %end; ) );
      %end;


   run;
   %put &_orclp_;
%EXIT:
%mend bibd;
```

The following statement invokes the macro to find a balanced incomplete block design (BIBD) for the parameters (19, 19, 9, 9, 4):

```
%bibd(19,19,9,9,4, out=mycas.bibdout);
```

The output is displayed in Output 4.6.1.

Output 4.6.1 Balanced Incomplete Block Design for (19,19,9,9,4)

Balanced Incomplete Block Design Problem
(19, 19, 9, 9, 4)

Obs	Block1	Block2	Block3	Block4	Block5	Block6	Block7	Block8	Block9	Block10	Block11	Block12	Block13	Block14	Block15	Block16	Block17	Block18	Block19
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
3	1	1	1	0	1	0	0	0	0	1	0	0	0	0	1	1	1	1	0
4	1	1	0	0	0	1	1	0	0	0	1	1	0	0	1	1	0	0	1
5	1	0	1	0	0	1	1	0	0	0	0	0	1	1	0	0	1	1	1
6	1	0	0	1	1	0	0	1	0	0	1	1	0	0	0	0	1	1	1
7	1	0	0	1	1	0	0	0	1	0	0	0	1	1	1	1	0	0	1
8	1	0	0	0	0	1	0	1	1	1	1	0	1	0	1	0	1	0	0
9	1	0	0	0	0	0	1	1	1	1	0	1	0	1	0	1	0	1	0
10	0	1	1	0	0	0	0	1	1	0	1	0	1	0	0	1	0	1	1
11	0	1	0	1	0	1	0	1	0	1	0	0	0	1	1	0	0	1	1
12	0	1	0	1	0	0	1	0	1	0	0	1	1	0	1	0	1	1	0
13	0	1	0	0	1	1	0	1	0	0	0	1	1	1	0	1	1	0	0
14	0	1	0	0	1	0	1	0	1	1	1	0	0	1	0	0	1	0	1
15	0	0	1	1	0	1	0	0	1	1	0	1	0	0	0	1	1	0	1
16	0	0	1	1	0	0	1	1	0	0	1	0	0	1	1	1	1	0	0
17	0	0	1	0	1	1	0	0	1	0	1	1	0	1	1	0	0	1	0
18	0	0	1	0	1	0	1	1	0	1	0	1	1	0	1	0	0	0	1
19	0	0	0	1	1	1	1	0	0	1	1	0	1	0	0	1	0	1	0

Finally, the following statement invokes the macro to find all solutions for the (8, 14, 7, 4, 3) instance:

```
%bibd(8,14,7,4,3,out=mycas.bibdout, soln=findall);
```

The solution summary shown in Output 4.6.2 verifies the number of solutions for this instance when you use lexicographic ordering to break symmetries (Flener et al. 2002).

Output 4.6.2 Balanced Incomplete Block Design for (8,14,7,4,3)

The CLP Procedure

Solution Summary	
Solution Status	All Solutions
Variable Selection	FIFO
Value Selection	MAX
Solutions Found	92
Solution Time	0.11

Example 4.7: Progressive Party Problem

This example demonstrates the use of the PACK constraint to solve an instance of the progressive party problem (Smith et al. 1996). In the original progressive party problem, a number of yacht crews and their boats congregate at a yachting rally. In order for each crew to socialize with as many other crews as possible, some of the boats are selected to serve as "host boats" for six rounds of parties. The crews of the host boats stay with their boats for all six rounds. The crews of the remaining boats, called "guest crews," are assigned to visit a different host boat in each round.

Given the number of boats at the rally, the capacity of each boat, and the size of each crew, the objective of the original problem is to assign all the guest crews to host boats for each of the six rounds, using the minimum number of host boats. The partitioning of crews into guests and hosts is fixed throughout all rounds. No two crews should meet more than once. The assignments are constrained by the spare capacities (total capacity minus crew size) of the host boats and the crew sizes of the guest boats. Some boats cannot be hosts (zero spare capacity), and other boats must be hosts.

In this instance of the problem, the designation of the minimum requirement of thirteen hosts is assumed (boats 1 through 12 and 14). The formulation solves up to nine rounds in distributed mode with 142 workers. The total capacities and crew sizes of the boats are shown in Figure 4.5.

Figure 4.5 Progressive Party Problem Input

Progressive Party Problem Input

boatnum	capacity	crewsize
1	6	2
2	8	2
3	12	2
4	12	2
5	12	4
6	12	4
7	12	4
8	10	1
9	10	2
10	10	2
11	10	2
12	10	3
13	8	4
14	8	2
15	8	3
16	12	6
17	8	2
18	8	2
19	8	4
20	8	2
21	8	4

boatnum	capacity	crewsize
22	8	5
23	7	4
24	7	4
25	7	2
26	7	2
27	7	4
28	7	5
29	6	2
30	6	4
31	6	2
32	6	2
33	6	2
34	6	2
35	6	2
36	6	2
37	6	4
38	6	5
39	9	7
40	0	2
41	0	3
42	0	4

The following statements and DATA steps process the data and designate host boats:

```
data hostability;
   set capacities;
   spareCapacity = capacity - crewsize;
run;

data hosts guests;
   set hostability;
   if (boatnum <= 12 or boatnum eq 14) then do;
      output hosts;
   end;
   else do;
      output guests;
   end;
run;

/* sort so guest boats with larger crews appear first */
proc sort data=guests;
   by descending crewsize;
run;

data capacities;
   format boatnum capacity 2.;
   set hosts guests;
   seqno = _n_;
run;
```

To model the progressive party problem for the CLP solver, first define the following sets of variables:

- Item variables x_{it} contain the host boat number for the assignment of guest boat i in round t.
- Load variables L_{ht} contain the load of host boat h in round t.
- Variable m_{ijt} are binary variables that take a value of 1 if and only if guest boats i and j are assigned to the same host boat in round t.

Next, describe the set of constraints that are used in the model:

- Alldifferent constraints ensure that a guest boat is not assigned to the same host boat in different rounds.
- Reify constraints regulate the values that are assigned to the aforementioned indicator variables m_{ijt}.
- The reified indicator variables appear in linear constraints to enforce the requirement to meet no more than once.
- One pack constraint per round maintains the capacity limits of the host boats.
- Finally, a symmetry-breaking linear constraint orders the host boat assignments for the highest-numbered guest boat across rounds.

The following statements call the CLP procedure to define the variables, specify the constraints, and solve the problem.

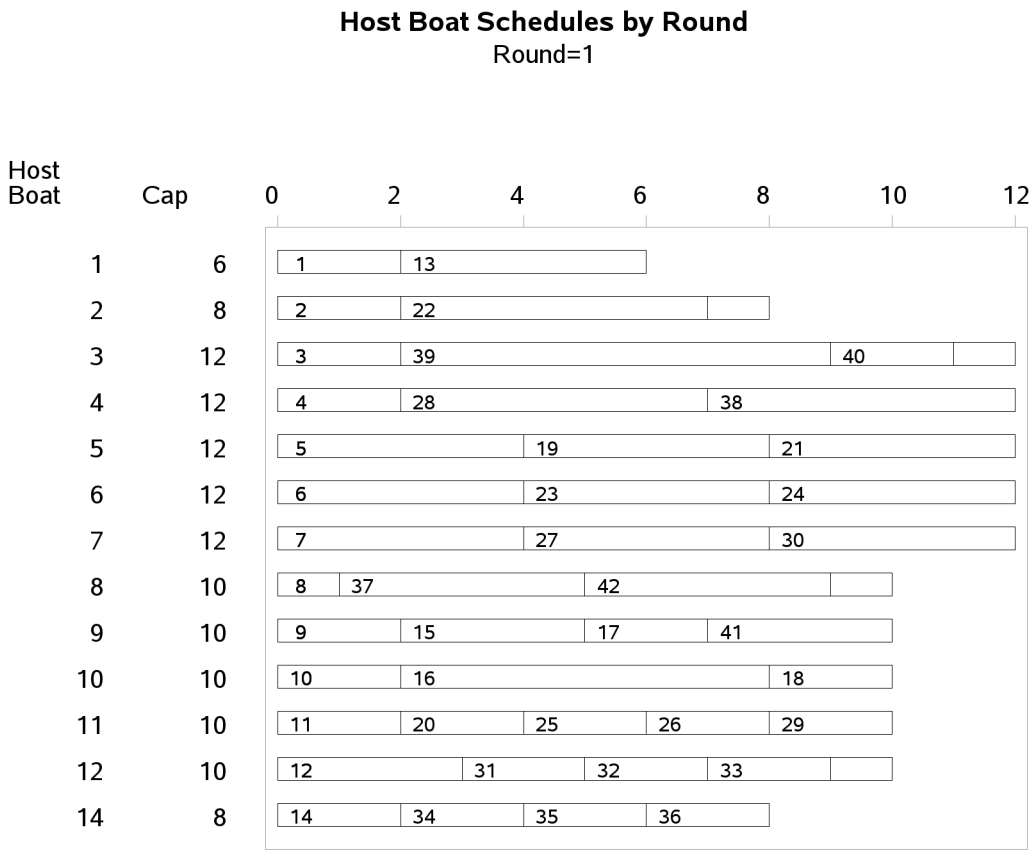
```
%let rounds=9;
%let numhosts=13;
%global maxcap;

%macro ppp(maxtime=600);
   proc sql noprint;
      select count(*) into :numboats from capacities;
      select max(capacity) into :maxcap from capacities;
      %do i = 0 %to &maxcap;
         select count(*) into :numclass_&i from capacities where capacity = &i;
      %end;
      select crewsize, spareCapacity into
         :crewsize_1-:crewsize_%scan(&numboats,1),
         :cap_1-:cap_%scan(&numboats,1) from capacities order by seqno;
   quit;

   proc clp out=mycas.out varselect=FIFO
            maxtime=&maxtime timetype=real;
      /* assume first &numhosts boats are hosts */
      /* process each round in turn */
      %do t = 1 %to &rounds;
         %do i = &numhosts+1 %to &numboats;
            /* boat i assigned host value for round t */
            var x_&i._&t = [1,&numhosts];
         %end;
         %do h = 1 %to &numhosts;
            var L_&h._&t = [0,&&cap_&h]; /* load of host boat */
         %end;
      %end;

      %do i = &numhosts+1 %to &numboats;
         /* assign different host each round */
         alldiff (x_&i._1-x_&i._&rounds);
      %end;

      %do t = 1 %to &rounds;
         %do i = &numhosts+1 %to &numboats-1;
            /* boat i assigned host value for round t */
            %do j = &i+1 %to &numboats;
               var m_&i._&j._&t = [0,1];
               reify m_&i._&j._&t : (x_&i._&t = x_&j._&t);
            %end;
         %end;
      %end;

      %do i = &numhosts+1 %to &numboats-1;
         %do j = &i+1 %to &numboats;
            lincon 1 >= 0
            %do t = 1 %to &rounds;
               + m_&i._&j._&t
            %end;
            ;
         %end;
```

```
      %end;

      /* honor capacities */
      %do t = 1 %to &rounds;
         PACK((
         %do i = &numhosts+1 %to &numboats;
            x_&i._&t
         %end;
         ) (
         %do i = &numhosts+1 %to &numboats;
            &&crewsize_&i
         %end;
         ) (
         %do h = 1 %to &numhosts;
            L_&h._&t
         %end;
         ));
      %end;

      /* break symmetries */
      %do t = 1 %to &rounds-1;
         lincon x_%scan(&numboats,1)_&t < x_%scan(&numboats,1)_%eval(&t+1);
      %end;

   run;
%mend ppp;

%ppp;
```

The two charts in Output 4.7.1 show the boat assignments for the first two rounds.

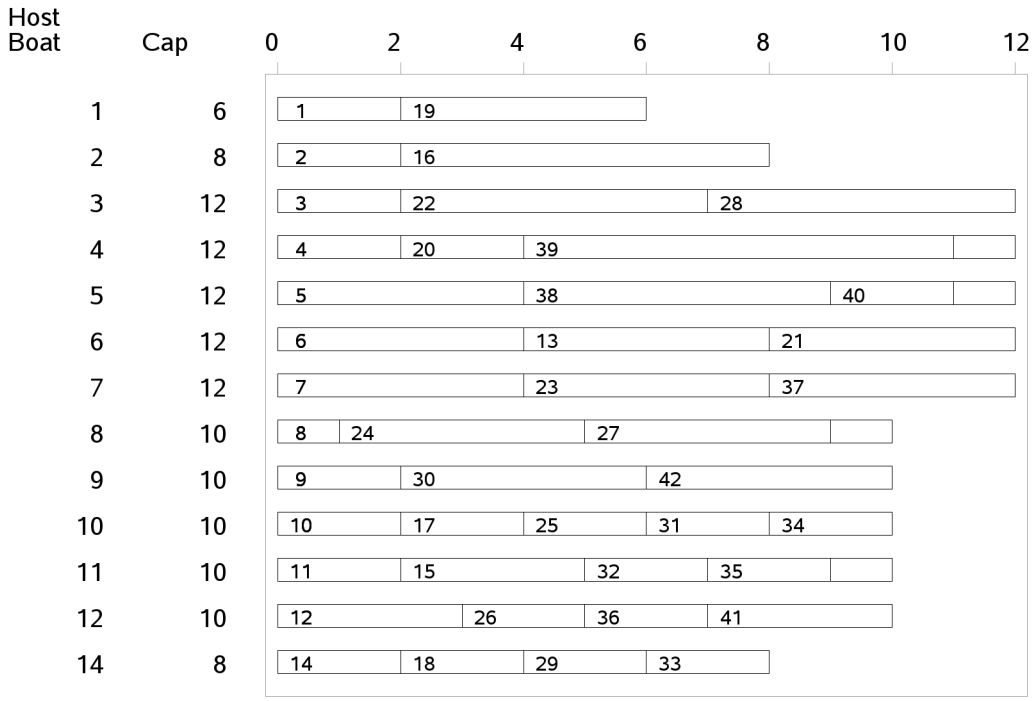
The first segment of each row indicates the host boat, and the remaining labeled segments indicate the guest boats that visit it. The horizontal axis represents host boat capacity. The length of each labeled segment indicates the crew size of the boat. The length of an unlabeled segment indicates excess capacity of the host boat.

Output 4.7.1 Gantt Chart: Host Boat Schedule by Round



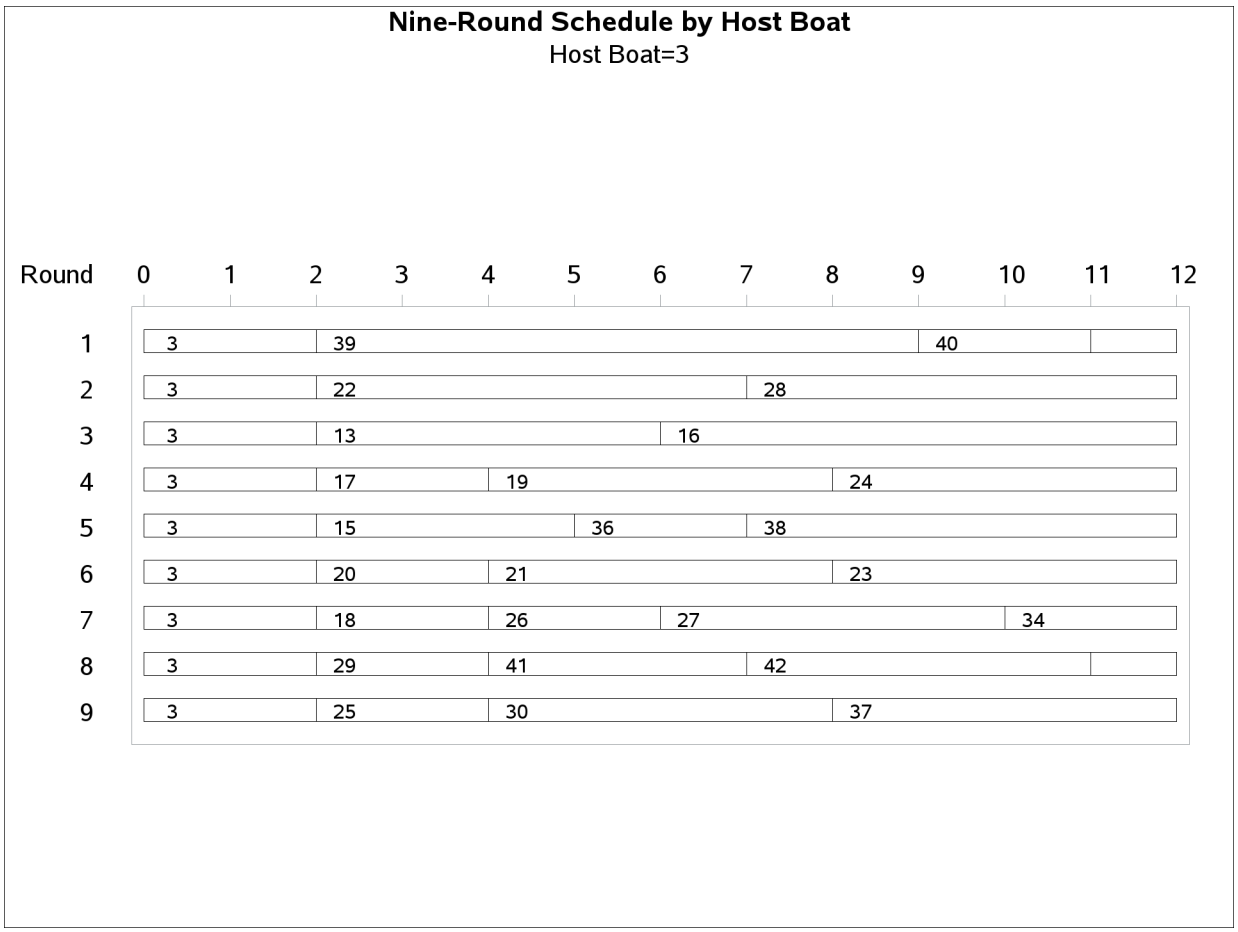
Output 4.7.1 *continued*

Host Boat Schedules by Round
Round=2



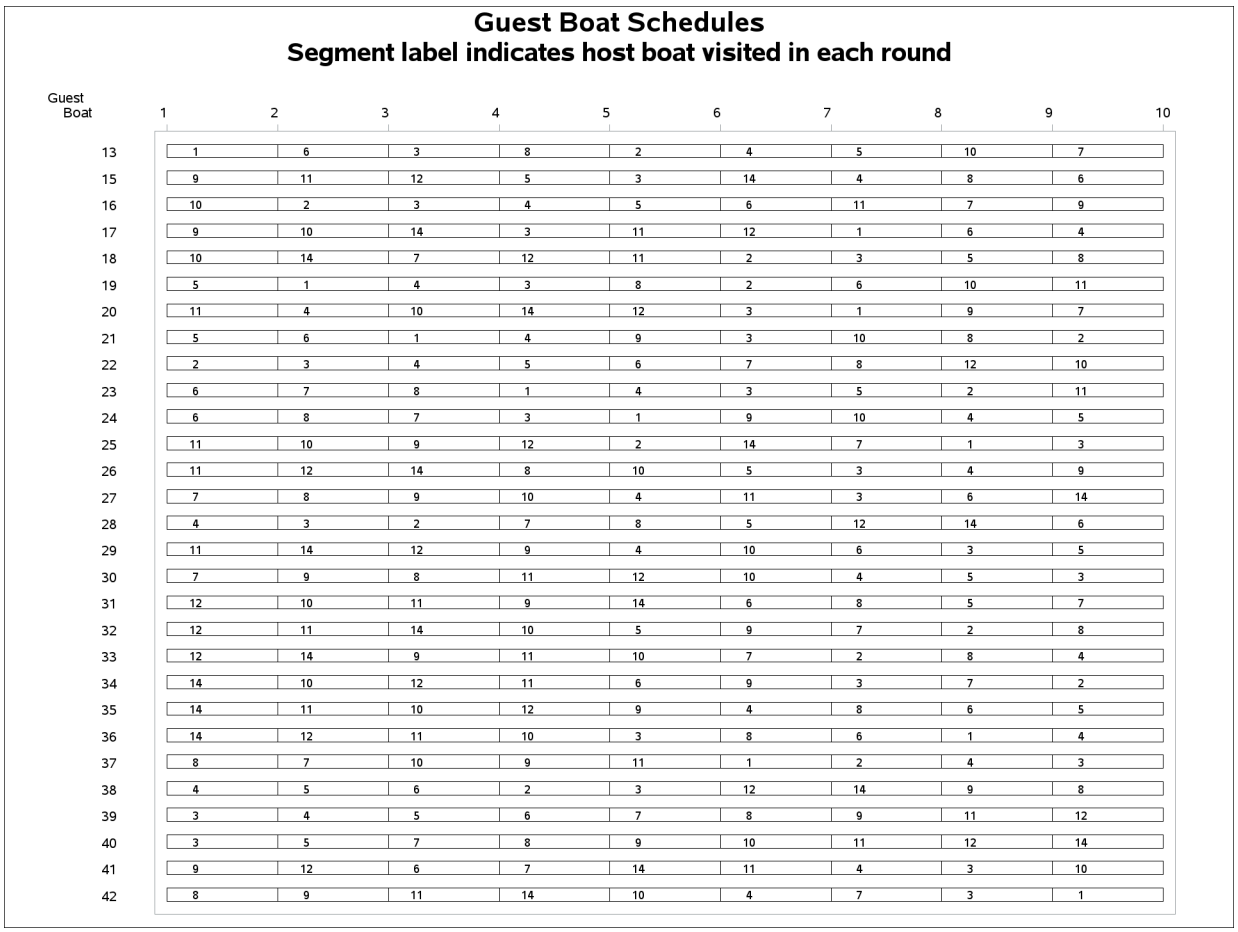
The chart in Output 4.7.2 shows all the guest boats that visit host boat 3 in each of the nine rounds. Once again, the horizontal axis represents capacity, and segment length indicates the crew size of the boat.

Output 4.7.2 Gantt Chart: Nine-Round Schedule by Host Boat



Finally, the chart in Output 4.7.3 displays the visitation schedule for all guest boats. The horizontal axis indicates the round, and the segment number identifies the host boat that is visited in that round.

Output 4.7.3 Gantt Chart: Guest Boat Schedules



Example 4.8: Radio Link Frequency Assignment Problem

This example uses element and reified constraints to solve a radio link frequency assignment problem (Cabon et al. 1999), in which frequencies must be assigned to communication links from limited spectral resources in such a way that no interference occurs. The simplest case is considered, with only two types of constraints:

- soft constraints that specify that the absolute difference between two frequencies should be greater than a given distance k; that is, $|f_x - f_y| > k$
- hard constraints that specify that the absolute difference between two frequencies should be exactly equal to a given distance k; that is, $|f_x - f_y| = k$

Violation of a soft constraint incurs a cost that depends on the cost category that is associated with the constraint.

The data for the CELAR6-SUB0 instance come from MiniZinc Challenge 2016 (Stuckey, Becket, and Fischer 2010), a partial description of which is shown in Table 4.9.

Table 4.9 Instance Data Description

Name	Description	Value
cost	Objective function weights	[1000, 100, 10, 1]
num_categories	Number of categories	2
categories	Domain categories for the frequency variables	[{16,30,44,. . . ,792}, {30,44,58,. . . ,778}]
min_freq	Minimum frequency	16
max_freq	Maximum frequency	792
num_variables	Number of frequency variables	32
domains	Domain category index for each variable	[1,1,1,1,1,1,1,1,2,2,. . . ,1]
num_hardconstraints	Number of hard constraints	16
hardctrx	Index x of each hard constraint	[1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31]
hardctry	Index y of each hard constraint	[2,4,6,8,10,12,14,16,18,20,22,24,26,28,30,32]
hardctrk	Given distance k between two frequencies for each hard constraint	[238,238,238,. . . ,238]
num_softconstraints	Number of soft constraints	207
softctrx	Index x of each soft constraint	[1,1,1,1,1,1,1,1,1,1,1,1,1,2,. . . ,30]
softctry	Index y of each soft constraint	[3,4,5,6,7,8,11,12,17,18,25,26,. . . ,31]
softctrk	Given distance k between two frequencies for each soft constraint	[59,186,10,186,168,56,91,265,26,. . . ,259]
softctrw	Cost categories for each soft constraint	[1,2,1,2,1,4,3,3,4,4,2,. . . ,3]

The instance data are used to generate the SAS macro variables that the CLP procedure uses. In the following SAS statements, f1-f&num_variables are the frequency variables. Other variables include TotalCost and several sets of binary variables for the element and reified constraints. A set of element constraints is created to ensure that each frequency variable takes a value from its noncontiguous domain. A set of linear and element constraints specifies the absolute difference between two frequencies to be the exact given distance. The soft constraints are implemented using binary variables and reified constraints. The binary variable ri indicates whether the corresponding soft constraint is violated and is used in the linear expression that represents the total cost.

```
%macro celar(maxtime);
   proc clp out=mycas.out varselect=wdeg maxtime=&maxtime timetype=real;
      /* Declare variables */
      var (f1-f&num_variables) = [&min_freq, &max_freq];
      var (TotalCost) = [0, 159];
      var eley = [1, 1];
      /* Each variable takes a value in its domain */
      %do i=1 %to &num_variables;
         %do j=1 %to &num_categories;
            %if (&&domain&i. eq &j.) %then %do;
               element(f&i., (&&elecategory&j.), eley);
            %end;
         %end;
      %end;
```

```
      /* Hard constraints */
      %do i=1 %to &num_hardconstraints;
         %let fx = f&&hardctrx&i.;
         %let fy = f&&hardctry&i.;
         %let k = &&hardctrk&i.;
         var (hx&i. hy&i.) = [%eval(-&k), &k];
         lincon hx&i. = &fx - &fy;
         element (hx&i. = (%eval(-&k), &k), (&k, &k), hy&i.);
      %end;

      /* Soft constraints */
      %do i=1 %to &num_softconstraints;
         %let fx = f&&softctrx&i.;
         %let fy = f&&softctry&i;
         var (sa1_&i. sa2_&i. sb1_&i. sb2_&i. ss&i. st&i. r&i.)=[0, 1];
         reify sa1_&i.: (&fx >= &fy);
         reify sa2_&i.: (&fx-&fy <= &&softctrk&i.);
         reify sb1_&i.: (&fx < &fy);
         reify sb2_&i.: (&fy-&fx <= &&softctrk&i.);
         reify ss&i.: (sa1_&i. + sa2_&i. = 2);
         reify st&i.: (sb1_&i. + sb2_&i. = 2);
         reify r&i.: (ss&i. + st&i. = 1);
      %end;

      /* Cost constraint */
      lincon TotalCost = &costw1 * r1
         %do i=2 %to &num_softconstraints;
             + &&costw&i. * r&i.
         %end;;
   run;
   %put &_orclp_;

%mend celar;
```

The following statement invokes the %celar macro with a maximum time of 60 seconds to find a feasible solution that corresponds to the known minimum cost of 159:

```
%celar(maxtime=60);
```

The solution summary that corresponds to running in distributed mode with 100 workers is shown in Output 4.8.1. By contrast, running in single-machine mode with a maximum time of 600 seconds failed to yield a solution.

Output 4.8.1 Radio Link Frequency Assignment Problem

The CLP Procedure

Solution Summary	
Solution Status	Solution Limit Reached
Variable Selection	WDEG
Value Selection	MIN
Solutions Found	1
Solution Time	45.927956

Example 4.9: Resource-Constrained Project Scheduling Problem with Time Windows

The general RCPSP/max (resource-constrained project scheduling problem with time windows) problem can be described as a single project that consists of a set of tasks (activities) that have to be scheduled. Each task requires time and renewable resources in order to be scheduled. In general, tasks are interrelated by two types of constraints:

- General temporal constraints restrict minimal and maximal time lags between two tasks. The temporal constraint between Task i and Task j has the form

  $$\text{start_time}[j] - \text{start_time}[i] \in [\mathrm{T}^{\min}_{i,j}, \mathrm{T}^{\max}_{i,j}]$$

  where $\mathrm{T}^{\min}_{i,j}$ and $\mathrm{T}^{\max}_{i,j}$ are the minimum and maximum time lags between tasks i and j.

- Resource constraints enforce the requirement that resource capacities are not exceeded at any time.

The objective of RCPSP/max is to find a feasible schedule that satisfies all temporal and resource constraints and that minimizes the makespan (duration) of the project.

Scheduling with Calendars

In many real-world scheduling problems, resources might not be available at all times, or they might have only partial capacities at some predetermined time periods (for example, because of weekends, holidays, or periods of machine maintenance). For each resource, a calendar indicates the time periods during which the resource is not available or has only partial capacity. The resource calendars impose additional restrictions on the problems.

This example illustrates the use of the cumulative constraint to model resource calendars in solving a single resource-constrained project scheduling problem.

This example considers a simple case of RCPSP/max that uses resource calendars and contains 12 uninterruptible tasks, each with fixed duration and demand. These tasks need to be scheduled on a single renewable resource that has a capacity of eight units. In addition, the resource has only half its capacity available during time period 5 and is unavailable in time period 6.

To simplify the specification, this example considers only the standard finish-to-start precedence relationships between two tasks. That is, Task i immediately precedes Task j, which implies:

$$\text{start_time}[j] - \text{start_time}[i] \geq \text{duration}[i]$$

More general forms of temporal relationships that involve nonstandard relationships and lags can be easily formulated using linear constraints.

Table 4.10 shows the durations, demands, and precedence relations of the tasks.

Table 4.10 Durations, Demands, and Successors of Tasks

Task	Duration	Demand	Successors
1	1	4	4
2	2	2	5
3	2	3	
4	6	3	
5	3	2	
6	6	3	12
7	1	1	8, 9, 10
8	3	2	11
9	3	2	12
10	4	1	12
11	2	2	12
12	4	2	

In order to accommodate the resource calendar, two artificial tasks, Task 13 and Task 14, are introduced, each with a duration of 1. Task 13 starts at time period 5 and uses four units of the resource, leaving half the capacity for other tasks during that period. Similarly, Task 14 starts at time period 6 and consumes the full capacity, thus making the corresponding resource unavailable to other tasks during that period.

Two additional tasks, S and T, are introduced to represent the beginning and completion of the project, respectively. The durations of both S and T are 0, and they do not require any of the resources. Note that the start time and the end time are equal for these two tasks. To simplify the notation, you can use S as the start-time variable of the project and T as the end-time variable. The makespan of the project can be expressed as T – S. Without loss of generality, the start time of the project is assumed to be 0, so that the objective of the problem is to minimize T.

There are two ways to declare start-time variables and specify temporal constraints:

- VARIABLE and LINCON statements
- Constraint data table

This example illustrates using the Constraint data table, which is created by merging three data sets. The StartTime data set, shown in Output 4.9.1, specifies the lower and upper bounds of the start-time variables for the real and artificial tasks. Note that the domains of artificial variables Start13, Start14, and S are fixed. A lower bound on variable T is determined by considering the (Task 6, Task 12) subpath, and an upper bound on T is determined by aggregating the durations of Task 1 through Task 14. The lower and upper bounds for the other variables are temporarily set to the lower bound of S and the upper bound of T, respectively, for convenience. Tighter bounds will be determined by the precedence constraints.

Output 4.9.1 StartTime Data Set

Obs	Start1	Start2	Start3	Start4	Start5	Start6	Start7	Start8	Start9	Start10	Start11	Start12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	40	40	40	40	40	40	40	40	40	40	40	40
3	.	.	.	.	.	.	.	.	.	.	.	.

Obs	Start13	Start14	S	T	_TYPE_	_RHS_
1	.	.	.	10	LOWERBD	.
2	.	.	.	40	UPPERBD	.
3	5	6	0	.	FIXED	.

The Precedence data set shown in Output 4.9.2 specifies linear constraints that represent the precedence relations between tasks.

Output 4.9.2 Precedence Constraints

Obs	S	Start1	Start2	Start3	Start4	Start5	Start6	Start7	Start8	Start9	Start10	Start11	Start12	T	_TYPE_	_RHS_
1	-1	1	.	.	.	.	.	.	.	.	.	.	.	.	GE	0
2	-1	.	1	.	.	.	.	.	.	.	.	.	.	.	GE	0
3	-1	.	.	1	.	.	.	.	.	.	.	.	.	.	GE	0
4	-1	.	.	.	.	.	1	.	.	.	.	.	.	.	GE	0
5	-1	.	.	.	.	.	.	1	.	.	.	.	.	.	GE	0
6	.	-1	.	.	1	.	.	.	.	.	.	.	.	.	GE	1
7	.	.	-1	.	.	1	.	.	.	.	.	.	.	.	GE	2
8	.	.	.	-1	.	.	.	.	.	.	.	.	.	1	GE	2
9	.	.	.	.	-1	.	.	.	.	.	.	.	.	1	GE	6
10	.	.	.	.	.	-1	.	.	.	.	.	.	.	1	GE	3
11	.	.	.	.	.	.	-1	.	.	.	.	.	1	.	GE	6
12	.	.	.	.	.	.	.	-1	1	.	.	.	.	.	GE	1
13	.	.	.	.	.	.	.	-1	.	1	.	.	.	.	GE	1
14	.	.	.	.	.	.	.	-1	.	.	1	.	.	.	GE	1
15	.	.	.	.	.	.	.	.	-1	.	.	1	.	.	GE	3
16	.	.	.	.	.	.	.	.	.	-1	.	.	1	.	GE	3
17	.	.	.	.	.	.	.	.	.	.	-1	.	1	.	GE	4
18	.	.	.	.	.	.	.	.	.	.	.	-1	1	.	GE	2
19	.	.	.	.	.	.	.	.	.	.	.	.	-1	1	GE	4

Finally, the Objective data set shown in Output 4.9.3 specifies the objective function of this problem.

Output 4.9.3 Objective Function

Obs	T	_TYPE_	_RHS_
1	1	MIN	.

The following statements merge these three data sets to create the Constraint data table that the CLP procedure uses to find a schedule that minimizes the makespan. These statements assume that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
data mycas.ConData;
   set StartTime Precedence Objective;
run;



proc clp condata=mycas.ConData out=mycas.OutData usecondatavars=1;
   /* set lower and upper bounds for the objective function */
   obj lb=10 ub=40;

   /* Post a cumulative constraint for the resource */
   cumulative (start=(Start1-Start14)
               duration=(1 2 2 6 3 6 1 3 3 4 2 4 1 1)
               demand=(4 2 3 3 2 3 1 2 2 1 2 2 4 8)
               capacity=8);
run;
```

The USECONDATAVARS=1 specification in the PROC CLP statement indicates that all variables are implicitly defined in the Constraint data table ConData. The OBJ statement specifies the lower and upper bounds on the objective function. In this example, they are actually the lower and upper bounds of variable T, the completion time of the project. The CUMULATIVE statement defines the task start times, task durations, and task demands, and it enforces the constraint that the cumulative resource usage of Task 1 though Task 14 not exceed the resource capacity at any point in time.

The solution summary, displayed in Output 4.9.4, reports that the minimum makespan of the problem is 14 time periods.

Output 4.9.4 Solution Summary Showing Minimum Makespan

The CLP Procedure

Solution Summary	
Solution Status	Optimal
Variable Selection	MINR
Value Selection	MIN
Objective Sense	Minimization
Objective Value	14
Solutions Found	1
Solution Time	0.04

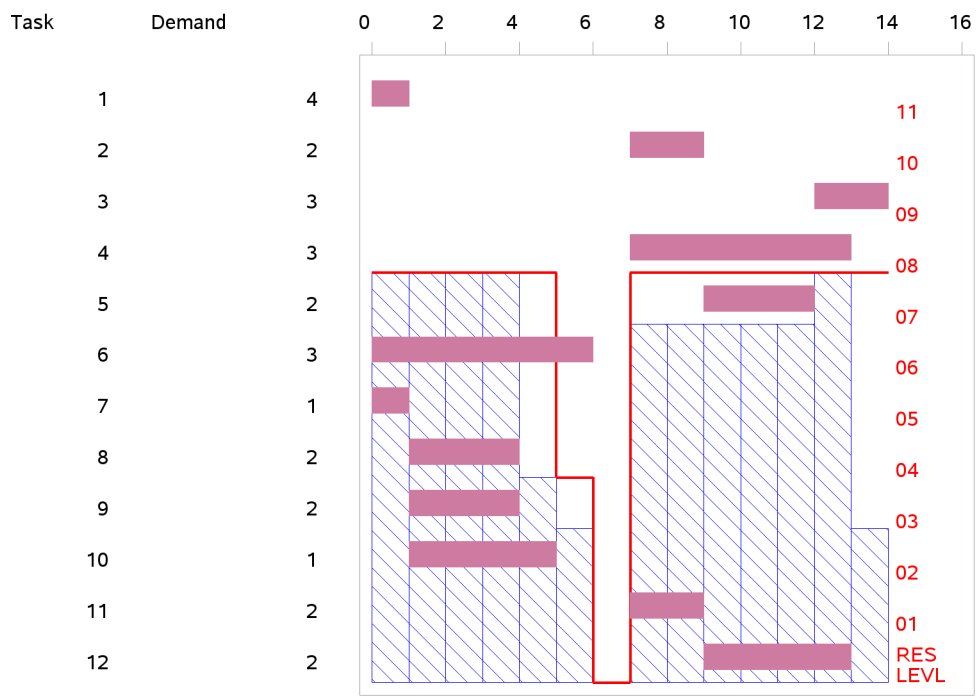
The table in Output 4.9.5, which is derived from the solution table, shows a corresponding schedule for the 12 tasks.

Output 4.9.5 RCPSP/max Schedule with Calendars

Task	Start	Duration	End	Demand
1	0	1	1	4
2	7	2	9	2
3	12	2	14	3
4	7	6	13	3
5	9	3	12	2
6	0	6	6	3
7	0	1	1	1
8	1	3	4	2
9	1	3	4	2
10	1	4	5	1
11	7	2	9	2
12	9	4	13	2

The Gantt chart shown in Output 4.9.6 reports the resource demand and displays the resource-constrained schedule for each of the 12 tasks. The chart also overlays a plot of the resource capacity with time and a histogram of the resource demand with time. The resource quantity axis is on the right. Notice the decreased consumption in time periods 5 and 6.

Output 4.9.6 Gantt Chart Showing Task Schedule and Resource Consumption



Scheduling with Optional Tasks

The second part of this example illustrates how you can use the cumulative constraint to model optional tasks. Optional tasks are tasks that might or might not occur; they can arise in scenarios such as project selection, job contracting, and so on.

Consider the previous resource-constrained project scheduling problem with calendars that completed in 14 time periods. Suppose that the project must now be completed in 12 time periods and can assign certain tasks to external contractors at additional cost in order to complete in fewer time periods. Assume that Task 1, Task 2, Task 3, Task 4, and Task 5 can be contracted out subject to the following pairwise conditions:

- If Task 1 is contracted out, then Task 4 also be contracted out, and vice-versa. The cost of jointly contracting out Task 1 and Task 4 is $15,000.
- Similarly, Task 2 and Task 5 must be either jointly contracted out or processed in-house together. The cost of jointly contracting out Task 2 and Task 5 is $12,000.
- The cost of contracting out Task 3 is $5,000.

The objective is to minimize the total cost, subject to finishing the project within 12 time periods.

The StartTime*2* data set shown in Output 4.9.7 specifies the new lower and upper bounds of the start-time variables for all tasks. Note that the variable T is now fixed to 12 to reflect the new makespan restriction. Although not necessary, the upper bounds of all variables Start1 to Start12 can also be set to 12.

Output 4.9.7 StartTime2 Data Set

Obs	Start1	Start2	Start3	Start4	Start5	Start6	Start7	Start8	Start9	Start10	Start11	Start12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	12	12	12	12	12	12	12	12	12	12	12	12
3	.	.	.	.	.	.	.	.	.	.	.	.

Obs	Start13	Start14	S	T	_TYPE_	_RHS_
1	.	.	.	.	LOWERBD	.
2	.	.	.	.	UPPERBD	.
3	5	6	0	12	FIXED	.

One way to model the fact that tasks might or might not be executed in-house is to introduce a demand variable for each such task. The lower bound for this demand variable is equal to 0, and its upper bound is equal to the demand it would have had if it had been processed in-house. The demand variable for a task is assigned to its lower bound if the task is contracted out, or to its upper bound if the task is not contracted out. The usage variables are declared in the Demand data set as shown in Output 4.9.8.

Output 4.9.8 Demand Data Set

Obs	Demand1	Demand2	Demand3	Demand4	Demand5	Demand6	Demand7	Demand8	Demand9
1	0	0	0	0	0	.	.	.	.
2	4	2	3	3	2	.	.	.	.
3	.	.	.	.	.	2	1	1	2

Obs	Demand10	Demand11	Demand12	Demand13	Demand14	_TYPE_	_RHS_
1	.	.	.	.	.	LOWERBD	.
2	.	.	.	.	.	UPPERBD	.
3	1	2	2	4	8	FIXED	.

A binary variable is created for each task that can be contracted out. The value of the binary variable is 1 if the corresponding task is contracted out, or 0 if is not contracted out. The relationship between the binary variable X_i and demand variable Demand_i for task i can be expressed by the linear constraint

$$\mathrm{Demand}_i = \mathrm{demand}[i] \times (1 - \mathrm{X}_i)$$

where $\mathrm{demand}[i]$ is the demand for the task i.

Because Tasks 1 and 4 and Tasks 2 and 5 must be jointly processed, the number of binary variables can be reduced to three.

$$X_1 = \begin{cases} 1 & \text{if Task 1 and Task 4 are contracted out} \\ 0 & \text{otherwise} \end{cases}$$

$$X_2 = \begin{cases} 1 & \text{if Task 2 and Task 5 are contracted out} \\ 0 & \text{otherwise} \end{cases}$$

$$X_3 = \begin{cases} 1 & \text{if Task 3 is contracted out} \\ 0 & \text{otherwise} \end{cases}$$

The Binary data set shown in Output 4.9.9 declares these three binary variables.

Output 4.9.9 Binary Variables

Obs	X1	X2	X3	_TYPE_	_RHS_
1	1	1	1	BINARY	.

The Usage data set shown in Output 4.9.10 contains the linear constraints that relate the binary variables and the demand variables.

Output 4.9.10 Usage Constraints

Obs	Demand1	Demand2	Demand3	Demand4	Demand5	X1	X2	X3	_TYPE_	_RHS_
1	1	.	.	.	.	4	.	.	EQ	4
2	.	1	.	.	.	.	2	.	EQ	2
3	.	.	1	.	.	.	.	3	EQ	3
4	.	.	.	1	.	3	.	.	EQ	3
5	.	.	.	.	1	.	2	.	EQ	2

Finally, the objective function shown in Output 4.9.11 defines the total contracting cost of the project that is to be minimized.

Output 4.9.11 Objective Function

Obs	X1	X2	X3	_TYPE_	_RHS_
1	15	12	5	MIN	.

As before, the data sets are merged to create the Constraint data table, and the CLP procedure is invoked to find the best solution as follows:

```
data mycas.ConData2;
   set StartTime2 Precedence Demand Binary Usage Objective2;
run;


proc clp condata=mycas.ConData2 out=mycas.OutData2 usecondatavars=1;
   /* set lower and upper bounds for the objective function */
   obj lb=0 ub=32;

   /* Define a cumulative constraint for the resource */
   cumulative (start=(Start1-Start14)
               demand=(Demand1-Demand14)
               dur=(1 2 2 6 3 6 1 3 3 4 2 4 1 1)
               capacity=8);
run;
```

The solution summary, shown in Output 4.9.12, indicates that the optimal cost of completing the project within the desired time frame of 12 time periods is $15,000.

Output 4.9.12 Solution Summary Showing Minimum Cost

The CLP Procedure

Solution Summary	
Solution Status	Optimal
Variable Selection	MINR
Value Selection	MIN
Objective Sense	Minimization
Objective Value	15
Solutions Found	1
Solution Time	0

The table in Output 4.9.13, derived from the Solution data table, displays the optimal schedule that has a makespan of 11 time periods and contracts out Task 1 and Task 4.

Output 4.9.13 RCPSP Schedule with Optional Tasks

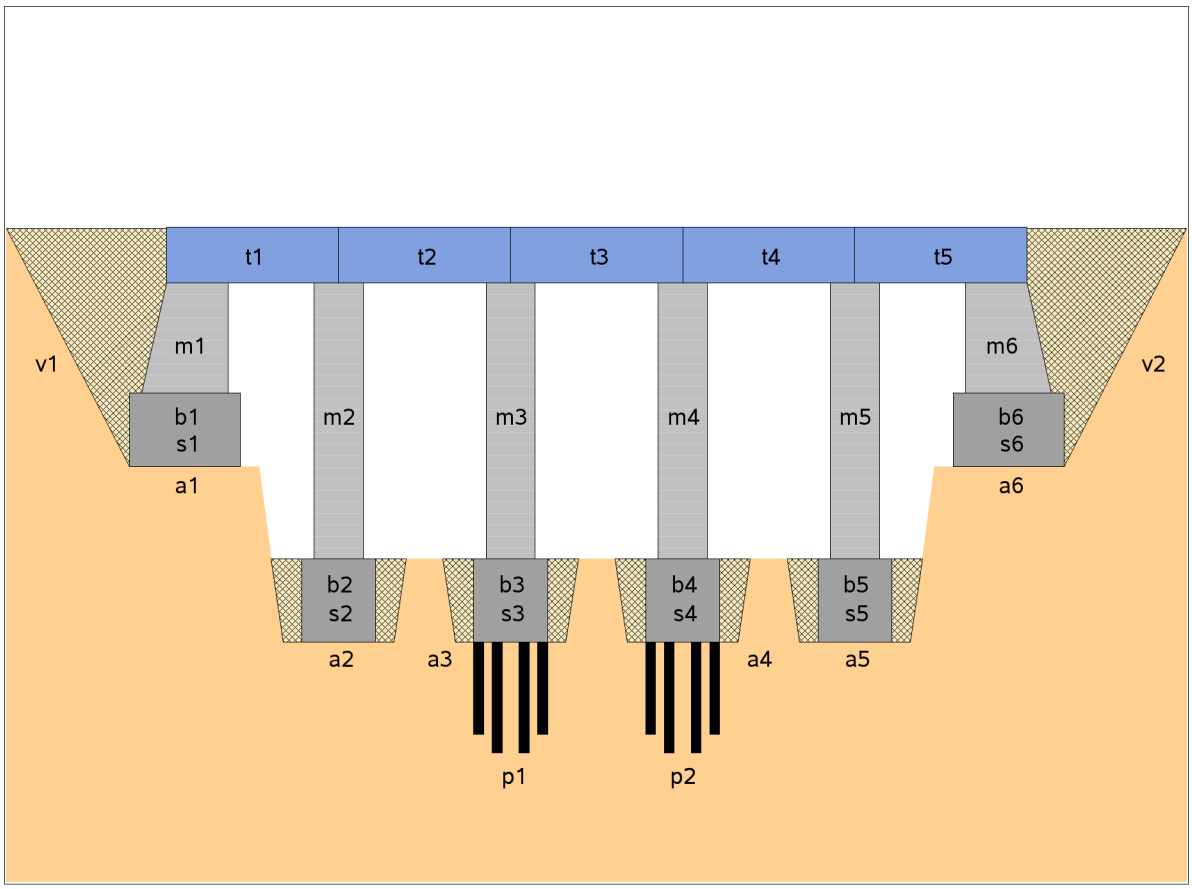
Task	Start	Duration	End	Demand
2	0	2	2	2
3	7	2	9	3
5	2	3	5	2
6	0	6	6	2
7	0	1	1	1
8	1	3	4	1
9	1	3	4	2
10	1	4	5	1
11	4	2	6	2
12	7	4	11	2

Example 4.10: Resource-Constrained Scheduling Problem with Nonstandard Temporal Constraints

This example illustrates the use of the cumulative constraint to solve a resource-constrained project scheduling problem that has nonstandard temporal constraints.

For more information about this example, see the same example in *SAS/OR User's Guide: Constraint Programming*, which illustrates the capabilities of the scheduling solver.

Output 4.10.1 The Bridge Problem



The project consists of 44 tasks and a set of constraints that relate these tasks. Table 4.11 displays the activity information, standard precedence constraints, and resource constraints. The sharing of a unary resource by multiple activities results in the resource constraints being disjunctive in nature.

Table 4.11 Data for Bridge Construction

Activity	Description	Duration	Predecessors	Resource
pa	Beginning of project	0		
a1	Excavation (abutment 1)	4	pa	Excavator
a2	Excavation (pillar 1)	2	pa	Excavator
a3	Excavation (pillar 2)	2	pa	Excavator
a4	Excavation (pillar 3)	2	pa	Excavator
a5	Excavation (pillar 4)	2	pa	Excavator
a6	Excavation (abutment 2)	5	pa	Excavator
p1	Foundation piles 2	20	a3	Pile driver
p2	Foundation piles 3	13	a4	Pile driver
ue	Erection of temporary housing	10	pa	
s1	Formwork (abutment 1)	8	a1	Carpentry
s2	Formwork (pillar 1)	4	a2	Carpentry

Table 4.11 *continued*

Activity	Description	Duration	Predecessors	Resource
s3	Formwork (pillar 2)	4	p1	Carpentry
s4	Formwork (pillar 3)	4	p2	Carpentry
s5	Formwork (pillar 4)	4	a5	Carpentry
s6	Formwork (abutment 2)	10	a6	Carpentry
b1	Concrete foundation (abutment 1)	1	s1	Concrete mixer
b2	Concrete foundation (pillar 1)	1	s2	Concrete mixer
b3	Concrete foundation (pillar 2)	1	s3	Concrete mixer
b4	Concrete foundation (pillar 3)	1	s4	Concrete mixer
b5	Concrete foundation (pillar 4)	1	s5	Concrete mixer
b6	Concrete foundation (abutment 2)	1	s6	Concrete mixer
ab1	Concrete setting time (abutment 1)	1	b1	
ab2	Concrete setting time (pillar 1)	1	b2	
ab3	Concrete setting time (pillar 2)	1	b3	
ab4	Concrete setting time (pillar 3)	1	b4	
ab5	Concrete setting time (pillar 4)	1	b5	
ab6	Concrete setting time (abutment 2)	1	b6	
m1	Masonry work (abutment 1)	16	ab1	Bricklaying
m2	Masonry work (pillar 1)	8	ab2	Bricklaying
m3	Masonry work (pillar 2)	8	ab3	Bricklaying
m4	Masonry work (pillar 3)	8	ab4	Bricklaying
m5	Masonry work (pillar 4)	8	ab5	Bricklaying
m6	Masonry work (abutment 2)	20	ab6	Bricklaying
l	Delivery of the preformed bearers	2		Crane
t1	Positioning (preformed bearer 1)	12	m1, m2, l	Crane
t2	Positioning (preformed bearer 2)	12	m2, m3, l	Crane
t3	Positioning (preformed bearer 3)	12	m3, m4, l	Crane
t4	Positioning (preformed bearer 4)	12	m4, m5, l	Crane
t5	Positioning (preformed bearer 5)	12	m5, m6, l	Crane
ua	Removal of the temporary housing	10		
v1	Filling 1	15	t1	Caterpillar
v2	Filling 2	10	t5	Caterpillar
pe	End of project	0	t2, t3, t4, v1, v2, ua	

The following constraints are added to the standard precedence constraints:

- The time between the completion of a particular formwork and the completion of its corresponding concrete foundation is at most four days:

$$f(\mathrm{s}i) \geq f(\mathrm{b}i) - 4, \quad i = 1, \ldots, 6$$

- There are at most three days between the end of a particular excavation (or foundation piles) and the beginning of the corresponding formwork:

$$f(\mathrm{a}i) \geq s(\mathrm{s}i) - 3, \quad i = 1, 2, 5, 6$$

and

$$f(\mathrm{p1}) \geq s(\mathrm{s3}) - 3$$

$$f(\mathrm{p2}) \geq s(\mathrm{s4}) - 3$$

- The formworks must start at least six days after the beginning of the erection of the temporary housing:

$$s(\mathrm{s}i) \geq s(\mathrm{ue}) + 6, \quad i = 1, \ldots, 6$$

- The removal of the temporary housing can start at most two days before the end of the last masonry work:

$$s(\mathrm{ua}) \geq f(\mathrm{m}i) - 2, \quad i = 1, \ldots, 6$$

- The delivery of the preformed bearers occurs exactly 30 days after the beginning of the project:

$$s(\mathrm{l}) = s(\mathrm{pa}) + 30$$

For convenience, the activity name is used to represent the start time variable of the activity. Each temporal constraint is represented by a linear constraint in the Constraint data table. An additional observation is added to the Constraint data table to define the objective of minimizing the makespan, which in this case is the milestone pe, indicating the end of the project. The CLP procedure is invoked with the WDEG variable selection strategy along with seven cumulative constraints, one corresponding to each of the resources: Excavator, Pile Driver, Carpentry, Concrete Mixer, Bricklaying, Crane, and Caterpillar.

```
proc clp condata=mycas.condata varselect=wdeg out=mycas.out usecondatavars=1;
   obj lb=0 ub=2000;
   cumulative (start=( m1-m6 ) dur=( 16 8 8 8 8 20 ))
              (start=( s1-s6 ) dur=( 8 4 4 4 4 10 ))
              (start=( v1 v2 ) dur=( 15 10 ))
              (start=( b1-b6 ) dur=( 1 1 1 1 1 1))
              (start=( l t1-t5 ) dur=( 2 12 12 12 12 12 ))
              (start=( a1-a6 ) dur=( 4 2 2 2 2 5))
              (start=( p1 p2 ) dur=( 20 13 ));
run;
```

The solution summary shown in Output 4.10.2 reports an optimal objective value of 104 days.

Output 4.10.2 Bridge Construction Solution Summary

The CLP Procedure

Solution Summary	
Solution Status	Optimal
Variable Selection	WDEG
Value Selection	MIN
Objective Sense	Minimization
Objective Value	104
Solutions Found	1
Solution Time	3.59

The solution data table shown in Output 4.10.3 displays the corresponding start times for all the tasks.

Output 4.10.3 Bridge Construction Task Start Times

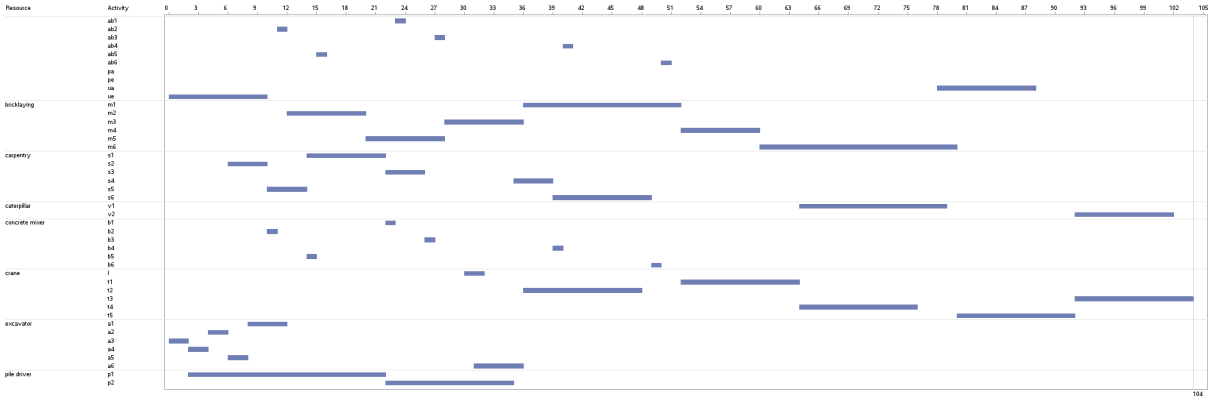
s1	a1	s2	a2	p1	a3	p2	a4	s5	a5	s6	a6	m1	ab1	m2	ab2	m3	ab3	m4	ab4	m5	ab5	m6	ab6	b1	b2
14	8	6	4	2	0	22	2	10	6	39	31	36	23	12	11	28	27	52	40	20	15	60	50	22	10

b3	s3	b4	s4	b5	b6	t1	l	t2	t3	t4	t5	ua	pa	ue	v1	pe	v2
26	22	39	35	14	49	52	30	36	92	64	80	78	0	0	64	104	92

A Gantt chart of the resulting schedule, zoned by resource, is shown in Output 4.10.4.

Output 4.10.4 Bridge Construction Schedule

Zoned by Resource



Statement and Option Cross-Reference Table

Table 4.12 shows which examples in this section use each of the statements and options in the CLP procedure.

Table 4.12 Statements and Options Specified in Examples 4.1–4.10

Statement	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
ALLDIFF	X	X			X		X			
CUMULATIVE									X	X
ELEMENT		X		X	X			X		
GCC	X		X	X		X				
LEXICO						X				
LINCON	X	X	X	X	X		X	X		
OBJ			X						X	X
PACK							X			
REIFY		X			X	X	X	X		
VARIABLE	X	X	X	X	X	X	X	X		
Option	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
CONDATA=			X						X	X
DOMAIN=						X	X			
EVALVARSEL=	X									
FINDALLSOLNS		X		X	X					
LB=			X						X	X
MAXTIME=	X						X	X		
OUT=	X	X	X	X	X	X	X	X	X	X
UB=			X						X	X
USECONDATAVARS=									X	X
VARASSIGN=						X				
VARSELECT=	X		X	X	X	X	X	X		X

References

Applegate, D. L., and Cook, W. (1991). "A Computational Study of the Job Shop Scheduling Problem." *ORSA Journal on Computing* 3:149–156.

Boussemart, F., Hemery, F., Lecoutre, C., and Sais, L. (2004). "Boosting Systematic Search by Weighting Constraints." In *ECAI 2004: Proceedings of the Sixteenth European Conference on Artificial Intelligence*, 146–150. Amsterdam: IOS Press.

Brualdi, R. A. (2010). *Introductory Combinatorics*. 5th ed. Englewood Cliffs, NJ: Prentice-Hall.

Cabon, B., de Givry, S., Lobjois, L., Schiex, T., and Warners, J. P. (1999). "Radio Link Frequency Assignment." *Constraints* 4:79–89.

Carlier, J., and Pinson, E. (1989). "An Algorithm for Solving the Job-Shop Scheduling Problem." *Management Science* 35:164–176.

Colmerauer, A. (1990). "An Introduction to PROLOG III." *Communications of the ACM* 33:70–90.

Dincbas, M., Simonis, H., and Van Hentenryck, P. (1988). "Solving the Car-Sequencing Problem in Constraint Logic Programming." In *Proceedings of the European Conference on Artificial Intelligence, ECAI-88*, edited by Y. Kodratoff, 290–295. London: Pitman.

Flener, P., Frisch, A. M., Hnich, B., Kiziltan, Z., Miguel, I., Pearson, J., and Walsh, T. (2002). "Breaking Row and Column Symmetries in Matrix Models." In *Proceedings of the Eighth International Conference on Principles and Practice of Constraint Programming (CP 2002)*, edited by P. Van Hentenryck, 462–476. Berlin: Springer-Verlag.

Floyd, R. W. (1967). "Nondeterministic Algorithms." *Journal of the ACM* 14:636–644.

Frisch, A. M., Hnich, B., Kiziltan, Z., Miguel, I., Pearson, J., and Walsh, T. (2002). "Global Constraints for Lexicographic Orderings." In *Proceedings of the Eighth International Conference on Principles and Practice of Constraint Programming (CP 2002)*, edited by P. Van Hentenryck, 93–108. Berlin: Springer-Verlag.

Garey, M. R., and Johnson, D. S. (1979). *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York: W. H. Freeman.

Gravel, M., Gagne, C., and Price, W. L. (2005). "Review and Comparison of Three Methods for the Solution of the Car Sequencing Problem." *Journal of the Operational Research Society* 56:1287–1295.

Haralick, R. M., and Elliott, G. L. (1980). "Increasing Tree Search Efficiency for Constraint Satisfaction Problems." *Artificial Intelligence* 14:263–313.

Henz, M. (2001). "Scheduling a Major College Basketball Conference—Revisited." *Operations Research* 49:163–168.

Jaffar, J., and Lassez, J. (1987). "Constraint Logic Programming." In *Proceedings of the Fourteenth Annual ACM SIGACT-SIGPLAN Symposium on Principles of Programming Languages*, 111–119. New York: Association for Computing Machinery.

Kumar, V. (1992). "Algorithms for Constraint-Satisfaction Problems: A Survey." *AI Magazine* 13:32–44.

Mackworth, A. K. (1977). "Consistency in Networks of Relations." *Artificial Intelligence* 8:99–118.

Meseguer, P., and Torras, C. (2001). "Exploiting Symmetries within Constraint Satisfaction Search." *Artificial Intelligence* 129:133–163.

Muth, J. F., and Thompson, G. L., eds. (1963). *Industrial Scheduling*. Englewood Cliffs, NJ: Prentice-Hall.

Nemhauser, G. L., and Trick, M. A. (1998). "Scheduling a Major College Basketball Conference." *Operations Research* 46:1–8.

Nemhauser, G. L., and Wolsey, L. A. (1988). *Integer and Combinatorial Optimization*. New York: John Wiley & Sons.

Prestwich, S. D. (2001). "Balanced Incomplete Block Design as Satisfiability." In *Twelfth Irish Conference on Artificial Intelligence and Cognitive Science*, 189–198. Maynooth: National University of Ireland.

Riley, P., and Taalman, L. (2008). "Brainfreeze Puzzles." http://www.geekhaus.com/brainfreeze/piday2008.html.

Smith, B. M., Brailsford, S. C., Hubbard, P. M., and Williams, H. P. (1996). "The Progressive Party Problem: Integer Linear Programming and Constraint Programming Compared." *Constraints* 1:119–138.

Sokol, J. (2002). "Modeling Automobile Paint Blocking: A Time Window Traveling Salesman Problem." Ph.D. diss., Massachusetts Institute of Technology.

Solnon, C., Cung, V. D., Nguyen, A., and Artigues, C. (2008). "The Car Sequencing Problem: Overview of State-of-the-Art Methods and Industrial Case-Study of the ROADEF 2005 Challenge Problem." *European Journal of Operational Research* 191:912–927.

Stuckey, P., Becket, R., and Fischer, J. (2010). "Philosophy of the MiniZinc Challenge." *Constraints* 15:307–316.

Trick, M. A. (2004). "Constraint Programming: A Tutorial." https://mat.tepper.cmu.edu/trick/cp.ppt.

Tsang, E. (1993). *Foundations of Constraint Satisfaction*. London: Academic Press.

Van Hentenryck, P. (1989). *Constraint Satisfaction in Logic Programming*. Cambridge, MA: MIT Press.

Van Hentenryck, P. (2002). "Constraint and Integer Programming in OPL." *INFORMS Journal on Computing* 14:345–372.

Van Hentenryck, P., Deville, Y., and Teng, C. (1992). "A Generic Arc-Consistency Algorithm and Its Specializations." *Artificial Intelligence* 57:291–321.

Vilím, P. (2011). "Timetable Edge Finding Filtering Algorithm for Discrete Cumulative Resources." In *Integration of AI and OR Techniques in Constraint Programming for Combinatorial Optimization Problems (CPAIOR 2011)*, edited by T. Achterberg and J. C. Beck, vol. 6697 of Lecture Notes in Computer Science, 230–245. Heidelberg: Springer.

Waltz, D. L. (1975). "Understanding Line Drawings of Scenes with Shadows." In *The Psychology of Computer Vision*, edited by P. H. Winston, 19–91. New York: McGraw-Hill.

Williams, H. P., and Wilson, J. M. (1998). "Connections between Integer Linear Programming and Constraint Logic Programming: An Overview and Introduction to the Cluster of Articles." *INFORMS Journal on Computing* 10:261–264.

Chapter 5
The OPTLP Procedure

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Overview: OPTLP Procedure

The OPTLP procedure provides four methods of solving linear programs (LPs). A linear program has the following formulation:

$$\begin{aligned} \min \quad & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} \quad & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{aligned}$$

where

$\mathbf{x}$	$\in$	$\mathbb{R}^n$	is the vector of decision variables
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the matrix of constraints
$\mathbf{c}$	$\in$	$\mathbb{R}^n$	is the vector of objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^m$	is the vector of constraints' right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^n$	is the vector of lower bounds on variables
$\mathbf{u}$	$\in$	$\mathbb{R}^n$	is the vector of upper bounds on variables

The following LP algorithms are available in the OPTLP procedure:

- primal simplex algorithm
- dual simplex algorithm
- network simplex algorithm
- interior point algorithm

The primal and dual simplex algorithms implement the two-phase simplex method. In phase I, the algorithm tries to find a feasible solution. If no feasible solution is found, the LP is infeasible; otherwise, the algorithm enters phase II to solve the original LP. The network simplex algorithm extracts a network substructure, solves this using network simplex, and then constructs an advanced basis to feed to either primal or dual simplex. The interior point algorithm implements a primal-dual predictor-corrector interior point algorithm.

PROC OPTLP requires a linear program to be specified using a data table that adheres to the MPS format, a widely accepted format in the optimization community. For details about the MPS format see Chapter 8, "The MPS-Format Data Table."

Getting Started: OPTLP Procedure

The following example illustrates how you can use the OPTLP procedure to solve linear programs. Suppose you want to solve the following problem:

$$
\begin{array}{rrcrcrcrl}
\min & 2x_1 & - & 3x_2 & - & 4x_3 & & & \\
\text{subject to} & & - & 2x_2 & - & 3x_3 & \geq & -5 & \text{(R1)} \\
 & x_1 & + & x_2 & + & 2x_3 & \leq & 4 & \text{(R2)} \\
 & x_1 & + & 2x_2 & + & 3x_3 & \leq & 7 & \text{(R3)} \\
 & & & x_1, & x_2, & x_3 & \geq & 0 &
\end{array}
$$

The corresponding MPS-format SAS data set is as follows:

```
data example;
   input field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
NAME        .      EXAMPLE   .    .     .
ROWS        .      .         .    .     .
N           COST   .         .    .     .
G           R1     .         .    .     .
L           R2     .         .    .     .
L           R3     .         .    .     .
COLUMNS     .      .         .    .     .
.           X1     COST      2    R2    1
.           X1     R3        1    .     .
.           X2     COST     -3    R1   -2
.           X2     R2        1    R3    2
.           X3     COST     -4    R1   -3
.           X3     R2        2    R3    3
RHS         .      .         .    .     .
.           RHS    R1       -5    R2    4
.           RHS    R3        7    .     .
ENDATA      .      .         .    .     .
;
```

You can also create this data set from an MPS-format flat file (examp.mps) by using the following SAS macro:

```
%mps2sasd(mpsfile = "examp.mps", outdata = example);
```

NOTE: The SAS macro %MPS2SASD is provided in SAS Optimization software. See "Converting an MPS/QPS-Format File: %MPS2SASD" on page 295 for details.

To make the created data set available on the CAS server, you need to upload it. At the same time, you also add an _id_ column to ensure that the MPS reader can read the file in the correct order even if it is distributed across several machines and hence loses the original ordering. For more information about the MPS-format, see Chapter 8, "The MPS-Format Data Table."

```
data mycas.example;
   set example;
   _id_ = _n_;
run;
```

Alternatively, you can create the MPS data table directly in CAS and include the _id_ column in the datalines input.

You can use the following statement to call the OPTLP procedure:

```
title1 'The OPTLP Procedure';
proc optlp data = mycas.example
  objsense  = min
  presolver = automatic
  algorithm = primal
  primalout = mycas.expout
  dualout   = mycas.exdout;
run;
```

NOTE: The "N" designation for "COST" in the rows section of the data table example also specifies a minimization problem. See the section "ROWS Section" on page 287 for details.

The optimal primal and dual solutions are stored in the data tables expout and exdout, respectively, and are displayed in Figure 5.1.

```
title2 'Primal Solution';
proc print data=mycas.expout label;
run;

title2 'Dual Solution';
proc print data=mycas.exdout label;
run;
```

Figure 5.1 Primal and Dual Solution Output

The OPTLP Procedure
Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	COST	RHS	X1	N	2	0	1.7977E308	0.0	L	2.0
2	COST	RHS	X2	N	-3	0	1.7977E308	2.5	B	0.0
3	COST	RHS	X3	N	-4	0	1.7977E308	0.0	L	0.5

The OPTLP Procedure
Dual Solution

Obs	Objective Function ID	RHS ID	Constraint Name	Constraint Type	Constraint RHS	Constraint Lower Bound	Constraint Upper Bound	Dual Solution	Constraint Status	Constraint Activity
1	COST	RHS	R1	G	-5	.	.	1.5	U	-5.0
2	COST	RHS	R2	L	4	.	.	0.0	B	2.5
3	COST	RHS	R3	L	7	.	.	0.0	B	5.0

For details about the type and status codes displayed for variables and constraints, see the section "Data Input and Output" on page 134.

Syntax: OPTLP Procedure

The following statements are available in the OPTLP procedure:

PROC OPTLP < *options* > **;**
  DECOMP < *options* > **;**
  DECOMPMASTER < *options* > **;**
  DECOMPSUBPROB < *options* > **;**
  SENSITIVITY < *options* > **;**

Functional Summary

Table 5.1 summarizes the list of options available for the OPTLP procedure, classified by function.

Table 5.1 Options for the OPTLP Procedure

Description	Option
Data Table Options	
Specifies the input data table	DATA=
Specifies the dual input data table for warm start	DUALIN=
Specifies the dual solution output data table	DUALOUT=
Specifies the constant part of the objective	OBJCONSTANT=
Specifies whether the LP model is a maximization or minimization problem	OBJSENSE=
Specifies the primal input data table for warm start	PRIMALIN=
Specifies the primal solution output data table	PRIMALOUT=
Solver Options	
Specifies the type of algorithm	ALGORITHM=
Specifies the type of algorithm called after network simplex	ALGORITHM2=
Enables or disables IIS detection	IIS=
Presolve Options	
Controls the dualization of the problem	DUALIZE=
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the feasibility tolerance	FEASTOL=
Specifies the frequency of printing solution progress	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the optimality tolerance	OPTTOL=

Table 5.1 *continued*

Description	Option
Enables or disables printing summary	PRINTLEVEL=
Specifies units of CPU time or real time	TIMETYPE=
Simplex Algorithm Options	
Specifies the type of initial basis	BASIS=
Specifies the type of pricing strategy	PRICETYPE=
Specifies the queue size for pricing	QUEUESIZE=
Enables or disables scaling of the problem	SCALE=
Specifies the initial seed for the random number generator	SEED=
Interior Point Algorithm Options	
Enables or disables interior crossover	CROSSOVER=
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Parallel Options	
Enables the OPTLP procedure to run deterministically	DETERMINISTIC=
Specifies number of threads for the parallel OPTLP procedure to use	NTHREADS=

PROC OPTLP Statement

PROC OPTLP < *options* > **;**

You can specify the following options in the PROC OPTLP statement.

Data Table Options

DATA=*CAS-libref.data-table*

specifies the input data table that corresponds to the LP model. If this option is not specified, PROC OPTLP uses the most recently created data table. For more information about the input data table, see Chapter 8, "The MPS-Format Data Table." *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

DUALIN=*CAS-libref.data-table*

DIN=*CAS-libref.data-table*

specifies the input data table that corresponds to the dual solution that is required for warm starting the primal and dual simplex algorithms. For more information, see the section "Data Input and Output" on page 134. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

DUALOUT=*CAS-libref.data-table*

DOUT=*CAS-libref.data-table*

specifies the output data table for the dual solution. This data table contains the dual solution information. For more information, see the section "Data Input and Output" on page 134. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

OBJCONSTANT=*number*

OBJECTIVECONSTANT=*number*

specifies the constant part of the objective, where *number* can be any number. This option supersedes the objective right-hand side that is specified in the input data table. By default, OBJCONSTANT=0.

OBJSENSE=MIN | MAX

specifies whether the LP model is a minimization or a maximization problem. Specify OBJSENSE=MIN for a minimization problem and OBJSENSE=MAX for a maximization problem. Alternatively, you can specify the objective sense in the input data table; for more information, see the section "ROWS Section" on page 287. If the objective sense is specified differently in this option and in the input data table, this option supersedes the objective sense that is specified in the input data table. If the objective sense is not specified anywhere, then PROC OPTLP interprets and solves the linear program as a minimization problem.

PRIMALIN=*CAS-libref.data-table*

PIN=*CAS-libref.data-table*

specifies the input data table corresponding to the primal solution that is required for warm starting the primal and dual simplex algorithms. See the section "Data Input and Output" on page 134 for details. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

PRIMALOUT=*CAS-libref.data-table*

POUT=*CAS-libref.data-table*

specifies the output data table for the primal solution. This data table contains the primal solution information. See the section "Data Input and Output" on page 134 for details. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

Solver Options

ALGORITHM=*option*

SOLVER=*option*

SOL=*option*

specifies an LP algorithm. You can specify the following *options*:

PRIMAL (PS) uses the primal simplex algorithm.

DUAL (DS) uses the dual simplex algorithm.

NETWORK (NS) uses the network simplex algorithm.

INTERIORPOINT (IP) uses the interior point algorithm.

CONCURRENT (CON) uses several different algorithms in parallel.

SIFTING (SIFT) uses the sifting algorithm.

SIMPLEX (SPX) uses one of the simplex-based algorithms: PS, DS, NS, and SIFT. The algorithm is determined automatically on the basis of the problem structure.

The valid abbreviated value for each option is indicated in parentheses. By default, ALGORITHM=SIMPLEX.

ALGORITHM2=*option*
SOLVER2=*option*

specifies an LP algorithm if ALGORITHM=NS. You can specify the following values:

PRIMAL (PS) uses the primal simplex algorithm (after network simplex).

DUAL (DS) uses the dual simplex algorithm (after network simplex).

The valid abbreviated value for each option is indicated in parentheses. By default, the OPTLP procedure decides which algorithm is best to use after calling the network simplex algorithm on the extracted network.

IIS=FALSE | TRUE

specifies whether PROC OPTLP attempts to identify a set of constraints and variables that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection.

If an IIS is found, information about infeasible constraints or variable bounds can be found in the DUALOUT= and PRIMALOUT= data tables. For more information about IIS, see the section "Irreducible Infeasible Set" on page 150. By default, IIS=FALSE.

Presolve Options

DUALIZE=AUTOMATIC | OFF | ON

controls the dualization of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to dualize the problem or not.

OFF disables dualization. The optimization problem is solved in the form that you specify.

ON specifies that the presolver formulate the dual of the linear optimization problem.

Dualization is usually helpful for problems that have many more constraints than variables. You can use this option with all simplex algorithms in PROC OPTLP, but it is most effective with the primal and dual simplex algorithms.

By default, DUALIZE=AUTOMATIC.

FOLD=AUTOMATIC | OFF | ON

controls the folding of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to fold the problem or not.

OFF disables folding. The optimization problem is not further reduced by folding.

ON specifies that the presolver try to fold the linear optimization problem.

Folding is helpful for problems that have a symmetric structure. When you use this option with a simplex algorithm in PROC OPTLP, a crossover step must be used to find a basic solution.

By default, FOLD=AUTOMATIC.

PRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

PRESOL=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the level of presolve processing. You can specify the following values:

AUTOMATIC applies the presolver by using the default settings. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

NONE disables the presolver. Only the necessary problem transformation steps are performed.

BASIC performs a basic presolve, such as removing empty rows, columns, and fixed variables. Only some very fast operations are performed.

MODERATE performs a basic presolve and applies other inexpensive presolve techniques. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

AGGRESSIVE performs a moderate presolve and applies other aggressive (but computationally expensive) presolve techniques. All the presolver techniques are called with no limits. This reduces the problem the most, but can take a very long time.

By default, PRESOLVER=AUTOMATIC. For more information, see the section "Presolve" on page 139.

Control Options

FEASTOL=ϵ

specifies the feasibility tolerance $\epsilon \in$[1E–9, 1E–4] for determining the feasibility of variable and constraint values. The default value is 1E–6. Both simplex and interior point algorithms use the relative error for the computation of feasibility tolerance.

LOGFREQ=*k*

PRINTFREQ=*k*

specifies that the printing of the solution progress to the iteration log is to occur after every k iterations. The print frequency, k, is an integer between zero and the largest four-byte signed integer, which is $2^{31} - 1$.

The value $k = 0$ disables the printing of the progress of the solution.

If the LOGFREQ= option is not specified, then PROC OPTLP displays the iteration log with a dynamic frequency according to the problem size if the primal or dual simplex algorithm is used, with frequency 10,000 if the network simplex algorithm is used, or with frequency 1 if the interior point algorithm is used.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that PROC OPTLP displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE	turns off all solver-related messages in the SAS log.
BASIC	displays a solver summary after stopping.
MODERATE	prints a solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.
AGGRESSIVE	prints a detailed solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXITER=*k*

specifies the maximum number of iterations. The value k can be any integer between one and the largest four-byte signed integer, which is $2^{31} - 1$. If you do not specify this option, the procedure does not stop based on the number of iterations performed. For network simplex, this iteration limit corresponds to the algorithm called after network simplex (either primal or dual simplex).

MAXTIME=*t*

specifies an upper limit of t units of time for reading in the data and performing the optimization process. The value of the TIMETYPE= option determines the type of units used. If you do not specify this option, the procedure does not stop based on the amount of time elapsed. The value of t can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

OPTTOL=ϵ

specifies the optimality tolerance $\epsilon \in$[1E–9, 1E–4] for declaring optimality. The default value is 1E–6. Both simplex and interior point algorithms use the relative error for the computation of optimality tolerance.

PRINTLEVEL=0 | 1 | 2

specifies whether to print a summary of the problem and solution. You can specify the following values:

0	neither produces nor prints any Output Delivery System (ODS) tables.
1	prints the ODS tables ProblemSummary, SolutionSummary, and PerformanceInfo.
2	prints the same tables as PRINTLEVEL=1 along with an additional table called ProblemStatistics.

For more information about the ODS tables created by PROC OPTLP, see the section "ODS Tables" on page 147. By default, PRINTLEVEL=1.

TIMETYPE=CPU | REAL

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTLP_ macro variable. You can specify the following values:

CPU	specifies units of CPU time.
REAL	specifies units of real time.

By default, TIMETYPE=REAL.

Simplex Algorithm Options

BASIS=CRASH | SLACK | WARMSTART

specifies the option for generating an initial basis. You can specify the following values:

CRASH	generates an initial basis by using crash techniques (Maros 2003). The procedure creates a triangular basic matrix consisting of both decision variables and slack variables.
SLACK	generates an initial basis by using all slack variables.
WARMSTART	starts the primal and dual simplex algorithms with a user-specified initial basis. The PRIMALIN= and DUALIN= data tables are required to specify an initial basis.

The default option is determined automatically based on the problem structure. For network simplex, this option has no effect.

PRICETYPE=DEVEX | FULL | HYBRID | PARTIAL | STEEPESTEDGE

specifies the pricing strategy for the primal and dual simplex algorithms. You can specify the following values:

DEVEX	uses the Devex pricing strategy.
FULL	uses Dantzig's rule on all decision variables.

HYBRID uses a hybrid of the Devex and steepest-edge pricing strategies. This strategy is available only for the primal simplex algorithm.

PARTIAL uses Dantzig's rule on a queue of decision variables. Optionally, you can specify QUEUESIZE=*k*. This strategy is available only for the primal simplex algorithm.

STEEPESTEDGE uses the steepest-edge pricing strategy.

The default option is determined automatically according to the problem structure. For the network simplex algorithm, this option applies only to the algorithm that is specified in the ALGORITHM2= option. For more information, see the section "Pricing Strategies for the Primal and Dual Simplex Algorithms" on page 139.

QUEUESIZE=*k*

specifies the queue size $k \in [1, n]$, where n is the number of decision variables. This queue is used for finding an entering variable in the simplex iteration. The default value is chosen adaptively based on the number of decision variables. This option is used only when PRICETYPE=PARTIAL.

SCALE=AUTOMATIC | NONE

specifies a scaling option. You can specify the following values:

AUTOMATIC automatically applies scaling procedure if necessary.

NONE disables scaling.

By default, SCALE=AUTOMATIC.

SEED=*number*

specifies the initial seed for the random number generator. Because the seed affects the perturbation in the simplex algorithms, the result might be a different optimal solution and a different solver path, but the effect is usually negligible. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. By default, SEED=100.

Interior Point Algorithm Options

CROSSOVER=FALSE | TRUE

specifies whether to convert the interior point solution to a basic simplex solution. If the interior point algorithm terminates with a solution, the crossover algorithm uses the interior point solution to create an initial basic solution. After performing primal fixing and dual fixing, the crossover algorithm calls a simplex algorithm to locate an optimal basic solution.

You can specify the following values:

FALSE does not convert the interior point solution to a basic simplex solution.

TRUE converts the interior point solution to a basic simplex solution.

By default, CROSSOVER=TRUE.

DUALITYGAP=δ
specifies the desired relative duality gap $\delta \in$[1E–9, 1E–4], which is the relative difference between the primal and dual objective function values and is the primary solution quality parameter. For more information, see the section "The Interior Point Algorithm" on page 141. The default value is 1E–6.

Parallel Options

The OPTLP procedure has several components that take advantage of shared-memory parallel architectures. You can use the following options to control parallel processing:

DETERMINISTIC=TRUE | FALSE
specifies whether to run PROC OPTLP in deterministic or nondeterministic parallel mode. You can specify the following values:

TRUE	runs PROC OPTLP in deterministic parallel mode.
FALSE	runs PROC OPTLP in nondeterministic parallel mode.

By default, DETERMINISTIC=TRUE.

NTHREADS=*number*
specifies the maximum number of threads for PROC OPTLP to use for multithreaded processing. The value of *number* can be any integer between 1 and 256, inclusive. The default is the number of cores on the machine that executes the process or the number of cores permissible based on your installation (whichever is less). The number of simultaneously active CPUs is limited by your installation and license configuration.

Sensitivity Analysis Statement

The following option enables sensitivity analysis in PROC OPTLP:

SENSITIVITY *options*;
enables sensitivity analysis and specifies overall control options for the algorithm. You can specify the following *options*:

CHANGE=ALL LB OBJ RANGE RHS UB
specifies which parts of the problem data to run the sensitivity analysis algorithm on. You can specify the following values:

ALL	runs sensitivity analysis on all the supported pieces of the input data.
LB	runs sensitivity analysis on the variable lower bounds.
OBJ	runs sensitivity analysis on the objective coefficients.
RANGE	runs sensitivity analysis on the range row bounds.
RHS	runs sensitivity analysis on the row right-hand sides.
UB	runs sensitivity analysis on the variable upper bounds.

This is a required option with no default value.

For more information about sensitivity analysis, see the section "Sensitivity Analysis" on page 146.

Decomposition Algorithm Statements

The following statements are available for the decomposition algorithm in the OPTLP procedure:

DECOMP < *options* > **;**

DECOMPMASTER < *options* > **;**

DECOMPSUBPROB < *options* > **;**

For more information about these statements, see Chapter 18, "The Decomposition Algorithm."

Details: OPTLP Procedure

Data Input and Output

This subsection describes the PRIMALIN= and DUALIN= data tables required to warm start the primal and dual simplex algorithms, and the PRIMALOUT= and DUALOUT= output data tables.

Definitions of Variables in the PRIMALIN= Data Table

The PRIMALIN= data table must contain the following variables:

VAR
specifies the name of the decision variable.

STATUS
specifies the status of the decision variable. It can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A newly added variable in the modified LP model when using the BASIS=WARMSTART option

NOTE: The PRIMALIN= data table is created from the PRIMALOUT= data table that is obtained from a previous "normal" run of PROC OPTLP (one that uses only the DATA= data table as the input).

Definitions of Variables in the DUALIN= Data Table

The DUALIN= data table also must contain the following variables:

ROW
specifies the name of the constraint.

STATUS
specifies the status of the slack variable for a given constraint. It can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A newly added variable in the modified LP model when using the BASIS=WARMSTART option

NOTE: The DUALIN= data table is created from the DUALOUT= data table that is obtained from a previous "normal" run of PROC OPTLP (one that uses only the DATA= data table as the input).

Definitions of Variables in the PRIMALOUT= Data Table

The PRIMALOUT= data table contains the primal solution to the LP model; each observation corresponds to a variable of the LP problem. The PRIMALOUT= data table can contain an intermediate solution, if one is available. See Example 5.1 for an example of the PRIMALOUT= data table. The variables in the data table have the following names and meanings:

_OBJ_ID_
specifies the name of the objective function. This is particularly useful when there are multiple objective functions, in which case each objective function has a unique name.

NOTE: PROC OPTLP does not support simultaneous optimization of multiple objective functions in this release.

_RHS_ID_
specifies the name of the variable that contains the right-hand-side value of each constraint.

VAR
specifies the name of the decision variable.

TYPE
specifies the type of the decision variable. _TYPE_ can take one of the following values:

N nonnegative

D bounded (with both lower and upper bound)

F free

X fixed

O other (with either lower or upper bound)

OBJCOEF
specifies the coefficient of the decision variable in the objective function.

LBOUND
specifies the lower bound on the decision variable.

UBOUND
specifies the upper bound on the decision variable.

VALUE
specifies the value of the decision variable.

STATUS
specifies the status of the decision variable. _STATUS_ can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A superbasic variable (a nonbasic variable that has a value strictly between its bounds)

I LP model infeasible (all decision variables have _STATUS_ equal to I)

For the interior point algorithm when IIS=FALSE, _STATUS_ is blank.

The following values can appear only if IIS=TRUE. For more information, see the section "Irreducible Infeasible Set" on page 150.

I_L the lower bound of the variable is needed for the IIS

I_U the upper bound of the variable is needed for the IIS

I_F both bounds of the variable needed for the IIS (the variable is fixed or has conflicting bounds)

_R_COST_
specifies the reduced cost of the decision variable, which is the amount by which the objective function is increased per unit increase in the decision variable. The reduced cost associated with the *i*th variable is the *i*th entry of the following vector:

$$\left(\mathbf{c}^{\mathrm{T}} - \mathbf{c}_{\boldsymbol{B}}^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{A}\right)$$

where $\mathbf{B} \in \mathbb{R}^{m \times m}$ denotes the basis (matrix composed of *basic* columns of the constraints matrix $\mathbf{A} \in \mathbb{R}^{m \times n}$), $\mathbf{c} \in \mathbb{R}^{n}$ is the vector of objective function coefficients, and $\mathbf{c}_{\boldsymbol{B}} \in \mathbb{R}^{m}$ is the vector of objective coefficients of the variables in the basis.

In addition, the following variables are returned if sensitivity analysis is used for the corresponding pieces of the input data:

LBOUNDMIN
specifies the smallest value of the stability interval for _LBOUND_.

LBOUNDMAX
specifies the largest value of the stability interval for _LBOUND_.

UBOUNDMIN
specifies the smallest value of the stability interval for _UBOUND_.

UBOUNDMAX
specifies the largest value of the stability interval for _UBOUND_.

OBJCOEFMIN
specifies the smallest value of the stability interval for _OBJCOEF_.

OBJCOEFMAX
specifies the largest value of the stability interval for _OBJCOEF_.

Definitions of Variables in the DUALOUT= Data Table

The DUALOUT= data table contains the dual solution to the LP model; each observation corresponds to a constraint of the LP problem. The DUALOUT= data table can contain an intermediate solution, if one is available. Information about the objective rows of the LP problems is not included. See Example 5.1 for an example of the DUALOUT= data table. The variables in the data table have the following names and meanings:

_OBJ_ID_
specifies the name of the objective function. This is particularly useful when there are multiple objective functions, in which case each objective function has a unique name.

NOTE: PROC OPTLP does not support simultaneous optimization of multiple objective functions in this release.

_RHS_ID_
specifies the name of the variable that contains the right-hand-side value of each constraint.

ROW
specifies the name of the constraint.

TYPE
specifies the type of the constraint. _TYPE_ can take one of the following values:

L “less than or equals” constraint

E equality constraint

G “greater than or equals” constraint

R ranged constraint (both “less than or equals” and “greater than or equals”)

RHS
specifies the value of the right-hand side of the constraint. It takes a missing value for a ranged constraint.

_L_RHS_
specifies the lower bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

_U_RHS_
specifies the upper bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

VALUE
specifies the value of the dual variable associated with the constraint.

STATUS
specifies the status of the slack variable for the constraint. _STATUS_ can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A superbasic variable (a nonbasic variable that has a value strictly between its bounds)

I LP model infeasible (all decision variables have _STATUS_ equal to I)

The following values can appear only if IIS=TRUE. For more information, see the section "Irreducible Infeasible Set" on page 150.

I_L the "GE" ($\geq$) condition of the constraint is needed for the IIS

I_U the "LE" ($\leq$) condition of the constraint is needed for the IIS

I_F both conditions of the constraint are needed for the IIS (the constraint is an equality or a range constraint with conflicting bounds)

ACTIVITY
specifies the left-hand-side value of a constraint. In other words, the value of _ACTIVITY_ for the ith constraint would be equal to $\mathbf{a}_i^{\mathrm{T}}\mathbf{x}$, where $\mathbf{a}_i$ refers to the ith row of the constraints matrix and $\mathbf{x}$ denotes the vector of current decision variable values.

In addition, the following variables are returned if sensitivity analysis is used for the corresponding pieces of the input data:

RHSMIN
specifies the smallest value of the stability interval for _RHS_, for one-sided rows. It takes a missing value for a ranged constraint.

RHSMAX
specifies the largest value of the stability interval for _RHS_, for one-sided rows. It takes a missing value for a ranged constraint.

_L_RHSMIN_
specifies the smallest value of the stability interval for _L_RHS_ (that is, the lower bound of a ranged row). It takes a missing value for a nonranged constraint.

_L_RHSMAX_
specifies the largest value of the stability interval for _L_RHS_ (that is, the lower bound of a ranged row). It takes a missing value for a nonranged constraint.

_U_RHSMIN_
specifies the smallest value of the stability interval for _U_RHS_ (that is, the upper bound of a ranged row). It takes a missing value for a nonranged constraint.

_U_RHSMAX_
specifies the largest value of the stability interval for _U_RHS_ (that is, the upper bound of a ranged row). It takes a missing value for a nonranged constraint.

Presolve

Presolve in PROC OPTLP uses a variety of techniques to reduce the problem size, improve numerical stability, and detect infeasibility or unboundedness (Andersen and Andersen 1995; Gondzio 1997). During presolve, redundant constraints and variables are identified and removed. Presolve can further reduce the problem size by substituting variables. Variable substitution is a very effective technique, but it might occasionally increase the number of nonzero entries in the constraint matrix.

In most cases, using presolve is very helpful in reducing solution times. You can enable presolve at different levels or disable it by specifying the PRESOLVER= option.

Pricing Strategies for the Primal and Dual Simplex Algorithms

Several pricing strategies for the primal and dual simplex algorithms are available. Pricing strategies determine which variable enters the basis at each simplex pivot. They can be controlled by specifying the PRICETYPE= option.

The primal simplex algorithm has the following five pricing strategies:

DEVEX	implements the Devex pricing strategy developed by Harris (1973).
FULL	uses Dantzig's most violated reduced cost rule. It compares the reduced costs of all decision variables and selects the variable with the most violated reduced cost as the entering variable.
HYBRID	uses a hybrid of the Devex and steepest-edge pricing strategies.
PARTIAL	uses Dantzig's most violated reduced cost rule (Dantzig 1963). It scans a queue of decision variables and selects the variable with the most violated reduced cost as the

entering variable. You can optionally specify the QUEUESIZE= option to control the length of this queue.

STEEPESTEDGE uses the steepest-edge pricing strategy developed by Forrest and Goldfarb (1992).

The dual simplex algorithm has only three pricing strategies available: DEVEX, FULL, and STEEPEST-EDGE.

Warm Start for the Primal and Dual Simplex Algorithms

You can warm-start the primal and dual simplex algorithms by specifying the option BASIS=WARMSTART. Additionally you need to specify the PRIMALIN= and DUALIN= data tables. The primal and dual simplex algorithms start with the basis thus provided. If the given basis cannot form a valid basis, the algorithms use the basis that is generated using their *crash* techniques.

After an LP model is solved using the primal and dual simplex algorithms, the BASIS=WARMSTART option enables you to perform sensitivity analysis, such as modifying the objective function, changing the right-hand sides of the constraints, adding or deleting constraints or decision variables, and combinations of these cases. You can usually obtain a faster solution to such a modified LP model by starting with the basis in the optimal solution to the original LP model. This can be done by using the BASIS=WARMSTART option, modifying the DATA= input data table, and specifying the PRIMALIN= and DUALIN= data tables. Example 5.4 and Example 5.5 illustrate how to reoptimize an LP problem with a modified objective function and a modified right-hand side by using this technique. Example 5.6 shows how to reoptimize an LP problem after adding a new constraint.

The network simplex algorithm ignores the BASIS=WARMSTART option.

CAUTION: Since the presolver uses the objective function and/or right-hand-side information, the basis provided by you might not be valid for the presolved model. It is therefore recommended that you turn the PRESOLVER= option off when using BASIS=WARMSTART.

The Network Simplex Algorithm

The network simplex algorithm in PROC OPTLP attempts to leverage the speed of the network simplex algorithm to more efficiently solve linear programs by using the following process:

1. It heuristically extracts the largest possible network substructure from the original problem.
2. It uses the network simplex algorithm to solve for an optimal solution to this substructure.
3. It uses this solution to construct an advanced basis to warm-start either the primal or dual simplex algorithm on the original linear programming problem.

The network simplex algorithm is a specialized version of the simplex algorithm that uses spanning-tree bases to more efficiently solve linear programming problems that have a pure network form. Such LPs can be modeled using a formulation over a directed graph, as a minimum-cost flow problem. Let $G = (N, A)$ be a directed graph, where N denotes the nodes and A denotes the arcs of the graph. The decision variable x_{ij}

denotes the amount of flow sent from node i to node j. The cost per unit of flow on the arcs is designated by c_{ij}, and the amount of flow sent across each arc is bounded to be within $[l_{ij}, u_{ij}]$. The demand (or supply) at each node is designated as b_i, where $b_i > 0$ denotes a supply node and $b_i < 0$ denotes a demand node. The corresponding linear programming problem is as follows:

$$\begin{array}{rrcll} \min & \sum_{(i,j)\in A} c_{ij} x_{ij} & & & \\ \text{subject to} & \sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} & = & b_i & \forall i \in N \\ & x_{ij} & \leq & u_{ij} & \forall (i,j) \in A \\ & x_{ij} & \geq & l_{ij} & \forall (i,j) \in A \end{array}$$

The network simplex algorithm used in PROC OPTLP is the primal network simplex algorithm. This algorithm finds the optimal primal feasible solution and a dual solution that satisfies complementary slackness. Sometimes the directed graph G is disconnected. In this case, the problem can be decomposed into its weakly connected components and each minimum-cost flow problem can be solved separately. After solving each component, the optimal basis for the network substructure is augmented with the non-network variables and constraints from the original problem. This advanced basis is then used as a starting point for the primal or dual simplex method. The solver automatically selects the algorithm to use after network simplex. However, you can override this selection with the ALGORITHM2= option.

The network simplex algorithm can be more efficient than the other algorithms on problems with a large network substructure. You can view the size of the network structure in the log.

The Interior Point Algorithm

The interior point algorithm in PROC OPTLP implements an infeasible primal-dual predictor-corrector interior point algorithm. To illustrate the algorithm and the concepts of duality and dual infeasibility, consider the following LP formulation (the primal):

$$\begin{array}{rl} \min & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{array}$$

The corresponding dual formulation is as follows:

$$\begin{array}{rrcrcl} \max & \mathbf{b}^{\mathrm{T}}\mathbf{y} & & & & \\ \text{subject to} & \mathbf{A}^{\mathrm{T}}\mathbf{y} & + & \mathbf{w} & = & \mathbf{c} \\ & & & \mathbf{y} & \geq & \mathbf{0} \\ & & & \mathbf{w} & \geq & \mathbf{0} \end{array}$$

where $\mathbf{y} \in \mathbb{R}^m$ refers to the vector of dual variables and $\mathbf{w} \in \mathbb{R}^n$ refers to the vector of dual slack variables.

The dual formulation makes an important contribution to the certificate of optimality for the primal formulation. The primal and dual constraints combined with complementarity conditions define the first-order optimality conditions, also known as KKT (Karush-Kuhn-Tucker) conditions, which can be stated as follows:

$$\begin{array}{rcll} \mathbf{A}\mathbf{x} - \mathbf{s} & = & \mathbf{b} & \text{(primal feasibility)} \\ \mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{w} & = & \mathbf{c} & \text{(dual feasibility)} \\ \mathbf{W}\mathbf{X}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{S}\mathbf{Y}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{x},\ \mathbf{y},\ \mathbf{w},\ \mathbf{s} & \geq & \mathbf{0} & \end{array}$$

where $\mathbf{e} \equiv (1, \ldots, 1)^{\mathrm{T}}$ of appropriate dimension and $\mathbf{s} \in \mathbb{R}^m$ is the vector of primal *slack* variables.

NOTE: Slack variables (the s vector) are automatically introduced by the algorithm when necessary; it is therefore recommended that you not introduce any slack variables explicitly. This enables the algorithm to handle slack variables much more efficiently.

The letters $\mathbf{X}$, $\mathbf{Y}$, $\mathbf{W}$, and $\mathbf{S}$ denote matrices with corresponding x, y, w, and s on the main diagonal and zero elsewhere, as in the following example:

$$\mathbf{X} \equiv \begin{bmatrix} x_1 & 0 & \cdots & 0 \\ 0 & x_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x_n \end{bmatrix}$$

If $(\mathbf{x}^*, \mathbf{y}^*, \mathbf{w}^*, \mathbf{s}^*)$ is a solution of the previously defined system of equations that represent the KKT conditions, then $\mathbf{x}^*$ is also an optimal solution to the original LP model.

At each iteration the interior point algorithm solves a large, sparse system of linear equations,

$$\begin{bmatrix} \mathbf{Y}^{-1}\mathbf{S} & \mathbf{A} \\ \mathbf{A}^{\mathrm{T}} & -\mathbf{X}^{-1}\mathbf{W} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{y} \\ \Delta\mathbf{x} \end{bmatrix} = \begin{bmatrix} \Xi \\ \Theta \end{bmatrix}$$

where $\Delta\mathbf{x}$ and $\Delta\mathbf{y}$ denote the vector of *search directions* in the primal and dual spaces, respectively, and Θ and Ξ constitute the vector of the right-hand sides.

The preceding system is known as the reduced KKT system. The interior point algorithm uses a preconditioned quasi-minimum residual algorithm to solve this system of equations efficiently.

An important feature of the interior point algorithm is that it takes full advantage of the sparsity in the constraint matrix, thereby enabling it to efficiently solve large-scale linear programs.

The interior point algorithm works simultaneously in the primal and dual spaces. It attains optimality when both primal and dual feasibility are achieved and when complementarity conditions hold. Therefore, it is of interest to observe the following four measures:

- Relative primal infeasibility measure α:

$$\alpha = \frac{\|\mathbf{Ax} - \mathbf{b} - \mathbf{s}\|_2}{\|\mathbf{b}\|_2 + 1}$$

- Relative dual infeasibility measure β:

$$\beta = \frac{\|\mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y} - \mathbf{w}\|_2}{\|\mathbf{c}\|_2 + 1}$$

- Relative duality gap δ:

$$\delta = \frac{|\mathbf{c}^{\mathrm{T}}\mathbf{x} - \mathbf{b}^{\mathrm{T}}\mathbf{y}|}{|\mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

- Absolute complementarity γ:

$$\gamma = \sum_{i=1}^{n} x_i w_i + \sum_{i=1}^{m} y_i s_i$$

where $\|v\|_2$ is the Euclidean norm of the vector v. These measures are displayed in the iteration log.

The Sifting Algorithm

The sifting algorithm is a simplex-based column-generation algorithm. This algorithm starts by solving a reduced problem that includes a subset of variables. At each iteration, the algorithm adds new variables and solves the problem again. The algorithm stops when the optimal solution of the current iteration is found to be optimal for the original problem.

The sifting algorithm is usually helpful for problems that have many more variables than constraints.

Iteration Log for the Primal and Dual Simplex Algorithms

The primal and dual simplex algorithms implement a two-phase simplex algorithm. Phase I finds a feasible solution, which phase II improves to an optimal solution.

When LOGFREQ=1, the following information is printed in the iteration log:

Algorithm	indicates which simplex method is running by printing the letter P (primal) or D (dual).
Phase	indicates whether the algorithm is in phase I or phase II of the simplex method.
Iteration	indicates the iteration number.
Objective Value	indicates the current amount of infeasibility in phase I and the primal objective value of the current solution in phase II.
Time	indicates the time elapsed (in seconds).
Entering Variable	indicates the entering pivot variable. A slack variable that enters the basis is indicated by the corresponding row name followed by “(S)”. If the entering nonbasic variable has distinct and finite lower and upper bounds, then a “bound swap” can take place in the primal simplex method.
Leaving Variable	indicates the leaving pivot variable. A slack variable that leaves the basis is indicated by the corresponding row name followed by “(S)”. The leaving variable is the same as the entering variable if a bound swap has taken place.

When you omit the LOGFREQ= option or specify a value greater than 1, only the algorithm, phase, iteration, objective value, and time information is printed in the iteration log.

The behavior of objective values in the iteration log depends on both the current phase and the chosen algorithm. In phase I, both simplex methods have artificial objective values that decrease to 0 when a feasible solution is found. For the dual simplex method, phase II maintains a dual feasible solution, so a minimization problem has increasing objective values in the iteration log. For the primal simplex method, phase II maintains a primal feasible solution, so a minimization problem has decreasing objective values in the iteration log.

During the solution process, some elements of the LP model might be perturbed to improve performance. In this case the objective values that are printed correspond to the perturbed problem. After reaching optimality for the perturbed problem, PROC OPTLP solves the original problem by switching from the primal simplex method to the dual simplex method (or from the dual to the primal simplex method). Because the problem might be perturbed again, this process can result in several changes between the two algorithms.

Iteration Log for the Network Simplex Algorithm

After finding the embedded network and formulating the appropriate relaxation, the network simplex algorithm uses a primal network simplex algorithm. In the case of a connected network, with one (weakly connected) component, the log shows the progress of the simplex algorithm. The following information is displayed in the iteration log:

Iteration	indicates the iteration number.
PrimalObj	indicates the primal objective value of the current solution.
Primal Infeas	indicates the maximum primal infeasibility of the current solution.
Time	indicates the time spent on the current component by network simplex.

The frequency of the simplex iteration log is controlled by the LOGFREQ= option. The default value of the LOGFREQ= option is 10,000.

If the network relaxation is disconnected, the information in the iteration log shows progress at the component level. The following information is displayed in the iteration log:

Component	indicates the component number being processed.
Nodes	indicates the number of nodes in this component.
Arcs	indicates the number of arcs in this component.
Iterations	indicates the number of simplex iterations needed to solve this component.
Time	indicates the time spent so far in network simplex.

The frequency of the component iteration log is controlled by the LOGFREQ= option. In this case, the default value of the LOGFREQ= option is determined by the size of the network.

The LOGLEVEL= option adjusts the amount of detail shown. By default, LOGLEVEL= is set to MODERATE and reports as described previously. If set to NONE, no information is shown. If set to BASIC, the only information shown is a summary of the network relaxation and the time spent solving the relaxation. If set to AGGRESSIVE, in the case of one component, the log displays as described previously; in the case of multiple components, for each component, a separate simplex iteration log is displayed.

Iteration Log for the Interior Point Algorithm

The interior point algorithm implements an infeasible primal-dual predictor-corrector interior point algorithm. The following information is displayed in the iteration log:

Iter	indicates the iteration number.
Complement	indicates the (absolute) complementarity.
Duality Gap	indicates the (relative) duality gap.
Primal Infeas	indicates the (relative) primal infeasibility measure.
Bound Infeas	indicates the (relative) bound infeasibility measure.

Dual Infeas	indicates the (relative) dual infeasibility measure.
Time	indicates the time elapsed (in seconds).

If the sequence of solutions converges to an optimal solution of the problem, you should see all columns in the iteration log converge to zero or very close to zero. If they do not, it can be the result of insufficient iterations being performed to reach optimality. In this case, you might need to increase the value specified in the MAXITER= or MAXTIME= options. If the complementarity or the duality gap do not converge, the problem might be infeasible or unbounded. If the infeasibility columns do not converge, the problem might be infeasible.

Iteration Log for the Crossover Algorithm

The crossover algorithm takes an optimal solution from the interior point algorithm and transforms it into an optimal basic solution. The iterations of the crossover algorithm are similar to simplex iterations; this similarity is reflected in the format of the iteration logs.

When LOGFREQ=1, the following information is printed in the iteration log:

Phase	indicates whether the primal crossover (PC) or dual crossover (DC) technique is used.
Iteration	indicates the iteration number.
Objective Value	indicates the total amount by which the superbasic variables are off their bound. This value decreases to 0 as the crossover algorithm progresses.
Time	indicates the time elapsed (in seconds).
Entering Variable	indicates the entering pivot variable. A slack variable that enters the basis is indicated by the corresponding row name followed by “(S).”
Leaving Variable	indicates the leaving pivot variable. A slack variable that leaves the basis is indicated by the corresponding row name followed by “(S).”

When you omit the LOGFREQ= option or specify a value greater than 1, only the phase, iteration, objective value, and time information is printed in the iteration log.

After all the superbasic variables have been eliminated, the crossover algorithm continues with regular primal or dual simplex iterations.

Concurrent LP

The ALGORITHM=CON option starts several different linear optimization algorithms in parallel in a single-machine mode. The OPTLP procedure automatically determines which algorithms to run and how many threads to assign to each algorithm. When the first algorithm finishes, the procedure returns the results from that algorithm and terminates any other algorithms that are still running. If you specify a value of TRUE for the DETERMINISTIC= option, the algorithm for which the results are returned is not necessarily the one that finished first. The OPTLP procedure deterministically selects the algorithm for which the results are returned. Regardless of which mode (deterministic or nondeterministic) is in effect, terminating algorithms that are still running might take a significant amount of time.

During concurrent optimization, the procedure displays the iteration log for the dual simplex algorithm. For more information about this iteration log, see the section "Iteration Log for the Primal and Dual Simplex Algorithms" on page 143. Upon termination, the procedure displays the iteration log for the algorithm that finishes first, unless the dual simplex algorithm finishes first. If you specify LOGLEVEL=AGGRESSIVE, the OPTLP procedure displays the iteration logs for all algorithms that are run concurrently.

If you specify PRINTLEVEL=2 and ALGORITHM=CON, the OPTLP procedure produces an ODS table called ConcurrentSummary. This table contains a summary of the solution statuses of all algorithms that are run concurrently.

Sensitivity Analysis

The optimal basis, solution, and objective value of a linear optimization problem are functions of the input data. You can use sensitivity analysis to quantify this dependence. You can invoke sensitivity analysis by specifying the SENSITIVITY statement.

The sensitivity analysis algorithm in PROC OPTLP supports analyzing the dependence with respect to the variable bounds, row bounds, or objective coefficients. Sensitivities to the matrix coefficients are not supported. You can use the CHANGE= option to select which parts of the data to run the algorithm on. Sensitivity analysis calculates a stability interval for each of these pieces of the problem data. Changing the data within the stability interval guarantees that the current optimal basis stays optimal.

The output of sensitivity analysis is returned in the data tables that you specify in the PRIMALOUT= and DUALOUT= options. See Example 5.9 for an example of how to use sensitivity analysis.

Parallel Processing

The interior point, concurrent LP, and decomposition algorithms can be run in single-machine mode; in this mode, the computation is executed by multiple threads on a single computer.

ODS Tables

PROC OPTLP creates two Output Delivery System (ODS) tables by default. The first table, ProblemSummary, is a summary of the input LP problem. The second table, SolutionSummary, is a brief summary of the solution status. You can use ODS table names to select tables and create output data sets. For more information about ODS, see *SAS Output Delivery System: Procedures Guide*.

If you specify PRINTLEVEL=2, then the ProblemStatistics table and the Timing table are produced. The ProblemStatistics table contains information about the problem data. For more information, see the section "Problem Statistics" on page 149. The Timing table contains detailed information about the solution time. If you specify PRINTLEVEL=2 and ALGORITHM=CON, the ConcurrentSummary table is produced. This table contains solution status information for all algorithms that are run concurrently. For more information, see the section "Concurrent LP" on page 146.

Table 5.2 lists all the ODS tables that can be produced by the OPTLP procedure, along with the statement and option specifications required to produce each table.

Table 5.2 ODS Tables Produced by PROC OPTLP

ODS Table Name	Description	Statement	Option
ProblemSummary	Summary of the input LP problem	PROC OPTLP	PRINTLEVEL=1 (default)
SolutionSummary	Summary of the solution status	PROC OPTLP	PRINTLEVEL=1 (default)
ProblemStatistics	Description of input problem data	PROC OPTLP	PRINTLEVEL=2
ConcurrentSummary	Summary of the solution status for all algorithms run concurrently	PROC OPTLP	PRINTLEVEL=2, ALGORITHM=CON
Timing	Detailed solution timing	PROC OPTLP	PRINTLEVEL=2

A typical output of PROC OPTLP is shown in Figure 5.2.

Figure 5.2 Typical OPTLP Output

The OPTLP Procedure

Problem Summary	
Problem Name	ADLITTLE
Objective Sense	Minimization
Objective Function	.Z....
RHS	ZZZZ0001
Number of Variables	97
Bounded Above	0
Bounded Below	97
Bounded Above and Below	0
Free	0
Fixed	0
Number of Constraints	56
LE (<=)	40
EQ (=)	15
GE (>=)	1
Range	0
Constraint Coefficients	383

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	.Z....
Solution Status	Optimal
Objective Value	225494.96316
Primal Infeasibility	1.065814E-14
Dual Infeasibility	1.421085E-13
Bound Infeasibility	0
Iterations	111
Presolve Time	0.00
Solution Time	0.00

You can create output data sets from these tables by using the ODS OUTPUT statement. This can be useful, for example, when you want to create a report to summarize multiple PROC OPTLP runs. The output data sets corresponding to the preceding output are shown in Figure 5.3, where you can also find (at the row following the heading of each data set in display) the variable names that are used in the table definition (template) of each table.

Figure 5.3 ODS Output Data Sets

Problem Summary

Obs	Name1	Label1	cValue1	nValue1
1	problemName	Problem Name	ADLITTLE	.
2	objectiveSense	Objective Sense	Minimization	.
3	objectiveName	Objective Function	.Z....	.
4	rhs	RHS	ZZZZ0001	.
5				.
6	numVars	Number of Variables	97	97.000000
7	numBoundedAbove	Bounded Above	0	0
8	numBoundedBelow	Bounded Below	97	97.000000
9	numBounded	Bounded Above and Below	0	0
10	numFree	Free	0	0
11	numFixed	Fixed	0	0
12				.
13	numRows	Number of Constraints	56	56.000000
14	numLE	LE (<=)	40	40.000000
15	numEQ	EQ (=)	15	15.000000
16	numGE	GE (>=)	1	1.000000
17	numRange	Range	0	0
18				.
19	numElems	Constraint Coefficients	383	383.000000

Solution Summary

Obs	Name1	Label1	cValue1	nValue1
1	solver	Solver	LP	.
2	algorithm	Algorithm	Dual Simplex	.
3	objectiveName	Objective Function	.Z....	.
4	solStatus	Solution Status	Optimal	.
5	objective	Objective Value	225494.96316	225495
6				.
7	primalInfeasibility	Primal Infeasibility	1.065814E-14	1.065814E-14
8	dualInfeasibility	Dual Infeasibility	1.421085E-13	1.421085E-13
9	boundInfeasibility	Bound Infeasibility	0	0
10				.
11	iterations	Iterations	111	111.000000
12	presolveTime	Presolve Time	0.00	0.000570
13	solutionTime	Solution Time	0.00	0.002636

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTLP procedure causes the ODS table ProblemStatistics to be generated. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 5.4 demonstrates the contents of the ODS table ProblemStatistics.

Figure 5.4 ODS Table ProblemStatistics

The OPTLP Procedure

Problem Statistics	
Number of Constraint Matrix Nonzeros	8
Maximum Constraint Matrix Coefficient	3
Minimum Constraint Matrix Coefficient	1
Average Constraint Matrix Coefficient	1.875
Number of Objective Nonzeros	3
Maximum Objective Coefficient	4
Minimum Objective Coefficient	2
Average Objective Coefficient	3
Number of RHS Nonzeros	3
Maximum RHS	7
Minimum RHS	4
Average RHS	5.3333333333
Maximum Number of Nonzeros per Column	3
Minimum Number of Nonzeros per Column	2
Average Number of Nonzeros per Column	2.67
Maximum Number of Nonzeros per Row	3
Minimum Number of Nonzeros per Row	2
Average Number of Nonzeros per Row	2.67

Irreducible Infeasible Set

For a linear programming problem, an irreducible infeasible set (IIS) is an infeasible subset of constraints and variable bounds that will become feasible if any single constraint or variable bound is removed. It is possible to have more than one IIS in an infeasible LP. Identifying an IIS can help isolate the structural infeasibility in an LP.

The presolver in the OPTLP procedure can detect infeasibility, but it identifies only the variable bound or constraint that triggers the infeasibility.

The IIS=TRUE option directs the OPTLP procedure to search for an IIS in a specified LP. The OPTLP procedure does not apply the presolver to the problem during the IIS search. If PROC OPTLP detects an IIS, it first outputs the IIS to the data sets that are specified by the PRIMALOUT= and DUALOUT= options, and then it stops. The number of iterations that are reported in the macro variable and the ODS table is the total number of simplex iterations. This total includes the initial LP solve and all subsequent iterations during the constraint deletion phase.

The IIS= option can add special values to the _STATUS_ variables in the output data sets. (For more information, see the section "Data Input and Output" on page 134.) For constraints, a status of "I_L", "I_U", or "I_F" indicates that the "GE" ($\geq$), "LE" ($\leq$), or "EQ" (=) constraint, respectively, is part of the IIS.

For range constraints, a status of “I_L” or “I_U” indicates that the lower or upper bound of the constraint, respectively, is needed for the IIS, and “I_F” indicates that the bounds in the constraint are conflicting. For variables, a status of “I_L”, “I_U”, or “I_F” indicates that the lower, upper, or both bounds of the variable, respectively, are needed for the IIS. From this information, you can identify both the names of the constraints (variables) in the IIS and the corresponding bound where infeasibility occurs.

Making any one of the constraints or variable bounds in the IIS nonbinding removes the infeasibility from the IIS. In some cases, changing a right-hand side or bound by a finite amount removes the infeasibility. However, the only way to guarantee removal of the infeasibility is to set the appropriate right-hand side or bound to ∞ or $-\infty$. Because it is possible for an LP to have multiple irreducible infeasible sets, simply removing the infeasibility from one set might not make the entire problem feasible. To make the entire problem feasible, you can specify IIS=TRUE and rerun PROC OPTLP after removing the infeasibility from an IIS. Repeating this process until the LP solver no longer detects an IIS results in a feasible problem. This approach to infeasibility repair can produce different end problems depending on which right-hand sides and bounds you choose to relax.

Changing different constraints and bounds can require considerably different changes to the MPS-format SAS data set. For example, if you use the default lower bound of 0 for a variable but you want to relax the lower bound to $-\infty$, you might need to add an MI row to the BOUNDS section of the data set. For more information about changing variable and constraint bounds, see Chapter 8, “The MPS-Format Data Table.”

The IIS= option in PROC OPTLP uses two different methods to identify an IIS:

1. Based on the result of the initial solve, the *sensitivity filter* removes several constraints and variable bounds immediately while still maintaining infeasibility. This phase is quick and dramatically reduces the size of the IIS.

2. Next, the *deletion filter* removes each remaining constraint and variable bound one by one to check which of them are needed to obtain an infeasible system. This second phase is more time consuming, but it ensures that the IIS set that PROC OPTLP returns is indeed irreducible. The progress of the deletion filter is reported at regular intervals. Occasionally, the sensitivity filter might be called again during the deletion filter to improve performance.

See Example 5.7 for an example that demonstrates the use of the IIS= option in locating and removing infeasibilities. You can find more details about IIS algorithms in Chinneck (2008).

Macro Variable _OROPTLP_

The OPTLP procedure defines a macro variable named _OROPTLP_. This variable contains a character string that indicates the status of the OPTLP procedure upon termination. The various terms of the variable are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The procedure terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data were inconsistent.

OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produces the solution data in the macro variable. This term appears only when STATUS=OK. It can take one of the following values:

PS	The primal simplex algorithm produced the solution data.
DS	The dual simplex algorithm produced the solution data.
NS	The network simplex algorithm produced the solution data.
IP	The interior point algorithm produced the solution data.
DECOMP	The decomposition algorithm produced the solution data.
SIFT	The sifting algorithm produced the solution data.
SPX	The presolver produced the solution data, and the ALGORITHM=SIMPLEX option was specified.

When you run algorithms concurrently (ALGORITHM=CON), this term indicates which algorithm is the first to terminate.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The solution is optimal, but some infeasibilities (primal, dual or bound) exceed tolerances due to scaling or preprocessing.
FEASIBLE	The problem is feasible.
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
ITERATION_LIMIT_REACHED	The maximum allowable number of iterations was reached.
TIME_LIMIT_REACHED	The solver reached its execution time limit.
ABORTED	The solver was interrupted externally.
FAILED	The solver failed to converge, possibly due to numerical issues.

OBJECTIVE

indicates the objective value obtained by the solver at termination.

PRIMAL_INFEASIBILITY
indicates the relative violation of the primal constraints by the primal solution.

DUAL_INFEASIBILITY
indicates the relative violation of the dual constraints by the dual solution.

BOUND_INFEASIBILITY
indicates the relative violation of the lower or upper bounds (or both) by the primal solution.

DUALITY_GAP
indicates the (relative) duality gap. This term appears only if the interior point algorithm is used.

COMPLEMENTARITY
indicates the (absolute) complementarity. This term appears only if the interior point algorithm is used.

ITERATIONS
indicates the number of iterations taken to solve the problem. When the network simplex algorithm is used, this term indicates the number of network simplex iterations taken to solve the network relaxation. When crossover is enabled, this term indicates the number of interior point iterations taken to solve the problem.

ITERATIONS2
indicates the number of simplex iterations performed by the secondary algorithm. In network simplex, the secondary algorithm is selected automatically, unless a value has been specified for the ALGORITHM2= option. When crossover is enabled, the secondary algorithm is selected automatically. This term appears only if the network simplex algorithm is used or if crossover is enabled.

PRESOLVE_TIME
indicates the time (in seconds) used in preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

When SOLUTION_STATUS has a value of OPTIMAL, CONDITIONAL_OPTIMAL, ITERATION_LIMIT_REACHED, or TIME_LIMIT_REACHED, all terms of the _OROPTLP_ macro variable are present; for other values of SOLUTION_STATUS, some terms do not appear.

Examples: OPTLP Procedure

Example 5.1: Oil Refinery Problem

Consider an oil refinery scenario. A step in refining crude oil into finished oil products involves a distillation process that splits crude into various streams. Suppose there are three types of crude available: Arabian light (a_l), Arabian heavy (a_h), and Brega (br). These crudes are distilled into light naphtha (na_l), intermediate naphtha (na_i), and heating oil (h_o). These in turn are blended into two types of jet fuel. Jet fuel j_1 is made up of 30% intermediate naphtha and 70% heating oil, and jet fuel j_2 is made up of 20% light naphtha and 80% heating oil. What amounts of the three crudes maximize the profit from producing jet fuel (j_1, j_2)? This problem can be formulated as the following linear program:

$$\max \quad -175\text{a_l} - 165\text{a_h} - 205\text{br} + 350\text{j_1} + 350\text{j_2}$$

subject to

$$\begin{array}{lrcrcrcl}
(\text{napha_l}) & 0.035\,\text{a_l} & + & 0.03\,\text{a_h} & + & 0.045\,\text{br} & = & \text{na_l} \\
(\text{napha_i}) & 0.1\,\text{a_l} & + & 0.075\,\text{a_h} & + & 0.135\,\text{br} & = & \text{na_i} \\
(\text{htg_oil}) & 0.39\,\text{a_l} & + & 0.3\,\text{a_h} & + & 0.43\,\text{br} & = & \text{h_o} \\
(\text{blend1}) & & & 0.3\,\text{j_1} & & & \leq & \text{na_i} \\
(\text{blend2}) & & & & & 0.2\,\text{j_2} & \leq & \text{na_l} \\
(\text{blend3}) & & & 0.7\,\text{j_1} & + & 0.8\,\text{j_2} & \leq & \text{h_o} \\
 & \text{a_l} & & & & & \leq & 110 \\
 & & & \text{a_h} & & & \leq & 165 \\
 & & & & & \text{br} & \leq & 80
\end{array}$$

and

$$\text{a_l}, \text{a_h}, \text{br}, \text{na_1}, \text{na_i}, \text{h_o}, \text{j_1}, \text{j_2} \geq 0$$

The constraints “blend1” and “blend2” ensure that j_1 and j_2 are made with the specified amounts of na_i and na_l, respectively. The constraint “blend3” is actually the reduced form of the following constraints:

$$\begin{array}{lcrcl}
\text{h_o1} & & & \geq & 0.7\,\text{j_1} \\
 & & \text{h_o2} & \geq & 0.8\,\text{j_2} \\
\text{h_o1} & + & \text{h_o2} & \leq & \text{h_o}
\end{array}$$

where h_o1 and h_o2 are dummy variables.

You can use the following SAS code to create the input data table ex1:

```
data mycas.ex1;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX1      .     .         .
2  ROWS        .          .        .     .         .
3  N           profit     .        .     .         .
4  E           napha_l    .        .     .         .
5  E           napha_i    .        .     .         .
6  E           htg_oil    .        .     .         .
7  L           blend1     .        .     .         .
8  L           blend2     .        .     .         .
9  L           blend3     .        .     .         .
10 COLUMNS     .          .        .     .         .
11 .           a_l        profit   -175  napha_l   .035
12 .           a_l        napha_i  .100  htg_oil   .390
13 .           a_h        profit   -165  napha_l   .030
14 .           a_h        napha_i  .075  htg_oil   .300
15 .           br         profit   -205  napha_l   .045
16 .           br         napha_i  .135  htg_oil   .430
17 .           na_l       napha_l  -1    blend2    -1
18 .           na_i       napha_i  -1    blend1    -1
19 .           h_o        htg_oil  -1    blend3    -1
20 .           j_1        profit   350   blend1    .3
21 .           j_1        blend3   .7    .         .
22 .           j_2        profit   350   blend2    .2
23 .           j_2        blend3   .8    .         .
24 BOUNDS      .          .        .     .         .
25 UP          .          a_l      110   .         .
26 UP          .          a_h      165   .         .
27 UP          .          br       80    .         .
28 ENDATA      .          .        .     .         .
;
```

You can use the following call to PROC OPTLP to solve the LP problem:

```
proc optlp data=mycas.ex1
   objsense  = max
   algorithm = primal
   primalout = mycas.ex1pout
   dualout   = mycas.ex1dout
   logfreq   = 1;
run;
%put &_OROPTLP_;
```

Note that the OBJSENSE=MAX option is used to indicate that the objective function is to be maximized.

The primal and dual solutions are displayed in Output 5.1.1.

Output 5.1.1 Example 1: Primal and Dual Solution Output

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	profit		a_l	D	-175	0	110	110.000	U	10.2083
2	profit		a_h	D	-165	0	165	0.000	L	-22.8125
3	profit		br	D	-205	0	80	80.000	U	2.8125
4	profit		na_l	N	0	0	1.7977E308	7.450	B	0.0000
5	profit		na_i	N	0	0	1.7977E308	21.800	B	0.0000
6	profit		h_o	N	0	0	1.7977E308	77.300	B	0.0000
7	profit		j_1	N	350	0	1.7977E308	72.667	B	0.0000
8	profit		j_2	N	350	0	1.7977E308	33.042	B	0.0000

Dual Solution

Obs	Objective Function ID	RHS ID	Constraint Name	Constraint Type	Constraint RHS	Constraint Lower Bound	Constraint Upper Bound	Dual Solution	Constraint Status	Constraint Activity
1	profit		napha_l	E	0	.	.	0.000	U	0.00000
2	profit		napha_i	E	0	.	.	-145.833	U	0.00000
3	profit		htg_oil	E	0	.	.	-437.500	U	0.00000
4	profit		blend1	L	0	.	.	145.833	L	0.00000
5	profit		blend2	L	0	.	.	0.000	B	-0.84167
6	profit		blend3	L	0	.	.	437.500	L	-0.00000

The progress of the solution is printed to the log as follows.

Output 5.1.2 Log: Solution Progress

```
NOTE: The problem EX1 has 8 variables (0 free, 0 fixed).
NOTE: The problem has 6 constraints (3 LE, 3 EQ, 0 GE, 0 range).
NOTE: The problem has 19 constraint coefficients.
WARNING: The objective sense has been changed to maximization.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 3 variables and 3 constraints.
NOTE: The LP presolver removed 6 constraint coefficients.
NOTE: The presolved problem has 5 variables, 3 constraints, and 13 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       P 2          1    0.000000E+00         0        j_1         blend1 (S)
       P 2          2    2.022784E-03         0        j_2         blend2 (S)
       P 2          3    3.902347E-03         0         br         blend3 (S)
       P 2          4    4.025073E-03         0        a_l            a_l
       P 2          5    1.202248E+03         0     blend2 (S)         br
       P 2          6    1.347921E+03         0
       D 2          7    1.347917E+03         0
NOTE: Optimal.
NOTE: Objective = 1347.9166667.
NOTE: The Primal Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.105321
      seconds.
NOTE: The data set MYCAS.EX1POUT has 8 observations and 10 variables.
NOTE: The data set MYCAS.EX1DOUT has 6 observations and 10 variables.
```

Note that the %put statement immediately after the OPTLP procedure prints value of the macro variable _OROPTLP_ to the log as follows.

Output 5.1.3 Log: Value of the Macro Variable _OROPTLP_

```
STATUS=OK ALGORITHM=PS SOLUTION_STATUS=OPTIMAL OBJECTIVE=1347.9166667
PRIMAL_INFEASIBILITY=3.552714E-15 DUAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0
ITERATIONS=7 PRESOLVE_TIME=0.00 SOLUTION_TIME=0.00
```

The value briefly summarizes the status of the OPTLP procedure upon termination.

Example 5.2: Using the Interior Point Algorithm

You can also solve the oil refinery problem described in Example 5.1 by using the interior point algorithm. You can create the input data table from an external MPS-format flat file by using the SAS macro %MPS2SASD or SAS DATA step code, both of which are described in "Getting Started: OPTLP Procedure" on page 123. You can use the following SAS code to solve the problem:

```
proc optlp data=mycas.ex1
  objsense  = max
  algorithm = ip
  primalout = mycas.ex1ipout
  dualout   = mycas.ex1idout
  logfreq   = 1;
run;
```

The optimal solution is displayed in Output 5.2.1.

Output 5.2.1 Interior Point Algorithm: Primal Solution Output

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	profit		a_l	D	-175	0	110	110.000	U	10.2083
2	profit		a_h	D	-165	0	165	0.000	L	-22.8125
3	profit		br	D	-205	0	80	80.000	U	2.8125
4	profit		na_l	N	0	0	1.7977E308	7.450	B	0.0000
5	profit		na_i	N	0	0	1.7977E308	21.800	B	0.0000
6	profit		h_o	N	0	0	1.7977E308	77.300	B	0.0000
7	profit		j_1	N	350	0	1.7977E308	72.667	B	0.0000
8	profit		j_2	N	350	0	1.7977E308	33.042	B	0.0000

The iteration log is displayed in Output 5.2.2.

Output 5.2.2 Log: Solution Progress

```
NOTE: The problem EX1 has 8 variables (0 free, 0 fixed).
NOTE: The problem has 6 constraints (3 LE, 3 EQ, 0 GE, 0 range).
NOTE: The problem has 19 constraint coefficients.
WARNING: The objective sense has been changed to maximization.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 3 variables and 3 constraints.
NOTE: The LP presolver removed 6 constraint coefficients.
NOTE: The LP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 5 variables, 3 constraints, and 13 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Interior Point algorithm is used.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Interior Point algorithm is using up to 32 threads.
                                      Primal       Bound        Dual
      Iter  Complement Duality Gap      Infeas      Infeas      Infeas   Time
         0  3.3251E+01  2.3083E+00  8.6736E+00  1.1031E-01  4.6594E-02      0
         1  1.0375E+01  6.4835E+00  1.9621E+00  2.4953E-02  1.9755E-02      0
         2  9.3435E+00  7.2154E-01  1.8603E+00  2.3659E-02  1.9164E-02      0
         3  1.8905E+00  2.1409E-01  1.8603E-02  2.3659E-04  4.0457E-03      0
         4  7.3674E-01  9.6443E-02  8.9943E-03  1.1439E-04  7.5732E-04      0
         5  1.3869E-02  1.4941E-03  8.9943E-05  1.1439E-06  1.9849E-05      0
         6  1.3879E-04  1.4940E-05  9.0069E-07  1.1455E-08  1.9850E-07      0
         7  3.7555E-04  1.7926E-07  2.6999E-09  1.7419E-10  4.3230E-07      0
         8  0.0000E+00  4.2358E-09  1.3194E-08  2.8639E-13  1.6401E-08      0
NOTE: The Interior Point solve time is 0.00 seconds.
NOTE: The CROSSOVER option is enabled.
NOTE: The crossover basis contains 0 primal and 0 dual superbasic variables.
                           Objective
      Phase Iteration        Value         Time
       P C          1    0.000000E+00         0
       P 2          2    1.347917E+03         0
       D 2          3    1.347917E+03         0
       P 2          4    1.347917E+03         0
NOTE: The Crossover time is 0.00 seconds.
NOTE: Optimal.
NOTE: Objective = 1347.9166667.
NOTE: The Cloud Analytic Services server processed the request in 0.095999
      seconds.
NOTE: The data set MYCAS.EX1IPOUT has 8 observations and 10 variables.
NOTE: The data set MYCAS.EX1IDOUT has 6 observations and 10 variables.
```

Example 5.3: The Diet Problem

Consider the problem of diet optimization. There are six different foods: bread, milk, cheese, potato, fish, and yogurt. The cost and nutrition values per unit are displayed in Table 5.3.

Table 5.3 Cost and Nutrition Values

	Bread	Milk	Cheese	Potato	Fish	Yogurt
Cost	2.0	3.5	8.0	1.5	11.0	1.0
Protein, g	4.0	8.0	7.0	1.3	8.0	9.2
Fat, g	1.0	5.0	9.0	0.1	7.0	1.0
Carbohydrates, g	15.0	11.7	0.4	22.6	0.0	17.0
Calories	90	120	106	97	130	180

The objective is to find a minimum-cost diet that contains at least 300 calories, not more than 10 grams of protein, not less than 10 grams of carbohydrates, and not less than 8 grams of fat. In addition, the diet should contain at least 0.5 unit of fish and no more than 1 unit of milk.

You can use the following SAS code to create the MPS-format input data table:

```
data mycas.ex3;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX3      .     .         .
2  ROWS        .          .        .     .         .
3  N           diet       .        .     .         .
4  G           calories   .        .     .         .
5  L           protein    .        .     .         .
6  G           fat        .        .     .         .
7  G           carbs      .        .     .         .
8  COLUMNS     .          .        .     .         .
9  .           br         diet     2     calories  90
10 .           br         protein  4     fat       1
11 .           br         carbs    15    .         .
12 .           mi         diet     3.5   calories  120
13 .           mi         protein  8     fat       5
14 .           mi         carbs    11.7  .         .
15 .           ch         diet     8     calories  106
16 .           ch         protein  7     fat       9
17 .           ch         carbs    .4    .         .
18 .           po         diet     1.5   calories  97
19 .           po         protein  1.3   fat       .1
20 .           po         carbs    22.6  .         .
21 .           fi         diet     11    calories  130
22 .           fi         protein  8     fat       7
23 .           fi         carbs    0     .         .
24 .           yo         diet     1     calories  180
25 .           yo         protein  9.2   fat       1
26 .           yo         carbs    17    .         .
27 RHS         .          .        .     .         .
```

```
28 .          .          calories 300   protein   10
29 .          .          fat      8     carbs     10
30 BOUNDS     .          .        .     .         .
31 UP         .          mi       1     .         .
32 LO         .          fi       .5    .         .
33 ENDATA     .          .        .     .         .
;
```

You can solve the diet problem by using PROC OPTLP as follows:

```
proc optlp data=mycas.ex3
   presolver = none
   algorithm = ps
   primalout = mycas.ex3pout
   dualout   = mycas.ex3dout
   logfreq   = 1;
run;
```

The solution summary and the optimal primal solution are displayed in Output 5.3.1.

Output 5.3.1 Diet Problem: Solution Summary and Optimal Primal Solution

Solution Summary

Obs	Name1	Label1	cValue1	nValue1
1	solver	Solver	LP	.
2	algorithm	Algorithm	Primal Simplex	.
3	objectiveName	Objective Function	diet	.
4	solStatus	Solution Status	Optimal	.
5	objective	Objective Value	12.081337881	12.081338
6				.
7	primalInfeasibility	Primal Infeasibility	0	0
8	dualInfeasibility	Dual Infeasibility	1.44329E-16	1.44329E-16
9	boundInfeasibility	Bound Infeasibility	0	0
10				.
11	iterations	Iterations	6	6.000000
12	presolveTime	Presolve Time	0.00	0.000162
13	solutionTime	Solution Time	0.00	0.001463

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	diet		br	N	2.0	0.0	1.7977E308	0.00000	L	1.19066
2	diet		mi	D	3.5	0.0	1	0.05360	B	0.00000
3	diet		ch	N	8.0	0.0	1.7977E308	0.44950	B	0.00000
4	diet		po	N	1.5	0.0	1.7977E308	1.86517	B	-0.00000
5	diet		fi	O	11.0	0.5	1.7977E308	0.50000	L	5.15641
6	diet		yo	N	1.0	0.0	1.7977E308	0.00000	L	1.10849

The cost of the optimal diet is 12.08 units.

Example 5.4: Reoptimizing after Modifying the Objective Function

Using the diet problem described in Example 5.3, this example illustrates how to reoptimize an LP problem after modifying the objective function.

Assume that the optimal solution of the diet problem is found and the optimal solutions are stored in the data sets ex3pout and ex3dout.

Suppose the cost of cheese increases from 8 to 10 per unit and the cost of fish decreases from 11 to 7 per serving unit. The COLUMNS section in the input data table ex3 is updated (and the data table is saved as ex4) as follows:

```
COLUMNS      .          .         .     .         .
   ...
.            ch         diet     10     calories  106
   ...
.            fi         diet     7      calories  130
   ...
RHS          .          .         .     .         .
   ...

ENDATA
;
```

You can use the following DATA step to create the data table ex4:

```
data mycas.ex4;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX3      .     .         .
2  ROWS        .          .        .     .         .
3  N           diet       .        .     .         .
4  G           calories   .        .     .         .
5  L           protein    .        .     .         .
6  G           fat        .        .     .         .
7  G           carbs      .        .     .         .
8  COLUMNS     .          .        .     .         .
9  .           br         diet     2     calories  90
10 .           br         protein  4     fat       1
11 .           br         carbs    15    .         .
12 .           mi         diet     3.5   calories  120
13 .           mi         protein  8     fat       5
14 .           mi         carbs    11.7  .         .
15 .           ch         diet     10     calories  106
16 .           ch         protein  7     fat       9
17 .           ch         carbs    .4    .         .
18 .           po         diet     1.5   calories  97
19 .           po         protein  1.3   fat       .1
20 .           po         carbs    22.6  .         .
21 .           fi         diet     7     calories  130
22 .           fi         protein  8     fat       7
```

```
23 .          fi         carbs    0      .          .
24 .          yo         diet     1      calories   180
25 .          yo         protein  9.2    fat        1
26 .          yo         carbs    17     .          .
27 RHS        .          .        .      .          .
28 .          .          calories 300    protein    10
29 .          .          fat      8      carbs      10
30 BOUNDS     .          .        .      .          .
31 UP         .          mi       1      .          .
32 LO         .          fi       .5     .          .
33 ENDATA     .          .        .      .          .
;
```

You can use the BASIS=WARMSTART option (and the ex3pout and ex3dout data tables from Example 5.3) in the following call to PROC OPTLP to solve the modified problem:

```
proc optlp data=mycas.ex4
   presolver = none
   basis     = warmstart
   primalin  = mycas.ex3pout
   dualin    = mycas.ex3dout
   algorithm = primal
   primalout = mycas.ex4pout
   dualout   = mycas.ex4dout
   logfreq   = 1;
run;
```

The following iteration log indicates that it takes the primal simplex algorithm no extra iterations to solve the modified problem by using BASIS=WARMSTART, since the optimal solution to the LP problem in Example 5.3 remains optimal after the objective function is changed.

Output 5.4.1 Iteration Log

```
NOTE: The problem EX3 has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       P 2          1    1.098034E+01         0
NOTE: Optimal.
NOTE: Objective = 10.980335514.
NOTE: The Primal Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.167147
      seconds.
NOTE: The data set MYCAS.EX4POUT has 6 observations and 10 variables.
NOTE: The data set MYCAS.EX4DOUT has 4 observations and 10 variables.
```

Note that the primal simplex algorithm is preferred because the primal solution to the original LP is still feasible for the modified problem in this case.

Example 5.5: Reoptimizing after Modifying the Right-Hand Side

You can also modify the right-hand side of your problem and use the BASIS=WARMSTART option to obtain an optimal solution more quickly. Since the dual solution to the original LP is still feasible for the modified problem in this case, the dual simplex algorithm is preferred. This case is illustrated by using the same diet problem as in Example 5.3. Assume that you now need a diet that supplies at least 150 calories. The RHS section in the input data table ex3 is updated (and the data set is saved as ex5) as follows:

```
   ...
RHS          .          .         .     .         .
.            .          calories 150   protein   10
.            .          fat      8     carbs     10
BOUNDS       .          .         .     .         .
   ...
```

You can use the following DATA step to create the data table ex5:

```
data mycas.ex5;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX3      .     .         .
2  ROWS        .          .        .     .         .
3  N           diet       .        .     .         .
4  G           calories   .        .     .         .
5  L           protein    .        .     .         .
6  G           fat        .        .     .         .
7  G           carbs      .        .     .         .
8  COLUMNS     .          .        .     .         .
9  .           br         diet     2     calories  90
10 .           br         protein  4     fat       1
11 .           br         carbs    15    .         .
12 .           mi         diet     3.5   calories  120
13 .           mi         protein  8     fat       5
14 .           mi         carbs    11.7  .         .
15 .           ch         diet     8     calories  106
16 .           ch         protein  7     fat       9
17 .           ch         carbs    .4    .         .
18 .           po         diet     1.5   calories  97
19 .           po         protein  1.3   fat       .1
20 .           po         carbs    22.6  .         .
21 .           fi         diet     11    calories  130
22 .           fi         protein  8     fat       7
23 .           fi         carbs    0     .         .
24 .           yo         diet     1     calories  180
25 .           yo         protein  9.2   fat       1
26 .           yo         carbs    17    .         .
27 RHS         .          .        .     .         .
28 .           .          calories 150   protein   10
29 .           .          fat      8     carbs     10
30 BOUNDS      .          .        .     .         .
31 UP          .          mi       1     .         .
32 LO          .          fi       .5    .         .
33 ENDATA      .          .        .     .         .
;
```

You can use the BASIS=WARMSTART option in the following call to PROC OPTLP to solve the modified problem:

```
proc optlp data=mycas.ex5
   presolver = none
   basis     = warmstart
   primalin  = mycas.ex3pout
   dualin    = mycas.ex3dout
   algorithm = dual
   primalout = mycas.ex5pout
   dualout   = mycas.ex5dout
   logfreq   = 1;
run;
```

Note that the dual simplex algorithm is preferred because the dual solution to the last solved LP is still feasible for the modified problem in this case.

The following iteration log indicates that it takes the dual simplex algorithm just one more phase II iteration to solve the modified problem by using BASIS=WARMSTART.

Output 5.5.1 Iteration Log

```
NOTE: The problem EX3 has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       D 2          1    8.813205E+00         0   calories (S)      carbs (S)
       D 2          2    9.174413E+00         0
NOTE: Optimal.
NOTE: Objective = 9.1744131985.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.16863
      seconds.
NOTE: The data set MYCAS.EX5POUT has 6 observations and 10 variables.
NOTE: The data set MYCAS.EX5DOUT has 4 observations and 10 variables.
```

Compare this with the following call to PROC OPTLP:

```
proc optlp data=mycas.ex5
   presolver = none
   algorithm = dual
   logfreq   = 1;
run;
```

This call to PROC OPTLP solves the modified problem “from scratch” (without using the BASIS=WARMSTART option) and produces the following iteration log.

Output 5.5.2 Iteration Log

```
NOTE: The problem EX3 has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       D 2          1    5.500000E+00         0         mi            fat (S)
       D 2          2    8.650000E+00         0         ch        protein (S)
       D 2          3    8.925676E+00         0         po          carbs (S)
       D 2          4    9.174413E+00         0
NOTE: Optimal.
NOTE: Objective = 9.1744131985.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.046467
      seconds.
```

It is clear that using the BASIS=WARMSTART option saves computation time. For larger or more complex examples, the benefits of using this option are more pronounced.

Example 5.6: Reoptimizing after Adding a New Constraint

Assume that after solving the diet problem in Example 5.3 you need to add a new constraint on sodium intake of no more than 550 mg/day for adults. The updated nutrition data are given in Table 5.4.

Table 5.4 Updated Cost and Nutrition Values

	Bread	Milk	Cheese	Potato	Fish	Yogurt
Cost	2.0	3.5	8.0	1.5	11.0	1.0
Protein, g	4.0	8.0	7.0	1.3	8.0	9.2
Fat, g	1.0	5.0	9.0	0.1	7.0	1.0
Carbohydrates, g	15.0	11.7	0.4	22.6	0.0	17.0
Calories, Cal	90	120	106	97	130	180
sodium, mg	148	122	337	186	56	132

The input data table ex3 is updated (and the data table is saved as ex6) as follows:

```
/* added a new constraint to the diet problem */
data mycas.ex6;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX6       .      .          .
2  ROWS        .          .         .      .          .
3  N          diet        .         .      .          .
```

```
4  G          calories   .         .     .         .
5  L          protein    .         .     .         .
6  G          fat        .         .     .         .
7  G          carbs      .         .     .         .
8  L          sodium     .         .     .         .
9  COLUMNS     .          .         .     .         .
10 .           br         diet     2     calories  90
11 .           br         protein  4     fat       1
12 .           br         carbs    15    sodium    148
13 .           mi         diet     3.5   calories  120
14 .           mi         protein  8     fat       5
15 .           mi         carbs    11.7  sodium    122
16 .           ch         diet     8     calories  106
17 .           ch         protein  7     fat       9
18 .           ch         carbs    .4    sodium    337
19 .           po         diet     1.5   calories  97
20 .           po         protein  1.3   fat       .1
21 .           po         carbs    22.6  sodium    186
22 .           fi         diet     11    calories  130
23 .           fi         protein  8     fat       7
24 .           fi         carbs    0     sodium    56
25 .           yo         diet     1     calories  180
26 .           yo         protein  9.2   fat       1
27 .           yo         carbs    17    sodium    132
28 RHS         .          .        .     .         .
29 .           .          calories 300   protein   10
30 .           .          fat      8     carbs     10
31 .           .          sodium   550   .         .
32 BOUNDS      .          .        .     .         .
33 UP          .          mi       1     .         .
34 LO          .          fi       .5    .         .
35 ENDATA      .          .        .     .         .
;
```

For the modified problem you can warm start the primal and dual simplex algorithms to get a solution faster. The dual simplex algorithm is preferred because a dual feasible solution can be readily constructed from the optimal solution to the diet optimization problem.

Since there is a new constraint in the modified problem, you can use the following SAS code to create a new DUALIN= data table ex6din with this information:

```
data mycas.ex6newcon;
   _ROW_='sodium  '; _STATUS_='A';
   output;
run;

/* create a new DUALIN= data set to include the new constraint */
data mycas.ex6din;
   set mycas.ex3dout mycas.ex6newcon;
run;
```

Note that this step is optional. In this example, you can still use the data table ex3dout as the DUALIN= data set to solve the modified LP problem by using the BASIS=WARMSTART option. PROC OPTLP validates the PRIMALIN= and DUALIN= data sets against the input model. Any new variable (or constraint) in the

model is added to the PRIMALIN= (or DUALIN=) data set, and its status is assigned to be 'A'. The primal and dual simplex algorithms decide its corresponding status internally. Any variable in the PRIMALIN= and DUALIN= data sets but not in the input model is removed.

The _ROW_ and _STATUS_ columns of the DUALIN= data table ex6din are shown in Output 5.6.1.

Output 5.6.1 DUALIN= Data Set with a Newly Added Constraint

Obs	_ROW_	_STATUS_
1	calories	U
2	protein	L
3	fat	U
4	carbs	B
5	sodium	A

The dual simplex algorithm is called to solve the modified diet optimization problem more quickly with the following SAS code:

```
proc optlp data=mycas.ex6
   objsense=min
   presolver=none
   algorithm=ds
   primalout=mycas.ex6pout
   dualout=mycas.ex6dout
   scale=none
   logfreq=1
   basis=warmstart
   primalin=mycas.ex3pout
   dualin=mycas.ex6din;
run;
```

The optimal primal and dual solutions of the modified problem are displayed in Output 5.6.2.

Output 5.6.2 Primal and Dual Solution Output

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	diet		br	N	2.0	0.0	1.7977E308	0.00000	L	1.19066
2	diet		mi	D	3.5	0.0	1	0.05360	B	-0.00000
3	diet		ch	N	8.0	0.0	1.7977E308	0.44950	B	0.00000
4	diet		po	N	1.5	0.0	1.7977E308	1.86517	B	0.00000
5	diet		fi	O	11.0	0.5	1.7977E308	0.50000	L	5.15641
6	diet		yo	N	1.0	0.0	1.7977E308	0.00000	L	1.10849

Output 5.6.2 *continued*

Dual Solution

Obs	Objective Function ID	RHS ID	Constraint Name	Constraint Type	Constraint RHS	Constraint Lower Bound	Constraint Upper Bound	Dual Solution	Constraint Status	Constraint Activity
1	diet		calories	G	300	.	.	0.02179	U	300.000
2	diet		protein	L	10	.	.	-0.55360	L	10.000
3	diet		fat	G	8	.	.	1.06286	U	8.000
4	diet		carbs	G	10	.	.	0.00000	B	42.960
5	diet		sodium	L	550	.	.	0.00000	B	532.941

The iteration log shown in Output 5.6.3 indicates that it takes the dual simplex algorithm no more iterations to solve the modified problem by using the BASIS=WARMSTART option, since the optimal solution to the original problem remains optimal after one more constraint is added.

Output 5.6.3 Iteration Log

```
NOTE: The problem EX6 has 6 variables (0 free, 0 fixed).
NOTE: The problem has 5 constraints (2 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 29 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       D 2          1    1.208134E+01         0
NOTE: Optimal.
NOTE: Objective = 12.081337881.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.196604
      seconds.
NOTE: The data set MYCAS.EX6POUT has 6 observations and 10 variables.
NOTE: The data set MYCAS.EX6DOUT has 5 observations and 10 variables.
```

Both this example and Example 5.4 illustrate the situation in which the optimal solution does not change after some perturbation of the parameters of the LP problem. The simplex algorithm starts from an optimal solution and quickly verifies the optimality. Usually the optimal solution of the slightly perturbed problem can be obtained after performing relatively small number of iterations if starting with the optimal solution of the original problem. In such cases you can expect a dramatic reduction of computation time, for instance, if you want to solve a large LP problem and a slightly perturbed version of this problem by using the BASIS=WARMSTART option rather than solving both problems from scratch.

Example 5.7: Finding an Irreducible Infeasible Set

This example demonstrates the use of the IIS= option to locate an irreducible infeasible set. Suppose you want to solve a linear program that has the following simple formulation:

$$
\begin{array}{rrcrcrcrl}
\min & & x_1 & + & x_2 & + & x_3 & & \text{(cost)} \\
\text{subject to} & & x_1 & + & x_2 & & & \geq\ 10 & \text{(con1)} \\
 & & x_1 & & & + & x_3 & \leq\ 4 & \text{(con2)} \\
 & 4 \leq & & & x_2 & + & x_3 & \leq\ 5 & \text{(con3)} \\
 & & & & & x_1, & x_2 & \geq\ 0 & \\
 & & & & 0 & \leq & x_3 & \leq\ 3 &
\end{array}
$$

The corresponding MPS-format data table is as follows:

```
/* infeasible */
data mycas.exiis;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
datalines;
1  NAME     .        .        .        .        .
2  ROWS     .        .        .        .        .
3  N       cost      .        .        .        .
4  G       con1      .        .        .        .
5  L       con2      .        .        .        .
6  G       con3      .        .        .        .
7  COLUMNS  .        .        .        .        .
8  .        x1       cost     1        con1     1
9  .        x1       con2     1        .        .
10 .        x2       cost     1        con1     1
11 .        x2       con3     1        .        .
12 .        x3       cost     1        con2     1
13 .        x3       con3     1        .        .
14 RHS      .        .        .        .        .
15 .        rhs      con1     10       con2     4
16 .        rhs      con3     4        .        .
17 RANGES   .        .        .        .        .
18 .        r1       con3     1        .        .
19 BOUNDS   .        .        .        .        .
20 UP       b1       x3       3        .        .
21 ENDATA   .        .        .        .        .
;
```

It is easy to verify that the following three constraints (or rows) and one variable (or column) bound form an IIS for this problem.

$$
\begin{array}{rcrcrcrl}
x_1 & + & x_2 & & & \geq & 10 & \text{(con1)} \\
x_1 & & & + & x_3 & \leq & 4 & \text{(con2)} \\
 & & x_2 & + & x_3 & \leq & 5 & \text{(con3)} \\
 & & & & x_3 & \geq & 0 &
\end{array}
$$

You can use the IIS=TRUE option to detect this IIS by using the following statements:

```
proc optlp data=mycas.exiis
   iis=true
   primalout=mycas.iis_vars
   dualout=mycas.iis_cons
   logfreq=1;
run;
```

The OPTLP procedure outputs the detected IIS to the data sets specified by the PRIMALOUT= and DUALOUT= options, then stops. The notes shown in Output 5.7.1 are printed to the log.

Output 5.7.1 The IIS= Option: Log

```
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 constraints (1 LE, 0 EQ, 1 GE, 1 range).
NOTE: The problem has 6 constraint coefficients.
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       P 1          1    6.000000E+00         0       con3 (S)       con3 (S)
       P 1          2    5.000000E+00         0         x1           con2 (S)
       P 1          3    1.000000E+00         0
NOTE: Applying the IIS sensitivity filter.
NOTE: The sensitivity filter removed 1 constraints and 3 variable bounds.
NOTE: Applying the IIS deletion filter.
NOTE: Processing constraints.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: Processing variable bounds.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: The deletion filter removed 0 constraints and 0 variable bounds.
NOTE: The IIS= option found this problem to be infeasible.
NOTE: The IIS= option found an irreducible infeasible set with 1 variables and
      3 constraints.
NOTE: The IIS solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.094349
      seconds.
NOTE: The data set MYCAS.IIS_VARS has 3 observations and 10 variables.
NOTE: The data set MYCAS.IIS_CONS has 3 observations and 10 variables.
```

The data sets iis_cons and iis_vars are shown in Output 5.7.2.

Output 5.7.2 Identify Rows and Columns in the IIS

Constraints in the IIS

Obs	Objective Function ID	RHS ID	Constraint Name	Constraint Type	Constraint RHS	Constraint Lower Bound	Constraint Upper Bound	Dual Solution	Constraint Status	Constraint Activity
1	cost	rhs	con1	G	10	.	.	.	I_L	.
2	cost	rhs	con2	L	4	.	.	.	I_U	.
3	cost	rhs	con3	R	.	5	4	.	I_U	.

Variables in the IIS

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	cost	rhs	x1	N	1	0	1.7977E308	.		.
2	cost	rhs	x2	N	1	0	1.7977E308	.		.
3	cost	rhs	x3	D	1	0	3	.	I_L	.

The constraint $x_2 + x_3 \leq 5$, which is an element of the IIS, is created by the RANGES section. The original constraint is con3, a "$\geq$" constraint with an RHS value of 4. If you choose to remove the constraint $x_2 + x_3 \leq 5$, you can accomplish this by removing con3 from the RANGES section in the MPS-format data table exiis. Since con3 is the only observation in the section, the identifier observation can also be removed. The modified LP problem is specified in the following SAS statements:

```
 /* dropping con3, feasible */
data mycas.exiisf;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
datalines;
1  NAME     .        .        .        .        .
2  ROWS     .        .        .        .        .
3  N        cost     .        .        .        .
4  G        con1     .        .        .        .
5  L        con2     .        .        .        .
6  G        con3     .        .        .        .
7  COLUMNS  .        .        .        .        .
8  .        x1       cost     1        con1     1
9  .        x1       con2     1        .        .
10 .        x2       cost     1        con1     1
11 .        x2       con3     1        .        .
12 .        x3       cost     1        con2     1
13 .        x3       con3     1        .        .
14 RHS      .        .        .        .        .
15 .        rhs      con1     10       con2     4
16 .        rhs      con3     4        .        .
17 BOUNDS   .        .        .        .        .
18 UP       b1       x3       3        .        .
19 ENDATA   .        .        .        .        .
;
```

Since one element of the IIS has been removed, the modified LP problem should no longer contain the infeasible set. Due to the size of this problem, there should be no additional irreducible infeasible sets. You can confirm this by submitting the following SAS statements:

```
proc optlp data=mycas.exiisf
   iis=true;
run;
```

The notes shown in Output 5.7.3 are printed to the log.

Output 5.7.3 The IIS= Option: Log

```
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 constraints (1 LE, 0 EQ, 2 GE, 0 range).
NOTE: The problem has 6 constraint coefficients.
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                          Objective
      Phase Iteration        Value         Time
       P 1          1    1.400000E+01         0
       P 1          2    0.000000E+00         0
NOTE: The IIS= option found this problem to be feasible.
NOTE: The IIS solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.044563
      seconds.
NOTE: The data set WORK.EXSS has 8 observations and 4 variables.
```

The solution summary is displayed in Output 5.7.4.

Output 5.7.4 Infeasibility Removed

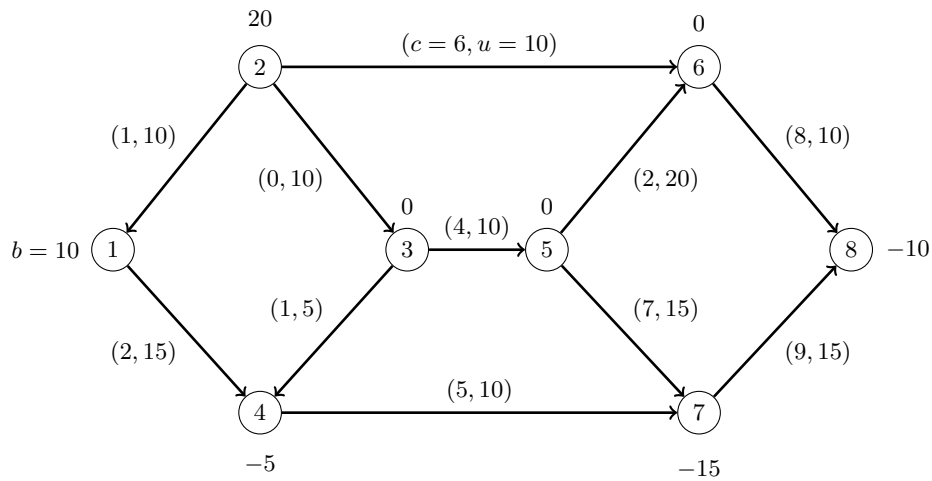
Solution Summary

Obs	Name1	Label1	cValue1	nValue1
1	solver	Solver	LP	.
2	algorithm	Algorithm	IIS	.
3	objectiveName	Objective Function	cost	.
4	solStatus	Solution Status	Feasible	.
5				.
6	iterations	Iterations	2	2.000000
7	presolveTime	Presolve Time	0.00	0
8	solutionTime	Solution Time	0.00	0.000327

Example 5.8: Using the Network Simplex Algorithm

This example demonstrates how to use the network simplex algorithm to find the minimum-cost flow in a directed graph. Consider the directed graph in Figure 5.5, which appears in Ahuja, Magnanti, and Orlin (1993).

Figure 5.5 Minimum-Cost Network Flow Problem: Data



You can use the following SAS statements to create the input data table ex8:

```
data mycas.ex8;
   input _id_ field1 $8. field2 $13. @28 field3 $13. field4 @56 field5 $13. field6;
   datalines;
1  NAME    .              .                    .      .                    .
2  ROWS    .              .                    .      .                    .
3  N       obj            .                    .      .                    .
4  E       balance['1']   .                    .      .                    .
5  E       balance['2']   .                    .      .                    .
6  E       balance['3']   .                    .      .                    .
7  E       balance['4']   .                    .      .                    .
8  E       balance['5']   .                    .      .                    .
9  E       balance['6']   .                    .      .                    .
10 E       balance['7']   .                    .      .                    .
11 E       balance['8']   .                    .      .                    .
12 COLUMNS .              .                    .      .                    .
13 .       x['1','4']     obj                  2      balance['1']         1
14 .       x['1','4']     balance['4']        -1      .                    .
15 .       x['2','1']     obj                  1      balance['1']        -1
16 .       x['2','1']     balance['2']         1      .                    .
17 .       x['2','3']     balance['2']         1      balance['3']        -1
18 .       x['2','6']     obj                  6      balance['2']         1
19 .       x['2','6']     balance['6']        -1      .                    .
20 .       x['3','4']     obj                  1      balance['3']         1
21 .       x['3','4']     balance['4']        -1      .                    .
22 .       x['3','5']     obj                  4      balance['3']         1
23 .       x['3','5']     balance['5']        -1      .                    .
24 .       x['4','7']     obj                  5      balance['4']         1
```

```
25 .       x['4','7']      balance['7']        -1      .                   .
26 .       x['5','6']      obj                  2      balance['5']        1
27 .       x['5','6']      balance['6']        -1      .                   .
28 .       x['5','7']      obj                  7      balance['5']        1
29 .       x['5','7']      balance['7']        -1      .                   .
30 .       x['6','8']      obj                  8      balance['6']        1
31 .       x['6','8']      balance['8']        -1      .                   .
32 .       x['7','8']      obj                  9      balance['7']        1
33 .       x['7','8']      balance['8']        -1      .                   .
34 RHS     .               .                    .      .                   .
35 .       .RHS.           balance['1']        10      .                   .
36 .       .RHS.           balance['2']        20      .                   .
37 .       .RHS.           balance['4']        -5      .                   .
38 .       .RHS.           balance['7']       -15      .                   .
39 .       .RHS.           balance['8']       -10      .                   .
40 BOUNDS  .               .                    .      .                   .
41 UP      .BOUNDS.        x['1','4']          15      .                   .
42 UP      .BOUNDS.        x['2','1']          10      .                   .
43 UP      .BOUNDS.        x['2','3']          10      .                   .
44 UP      .BOUNDS.        x['2','6']          10      .                   .
45 UP      .BOUNDS.        x['3','4']           5      .                   .
46 UP      .BOUNDS.        x['3','5']          10      .                   .
47 UP      .BOUNDS.        x['4','7']          10      .                   .
48 UP      .BOUNDS.        x['5','6']          20      .                   .
49 UP      .BOUNDS.        x['5','7']          15      .                   .
50 UP      .BOUNDS.        x['6','8']          10      .                   .
51 UP      .BOUNDS.        x['7','8']          15      .                   .
52 ENDATA  .               .                    .      .                   .
;
```

You can use the following call to PROC OPTLP to find the minimum-cost flow:

```
proc optlp
  presolver  = none
  printlevel = 2
  logfreq    = 1
  data       = mycas.ex8
  primalout  = mycas.ex8out
  algorithm  = ns;
run;
```

The optimal solution is displayed in Output 5.8.1.

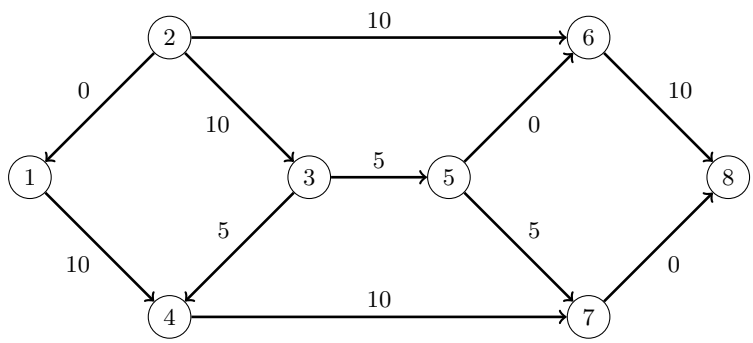
Output 5.8.1 Network Simplex Algorithm: Primal Solution Output

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost
1	obj	.RHS.	x['1','4']	D	2	0	15	10	B	0
2	obj	.RHS.	x['2','1']	D	1	0	10	0	L	2
3	obj	.RHS.	x['2','3']	D	0	0	10	10	B	0
4	obj	.RHS.	x['2','6']	D	6	0	10	10	B	0
5	obj	.RHS.	x['3','4']	D	1	0	5	5	B	0
6	obj	.RHS.	x['3','5']	D	4	0	10	5	B	0
7	obj	.RHS.	x['4','7']	D	5	0	10	10	U	-5
8	obj	.RHS.	x['5','6']	D	2	0	20	0	L	0
9	obj	.RHS.	x['5','7']	D	7	0	15	5	B	0
10	obj	.RHS.	x['6','8']	D	8	0	10	10	B	0
11	obj	.RHS.	x['7','8']	D	9	0	15	0	L	6

The optimal solution is represented graphically in Figure 5.6.

Figure 5.6 Minimum-Cost Network Flow Problem: Optimal Solution



The iteration log is displayed in Output 5.8.2.

Output 5.8.2 Log: Solution Progress

```
NOTE: The problem has 11 variables (0 free, 0 fixed).
NOTE: The problem has 8 constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 22 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Network Simplex algorithm is used.
NOTE: The network has 8 rows (100.00%), 11 columns (100.00%), and 1 component.
NOTE: The network extraction and setup time is 0.00 seconds.
                        Primal         Primal           Dual
      Iteration      Objective  Infeasibility  Infeasibility     Time
              1   0.000000E+00   2.000000E+01   8.900000E+01     0.00
              2   0.000000E+00   2.000000E+01   8.900000E+01     0.01
              3   5.000000E+00   1.500000E+01   8.400000E+01     0.01
              4   5.000000E+00   1.500000E+01   8.300000E+01     0.01
              5   7.500000E+01   1.500000E+01   8.300000E+01     0.01
              6   7.500000E+01   1.500000E+01   7.900000E+01     0.01
              7   1.300000E+02   1.000000E+01   7.600000E+01     0.01
              8   2.700000E+02   0.000000E+00   0.000000E+00     0.01
NOTE: The Network Simplex solve time is 0.01 seconds.
NOTE: The total Network Simplex solve time is 0.01 seconds.
NOTE: Optimal.
NOTE: Objective = 270.
NOTE: The Cloud Analytic Services server processed the request in 0.096455
      seconds.
NOTE: The data set MYCAS.EX8OUT has 11 observations and 10 variables.
```

Example 5.9: Sensitivity Analysis

In this example, consider again the diet problem from Example 5.3. Example 5.4 and Example 5.5 show how to reoptimize the optimization problem if the input data change. This is useful if you want to investigate other scenarios or see how the optimal solution changes as a function of the input data. Sensitivity analysis automates this process by providing stability intervals for the input data.

After solving the diet problem, you can ask how much the price of each food item can change without invalidating the optimal basis that is found. You can calculate this by using the following solver call:

```
proc optlp data=mycas.ex3
   presolver = none
   algorithm = ps
   primalout = mycas.ex3pout
   dualout   = mycas.ex3dout
   logfreq   = 1;
   sensitivity change=obj;
run;
```

The results are shown in Output 5.9.1.

Output 5.9.1 Optimal Solutions to the Original Diet Problem and Sensitivity Analysis for the Objective Coefficients

Primal Solution

Obs	Variable Name	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status	Reduced Cost	Objective Coefficient Minimum	Objective Coefficient Maximum
1	br	2.0	0.0	1.7977E308	0.00000	L	1.19066	0.80934	1.7977E308
2	mi	3.5	0.0	1	0.05360	B	0.00000	-1.7977E308	4.0884
3	ch	8.0	0.0	1.7977E308	0.44950	B	0.00000	6.82284	19.4228
4	po	1.5	0.0	1.7977E308	1.86517	B	-0.00000	-0.19189	3.5006
5	fi	11.0	0.5	1.7977E308	0.50000	L	5.15641	5.84359	1.7977E308
6	yo	1.0	0.0	1.7977E308	0.00000	L	1.10849	-0.10849	1.7977E308

Note that you can combine the sensitivity analysis with the initial solve of the optimization problem.

From the output, you can see that changing the price of cheese between 6.82284 and 19.4228 would result in the same optimal basis.

You can easily verify this by using the warm-start technique shown in Example 5.4. First, you change the price of cheese to 15.0. The COLUMNS section in the input data table ex3 is updated (and the data table is saved as ex9) as follows:

```
COLUMNS      .          .         .     .          .
   ...
.            ch         diet      15     calories  106
   ...
RHS          .          .         .     .          .
   ...

ENDATA
;
```

You can use the following DATA step to create the data table ex9:

```
data mycas.ex9;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME        .          EX3       .     .          .
2  ROWS        .          .         .     .          .
3  N           diet       .         .     .          .
4  G           calories   .         .     .          .
5  L           protein    .         .     .          .
6  G           fat        .         .     .          .
7  G           carbs      .         .     .          .
8  COLUMNS     .          .         .     .          .
9  .           br         diet      2     calories   90
10 .           br         protein   4     fat        1
11 .           br         carbs     15    .          .
12 .           mi         diet      3.5   calories   120
13 .           mi         protein   8     fat        5
```

```
14 .          mi        carbs    11.7  .         .
15 .          ch        diet     15    calories  106
16 .          ch        protein  7     fat       9
17 .          ch        carbs    .4    .         .
18 .          po        diet     1.5   calories  97
19 .          po        protein  1.3   fat       .1
20 .          po        carbs    22.6  .         .
21 .          fi        diet     11    calories  130
22 .          fi        protein  8     fat       7
23 .          fi        carbs    0     .         .
24 .          yo        diet     1     calories  180
25 .          yo        protein  9.2   fat       1
26 .          yo        carbs    17    .         .
27 RHS        .         .        .     .         .
28 .          .         calories 300   protein   10
29 .          .         fat      8     carbs     10
30 BOUNDS     .         .        .     .         .
31 UP         .         mi       1     .         .
32 LO         .         fi       .5    .         .
33 ENDATA     .         .        .     .         .
;
```

You can use the BASIS=WARMSTART option (and the ex3pout and ex3dout data tables from Example 5.3) in the following call to PROC OPTLP to solve the modified problem:

```
proc optlp data=mycas.ex9
   presolver = none
   basis     = warmstart
   primalin  = mycas.ex3pout
   dualin    = mycas.ex3dout
   algorithm = primal
   logfreq   = 1;
run;
```

The following iteration log indicates that it takes the primal simplex algorithm no extra iterations to solve the modified problem by using BASIS=WARMSTART, because the optimal basis to the LP problem in Example 5.3 remains optimal after the objective function is changed.

Output 5.9.2 Iteration Log

```
NOTE: The problem EX3 has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 constraint coefficients.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value         Time     Variable      Variable
       P 2          1    1.522783E+01         0
NOTE: Optimal.
NOTE: Objective = 15.227829598.
NOTE: The Primal Simplex solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.135523
      seconds.
```

References

Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993). *Network Flows: Theory, Algorithms, and Applications*. Englewood Cliffs, NJ: Prentice-Hall.

Andersen, E. D., and Andersen, K. D. (1995). "Presolving in Linear Programming." *Mathematical Programming* 71:221–245.

Chinneck, J. W. (2008). *Feasibility and Infeasibility in Optimization: Algorithms and Computational Methods.* Vol. 118 of International Series in Operations Research and Management Science. New York: Springer.

Dantzig, G. B. (1963). *Linear Programming and Extensions*. Princeton, NJ: Princeton University Press.

Forrest, J. J., and Goldfarb, D. (1992). "Steepest-Edge Simplex Algorithms for Linear Programming." *Mathematical Programming* 5:1–28.

Gondzio, J. (1997). "Presolve Analysis of Linear Programs Prior to Applying an Interior Point Method." *INFORMS Journal on Computing* 9:73–91.

Harris, P. M. J. (1973). "Pivot Selection Methods in the Devex LP Code." *Mathematical Programming* 57:341–374.

Maros, I. (2003). *Computational Techniques of the Simplex Method.* Boston: Kluwer Academic.

Chapter 6
The OPTMILP Procedure

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Overview: OPTMILP Procedure

The OPTMILP procedure solves general mixed integer linear programs (MILPs). A standard mixed integer linear program has the formulation

$$\begin{array}{rl} \min & \mathbf{c}^T\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \\ & \mathbf{x}_i \in \mathbb{Z} \quad \forall i \in \mathcal{S} \end{array} \qquad \text{(MILP)}$$

where

$\mathbf{x}$	$\in$	$\mathbb{R}^n$	is the vector of structural variables
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the matrix of technological coefficients
$\mathbf{c}$	$\in$	$\mathbb{R}^n$	is the vector of objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^m$	is the vector of constraints' right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^n$	is the vector of lower bounds on variables
$\mathbf{u}$	$\in$	$\mathbb{R}^n$	is the vector of upper bounds on variables
$\mathcal{S}$			is a nonempty subset of the set $\{1\ldots,n\}$ of indices

The OPTMILP procedure implements a linear-programming-based branch-and-cut algorithm. This divide-and-conquer approach attempts to solve the original problem by solving linear programming relaxations of a sequence of smaller subproblems. The OPTMILP procedure also implements advanced techniques such as presolving, generating cutting planes, and applying primal heuristics to improve the efficiency of the overall algorithm.

The OPTMILP procedure requires a mixed integer linear program to be specified using a data table that adheres to the mathematical programming system (MPS) format, a widely accepted format in the optimization community. Chapter 8 discusses the MPS format in detail. It is also possible to input an incumbent solution; see the section "Warm Start" on page 203 for details.

The OPTMILP procedure provides various control options and solution strategies. In particular, you can enable, disable, or set levels for the advanced techniques previously mentioned.

The OPTMILP procedure outputs an optimal solution or the best feasible solution found, if any, in data tables. This enables you to generate solution reports and perform additional analyses by using SAS software.

Getting Started: OPTMILP Procedure

The following example illustrates the use of the OPTMILP procedure to solve mixed integer linear programs. For more examples, see the section "Examples: OPTMILP Procedure" on page 221. Suppose you want to solve the following problem:

$$
\begin{array}{rrcrcrcrl}
\min & 2x_1 & - & 3x_2 & - & 4x_3 & & & \\
\text{s.t.} & & - & 2x_2 & - & 3x_3 & \geq & -5 & \text{(R1)} \\
 & x_1 & + & x_2 & + & 2x_3 & \leq & 4 & \text{(R2)} \\
 & x_1 & + & 2x_2 & + & 3x_3 & \leq & 7 & \text{(R3)} \\
 & & & x_1, & x_2, & x_3 & \geq & 0 & \\
 & & & x_1, & x_2, & x_3 & \in \mathbb{Z} & &
\end{array}
$$

The corresponding MPS-format data set is created as follows:

```
data ex_mip;
   input field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
NAME          .       EX_MIP       .    .         .
ROWS          .         .          .    .         .
N             COST      .          .    .         .
G             R1        .          .    .         .
L             R2        .          .    .         .
L             R3        .          .    .         .
COLUMNS       .         .          .    .         .
.             MARK00 'MARKER'      .    'INTORG'  .
.             X1     COST         2    R2        1
.             X1     R3           1    .         .
.             X2     COST        -3    R1       -2
.             X2     R2           1    R3        2
.             X3     COST        -4    R1       -3
.             X3     R2           2    R3        3
.             MARK01 'MARKER'      .    'INTEND'  .
RHS           .      .             .    .         .
.             RHS    R1          -5    R2        4
.             RHS    R3           7    .         .
ENDATA        .      .             .    .         .
;
```

To make the created data set available in the CAS server, you need to upload it. At the same time, you also need to add an _id_ column to ensure that the MPS reader can read the file in the correct order even if it is distributed across several machines and hence loses the original ordering. For more information about the MPS format, see Chapter 8, "The MPS-Format Data Table."

```
data mycas.ex_mip;
   set ex_mip;
   _id_ = _n_;
run;
```

Alternatively, you can create the MPS data table directly in CAS and include the _id_ column in the datalines input.

You can also create this data set from an MPS format flat file (ex_mip.mps) by using the following SAS macro:

```
%mps2sasd(mpsfile = "ex_mip.mps", outdata = mycas.ex_mip);
```

This problem can be solved by using the following statement to call the OPTMILP procedure:

```
proc optmilp data = mycas.ex_mip
   objsense   = min
   primalout  = mycas.primal_out
   dualout    = mycas.dual_out
   presolver  = automatic
   heuristics = automatic;
run;
```

The DATA= option names the MPS format data table that contains the problem data. The OBJSENSE= option specifies whether to maximize or minimize the objective function. The PRIMALOUT= option names the data table to contain the optimal solution or the best feasible solution found by the solver. The DUALOUT= option names the data table to contain the constraint activities. The PRESOLVER= and HEURISTICS= options specify the levels for presolving and applying heuristics, respectively. In this example, each option is set to its default value AUTOMATIC, meaning that the solver automatically determines the appropriate levels for presolve and heuristics.

The optimal integer solution and its corresponding constraint activities, stored in the data tables primal_out and dual_out, respectively, are displayed in Figure 6.1 and Figure 6.2.

Figure 6.1 Optimal Solution

The OPTMILP Procedure
Primal Integer Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Solution
1	COST	RHS	X1	B	2	0	1	0	1
2	COST	RHS	X2	B	-3	0	1	1	1
3	COST	RHS	X3	B	-4	0	1	1	1

Figure 6.2 Constraint Activities

The OPTMILP Procedure
Constraint Information

Obs	Objective Function ID	RHS ID	Constraint Name	Constraint Type	Constraint RHS	Constraint Lower Bound	Constraint Upper Bound	Constraint Activity	Solution
1	COST	RHS	R1	G	-5	.	.	-5	1
2	COST	RHS	R2	L	4	.	.	3	1
3	COST	RHS	R3	L	7	.	.	5	1

The solution summary stored in the macro variable _OROPTMILP_ can be viewed by issuing the following statement:

```
%put &_OROPTMILP_;
```

This produces the output shown in Figure 6.3.

Figure 6.3 Macro Output

```
STATUS=OK ALGORITHM=BAC SOLUTION_STATUS=OPTIMAL OBJECTIVE=-7 RELATIVE_GAP=0
ABSOLUTE_GAP=0 PRIMAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0
INTEGER_INFEASIBILITY=0 BEST_BOUND=-7 NODES=0 SOLUTIONS_FOUND=2 ITERATIONS=0
PRESOLVE_TIME=0.00 SOLUTION_TIME=0.00
```

See the section "Data Input and Output" on page 200 for details about the type and status codes displayed for variables and constraints.

Syntax: OPTMILP Procedure

The following statements are available in the OPTMILP procedure:

PROC OPTMILP < *options* > ;
  DECOMP < *options* > ;
  DECOMPMASTER < *options* > ;
  DECOMPMASTERIP < *options* > ;
  DECOMPSUBPROB < *options* > ;
  ROOTNODE < *options* > ;

Functional Summary

Table 6.1 summarizes the options available for the OPTMILP procedure, classified by function.

Table 6.1 Options for the OPTMILP Procedure

Description	Option
Data Table Options	
Specifies the input data table	DATA=
Specifies the constraint activities output data table	DUALOUT=
Specifies the constant part of the objective	OBJCONSTANT=
Specifies whether the MILP model is a maximization or minimization problem	OBJSENSE=
Specifies the primal solution input data table (warm start)	PRIMALIN=
Specifies the primal solution output data table	PRIMALOUT=

Table 6.1 *continued*

Description	Option
Presolve Options	
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the stopping criterion based on absolute objective gap	ABSOBJGAP=
Specifies the cutoff value for node removal	CUTOFF=
Emphasizes feasibility or optimality	EMPHASIS=
Specifies the maximum violation on variables and constraints	FEASTOL=
Enables or disables irreducible infeasible set (IIS) detection	IIS=
Specifies the maximum allowed difference between an integer variable's value and an integer	INTTOL=
Specifies the frequency of printing the node log	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of nodes to be processed	MAXNODES=
Specifies the gap criterion for the solutions that are returned when multiple solution algorithms are run	MAXPOOLGAP=
Specifies the maximum number of solutions to return from the pool	MAXPOOLSOLS=
Specifies the maximum number of solutions to be found	MAXSOLS=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the tolerance used in determining the optimality of nodes in the branch-and-bound tree	OPTTOL=
Toggles ODS output	PRINTLEVEL=
Specifies the probing level	PROBE=
Specifies the stopping criterion based on relative objective gap	RELOBJGAP=
Enables the use of scaling on the problem matrix	SCALE=
Specifies the initial seed for the random number generator	SEED=
Specifies the type of multiple solution algorithm	SOLTYPE=
Specifies the stopping criterion based on target objective value	TARGET=
Specifies whether time units are CPU time or real time	TIMETYPE=
Heuristics Option	
Specifies the primal heuristics level	HEURISTICS=
Search Options	
Specifies the level of conflict search	CONFLICTSEARCH=
Specifies the node selection strategy	NODESEL=
Enables use of variable priorities	PRIORITY=
Specifies the restarting strategy	RESTARTS=
Specifies the number of simplex iterations performed on each variable in the strong branching variable selection strategy	STRONGITER=
Specifies the number of candidates for the strong branching variable selection strategy	STRONGLEN=
Specifies the level of symmetry detection	SYMMETRY=
Specifies the rule for selecting the branching variable	VARSEL=

Table 6.1 *continued*

Description	Option
Cut Options	
Specifies the cut level for all cuts	ALLCUTS=
Specifies the clique cut level	CUTCLIQUE=
Specifies the flow cover cut level	CUTFLOWCOVER=
Specifies the flow path cut level	CUTFLOWPATH=
Specifies the Gomory cut level	CUTGOMORY=
Specifies the generalized upper bound (GUB) cover cut level	CUTGUB=
Specifies the implied bounds cut level	CUTIMPLIED=
Specifies the knapsack cover cut level	CUTKNAPSACK=
Specifies the lift-and-project cut level	CUTLAP=
Specifies the mixed lifted 0-1 cut level	CUTMILIFTED=
Specifies the mixed integer rounding (MIR) cut level	CUTMIR=
Specifies the multicommodity network flow cut level	CUTMULTICOMMODITY=
Specifies the path mixing cut level	CUTPATHMIXING=
Specifies the RLT cut level	CUTRLT=
Specifies the row multiplier factor for cuts	CUTSFACTOR=
Specifies the overall cut aggressiveness	CUTSTRATEGY=
Specifies the zero-half cut level	CUTZEROHALF=
Parallel Options	
Enables PROC OPTMILP to run in concurrent mode	CONCURRENT=
Enables PROC OPTMILP to run deterministically	DETERMINISTIC=
Enables PROC OPTMILP to run in distributed mode	DISTRIBUTED=
Specifies the number of threads for the parallel OPTMILP procedure to use	NTHREADS=

PROC OPTMILP Statement

PROC OPTMILP < *options* > **;**

You can specify the following options in the PROC OPTMILP statement.

Data Table Options

DATA=*CAS-libref.data-table*

specifies the input data table that corresponds to the MILP model. If this option is not specified, PROC OPTMILP uses the most recently created data table. See Chapter 8, "The MPS-Format Data Table," for more details about the input data table. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

DUALOUT=*CAS-libref.data-table*

DOUT=*CAS-libref.data-table*

specifies the output data table to contain the constraint activities. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

OBJCONSTANT=*number*

OBJECTIVECONSTANT=*number*

specifies the constant part of the objective, where *number* can be any number. This option supersedes the objective right-hand side that is specified in the input data table. By default, OBJCONSTANT=0.

OBJSENSE=MIN | MAX

specifies whether the MILP model is a minimization or a maximization problem. You can use OBJSENSE=MIN for a minimization problem and OBJSENSE=MAX for a maximization problem. Alternatively, you can specify the objective sense in the input data table. This option supersedes the objective sense specified in the input data table. If the objective sense is not specified anywhere, then PROC OPTMILP interprets and solves the MILP as a minimization problem.

PRIMALIN=*CAS-libref.data-table*

enables you to provide warm start solutions as input through a data table. PROC OPTMILP validates both the data table and the solutions that are stored in the data table. If the data table is not valid, then the PRIMALIN= data table is ignored. If a solution that is stored in a valid PRIMALIN= data table is an integer feasible solution, then it provides an incumbent solution and a bound for the branch-and-bound algorithm. If a solution that is stored in a valid PRIMALIN= data table is infeasible, contains missing values, or contains fractional values for integer variables, PROC OPTMILP tries to repair the solution with a number of specialized repair heuristics. For more information, see the section "Warm Start" on page 203. When you specify multiple input solutions, you must use the optional PRIMALIN numeric field _SOL_ to uniquely identify the corresponding solution. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

PRIMALOUT=*CAS-libref.data-table*

POUT=*CAS-libref.data-table*

specifies the output data table for the primal solution. This data table contains the primal solution information. See the section "Data Input and Output" on page 200 for details. *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

Presolve Options

FOLD=AUTOMATIC | OFF | ON

controls the folding of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to fold the problem or not.

OFF disables folding. The optimization problem is not further reduced by folding.

ON specifies that the presolver try to fold the continuous part of the optimization problem.

Folding is helpful for problems that have a symmetric structure in the continuous part of the variables.

By default, FOLD=AUTOMATIC.

PRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
specifies the level of presolve processing. You can specify the following values:

AUTOMATIC applies the default level of presolve processing. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

NONE disables the presolver. Only the necessary problem transformation steps are performed.

BASIC performs minimal presolve processing. Only some very fast operations are performed.

MODERATE applies a higher level of presolve processing. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

AGGRESSIVE applies the highest level of presolve processing. All the presolver techniques are called with no limits. This reduces the problem the most, but can take a very long time.

By default, PRESOLVER=AUTOMATIC.

Control Options

ABSOBJGAP=*number*
ABSOLUTEOBJECTIVEGAP=*number*
specifies a stopping criterion. When the absolute difference between the best integer objective and the best bound on the objective function value becomes smaller than the value of *number*, the procedure stops. The value of *number* can be any nonnegative number; the default value is 1E–6.

CUTOFF=*number*
cuts off any nodes in a minimization (maximization) problem that have an objective value at or above (below) *number*. The value of *number* can be any number; the default value is the largest (smallest) number that can be represented by a double.

EMPHASIS=BALANCE | OPTIMAL | FEASIBLE
specifies the type of search emphasis. You can specify the following values:

BALANCE performs a balanced search.

OPTIMAL emphasizes optimality over feasibility.

FEASIBLE emphasizes feasibility over optimality.

By default, EMPHASIS=BALANCE.

FEASTOL=*number*

specifies the tolerance that PROC OPTMILP uses to check the feasibility of a solution. This tolerance applies both to the maximum violation of bounds on variables and to the difference between the right-hand sides and left-hand sides of constraints. The value of *number* can be any value between 1E–4 and 1E–9, inclusive. However, the value of *number* cannot be larger than the integer feasibility tolerance. If the value of *number* is larger than the value of the INTTOL= option, then PROC OPTMILP sets FEASTOL= to the value of INTTOL=. The default value is 1E–6.

If PROC OPTMILP fails to find a feasible solution within this tolerance but does find a solution that has some violation, then the procedure stops with a solution status of OPTIMAL_COND (see the section "Macro Variable _OROPTMILP_" on page 218).

IIS=FALSE | TRUE

specifies whether PROC OPTMILP is to attempt to identify a set of constraints, variables, and integer restrictions that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection, and turns off certain options such as the SOLTYPE= option. If an IIS is found, information about infeasible constraints, integer restrictions, or variable bounds is written to the DUALOUT= and PRIMALOUT= data tables.

For more information about IIS, see the section "Irreducible Infeasible Set" on page 217. By default, IIS=FALSE.

INTTOL=*number*

INTEGERTOLERANCE=*number*

specifies the amount by which an integer variable value can differ from an integer and still be considered integer feasible. The value of *number* can be any number between 1E–9 and 0.5, inclusive. PROC OPTMILP attempts to find an optimal solution whose integer infeasibility is less than *number*. The default value is 1E–5.

If the best solution that PROC OPTMILP finds has an integer infeasibility larger than the value of *number*, then PROC OPTMILP stops with a solution status of OPTIMAL_COND (see the section "Macro Variable _OROPTMILP_" on page 218).

LOGFREQ=*k*

PRINTFREQ=*k*

prints information in the node log every *k* seconds, where *k* is any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If *k*=0, then the node log is disabled. If *k* is positive, then the root node processing information is printed and, if possible, an entry is made every *k* seconds. An entry is also made each time a better integer solution is found.

By default, LOGFREQ=5.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that PROC OPTMILP displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and a node log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and a node log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXNODES=*number*

specifies the maximum number of branch-and-bound nodes to be processed, where *number* can be any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you run PROC OPTMILP in concurrent mode, CONCURRENT=TRUE, then the procedure stops as soon as *number* is reached on any machine. If you run PROC OPTMILP in distributed mode, DISTRIBUTED=TRUE, then the procedure periodically checks and stops as soon as the total number of nodes that are processed by all grid nodes exceeds *number*. The default value is $2^{31} - 1$.

MAXPOOLGAP=*number*

specifies the gap criterion for the solutions to be returned when you specify a non-default SOLTYPE= option. Each of the returned solutions will have an objective value whose gap from the best integer objective value is less than or equal to *number*. The value of *number* can be any nonnegative number greater than or equal to the value of the RELOBJGAP= option. The default value is the value of the RELOBJGAP= option.

MAXPOOLSOLS=*number*

specifies the number of solutions to return in the output data tables, where *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. Only feasible and unique solutions are returned, and they are returned in order of objective value, with the best solution first. By default, MAXPOOLSOLS=10 if SOLTYPE=BEST or SOLTYPE=WITHINGAP; otherwise, MAXPOOLSOLS=1 by default.

MAXSOLS=*number*

specifies a stopping criterion, where *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If *number* of solutions have been found, then the procedure stops. The default value of *number* is $2^{31} - 1$.

MAXTIME=*t*

specifies an upper limit of *t* units of time for performing the optimization process, including time to read the data and the solution time. The value of the TIMETYPE= option determines the type of units used. If you do not specify MAXTIME= option, the procedure does not stop because of the amount of time elapsed. If concurrent or distributed mode of PROC OPTMILP is enabled, CONCURRENT=TRUE or DISTRIBUTED=TRUE, then the procedure stops as soon as *t* is reached on any machine. The value of *t* can be any positive number; the default value is the largest number that can be represented by a double.

OPTTOL=*number*

specifies the tolerance that is used to determine the optimality of nodes in the branch-and-bound tree. The value of *number* can be any value between (and including) 1E–4 and 1E–9. The default value is 1E–6.

PRINTLEVEL=0 | 1 | 2

specifies whether to print a summary of the problem and solution. You can specify the following values:

0 does not produce or print any Output Delivery System (ODS) tables.

1 produces and prints the following ODS tables: ProblemSummary and SolutionSummary.

2 produces and prints the following ODS tables: ProblemSummary, SolutionSummary, ProblemStatistics, and Timing table.

By default, PRINTLEVEL=1.

For more information about the ODS tables created by PROC OPTMILP, see the section "ODS Tables" on page 212.

PROBE=AUTOMATIC | NONE | MODERATE | AGGRESSIVE

specifies the probing strategy. You can specify the following values:

AUTOMATIC uses the probing strategy that is determined by PROC OPTMILP.

NONE disables probing.

MODERATE uses probing moderately.

AGGRESSIVE uses probing aggressively.

By default, PROBE=AUTOMATIC. For more information, see the section "Presolve and Probing" on page 207.

RELOBJGAP=*number*

specifies a stopping criterion based on the best integer objective (BestInteger) and the best bound on the objective function value (BestBound). The relative objective gap is equal to

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

When this value becomes smaller than the specified gap size *number*, the procedure stops. The value of *number* can be any nonnegative number; the default value is 1E–4.

SCALE=AUTOMATIC | NONE

indicates whether to scale the problem matrix. You can specify the following values:

AUTOMATIC scales the matrix as determined by PROC OPTMILP.

NONE disables scaling.

By default, SCALE=AUTOMATIC.

SEED=*number*

specifies the initial seed of the random number generator. This option affects the perturbation in the simplex solvers; thus it might result in a different optimal solution and a different solver path. This option usually has a significant, but unpredictable, effect on the solution time. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. The default value of the seed is 100.

SOLTYPE=POOL | BEST | WITHINGAP

specifies the type of multiple solution algorithm that PROC OPTMILP runs. You can specify this option when you need to obtain multiple optimal solutions or multiple feasible solutions within the value that is specified for the MAXPOOLGAP= option. You can specify the following values:

POOL runs the default branch-and-bound algorithm.

BEST runs the modified branch-and-bound algorithm in order to return the best (by objective value) number of solutions (as specified in the MAXPOOLSOLS= option) that have a gap value less than or equal to the value of the MAXPOOLGAP= option. If the problem has fewer solutions than the number that is specified in the MAXPOOLSOLS= option, then the procedure returns all the solutions that are found within the value that is specified in the MAXPOOLGAP= option. Note that there can exist no solution better than those returned by the procedure.

WITHINGAP runs the modified branch-and-bound algorithm in order to return the number of solutions (as specified in the MAXPOOLSOLS= option) that have a gap value less than or equal to the value of the MAXPOOLGAP= option. If the problem has fewer solutions than the number that is specified in the MAXPOOLSOLS= option, then the procedure returns all the solutions that are found within the value that is specified in the MAXPOOLGAP= option. Note that there can exist feasible solutions that are better than the solutions returned by the procedure.

By default, SOLTYPE=POOL.

NOTE: If you specify SOLTYPE=BEST or SOLTYPE=WITHINGAP, the procedure turns off certain techniques (such as symmetry detection) that can reduce the search space (by pruning off feasible or alternate optimal solutions). Hence, the procedure can take considerably longer to solve the problem compared to when SOLTYPE=POOL.

TARGET=*number*

specifies a stopping criterion for a minimization or maximization problem. If the best integer objective is better than or equal to *number*, the procedure stops. The value of *number* can be any number; the default value is the largest (in magnitude) negative number (for a minimization problem) or the largest (in magnitude) positive number (for a maximization problem) that can be represented by a double.

TIMETYPE=CPU | REAL

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMILP_ macro variable. You can specify the following values:

CPU specifies that units are in CPU time.

REAL specifies that units are in real time.

By default, TIMETYPE=REAL.

Heuristics Option

HEURISTICS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

controls the level of primal heuristics applied by PROC OPTMILP. This level determines how frequently primal heuristics are applied during the branch-and-bound tree search. It also affects the maximum number of iterations allowed in iterative heuristics. Some computationally expensive heuristics might be disabled by the solver at less aggressive levels. You can specify the following values:

AUTOMATIC applies the default level of heuristics, similar to MODERATE.

NONE disables all primal heuristics. This value does not disable the heuristics that repair an infeasible input solution that is specified in a PRIMALIN= data table.

BASIC applies basic primal heuristics at low frequency.

MODERATE applies most primal heuristics at moderate frequency.

AGGRESSIVE applies all primal heuristics at high frequency.

By default, HEURISTICS=AUTOMATIC. For more information about primal heuristics, see the section "Primal Heuristics" on page 209.

Search Options

CONFLICTSEARCH=AUTOMATIC | NONE | MODERATE | AGGRESSIVE

specifies the level of conflict search performed by PROC OPTMILP. Conflict search is used to find clauses resulting from infeasible subproblems that arise in the search tree. You can specify the following values:

AUTOMATIC performs conflict search based on a strategy that is determined by PROC OPTMILP.

NONE disables conflict search.

MODERATE performs a moderate conflict search.

AGGRESSIVE performs an aggressive conflict search.

By default, CONFLICTSEARCH=AUTOMATIC.

NODESEL=AUTOMATIC | BESTBOUND | BESTESTIMATE | DEPTH

specifies the node selection strategy. You can specify the following values:

AUTOMATIC uses automatic node selection.

BESTBOUND chooses the node with the best relaxed objective (best-bound-first strategy).

BESTESTIMATE chooses the node with the best estimate of the integer objective value (best-estimate-first strategy).

DEPTH chooses the most recently created node (depth-first strategy).

By default, NODESEL=AUTOMATIC. For more information about node selection, see the section "Node Selection" on page 205.

PRIORITY=TRUE | FALSE

indicates whether to use specified branching priorities for integer variables. You can specify the following values:

TRUE uses priorities when they exist.

FALSE ignores variable priorities.

By default, PRIORITY=TRUE. For more information, see the section "Branching Priorities" on page 207.

RESTARTS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the strategy for restarting the processing of the root node. You can specify the following values:

AUTOMATIC uses a restarting strategy determined by PROC OPTMILP.

NONE disables restarting.

BASIC uses a basic restarting strategy.

MODERATE uses a moderate restarting strategy.

AGGRESSIVE uses an aggressive restarting strategy.

By default, RESTARTS=AUTOMATIC.

STRONGITER=*number* **| AUTOMATIC**

specifies the number of simplex iterations performed for each variable in the candidate list when using the strong branching variable selection strategy. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you specify the keyword AUTOMATIC, PROC OPTMILP uses the default value; this value is calculated automatically.

STRONGLEN=*number* **| AUTOMATIC**

specifies the number of candidates used when performing the strong branching variable selection strategy. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you specify the keyword AUTOMATIC, PROC OPTMILP uses the default value; this value is calculated automatically.

SYMMETRY=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the level of symmetry detection. Symmetry detection identifies groups of equivalent decision variables and uses this information to solve the problem more efficiently. You can specify the following values:

AUTOMATIC performs symmetry detection based on a strategy that is determined by PROC OPTMILP.

NONE disables symmetry detection.

BASIC performs a basic symmetry detection.

MODERATE performs a moderate symmetry detection.

AGGRESSIVE performs an aggressive symmetry detection.

By default, SYMMETRY=AUTOMATIC. For more information about symmetry detection, see (Ostrowski 2008).

VARSEL=AUTOMATIC | MAXINFEAS | MININFEAS | PSEUDO | STRONG
specifies the rule for selecting the branching variable. You can specify the following values:

AUTOMATIC uses automatic branching variable selection.

MAXINFEAS chooses the variable with maximum infeasibility.

MININFEAS chooses the variable with minimum infeasibility.

PSEUDO chooses a branching variable based on pseudocost.

STRONG uses a strong branching variable selection strategy.

By default, VARSEL=AUTOMATIC. For details about variable selection, see the section "Variable Selection" on page 206.

Cut Options

Table 6.2 describes the *string* values for the cut options in PROC OPTMILP.

Table 6.2 Values for Individual Cut Options

string	**Description**
AUTOMATIC	Generates cutting planes on the basis of a strategy that PROC OPTMILP determines.
NONE	Disables generation of cutting planes
MODERATE	Uses a moderate cut strategy
AGGRESSIVE	Uses an aggressive cut strategy

You can specify the CUTSTRATEGY= option to set the overall aggressiveness of the cut generation in PROC OPTMILP. Alternatively, you can use the ALLCUTS= option to set all cut types to the same level. You can override the ALLCUTS= value by using the options that correspond to particular cut types. For example, if you want PROC OPTMILP to generate only Gomory cuts, specify ALLCUTS=NONE and CUTGOMORY=AUTOMATIC. If you want to generate all cuts aggressively but generate no lift-and-project cuts, set ALLCUTS=AGGRESSIVE and CUTLAP=NONE.

ALLCUTS=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
provides a shorthand way of setting all the cuts-related options in one setting. In other words, ALLCUTS=*string* is equivalent to setting each of the individual cuts parameters to the same value *string*. Thus, ALLCUTS=AUTOMATIC has the effect of setting CUTCLIQUE=AUTOMATIC, CUTFLOWCOVER=AUTOMATIC, . . . , and CUTZEROHALF=AUTOMATIC. Table 6.2 lists the values that can be assigned to *string*. In addition, you can override levels for individual cuts with the CUTCLIQUE=, CUTFLOWCOVER=, CUTFLOWPATH=, CUTGOMORY=, CUTGUB=, CUTIMPLIED=, CUTKNAPSACK=, CUTLAP=, CUTMILIFTED=, CUTMIR=, CUTMULTICOMMODITY=, CUTPATHMIXING=, CUTRLT=, and CUTZEROHALF= options. If the ALLCUTS= option is not specified, all the cuts-related options are either set to their individually specified values (if the corresponding option is specified) or to their default values (if that option is not specified).

CUTCLIQUE=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of clique cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTCLIQUE=AUTOMATIC.

CUTFLOWCOVER=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of flow cover cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTFLOWCOVER=AUTOMATIC.

CUTFLOWPATH=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of flow path cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTFLOWPATH=AUTOMATIC.

CUTGOMORY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of Gomory cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTGOMORY=AUTOMATIC.

CUTGUB=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of generalized upper bound (GUB) cover cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTGUB=AUTOMATIC.

CUTIMPLIED=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of implied bound cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTIMPLIED=AUTOMATIC.

CUTKNAPSACK=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of knapsack cover cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTKNAPSACK=AUTOMATIC.

CUTLAP=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of lift-and-project (LAP) cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTLAP=NONE.

CUTMILIFTED=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of mixed lifted 0-1 cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMILIFTED=AUTOMATIC.

CUTMIR=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of mixed integer rounding (MIR) cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMIR=AUTOMATIC.

CUTMULTICOMMODITY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of multicommodity network flow cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMULTICOMMODITY=AUTOMATIC.

CUTPATHMIXING=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of path mixing cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTPATHMIXING=AUTOMATIC.

CUTRLT=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of RLT cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTRLT=AUTOMATIC.

CUTSFACTOR=*number*
specifies a row multiplier factor for cuts. The number of cuts that are added is limited to *number* times the original number of rows. The value of *number* can be any nonnegative number less than or equal to 100; the default value is automatically calculated by PROC OPTMILP.

CUTSTRATEGY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
CUTS=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the overall aggressiveness of the cut generation in the procedure. By default, CUTSTRATEGY=AUTOMATIC. Setting a nondefault value adjusts a number of cut parameters such that the cut generation is none, moderate, or aggressive compared to the default value.

CUTZEROHALF=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of zero-half cuts generated by PROC OPTMILP. Table 6.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTZEROHALF=AUTOMATIC.

Decomposition Algorithm Statements

The following statements are available for the decomposition algorithm in the OPTMILP procedure:

DECOMP < *options* > **;**

DECOMPMASTER < *options* > **;**

DECOMPMASTERIP < *options* > **;**

DECOMPSUBPROB < *options* > **;**

For more information about these statements, see Chapter 18, "The Decomposition Algorithm."

Parallel Options

CONCURRENT=TRUE | FALSE
specifies whether to run PROC OPTMILP in concurrent mode. You can specify the following values:

TRUE	runs PROC OPTMILP in concurrent mode. The solver automatically runs the same problem on each grid node with different PROC OPTMILP options.
FALSE	turns off concurrent mode for PROC OPTMILP.

By default, CONCURRENT=FALSE.

DETERMINISTIC=TRUE | FALSE

specifies whether to enable PROC OPTMILP to run deterministically when distributed or concurrent mode is enabled. The DETERMINISTIC= option is valid only when DISTRIBUTED=TRUE or CONCURRENT=TRUE. You can specify the following values:

TRUE runs PROC OPTMILP in deterministic distributed or concurrent mode. The procedure always returns the same solution for subsequent runs on the same grid.

FALSE runs PROC OPTMILP in nondeterministic distributed or concurrent mode.

By default, DETERMINISTIC=FALSE when you specify CONCURRENT=TRUE, and DETERMINISTIC=TRUE when you specify DISTRIBUTED=TRUE.

DISTRIBUTED=TRUE | FALSE

specifies whether to run PROC OPTMILP in distributed mode. For more information about this option as it relates to the standard PROC OPTMILP processing, see the section "Parallel Processing" on page 209. For more information about this option as it relates to the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm." You can specify the following values:

TRUE runs PROC OPTMILP in distributed mode.

FALSE turns off distributed mode of PROC OPTMILP.

By default, DISTRIBUTED=FALSE.

NTHREADS=*number*

specifies the maximum number of threads for PROC OPTMILP to use for multithreaded processing. The branch-and-cut algorithm can take advantage of multicore machines and can potentially run faster when *number* is greater than 1. The value of *number* can be any integer between 1 and 256, inclusive. The default is the number of cores on the machine that executes the process or the number of cores permissible based on your installation (whichever is less). The number of simultaneously active CPUs is limited by your installation and license configuration.

Root Node Solver Statements

The following statements are available for choosing the root node linear programming solver in the OPTMILP procedure:

ROOTNODE < *options* > **;**

The available options are listed in Table 6.3 and are equivalent to the options that are used in the OPTLP procedure. For more information about these options, see Chapter 5, "The OPTLP Procedure."

Table 6.3 Options for the ROOTNODE Solver Statement

Description	Option
Solver Options	
Specifies the type of algorithm	ALGORITHM=

Table 6.3 *continued*

Description	Option
Presolve Options	
Controls the dualization of the problem	DUALIZE=
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the frequency of printing solution progress	LOGFREQ=
Specifies the detail of solution progress printed in log	LOGLEVEL=
Simplex Algorithm Options	
Specifies the type of initial basis	BASIS=
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Parallel Options	
Specifies the number of threads for the parallel OPTMILP procedure to use	NTHREADS=

Details: OPTMILP Procedure

Data Input and Output

This subsection describes the PRIMALIN= data table required to warm start PROC OPTMILP, in addition to the PRIMALOUT= and DUALOUT= data tables.

Definitions of Variables in the PRIMALIN= Data Table

The PRIMALIN= data table must contain the following variables:

VAR
specifies the variable (column) names of the problem. The values should match the column names in the DATA= data table for the current problem.

VALUE
specifies the solution value for each variable in the problem.

The PRIMALIN= data table can also contain the following optional variable:

SOL
specifies the identifier of the input solution. This optional numeric field is strictly needed only in cases where you specify multiple input solutions through the PRIMALIN= data table. Each solution needs to have a unique corresponding identifier.

NOTE: If PROC OPTMILP produces a feasible solution, the primal output data table from that run can be used as the PRIMALIN= data table for a subsequent run, provided that the variable names are the same. If this input solution is not feasible for the subsequent run, the solver automatically tries to repair it. For more information, see the section "Warm Start" on page 203.

Definitions of Variables in the PRIMALOUT= Data Table

PROC OPTMILP stores the current best integer feasible solution (or the IIS status of the variables if the problem is infeasible and the IIS=TRUE option is specified) of the problem in the data set that is specified in the PRIMALOUT= option. The variables in this data set are defined as follows:

_OBJ_ID_
specifies the identifier of the objective function.

_RHS_ID_
specifies the identifier of the right-hand side.

VAR
specifies the variable (column) names.

TYPE
specifies the variable type. _TYPE_ can take one of the following values:

C continuous variable

I general integer variable

B binary variable (0 or 1)

OBJCOEF
specifies the coefficient of the variable in the objective function.

LBOUND
specifies the lower bound on the variable.

UBOUND
specifies the upper bound on the variable.

VALUE
specifies the value of the variable in the current solution.

SOL
specifies the identifier of the output solution. You can specify the number of solutions to return in the PRIMALOUT= data table by setting the MAXPOOLSOLS= option. Each solution has its own identifier, starting from 1. Only feasible and unique solutions are returned.

NOTE: Both the PRIMALOUT= and DUALOUT= data tables are ordered by the _SOL_ identifier. Solutions that have the same or better objective value have a lower _SOL_ identifier. In the PRIMALOUT= and DUALOUT= data tables, the respective solutions and activities that have the same _SOL_ identifier correspond to each other.

IIS

specifies the variable bounds and integrality restrictions of a variable present in the irreducible infeasible set, if the problem is infeasible. This variable is included in the data table only if the IIS=TRUE option is specified and the problem is infeasible. For more information, see the section "Irreducible Infeasible Set" on page 217.

The following values can appear:

I_L The lower bound of the variable is needed for the IIS.

I_U The upper bound of the variable is needed for the IIS.

I_F The lower and upper bounds of the variable are needed for the IIS.

I_LI The lower bound and integrality restriction of the variable are needed for the IIS.

I_UI The upper bound and integrality restriction of the variable are needed for the IIS.

I_FI The lower bound, upper bound and integrality restriction of the variable are needed for the IIS.

I_I The integrality restriction of the variable is needed for the IIS.

Definitions of Variables in the DUALOUT= Data Table

The DUALOUT= data table contains the constraint activities (or the IIS status of the constraints if the problem is infeasible and IIS=TRUE option is specified) that correspond to the primal solution in the PRIMALOUT= data table. Information about additional objective rows of the MILP problem is not included. The variables in this data table are defined as follows:

_OBJ_ID_

specifies the identifier of the objective function from the input data table.

_RHS_ID_

specifies the identifier of the right-hand side from the input data table.

ROW

specifies the constraint (row) name.

TYPE

specifies the constraint type. _TYPE_ can take one of the following values:

L "less than or equal" constraint

E equality constraint

G "greater than or equal" constraint

R ranged constraint (both "less than or equal" and "greater than or equal")

RHS
specifies the value of the right-hand side of the constraint. It takes a missing value for a ranged constraint.

_L_RHS_
specifies the lower bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

_U_RHS_
specifies the upper bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

ACTIVITY
specifies the activity of a constraint for a given primal solution. In other words, the value of _ACTIVITY_ for the ith constraint is equal to $\mathbf{a}_i^T \mathbf{x}$, where $\mathbf{a}_i$ refers to the ith row of the constraint matrix and $\mathbf{x}$ denotes the vector of the current primal solution.

SOL
specifies the identifier of the corresponding solution in the PRIMALOUT= data table.

IIS
specifies the constraints present in the irreducible infeasible set, if the problem is infeasible. This variable is included in the data table only if the IIS=TRUE option is specified and the problem is infeasible. For more information, see the section "Irreducible Infeasible Set" on page 217.

The following values can appear:

I_L The "GE" ($\geq$) condition of the constraint is needed for the IIS.

I_U The "LE" ($\leq$) condition of the constraint is needed for the IIS.

I_F Both conditions of the constraint are needed for the IIS (the constraint is an equality or a range constraint).

Warm Start

PROC OPTMILP enables you to input warm start solutions by using the PRIMALIN= option. PROC OPTMILP checks that the decision variables named in _VAR_ are the same as those in the MPS-format data table. If they are not the same, PROC OPTMILP issues a warning and ignores an input solution. PROC OPTMILP also checks whether a solution is infeasible, contains missing values, or contains fractional values for integer variables. If this is the case, PROC OPTMILP attempts to repair the solution with a number of specialized repair heuristics. The success of the attempt largely depends both on the specific model and on the proximity between an input solution and an integer feasible solution. An infeasible input solution can be considered a hint for PROC OPTMILP that might or might not help to solve the problem.

An integer feasible or repaired input solution provides an incumbent solution in addition to an upper (min) or lower (max) bound for the branch-and-bound algorithm. PROC OPTMILP uses the input solution to reduce the search space and to guide the search process. When it is difficult to find a good integer feasible solution for a problem, warm start can reduce solution time significantly.

NOTE: When specifying multiple input solutions, the optional PRIMALIN numeric field _SOL_ is strictly needed to uniquely identify the corresponding solution.

Branch-and-Bound Algorithm

The branch-and-bound algorithm, first proposed by Land and Doig (1960), is an effective approach to solving mixed integer linear programs. The following discussion outlines the approach and explains how PROC OPTMILP enhances the basic algorithm by using several advanced techniques.

The branch-and-bound algorithm solves a mixed integer linear program by dividing the search space and generating a sequence of subproblems. The search space of a mixed integer linear program can be represented by a tree. Each node in the tree is identified with a subproblem derived from previous subproblems on the path that leads to the root of the tree. The subproblem (MILP^0) associated with the root is identical to the original problem, which is called (MILP), given in the section "Overview: OPTMILP Procedure" on page 182.

The linear programming relaxation (LP^0) of (MILP^0) can be written as

$$\begin{array}{rl} \min & \mathbf{c}^T\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{array}$$

The branch-and-bound algorithm generates subproblems along the nodes of the tree by using the following scheme. Consider $\bar{x}^0$, the optimal solution to (LP^0), which is usually obtained by using the dual simplex algorithm. If $\bar{x}_i^0$ is an integer for all $i \in \mathcal{S}$, then $\bar{x}^0$ is an optimal solution to (MILP). Suppose that for some $i \in \mathcal{S}$, $\bar{x}_i^0$ is nonintegral. In that case the algorithm defines two new subproblems (MILP^1) and (MILP^2), descendants of the parent subproblem (MILP^0). The subproblem (MILP^1) is identical to (MILP^0) except for the additional constraint

$$x_i \leq \lfloor \bar{x}_i^0 \rfloor$$

and the subproblem (MILP^2) is identical to (MILP^0) except for the additional constraint

$$x_i \geq \lceil \bar{x}_i^0 \rceil$$

The notation $\lfloor y \rfloor$ represents the largest integer that is less than or equal to y, and the notation $\lceil y \rceil$ represents the smallest integer that is greater than or equal to y. The two preceding constraints can be handled by modifying the bounds of the variable x_i rather than by explicitly adding the constraints to the constraint matrix. The two new subproblems do not have $\bar{x}^0$ as a feasible solution, but the integer solution to (MILP) must satisfy one of the preceding constraints. The two subproblems thus defined are called *active nodes* in the branch-and-bound tree, and the variable x_i is called the *branching variable*.

In the next step the branch-and-bound algorithm chooses one of the active nodes and attempts to solve the linear programming relaxation of that subproblem. The relaxation might be infeasible, in which case the subproblem is dropped (fathomed). If the subproblem can be solved and the solution is *integer feasible* (that is, x_i is an integer for all $i \in \mathcal{S}$), then its objective value provides an *upper bound* for the objective value in the minimization problem (MILP); if the solution is not integer feasible, then it defines two new subproblems. Branching continues in this manner until there are no active nodes. At this point the best integer solution found is an optimal solution for (MILP). If no integer solution has been found, then (MILP) is integer infeasible. You can specify other criteria to stop the branch-and-bound algorithm before it processes all the active nodes; see the section "Controlling the Branch-and-Bound Algorithm" on page 205 for details.

Upper bounds from integer feasible solutions can be used to *fathom* or *cut off* active nodes. Since the objective value of an optimal solution cannot be greater than an upper bound, active nodes with lower bounds

higher than an existing upper bound can be safely deleted. In particular, if z is the objective value of the current best integer solution, then any active subproblems whose relaxed objective value is greater than or equal to z can be discarded.

It is important to realize that mixed integer linear programs are nondeterministic polynomial-time hard (NP-hard). Roughly speaking, this means that the effort required to solve a mixed integer linear program grows exponentially with the size of the problem. For example, a problem with 10 binary variables can generate in the worst case $2^{10} = 1{,}024$ nodes in the branch-and-bound tree. A problem with 20 binary variables can generate in the worst case $2^{20} = 1{,}048{,}576$ nodes in the branch-and-bound tree. Although it is unlikely that the branch-and-bound algorithm has to generate every single possible node, the need to explore even a small fraction of the potential number of nodes for a large problem can be resource-intensive.

A number of techniques can speed up the search progress of the branch-and-bound algorithm. Heuristics are used to find feasible solutions, which can improve the upper bounds on solutions of mixed integer linear programs. Cutting planes can reduce the search space and thus improve the lower bounds on solutions of mixed integer linear programs. When using cutting planes, the branch-and-bound algorithm is also called the *branch-and-cut algorithm*. Preprocessing can reduce problem size and improve problem solvability. PROC OPTMILP employs various heuristics, cutting planes, preprocessing, and other techniques, which you can control through corresponding options.

Controlling the Branch-and-Bound Algorithm

There are numerous strategies that can be used to control the branch-and-bound search (see Linderoth and Savelsbergh 1998, Achterberg, Koch, and Martin 2005). PROC OPTMILP implements the most widely used strategies and provides several options that enable you to direct the choice of the next active node and of the branching variable. In the discussion that follows, let (LP^k) be the linear programming relaxation of subproblem (MILP^k). Also, let

$$f_i(k) = \bar{x}_i^k - \lfloor \bar{x}_i^k \rfloor$$

where $\bar{x}^k$ is the optimal solution to the relaxation problem (LP^k) solved at node k.

Node Selection

The NODESEL= option specifies the strategy used to select the next active node. The valid keywords for this option are AUTOMATIC, BESTBOUND, BESTESTIMATE, and DEPTH. The following list describes the strategy associated with each keyword:

AUTOMATIC — allows PROC OPTMILP to choose the best node selection strategy based on problem characteristics and search progress. This is the default setting.

BESTBOUND — chooses the node with the smallest (or largest, in the case of a maximization problem) relaxed objective value. The best-bound strategy tends to reduce the number of nodes to be processed and can improve lower bounds quickly. However, if there is no good upper bound, the number of active nodes can be large. This can result in the solver running out of memory.

BESTESTIMATE — chooses the node with the smallest (or largest, in the case of a maximization problem) objective value of the estimated integer solution. Besides improving lower bounds,

the best-estimate strategy also attempts to process nodes that can yield good feasible solutions.

DEPTH chooses the node that is deepest in the search tree. Depth-first search is effective in locating feasible solutions, since such solutions are usually deep in the search tree. Compared to the costs of the best-bound and best-estimate strategies, the cost of solving LP relaxations is less in the depth-first strategy. The number of active nodes is generally small, but it is possible that the depth-first search will remain in a portion of the search tree with no good integer solutions. This occurrence is computationally expensive.

Variable Selection

The VARSEL= option specifies the strategy used to select the next branching variable. The valid keywords for this option are AUTOMATIC, MAXINFEAS, MININFEAS, PSEUDO, and STRONG. The following list describes the action taken in each case when $\bar{x}^k$, a relaxed optimal solution of (MILP^k), is used to define two active subproblems. In the following list, "INTTOL" refers to the value assigned using the INTTOL= option. For details about the INTTOL= option, see the section "Control Options" on page 189.

AUTOMATIC enables PROC OPTMILP to choose the best variable selection strategy based on problem characteristics and search progress. This is the default setting.

MAXINFEAS chooses as the branching variable the variable x_i such that i maximizes

$$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \text{INTTOL} \leq f_i(k) \leq 1 - \text{INTTOL}\}$$

MININFEAS chooses as the branching variable the variable x_i such that i minimizes

$$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \text{INTTOL} \leq f_i(k) \leq 1 - \text{INTTOL}\}$$

PSEUDO chooses as the branching variable the variable x_i such that i maximizes the weighted up and down pseudocosts. Pseudocost branching attempts to branch on significant variables first, quickly improving lower bounds. Pseudocost branching estimates significance based on historical information; however, this approach might not be accurate for future search.

STRONG chooses as the branching variable the variable x_i such that i maximizes the estimated improvement in the objective value. Strong branching first generates a list of candidates, then branches on each candidate and records the improvement in the objective value. The candidate with the largest improvement is chosen as the branching variable. Strong branching can be effective for combinatorial problems, but it is usually computationally expensive.

Branching Priorities

In some cases, it is possible to speed up the branch-and-bound algorithm by branching on variables in a specific order. You can accomplish this in PROC OPTMILP by attaching branching priorities to the integer variables in your model.

You can set branching priorities for use by PROC OPTMILP in two ways. You can specify the branching priorities directly in the input MPS-format data table; see the section "BRANCH Section (Optional)" on page 293 for details. If you are constructing a model in PROC OPTMODEL, you can set branching priorities for integer variables by using the .priority suffix. More information about this suffix is available in the section "Integer Variable Suffixes" on page 424 in Chapter 9. For an example in which branching priorities are used, see Example 14.3.

Presolve and Probing

PROC OPTMILP includes a variety of presolve techniques to reduce problem size, improve numerical stability, and detect infeasibility or unboundedness (Andersen and Andersen 1995; Gondzio 1997). During presolve, redundant constraints and variables are identified and removed. Presolve can further reduce the problem size by substituting variables. Variable substitution is a very effective technique, but it might occasionally increase the number of nonzero entries in the constraint matrix. Presolve might also modify the constraint coefficients to tighten the formulation of the problem.

In most cases, using presolve is very helpful in reducing solution times. You can enable presolve at different levels by specifying the PRESOLVER= option.

Probing is a technique that tentatively sets each binary variable to 0 or 1, then explores the logical consequences (Savelsbergh 1994). Probing can expedite the solution of a difficult problem by fixing variables and improving the model. However, probing is often computationally expensive and can significantly increase the solution time in some cases. You can enable probing at different levels by specifying the PROBE= option.

Cutting Planes

The feasible region of every linear program forms a *polyhedron*. Every polyhedron in n-space can be written as a finite number of half-spaces (equivalently, inequalities). In the notation used in this chapter, this polyhedron is defined by the set $\mathcal{Q} = \{x \in \mathbb{R}^n \mid Ax \leq b, l \leq x \leq u\}$. After you add the restriction that some variables must be integral, the set of feasible solutions, $\mathcal{F} = \{x \in \mathcal{Q} \mid x_i \in \mathbb{Z}\ \forall i \in \mathcal{S}\}$, no longer forms a polyhedron.

The *convex hull* of a set X is the minimal convex set that contains X. In solving a mixed integer linear program, in order to take advantage of LP-based algorithms you want to find the convex hull, $\text{conv}(\mathcal{F})$, of $\mathcal{F}$. If you can find $\text{conv}(\mathcal{F})$ and describe it compactly, then you can solve a mixed integer linear program with a linear programming solver. This is generally very difficult, so you must be satisfied with finding an approximation. Typically, the better the approximation, the more efficiently the LP-based branch-and-bound algorithm can perform.

As described in the section "Branch-and-Bound Algorithm" on page 204, the branch-and-bound algorithm begins by solving the linear programming relaxation over the polyhedron $\mathcal{Q}$. Clearly, $\mathcal{Q}$ contains the convex hull of the feasible region of the original integer program; that is, $\text{conv}(\mathcal{F}) \subseteq \mathcal{Q}$.

Cutting plane techniques are used to tighten the linear relaxation to better approximate conv($\mathcal{F}$). Assume you are given a solution $\bar{x}$ to some intermediate linear relaxation during the branch-and-bound algorithm. A cut, or valid inequality ($\pi x \leq \pi^0$), is some half-space with the following characteristics:

- The half-space contains conv($\mathcal{F}$); that is, every integer feasible solution is feasible for the cut ($\pi x \leq \pi^0, \forall x \in \mathcal{F}$).
- The half-space does not contain the current solution $\bar{x}$; that is, $\bar{x}$ is not feasible for the cut ($\pi \bar{x} > \pi^0$).

Cutting planes were first made popular by Dantzig, Fulkerson, and Johnson (1954) in their work on the traveling salesman problem. The two major classifications of cutting planes are *generic cuts* and *structured cuts*. Generic cuts are based solely on algebraic arguments and can be applied to any relaxation of any integer program. Structured cuts are specific to certain structures that can be found in some relaxations of the mixed integer linear program. These structures are automatically discovered during the cut initialization phase of PROC OPTMILP. Table 6.4 lists the various types of cutting planes that are built into PROC OPTMILP. Included in each type are algorithms for numerous variations based on different relaxations and lifting techniques. For a survey of cutting plane techniques for mixed integer programming, see Marchand et al. (1999). For a survey of lifting techniques, see Atamturk (2004).

Table 6.4 Cutting Planes in PROC OPTMILP

Generic Cutting Planes	Structured Cutting Planes
Gomory mixed integer	Cliques
Lift-and-project	Flow cover
Mixed integer rounding	Flow path
Mixed lifted 0-1	Generalized upper bound cover
Zero-half	Implied bound
	Knapsack cover
	Multicommodity network flow
	Path mixing
	RLT

You can set levels for individual cuts by using the CUTCLIQUE=, CUTFLOWCOVER=, CUTFLOWPATH=, CUTGOMORY=, CUTGUB=, CUTIMPLIED=, CUTKNAPSACK=, CUTLAP=, CUTMILIFTED=, CUTMIR=, CUTMULTICOMMODITY=, CUTPATHMIXING=, CUTRLT=, and CUTZEROHALF= options. The valid levels for these options are given in Table 6.2.

The cut level determines the internal strategy used by PROC OPTMILP for generating the cutting planes. The strategy consists of several factors, including how frequently the cut search is called, the number of cuts allowed, and the aggressiveness of the search algorithms.

Sophisticated cutting planes, such as those included in PROC OPTMILP, can take a great deal of CPU time. Usually, the additional tightening of the relaxation helps speed up the overall process because it provides better bounds for the branch-and-bound tree and helps guide the LP solver toward integer solutions. In rare cases, shutting off cutting planes completely might lead to faster overall run times.

The default settings of PROC OPTMILP have been tuned to work well for most instances. However, problem-specific expertise might suggest adjusting one or more of the strategies. These options give you that flexibility.

Primal Heuristics

Primal heuristics, an important component of PROC OPTMILP, are applied during the branch-and-bound algorithm. They are used to find integer feasible solutions early in the search tree, thereby improving the upper bound for a minimization problem. Primal heuristics play a role that is complementary to cutting planes in reducing the gap between the upper and lower bounds, thus reducing the size of the branch-and-bound tree.

Applying primal heuristics in the branch-and-bound algorithm assists in the following areas:

- finding a good upper bound early in the tree search (this can lead to earlier fathoming, resulting in fewer subproblems to be processed)
- locating a reasonably good feasible solution when that is sufficient (sometimes a good feasible solution is the best the solver can produce within certain time or resource limits)
- providing upper bounds for some bound-tightening techniques

The OPTMILP procedure implements several heuristic methodologies. Some algorithms, such as rounding and iterative rounding (diving) heuristics, attempt to construct an integer feasible solution by using fractional solutions to the continuous relaxation at each node of the branch-and-cut tree. Other algorithms start with an incumbent solution and attempt to find a better solution within a neighborhood of the current best solution.

The HEURISTICS= option enables you to control the level of primal heuristics that are applied by PROC OPTMILP. This level determines how frequently primal heuristics are applied during the tree search. Some expensive heuristics might be disabled by the solver at less aggressive levels. Setting the HEURISTICS= option to a lower level also reduces the maximum number of iterations that are allowed in iterative heuristics.

Parallel Processing

You can run the branch-and-cut algorithm in the following modes:

- In single-machine mode, the computation is executed on a single computer by multiple threads. The number of threads is specified by the NTHREADS= option.
- In distributed mode, the branch-and-cut algorithm is executed on a cluster of nodes. You disable deterministic distributed mode by setting the DETERMINISTIC= option to FALSE. By default PROC OPTMILP is executed deterministically.
- In concurrent mode, the computation is executed on a cluster of nodes by solving the same problem across those nodes under different PROC OPTMILP settings. By default PROC OPTMILP is executed nondeterministically.

You can run the decomposition algorithm in either single-machine or distributed mode. In distributed mode, the computation is executed on multiple computing nodes in a distributed computing environment.

Node Log

The following information about the status of the branch-and-bound algorithm is printed in the node log:

Node	indicates the sequence number of the current node in the search tree.
Active	indicates the current number of active nodes in the branch-and-bound tree.
Sols	indicates the number of feasible solutions that are found so far. You can use the MAXPOOLSOLS= option to obtain more than one solution. Note that the number printed in the node log can be different from the number of found solutions that is reported in the solution summary .
BestInteger	indicates the best upper bound (assuming minimization) that is found so far.
BestBound	indicates the best lower bound (assuming minimization) that is found so far.
Gap	indicates the relative gap between BestInteger and BestBound, displayed as a percentage. If the relative gap is larger than 1,000, then the absolute gap is displayed. If no active nodes remain, the value of Gap is 0.
Time	indicates the elapsed real or CPU time.

If CONCURRENT=TRUE, then the following information about the status of the branch-and-bound algorithm is printed in the node log:

Node	indicates the total number of nodes that are processed by all concurrent solves.
Active	indicates the total number of active nodes among all concurrent solves.
Sols	indicates the number of feasible solutions that are found by all concurrent solves.
BestInteger	indicates the best upper bound (assuming minimization) that is found by all concurrent solves.
BestBound	indicates the best lower bound (assuming minimization) that is found by all concurrent solves.
Gap	indicates the relative gap between BestInteger and BestBound, displayed as a percentage. If the relative gap is larger than 1,000, then the absolute gap is displayed. If no active nodes remain, the value of Gap is 0.
Time	indicates the elapsed real or CPU time.

If CONCURRENT=TRUE or DISTRIBUTED=TRUE, the node log displays the progress of the overall grid. If DETERMINISTIC=TRUE, PROC OPTMILP returns a reproducible solution. Therefore, there might be discrepancies between the node log and the final solution that is reported by the deterministic concurrent or deterministic distributed OPTMILP procedure.

The LOGFREQ= and LOGLEVEL= options can be used to control the amount of information that is printed in the node log. By default, the root node processing information is printed and, if possible, an entry is made every five seconds. A new entry is also included each time a better integer solution is found. The LOGFREQ= option enables you to change the interval between entries in the node log. Figure 6.4 shows a sample node log.

Figure 6.4 Sample Node Log

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      0              .         869515        .       0
           683      603      1         891131         874032    1.96%       0
           691      609      2         890751         874032    1.91%       0
          1801      166      5         889219         874314    1.70%       0
          1894      249      6         888839         874314    1.66%       0
          2133      448      7         881651         874314    0.84%       0
          2694      562      8         880796         874314    0.74%       0
          2801      607      9         880796         874314    0.74%       0
          3246      838     10         880796         874458    0.72%       0
          3249      838     11         880796         874523    0.72%       0
          4594     1341     12         878430         874753    0.42%       0
          4608     1213     13         878430         874836    0.41%       0
          7884        0     13         878430         878430    0.00%       1
NOTE: Optimal.
NOTE: Objective = 878430.316.
NOTE: The Cloud Analytic Services server processed the request in 1.399546
      seconds.
```

IIS Log

If IIS=TRUE, then the following information about the status of the IIS algorithm is printed in the IIS log:

Processed	indicates the number of integer restrictions or constraints or variables that were processed for determining the IIS.
Added	indicates the number of integer restrictions or constraints or bound changes that were added to the IIS.
Time	indicates the elapsed real or CPU time.

The LOGFREQ= option enables you to change the interval between entries in the IIS log.

ODS Tables

PROC OPTMILP creates two Output Delivery System (ODS) tables by default. The first table, ProblemSummary, is a summary of the input MILP problem. The second table, SolutionSummary, is a brief summary of the solution status. You can use ODS table names to select tables and create output data tables. For more information about ODS, see *SAS Output Delivery System: User's Guide*.

If you specify a value of 2 for the PRINTLEVEL= option, then the ProblemStatistics table and a Timing table are produced. The ProblemStatistics table contains information about the problem data. See the section "Problem Statistics" on page 216 for more information. The Timing table contains detailed information about the solution time.

Table 6.5 lists all the ODS tables that can be produced by the OPTMILP procedure, along with the statement and option specifications required to produce each table.

Table 6.5 ODS Tables Produced by PROC OPTMILP

ODS Table Name	Description	Statement	Option
ProblemSummary	Summary of the input MILP problem	PROC OPTMILP	PRINTLEVEL=1 (default)
SolutionSummary	Summary of the solution status	PROC OPTMILP	PRINTLEVEL=1 (default)
ProblemStatistics	Description of input problem data	PROC OPTMILP	PRINTLEVEL=2
Timing	Detailed solution timing	PROC OPTMILP	PRINTLEVEL=2

A typical ProblemSummary table is shown in Figure 6.5.

Figure 6.5 Example PROC OPTMILP Output: Problem Summary

The OPTMILP Procedure

Problem Summary	
Problem Name	EX_MIP
Objective Sense	Minimization
Objective Function	COST
RHS	RHS
Number of Variables	3
Bounded Above	0
Bounded Below	0
Bounded Above and Below	3
Free	0
Fixed	0
Binary	3
Integer	0
Number of Constraints	3
LE (<=)	2
EQ (=)	0
GE (>=)	1
Range	0
Constraint Coefficients	8

A typical SolutionSummary table is shown in Figure 6.6.

Figure 6.6 Example PROC OPTMILP Output: Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	COST
Solution Status	Optimal
Objective Value	-7
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	-7
Nodes	0
Solutions Found	2
Iterations	0
Presolve Time	0.00
Solution Time	0.00

You can create output data tables from these tables by using the ODS OUTPUT statement. The output data tables from the preceding example are displayed in Figure 6.7 and Figure 6.8, where you can also find variable names for the tables used in the ODS template of the OPTMILP procedure.

Figure 6.7 ODS Output Data Table: Problem Summary

Problem Summary

Obs	Name1	Label1	cValue1	nValue1
1	problemName	Problem Name	EX_MIP	.
2	objectiveSense	Objective Sense	Minimization	.
3	objectiveName	Objective Function	COST	.
4	rhs	RHS	RHS	.
5				.
6	numVars	Number of Variables	3	3.000000
7	numBoundedAbove	Bounded Above	0	0
8	numBoundedBelow	Bounded Below	0	0
9	numBounded	Bounded Above and Below	3	3.000000
10	numFree	Free	0	0
11	numFixed	Fixed	0	0
12	numBinary	Binary	3	3.000000
13	numInteger	Integer	0	0
14				.
15	numRows	Number of Constraints	3	3.000000
16	numLE	LE (<=)	2	2.000000
17	numEQ	EQ (=)	0	0
18	numGE	GE (>=)	1	1.000000
19	numRange	Range	0	0
20				.
21	numElems	Constraint Coefficients	8	8.000000

Figure 6.8 ODS Output Data Table: Solution Summary

Solution Summary

Obs	Name1	Label1	cValue1	nValue1
1	solver	Solver	MILP	.
2	algorithm	Algorithm	Branch and Cut	.
3	objectiveName	Objective Function	COST	.
4	solStatus	Solution Status	Optimal	.
5	objective	Objective Value	-7	-7.000000
6				.
7	relativeGap	Relative Gap	0	0
8	absoluteGap	Absolute Gap	0	0
9	primalInfeasibility	Primal Infeasibility	0	0
10	boundInfeasibility	Bound Infeasibility	0	0
11	integerInfeasibility	Integer Infeasibility	0	0
12				.
13	bestBound	Best Bound	-7	-7.000000
14	nodes	Nodes	0	0
15	solutions	Solutions Found	2	2.000000
16	iterations	Iterations	0	0
17				.
18	presolveTime	Presolve Time	0.00	0.000013113
19	solutionTime	Solution Time	0.00	0.001575

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTMILP procedure causes the ODS table ProblemStatistics to be generated. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 6.9 demonstrates the contents of the ODS table ProblemStatistics.

Figure 6.9 ODS Table ProblemStatistics

ProblemStatistics

Obs	Name1	Label1	cValue1	nValue1
1	numMatElems	Number of Constraint Matrix Nonzeros	8	8.000000
2	maxMatValue	Maximum Constraint Matrix Coefficient	3	3.000000
3	minMatValue	Minimum Constraint Matrix Coefficient	1	1.000000
4	avgMatValue	Average Constraint Matrix Coefficient	1.875	1.875000
5				.
6	numObjElems	Number of Objective Nonzeros	3	3.000000
7	maxObjValue	Maximum Objective Coefficient	4	4.000000
8	minObjValue	Minimum Objective Coefficient	2	2.000000
9	avgObjValue	Average Objective Coefficient	3	3.000000
10				.
11	numRhsElems	Number of RHS Nonzeros	3	3.000000
12	maxRhsValue	Maximum RHS	7	7.000000
13	minRhsValue	Minimum RHS	4	4.000000
14	avgRhsValue	Average RHS	5.3333333333	5.333333
15				.
16	maxColElems	Maximum Number of Nonzeros per Column	3	3.000000
17	minColElems	Minimum Number of Nonzeros per Column	2	2.000000
18	avgColElems	Average Number of Nonzeros per Column	2.67	2.666667
19				.
20	maxRowElems	Maximum Number of Nonzeros per Row	3	3.000000
21	minRowElems	Minimum Number of Nonzeros per Row	2	2.000000
22	avgRowElems	Average Number of Nonzeros per Row	2.67	2.666667

The variable names in the ODS table ProblemStatistics are Label1, cValue1, and nValue1.

Irreducible Infeasible Set

For a mixed integer linear programming problem (MILP), an irreducible infeasible set (IIS) is an infeasible subset of constraints, variable bounds, and integer restrictions that becomes feasible if any single constraint, variable bound, or integer restriction is removed. It is possible to have more than one IIS in an infeasible MILP. Identifying an IIS can help isolate the structural infeasibility in a MILP.

The presolver in the OPTMILP procedure can detect infeasibility, but it identifies only the variable bound or constraint that triggers the infeasibility.

The IIS=TRUE option directs the OPTMILP procedure to search for an IIS in a specified MILP. If PROC OPTMILP detects an IIS, it outputs the status of variable bounds and integrality restrictions in the IIS to the data table that is specified in the PRIMALOUT= option and the status of the constraints in the IIS to data table that is specified in the DUALOUT= option, by populating the values of the _IIS_ variables in those data tables, and then it stops. For information about the values in the _IIS_ variables in those output data tables, see the sections "Definitions of Variables in the PRIMALOUT= Data Table" on page 201 and "Definitions of Variables in the DUALOUT= Data Table" on page 202. From the information in the _IIS_ variables, you can identify both the names of the constraints (variables) in the IIS and the corresponding bound (or integrality restrictions) where infeasibility occurs. The number of iterations and nodes that are reported in the macro variable and the ODS table is the total number of iterations and nodes from all the subproblem solves during the IIS determination.

Making any one of the constraints, variable bounds, or integrality restrictions in the IIS nonbinding removes the infeasibility from the IIS. However, in the process of determining the IIS, some of the subproblems might not be solved to completion within reasonable preset limits. In such cases, the infeasible subset is not guaranteed to be irreducible, and PROC OPTMILP prints a warning message that the infeasible subset is not irreducible. For these cases, making any one of the constraints, variable bounds, or integrality restrictions nonbinding does not eliminate the infeasibility from the IIS.

Macro Variable _OROPTMILP_

The OPTMILP procedure defines a macro variable named _OROPTMILP_. This variable contains a character string that indicates the status of the OPTMILP procedure upon termination. For PROC OPTMILP, the various terms of _OROPTMILP_ are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The procedure terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data was inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produced the solution data in the macro variable. This term appears only when STATUS=OK. It can take one of the following values:

BAC	The branch-and-cut algorithm produced the solution data.
DECOMP	The decomposition algorithm produced the solution data.
IIS	The IIS detection algorithm was used to find the IIS.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
OPTIMAL_AGAP	The solution is optimal within the absolute gap specified by the ABSOBJGAP= option.
OPTIMAL_RGAP	The solution is optimal within the relative gap specified by the RELOBJGAP= option.
OPTIMAL_COND	The solution is optimal, but some infeasibilities (primal, bound, or integer) exceed tolerances due to scaling or choice of a small INTTOL= value.
TARGET	The solution is not worse than the target specified by the TARGET= option.
INFEASIBLE	The problem is infeasible.
FEASIBLE	The problem is feasible. This status is displayed when the IIS=TRUE option is specified and the problem is feasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
SOLUTION_LIM	The solver reached the maximum number of solutions specified by the MAXSOLS= option.
NODE_LIM_SOL	The solver reached the maximum number of nodes specified by the MAXNODES= option and found a solution.
NODE_LIM_NOSOL	The solver reached the maximum number of nodes specified by the MAXNODES= option and did not find a solution.
TIME_LIM_SOL	The solver reached the execution time limit specified by the MAXTIME= option and found a solution.
TIME_LIM_NOSOL	The solver reached the execution time limit specified by the MAXTIME= option and did not find a solution.
ABORT_SOL	The solver was stopped by the user but still found a solution.
ABORT_NOSOL	The solver was stopped by the user and did not find a solution.
OUTMEM_SOL	The solver ran out of memory but still found a solution.
OUTMEM_NOSOL	The solver ran out of memory and either did not find a solution or failed to output the solution due to insufficient memory.
FAIL_SOL	The solver stopped due to errors but still found a solution.
FAIL_NOSOL	The solver stopped due to errors and did not find a solution.

OBJECTIVE
indicates the objective value obtained by the solver at termination.

RELATIVE_GAP
indicates the relative gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the OPTMILP procedure. The relative gap is equal to

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

ABSOLUTE_GAP
indicates the absolute gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the OPTMILP procedure. The absolute gap is equal to $|\text{BestInteger} - \text{BestBound}|$.

PRIMAL_INFEASIBILITY
indicates the maximum (absolute) violation of the primal constraints by the solution.

BOUND_INFEASIBILITY
indicates the maximum (absolute) violation by the solution of the lower or upper bounds (or both).

INTEGER_INFEASIBILITY
indicates the maximum (absolute) violation of the integrality of integer variables returned by the OPTMILP procedure.

BEST_BOUND
indicates the best bound on the objective function value at termination. A missing value indicates that the OPTMILP procedure was not able to obtain such a bound.

NODES
indicates the number of nodes enumerated by the OPTMILP procedure when using the branch-and-bound algorithm.

SOLUTIONS_FOUND
indicates the number of solutions that are found by the OPTMILP procedure.

ITERATIONS
indicates the number of simplex iterations taken to solve the problem.

PRESOLVE_TIME
indicates the time (in seconds) used in preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

Examples: OPTMILP Procedure

This section contains examples that illustrate the options and syntax of PROC OPTMILP. Example 6.1 demonstrates a model contained in an MPS-format SAS data set and finds an optimal solution by using PROC OPTMILP. Example 6.2 illustrates the use of standard MPS files and the usage of some of the options available in PROC OPTMILP. Example 6.3 demonstrates how to warm start PROC OPTMILP. More detailed examples of mixed integer linear programs, along with example SAS code, are given in Chapter 14.

Example 6.1: Simple Integer Linear Program

This example illustrates a model in an MPS-format data table. This data table is passed to PROC OPTMILP, and a solution is found.

Consider a scenario where you have a container with a set of limiting attributes (volume V and weight W) and a set I of items that you want to pack. Each item type i has a certain value p_i, a volume v_i, and a weight w_i. You must choose at most four items of each type so that the total value is maximized and all the chosen items fit into the container. Let x_i be the number of items of type i to be included in the container. This model can be formulated as the following integer linear program:

$$
\begin{array}{llll}
\max & \sum_{i \in I} p_i x_i & & \\
\text{s.t.} & \sum_{i \in I} v_i x_i \leq V & & \text{(volume_con)} \\
 & \sum_{i \in I} w_i x_i \leq W & & \text{(weight_con)} \\
 & x_i \leq 4 & \forall i \in I & \\
 & x_i \in \mathbb{Z}^+ & \forall i \in I &
\end{array}
$$

Constraint (volume_con) enforces the volume capacity limit, while constraint (weight_con) enforces the weight capacity limit. An instance of this problem can be saved in an MPS-format data table by using the following code:

```
data mycas.ex1data;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
1  NAME       .            ex1data          .     .                .
2  ROWS       .            .                .     .                .
3  MAX        z            .                .     .                .
4  L          volume_con   .                .     .                .
5  L          weight_con   .                .     .                .
6  COLUMNS    .            .                .     .                .
7  .          .MRK0        'MARKER'         .     'INTORG'         .
8  .          x[1]         z                1     volume_con      10
9  .          x[1]         weight_con      12     .                .
10 .          x[2]         z                2     volume_con     300
11 .          x[2]         weight_con      15     .                .
```

```
12 .          x[3]          z                 3     volume_con      250
13 .          x[3]          weight_con       72     .                 .
14 .          x[4]          z                 4     volume_con      610
15 .          x[4]          weight_con      100     .                 .
16 .          x[5]          z                 5     volume_con      500
17 .          x[5]          weight_con      223     .                 .
18 .          x[6]          z                 6     volume_con      120
19 .          x[6]          weight_con       16     .                 .
20 .          x[7]          z                 7     volume_con       45
21 .          x[7]          weight_con       73     .                 .
22 .          x[8]          z                 8     volume_con      100
23 .          x[8]          weight_con       12     .                 .
24 .          x[9]          z                 9     volume_con      200
25 .          x[9]          weight_con      200     .                 .
26 .          x[10]         z                10     volume_con       61
27 .          x[10]         weight_con      110     .                 .
28 .          .MRK1         'MARKER'          .     'INTEND'          .
29 RHS        .             .                 .     .                 .
30 .          .RHS.         volume_con     1000     .                 .
31 .          .RHS.         weight_con      500     .                 .
32 BOUNDS     .             .                 .     .                 .
33 UP         .BOUNDS.      x[1]              4     .                 .
34 UP         .BOUNDS.      x[2]              4     .                 .
35 UP         .BOUNDS.      x[3]              4     .                 .
36 UP         .BOUNDS.      x[4]              4     .                 .
37 UP         .BOUNDS.      x[5]              4     .                 .
38 UP         .BOUNDS.      x[6]              4     .                 .
39 UP         .BOUNDS.      x[7]              4     .                 .
40 UP         .BOUNDS.      x[8]              4     .                 .
41 UP         .BOUNDS.      x[9]              4     .                 .
42 UP         .BOUNDS.      x[10]             4     .                 .
43 ENDATA     .             .                 .     .                 .
;
```

In the COLUMNS section of this data table, the name of the objective is z, and the objective coefficients p_i appear in field4. The coefficients v_i of (volume_con) appear in field6. The coefficients w_i of (weight_con) appear in field4. In the RHS section, the bounds V and W appear in field4. The _id_ column ensures that the data can be read in the right order even if the table is stored on separate machines in CAS. This problem can be solved by using the following statements to call the OPTMILP procedure:

```
proc optmilp data=mycas.ex1data primalout=mycas.ex1soln;
run;
```

The progress of the solver is shown in Output 6.1.1.

Output 6.1.1 Simple Integer Linear Program PROC OPTMILP Log

```
NOTE: The problem ex1data has 10 variables (0 binary, 10 integer, 0 free, 0
      fixed).
NOTE: The problem has 2 constraints (2 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 20 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 2 variables and 0 constraints.
NOTE: The MILP presolver removed 4 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 8 variables, 2 constraints, and 16 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      4     85.0000000    158.0000000   46.20%       0
             0        1      4     85.0000000     88.0955497    3.51%       0
             0        1      4     85.0000000     87.4545455    2.81%       0
NOTE: The MILP presolver is applied again.
             0        1      5     87.0000000     87.4545455    0.52%       0
NOTE: Optimal.
NOTE: Objective = 87.
NOTE: The Cloud Analytic Services server processed the request in 0.813315
      seconds.
NOTE: The data set MYCAS.EX1SOLN has 10 observations and 9 variables.
```

The data table ex1soln is shown in Output 6.1.2.

Output 6.1.2 Simple Integer Linear Program Solution

Example 1 Solution Data

Objective Function ID	RHS ID	Variable Name	Variable Type	Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Solution
z	.RHS.	x[1]	I	1	0	4	0	1
z	.RHS.	x[2]	I	2	0	4	0	1
z	.RHS.	x[3]	I	3	0	4	0	1
z	.RHS.	x[4]	I	4	0	4	0	1
z	.RHS.	x[5]	I	5	0	4	0	1
z	.RHS.	x[6]	I	6	0	4	3	1
z	.RHS.	x[7]	I	7	0	4	1	1
z	.RHS.	x[8]	I	8	0	4	4	1
z	.RHS.	x[9]	I	9	0	4	0	1
z	.RHS.	x[10]	I	10	0	4	3	1

The optimal solution is $x_6 = 3, x_7 = 1, x_8 = 4$, and $x_{10} = 3$, with a total value of 87. From this solution, you can compute the total volume used, which is 988 ($\leq V = 1000$); the total weight used is 499 ($\leq W = 500$). The problem summary and solution summary are shown in Output 6.1.3.

Output 6.1.3 Simple Integer Linear Program Summary

The OPTMILP Procedure

Problem Summary	
Problem Name	ex1data
Objective Sense	Maximization
Objective Function	z
RHS	.RHS.
Number of Variables	10
Bounded Above	0
Bounded Below	0
Bounded Above and Below	10
Free	0
Fixed	0
Binary	0
Integer	10
Number of Constraints	2
LE (<=)	2
EQ (=)	0
GE (>=)	0
Range	0
Constraint Coefficients	20

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	z
Solution Status	Optimal
Objective Value	87
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	87
Nodes	1
Solutions Found	5
Iterations	14
Presolve Time	0.00
Solution Time	0.06

Example 6.2: MIPLIB Benchmark Instance

The following example illustrates the conversion of a standard MPS-format file into an MPS-format data table. The problem is re-solved several times, each time by using a different control option. For such a small example, it is helpful to disable cuts and heuristics in order to see the computational savings gained by using other options. For larger or more complex examples, the benefits of using the various control options are more pronounced.

The standard set of MILP benchmark cases are the various versions of MIPLIB (Bixby et al. 1998, Achterberg, Koch, and Martin 2003) and can be found at `http://miplib.zib.de/`. The following statement uses the %MPS2SASD macro to convert an example from MIPLIB to a data table:

```
%mps2sasd(mpsfile="bell3a.mps", outdata=mycas.mpsdata);
```

The problem can then be solved using PROC OPTMILP on the data table uploaded to CAS:

```
proc optmilp data=mycas.mpsdata allcuts=none heuristics=none;
run;
```

The resulting log is shown in Output 6.2.1.

Output 6.2.1 MIPLIB PROC OPTMILP Log

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      0              .         869515        .       0
           683      603      1         891131         874032    1.96%       0
           691      609      2         890751         874032    1.91%       0
          1801      166      5         889219         874314    1.70%       0
          1894      249      6         888839         874314    1.66%       0
          2133      448      7         881651         874314    0.84%       0
          2694      562      8         880796         874314    0.74%       0
          2801      607      9         880796         874314    0.74%       0
          3246      838     10         880796         874458    0.72%       0
          3249      838     11         880796         874523    0.72%       0
          4594     1341     12         878430         874753    0.42%       0
          4608     1213     13         878430         874836    0.41%       0
          7884        0     13         878430         878430    0.00%       1
NOTE: Optimal.
NOTE: Objective = 878430.316.
NOTE: The Cloud Analytic Services server processed the request in 1.399546
      seconds.
```

If there is an objective value that satisfies your requirements, even if it is not optimal, then you can save time by using the TARGET= option. The following PROC OPTMILP call solves the problem with a target value of 880,000:

```
proc optmilp data=mycas.mpsdata allcuts=none heuristics=none
   target=880000;
run;
```

The relevant results from this run are displayed in Output 6.2.2. In this case, there is a decrease in the number of nodes processed, but the objective value has increased.

Output 6.2.2 MIPLIB PROC OPTMILP Log with TARGET= Option

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 32 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      0              .         869515        .       0
           406      371      1         881651         873369    0.95%       0
           611      409      2         881584         874314    0.83%       0
          1085      261      4         881505         874502    0.80%       0
          1146      309      5         881438         874502    0.79%       0
          1188      334      6         880796         874502    0.72%       0
          1601       92      7         880717         874753    0.68%       0
          1627      114      8         878651         874753    0.45%       0
NOTE: Target reached.
NOTE: Objective of the best integer solution found = 878651.068.
NOTE: The Cloud Analytic Services server processed the request in 0.671221
      seconds.
```

When the objective value of a solution is within a certain relative gap of the optimal objective value, the procedure stops. The acceptable relative gap can be changed using the RELOBJGAP= option, as demonstrated in the following example:

```
proc optmilp data=mycas.mpsdata allcuts=none heuristics=none
   relobjgap=0.3;
run;
```

The relevant results from this run are displayed in Output 6.2.3. In this case, since the specified RELOBJGAP= value is larger than the default value, the number of nodes that are processed has decreased from their values in the original run. Note that these savings are possible because PROC OPTMILP makes a weaker statement about how good the found solution is, which is indicated by the decreased best bound value.

Output 6.2.3 MIPLIB PROC OPTMILP Log with RELOBJGAP= Option

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 32 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      0              .         869515        .       0
           406      371      1         881651         873369    0.95%       0
NOTE: Optimal within relative gap.
NOTE: Objective = 881650.93.
NOTE: The Cloud Analytic Services server processed the request in 0.292919
      seconds.
```

The MAXTIME= option enables you to accept the best solution produced by PROC OPTMILP in a specified amount of time. The following example illustrates the use of the MAXTIME= option:

```
proc optmilp data=mycas.mpsdata allcuts=none heuristics=none
   maxtime=0.1;
run;
```

The relevant results from this run are displayed in Output 6.2.4. In this case the solution process stopped early because the time limit was reached.

Output 6.2.4 MIPLIB PROC OPTMILP Log with MAXTIME= Option

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: Real time limit reached.
NOTE: The Cloud Analytic Services server processed the request in 0.244353
      seconds.
```

The MAXNODES= option enables you to limit the number of nodes generated by PROC OPTMILP. The following example illustrates the use of the MAXNODES= option:

```
proc optmilp data=mycas.mpsdata allcuts=none heuristics=none
   maxnodes=1000;
run;
```

The relevant results from this run are displayed in Output 6.2.5. PROC OPTMILP displays the best objective value of all the solutions produced within the first 1000 nodes.

Output 6.2.5 MIPLIB PROC OPTMILP Log with MAXNODES= Option

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 32 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      0              .         869515        .       0
           406      371      1         881651         873369    0.95%       0
           611      409      2         881584         874314    0.83%       0
           999      196      2         881584         874502    0.81%       0
NOTE: Node limit reached.
NOTE: Objective of the best integer solution found = 881583.916.
NOTE: The Cloud Analytic Services server processed the request in 0.389073
      seconds.
```

The SOLTYPE= option, in conjunction with the MAXPOOLGAP= and MAXPOOLSOLS= options, enables PROC OPTMILP to obtain multiple optimal or feasible solutions. Since these options can result in an increased solution time, this example enables cuts and heuristics. The following statements illustrate the usage of these options to obtain a maximum of 10 solutions that fall within a gap of 0.25 away from the best integer solution.

```
proc optmilp data=mycas.mpsdata soltype=withingap maxpoolsols=10
   maxpoolgap=0.25;
run;
```

The relevant results from this run are displayed in Output 6.2.6. PROC OPTMILP continues enumerating the nodes of the branch-and-bound tree until it finds the required number of solutions that satisfy the gap criterion. Note the increase in the number of nodes and solution times compared to the default branch-and-bound algorithm; in this case the solver turns off the pruning techniques that can potentially eliminate the solutions.

Output 6.2.6 MIPLIB PROC OPTMILP Log with SOLTYPE= Option

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 11 variables and 19 constraints.
NOTE: The MILP presolver removed 45 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 122 variables, 104 constraints, and 302
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 32 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      5        1445707         866172   66.91%       0
             0        1      5        1445707         870748   66.03%       0
             0        1      5        1445707         872978   65.61%       0
             0        1      5        1445707         873285   65.55%       0
             0        1      5        1445707         873792   65.45%       0
             0        1      7         878430         873792    0.53%       0
NOTE: The MILP solver added 11 cuts with 49 cut coefficients at the root.
         27222    11541      8         878430         876800    0.19%       1
         27829    11635      9         878430         876838    0.18%       1
NOTE: Processing nodes for multiple solutions.
         58667    29294     10         878430         878430    0.00%       3
         58670    29297     11         878430         878430    0.00%       3
         58695    29322     12         878430         878430    0.00%       3
         58697    29324     13         878430         878430    0.00%       3
         58699    29326     14         878430         878430    0.00%       3
         58702    29329     15         878430         878430    0.00%       3
         58714    29341     16         878430         878430    0.00%       3
         58727    29354     17         878430         878430    0.00%       3
NOTE: Optimal.
NOTE: Objective = 878430.316.
NOTE: The Cloud Analytic Services server processed the request in 3.639891
      seconds.
```

The ROOTNODE statement enables you to choose the root node LP solver of PROC OPTMILP. In the following statements, the ALGORITHM= option chooses the primal simplex algorithm for solving the root node LP and the LOGLEVEL= option requests that the progress log of the primal simplex algorithm be displayed:

```
proc optmilp data=mycas.mpsdata;
   rootnode algorithm=ps loglevel=2;
run;
```

The relevant results from this run are displayed in Output 6.2.7. The log shows that primal simplex algorithm was used to solve the root node LP, and its progress is displayed in the log.

Output 6.2.7 MIPLIB PROC OPTMILP Log with ROOTNODE= statement

```
NOTE: The problem BELL3A has 133 variables (39 binary, 32 integer, 0 free, 0
      fixed).
NOTE: The problem has 123 constraints (123 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 347 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 45 variables and 59 constraints.
NOTE: The MILP presolver removed 144 constraint coefficients.
NOTE: The MILP presolver modified 25 constraint coefficients.
NOTE: The presolved problem has 88 variables, 64 constraints, and 203
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
NOTE: The LP relaxation log follows.
NOTE: ----------------------------------------------------------
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                              Objective
      Phase Iteration         Value         Time
       P 1          1    1.513125E+02         0
       P 2         21    6.551597E+06         0
       P 2         67    1.207347E+06         0
       D 2         91    8.695151E+05         0
NOTE: Optimal.
NOTE: Objective = 869515.13091.
NOTE: The Primal Simplex solve time is 0.00 seconds.
NOTE: ----------------------------------------------------------
             0        1      3        1496902         869515   72.15%       0
             0        1      5         915321         869515    5.27%       0
             0        1      5         915321         871145    5.07%       0
             0        1      5         915321         871145    5.07%       0
NOTE: The MILP presolver is applied again.
             0        1      7         896793         871145    2.94%       0
             0        1      8         889802         871145    2.14%       0
             0        1      8         889802         871145    2.14%       0
             0        1     11         880072         871145    1.02%       0
             0        1     11         880072         873407    0.76%       0
             0        1     12         879001         873407    0.64%       0
NOTE: The MILP solver added 7 cuts with 29 cut coefficients at the root.
             2        3     13         878430         873407    0.58%       0
          1856      402     14         878430         874368    0.46%       0
          2024      439     15         878430         874368    0.46%       0
          2179      448     16         878430         874523    0.45%       0
          3108      464     17         878430         874942    0.40%       0
          3505      404     18         878430         875198    0.37%       0
          4867        0     18         878430         878430    0.00%       1
```

Output 6.2.7 *continued*

```
NOTE: Optimal.
NOTE: Objective = 878430.316.
NOTE: The Cloud Analytic Services server processed the request in 1.37162
      seconds.
```

Example 6.3: Facility Location

This advanced example demonstrates how to warm start PROC OPTMILP by using the PRIMALIN= option. The model is constructed in PROC OPTMODEL and saved in an MPS-format data table for use in PROC OPTMILP. This problem can also be solved from within PROC OPTMODEL; see Chapter 14 for details.

Consider the classical facility location problem. Given a set L of customer locations and a set F of candidate facility sites, you must decide on which sites to build facilities and assign coverage of customer demand to these sites so as to minimize cost. All customer demand d_i must be satisfied, and each facility has a demand capacity limit C. The total cost is the sum of the distances c_{ij} between facility j and its assigned customer i, plus a fixed charge f_j for building a facility at site j. Let $y_j = 1$ represent choosing site j to build a facility, and 0 otherwise. Also, let $x_{ij} = 1$ represent the assignment of customer i to facility j, and 0 otherwise. This model can be formulated as the following integer linear program:

$$
\begin{array}{llcll}
\min & \displaystyle\sum_{i\in L}\sum_{j\in F} c_{ij}x_{ij} + \sum_{j\in F} f_j y_j & & & \\
\text{s.t.} & \displaystyle\sum_{j\in F} x_{ij} & = & 1 \quad \forall i \in L & \text{(assign_def)} \\
 & x_{ij} & \leq & y_j \quad \forall i \in L, j \in F & \text{(link)} \\
 & \displaystyle\sum_{i\in L} d_i x_{ij} & \leq & C y_j \quad \forall j \in F & \text{(capacity)} \\
 & x_{ij} \in \{0,1\} & & \forall i \in L, j \in F & \\
 & y_j \in \{0,1\} & & \forall j \in F &
\end{array}
$$

Constraint (assign_def) ensures that each customer is assigned to exactly one site. Constraint (link) forces a facility to be built if any customer has been assigned to that facility. Finally, constraint (capacity) enforces the capacity limit at each site.

Consider also a variation of this same problem where there is no cost for building a facility. This problem is typically easier to solve than the original problem. For this variant, let the objective be

$$
\min \sum_{i\in L}\sum_{j\in F} c_{ij}x_{ij}
$$

First, construct a random instance of this problem by using the following DATA steps:

```
%let NumCustomers  = 30;
%let NumSites      = 6;
%let SiteCapacity  = 35;
%let MaxDemand     = 10;
%let xmax          = 200;
%let ymax          = 100;
%let seed          = 546;

/* generate random customer locations */
data mycas.cdata(drop=i);
   call streaminit(&seed);
   length name $8;
   do i = 1 to &NumCustomers;
      name = compress('C'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      demand = rand('UNIFORM') * &MaxDemand;
      output;
   end;
run;

/* generate random site locations and fixed charge */
data mycas.sdata(drop=i);
   call streaminit(&seed);
   length name $8;
   do i = 1 to &NumSites;
      name = compress('SITE'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      fixed_charge = 30 * (abs(&xmax/2-x) + abs(&ymax/2-y));
      output;
   end;
run;
```

The following PROC OPTMODEL statements generate the model and define both variants of the cost function:

```
proc optmodel;
   set <str> CUSTOMERS;
   set <str> SITES init {};

   /* x and y coordinates of CUSTOMERS and SITES */
   num x {CUSTOMERS union SITES};
   num y {CUSTOMERS union SITES};
   num demand {CUSTOMERS};
   num fixed_charge {SITES};

   /* distance from customer i to site j */
   num dist {i in CUSTOMERS, j in SITES}
      = sqrt((x[i] - x[j])^2 + (y[i] - y[j])^2);

   read data mycas.cdata into CUSTOMERS=[name] x y demand;
   read data mycas.sdata into SITES=[name] x y fixed_charge;
```

```
   var Assign {CUSTOMERS, SITES} binary;
   var Build {SITES} binary;
   /* each customer assigned to exactly one site */
   con assign_def {i in CUSTOMERS}:
      sum {j in SITES} Assign[i,j] = 1;

   /* if customer i assigned to site j, then facility must be */
   /* built at j                                              */
   con link {i in CUSTOMERS, j in SITES}:
      Assign[i,j] <= Build[j];

   /* each site can handle at most &SiteCapacity demand */
   con capacity {j in SITES}:
      sum {i in CUSTOMERS} demand[i] * Assign[i,j]
      <= &SiteCapacity * Build[j];

   min CostNoFixedCharge
      = sum {i in CUSTOMERS, j in SITES} dist[i,j] * Assign[i,j];

   save mps mycas.nofcdata;
   min CostFixedCharge
      = CostNoFixedCharge
        + sum {j in SITES} fixed_charge[j] * Build[j];

   save mps mycas.fcdata;

quit;
```

First solve the problem for the model with no fixed charge by using the following statements. The first PROC SQL call populates the macro variables varcostNo. This macro variable displays the objective value when the results are plotted. The second PROC SQL call generates a data table that is used to plot the results. The information printed in the log by PROC OPTMILP is displayed in Output 6.3.1.

```
proc optmilp data=mycas.nofcdata primalout=mycas.nofcout;
run;

proc sql noprint;
   select put(sum(_objcoef_ * _value_),6.1) into :varcostNo
   from mycas.nofcout;
quit;

proc sql;
   create table CostNoFixedCharge_Data as
   select
      scan(p._var_,2,'[],') as customer,
      scan(p._var_,3,'[],') as site,
      c.x as x1, c.y as y1, s.x as x2, s.y as y2
   from
      mycas.cdata as c,
      mycas.sdata as s,
      mycas.nofcout(where=(substr(_var_,1,6)='Assign' and
         round(_value_) = 1)) as p
   where calculated customer = c.name and calculated site = s.name;
quit;
```

Output 6.3.1 PROC OPTMILP Log for Facility Location with No Fixed Charges

```
NOTE: The problem nofcdata has 186 variables (186 binary, 0 integer, 0 free, 0
      fixed).
NOTE: The problem has 216 constraints (186 LE, 30 EQ, 0 GE, 0 range).
NOTE: The problem has 726 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 6 variables and 180 constraints.
NOTE: The MILP presolver removed 366 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 180 variables, 36 constraints, and 360
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 32 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1   1052.9414513    985.5035182    6.84%       0
NOTE: The MILP presolver is applied again.
             0        1      1   1052.9414513    985.5035182    6.84%       0
             0        1      2   1045.3217618    985.5035182    6.07%       0
             0        1      2   1045.3217618   1002.3380109    4.29%       0
             0        1      5   1025.8272473   1002.3380109    2.34%       0
             0        1      5   1025.8272473   1013.0691328    1.26%       0
NOTE: The MILP presolver is applied again.
             0        1      6   1021.5193163   1013.0691328    0.83%       0
             0        1      6   1021.5193163   1013.0691328    0.83%       0
             0        1      6   1021.5193163   1014.9738001    0.64%       0
NOTE: The MILP presolver is applied again.
             0        1      7   1021.5193163   1014.9738001    0.64%       0
NOTE: The MILP solver added 3 cuts with 17 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 1021.5193163.
NOTE: The Cloud Analytic Services server processed the request in 0.415259
      seconds.
NOTE: The data set MYCAS.NOFCOUT has 186 observations and 9 variables.
```

Next, solve the fixed-charge model by using the following statements. Note that the solution to the model with no fixed charge is feasible for the fixed-charge model and should provide a good starting point for PROC OPTMILP. The PRIMALIN= option provides an incumbent solution ("warm start"). The two PROC SQL calls perform the same functions as in the case with no fixed charges. The results from this approach are shown in Output 6.3.2.

```
proc optmilp data=mycas.fcdata primalin=mycas.nofcout primalout=mycas.fcout;
run;

proc sql noprint;
   select put(sum(_objcoef_ * _value_), 6.1) into :varcost
   from mycas.fcout(where=(substr(_var_,1,6)='Assign'));
   select put(sum(_objcoef_ * _value_), 5.1) into :fixcost
   from mycas.fcout(where=(substr(_var_,1,5)='Build'));
   select put(sum(_objcoef_ * _value_), 6.1) into :totalcost
   from mycas.fcout;
quit;

proc sql;
   create table CostFixedCharge_Data as
   select
      scan(p._var_,2,'[],') as customer,
      scan(p._var_,3,'[],') as site,
      c.x as x1, c.y as y1, s.x as x2, s.y as y2
   from
      mycas.cdata as c,
      mycas.sdata as s,
      mycas.fcout(where=(substr(_var_,1,6)='Assign' and
         round(_value_) = 1)) as p
   where calculated customer = c.name and calculated site = s.name;
quit;
```

Output 6.3.2 PROC OPTMILP Log for Facility Location with Fixed Charges, Using Warm Start

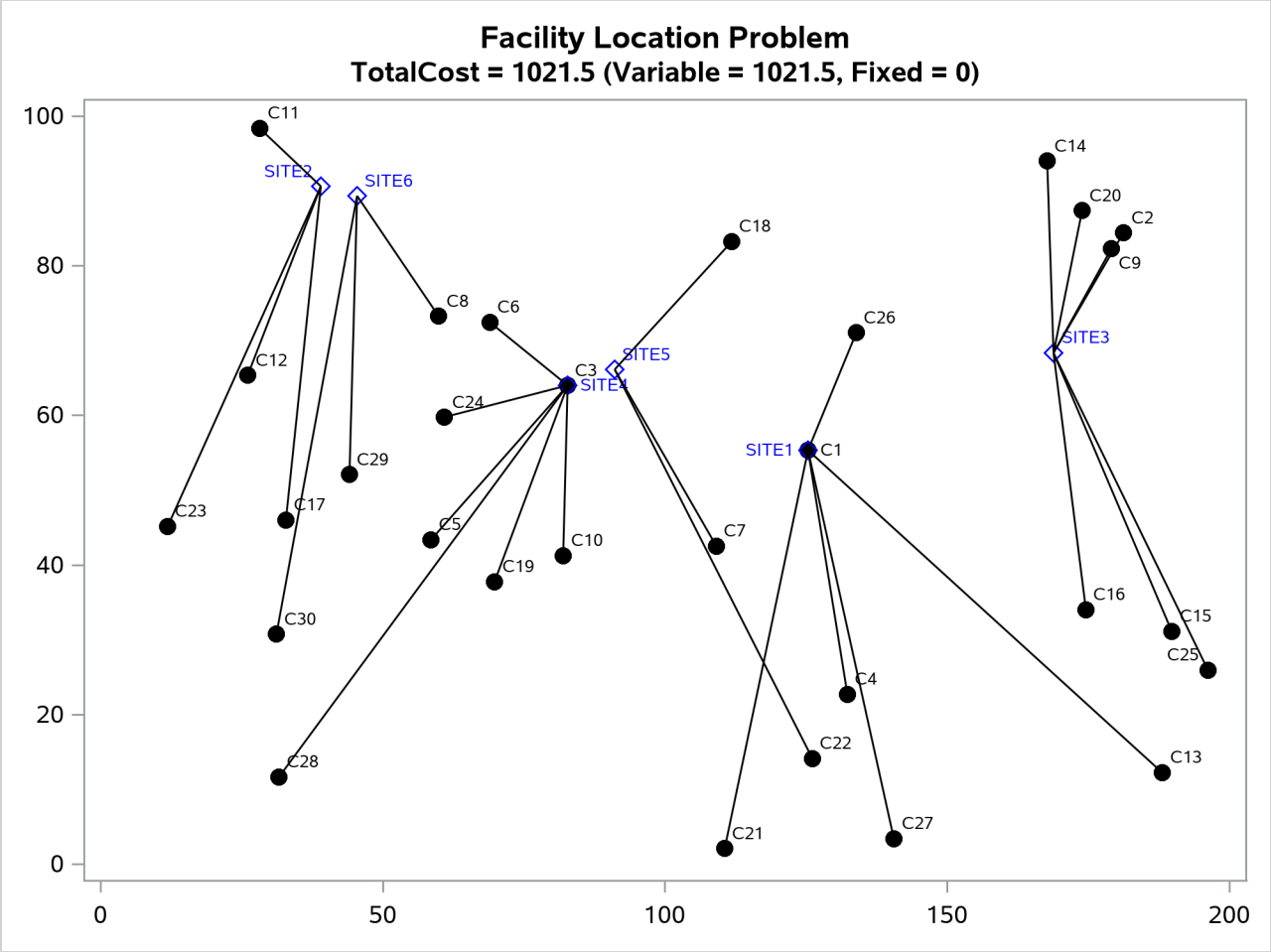
```
NOTE: The problem fcdata has 186 variables (186 binary, 0 integer, 0 free, 0
      fixed).
NOTE: The problem has 216 constraints (186 LE, 30 EQ, 0 GE, 0 range).
NOTE: The problem has 726 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 186 variables, 216 constraints, and 726
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      4   9113.7292152   6814.6940297   33.74%       0
             0        1      4   9113.7292152   9063.8415787    0.55%       0
NOTE: The MILP presolver is applied again.
             0        1      4   9113.7292152   9063.8415787    0.55%       0
             0        1      5   9106.1095257   9063.8415787    0.47%       0
             0        1      5   9106.1095257   9064.3666864    0.46%       0
             0        1      6   9086.6150112   9064.3666864    0.25%       0
             0        1      6   9086.6150112   9078.9354200    0.08%       0
NOTE: The MILP presolver is applied again.
             0        1      8   9082.3070802   9078.9354200    0.04%       0
             0        1      8   9082.3070802   9078.9354200    0.04%       0
             0        1      8   9082.3070802   9082.3070802    0.00%       0
NOTE: The MILP solver added 4 cuts with 31 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 9082.3070802.
NOTE: The Cloud Analytic Services server processed the request in 1.067011
      seconds.
NOTE: The data set MYCAS.FCOUT has 186 observations and 9 variables.
```

The following two SAS programs produce a plot of the solutions for both variants of the model, using data tables produced by PROC SQL from the PRIMALOUT= data tables produced by PROC OPTMILP.

```
title1 "Facility Location Problem";
title2 "TotalCost = &varcostNo (Variable = &varcostNo, Fixed = 0)";
data mycas.csdata;
   set mycas.cdata(rename=(y=cy)) mycas.sdata(rename=(y=sy));
run;
/* create Annotate data set to draw line between customer and */
/* assigned site                                              */
data anno;
   retain function "line" drawspace "datavalue"
      linethickness 1 linecolor "black";
   set CostNoFixedCharge_Data(keep=x1 y1 x2 y2);
run;
proc sgplot data=mycas.csdata sganno=anno noautolegend;
   scatter x=x y=cy / datalabel=name datalabelattrs=(size=6pt)
      markerattrs=(symbol=circlefilled color=black size=6pt);
   scatter x=x y=sy / datalabel=name datalabelattrs=(size=6pt)
      markerattrs=(symbol=diamond color=blue size=6pt);
   xaxis display=(nolabel);
   yaxis display=(nolabel);
run;
```

The output from the first program appears in Output 6.3.3.

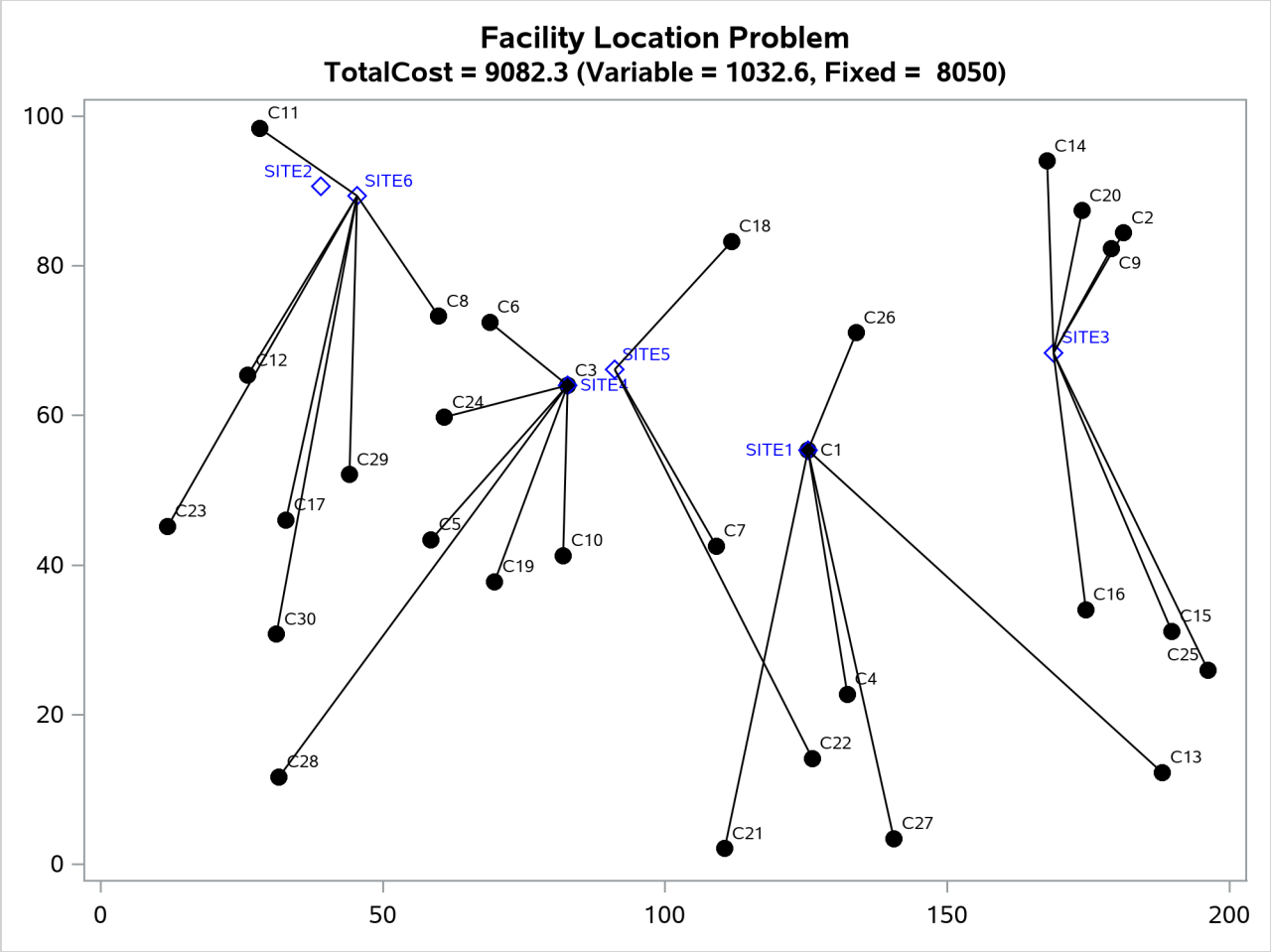
Output 6.3.3 Solution Plot for Facility Location with No Fixed Charges




```
title1 "Facility Location Problem";
title2 "TotalCost = &totalcost (Variable = &varcost, Fixed = &fixcost)";
/* create Annotate data set to draw line between customer and */
/* assigned site                                              */
data anno;
   retain function "line" drawspace "datavalue"
      linethickness 1 linecolor "black";
   set CostFixedCharge_Data(keep=x1 y1 x2 y2);
run;
proc sgplot data=mycas.csdata sganno=anno noautolegend;
   scatter x=x y=cy / datalabel=name datalabelattrs=(size=6pt)
      markerattrs=(symbol=circlefilled color=black size=6pt);
   scatter x=x y=sy / datalabel=name datalabelattrs=(size=6pt)
      markerattrs=(symbol=diamond color=blue size=6pt);
   xaxis display=(nolabel);
   yaxis display=(nolabel);
run;
```

The output from the second program appears in Output 6.3.4.

Output 6.3.4 Solution Plot for Facility Location with Fixed Charges



The economic trade-off for the fixed-charge model forces you to build fewer sites and push more demand to each site.

Example 6.4: Scheduling

This example is intended for users who prefer to use the SAS DATA step, PROC SQL, and similar programming methods to prepare data for input to SAS Optimization procedures. SAS Optimization users who prefer to use the algebraic modeling capabilities of PROC OPTMODEL to specify optimization models should consult Example 14.1 in Chapter 14, "The Mixed Integer Linear Programming Solver," for a discussion of the same business problem in a PROC OPTMODEL context.

Scheduling is an application area where techniques in model generation can be valuable. Problems that involve scheduling are often solved with integer programming and are similar to assignment problems. In this example, you have eight one-hour time slots in each of five days. You have to assign four people to these time slots so that each slot is covered every day. You allow the people to specify preference data for each slot on each day. In addition, there are constraints that must be satisfied:

- Each person has some slots for which he is unavailable.

- Each person must have either slot 4 or 5 off for lunch.
- Each person can work only two time slots in a row.
- Each person can work only a specified number of hours in the week.

To formulate this problem, let i denote person, j denote time slot, and k denote day. Then, let $x_{ijk} = 1$ if person i is assigned to time slot j on day k, and 0 otherwise; let p_{ijk} denote the preference of person i for slot j on day k; and let h_i denote the number of hours in a week that person i will work. Then, you get

$$
\begin{array}{lll}
\max & \sum_{ijk} p_{ijk} x_{ijk} & \\
\text{subject to} & \sum_i x_{ijk} = 1 & \text{for all } j \text{ and } k \\
 & x_{i4k} + x_{i5k} \le 1 & \text{for all } i \text{ and } k \\
 & x_{i,\ell,k} + x_{i,\ell+1,k} + x_{i,\ell+2,k} \le 2 & \text{for all } i \text{ and } k, \text{ and } \ell = 1, \ldots, 6 \\
 & \sum_{jk} x_{ijk} \le h_i & \text{for all } i \\
 & x_{ijk} = 0 \text{ or } 1 & \text{for all } i \text{ and } k \text{ such that } p_{ijk} > 0, \\
 & & \quad \text{otherwise } x_{ijk} = 0
\end{array}
$$

To solve this problem, create a data set that has the hours and preference data for each individual, time slot, and day. A 10 represents the most desirable time slot, and a 1 represents the least desirable time slot. In addition, a 0 indicates that the time slot is not available.

```
data raw;
   input name $ hour slot mon tue wed thu fri;
   datalines;
marc  20   1    10 10 10 10 10
marc  20   2     9  9  9  9  9
marc  20   3     8  8  8  8  8
marc  20   4     1  1  1  1  1
marc  20   5     1  1  1  1  1
marc  20   6     1  1  1  1  1
marc  20   7     1  1  1  1  1
marc  20   8     1  1  1  1  1
mike  20   1    10  9  8  7  6
mike  20   2    10  9  8  7  6
mike  20   3    10  9  8  7  6
mike  20   4    10  3  3  3  3
mike  20   5     1  1  1  1  1
mike  20   6     1  2  3  4  5
mike  20   7     1  2  3  4  5
mike  20   8     1  2  3  4  5
bill  20   1    10 10 10 10 10
bill  20   2     9  9  9  9  9
bill  20   3     8  8  8  8  8
bill  20   4     0  0  0  0  0
bill  20   5     1  1  1  1  1
bill  20   6     1  1  1  1  1
bill  20   7     1  1  1  1  1
bill  20   8     1  1  1  1  1
bob   20   1    10  9  8  7  6
bob   20   2    10  9  8  7  6
bob   20   3    10  9  8  7  6
```

```
bob   20   4    10  3  3  3  3
bob   20   5     1  1  1  1  1
bob   20   6     1  2  3  4  5
bob   20   7     1  2  3  4  5
bob   20   8     1  2  3  4  5
;
```

These data are read by the following DATA step, and an integer program is built to solve the problem. The model is saved in the data set named MODEL, which is constructed in the following steps:

1. The objective function is built using the data saved in the RAW data set.
2. The constraints that ensure that no one works during a time slot during which he is unavailable are built.
3. The constraints that require a person to be working in each time slot are built.
4. The constraints that allow each person time for lunch are added.
5. The constraints that restrict people to only two consecutive hours are added.
6. The constraints that limit the time that any one person works in a week are added.

The statements to build each of these constraints follow the formulation closely, as shown in the following example:

```
data model;
   array workweek{5} mon tue wed thu fri;
   array hours{4} hours1 hours2 hours3 hours4;
   retain hours1-hours4;

   set raw end=eof;

   length _row_ $ 8 _col_ $ 8 _type_ $ 8;
   keep _type_ _col_ _row_ _coef_;

   if name='marc' then i=1;
   else if name='mike' then i=2;
   else if name='bill' then i=3;
   else if name='bob'  then i=4;

   hours{i}=hour;

   /* build the objective function */

   do k=1 to 5;
      _col_='x'||put(i,1.)||put(slot,1.)||put(k,1.);

      _row_='object';
      _coef_=workweek{k} * 1000;
      output;
   end;

   /* build the rest of the model */

   /* cannot work during unavailable slots */
```

```
do k=1 to 5;
   if workweek{k}=0 then do;
      _row_='off'||put(i,1.)||put(slot,1.)||put(k,1.);
      _type_='eq';
      _col_='_RHS_';
      _coef_=0;
      output;
      _col_='x'||put(i,1.)||put(slot,1.)||put(k,1.);
      _coef_=1;
      _type_=' ';
      output;
   end;
end;

if eof then do;
   _coef_=.;
   _col_=' ';

   /* every hour 1 person working */
   do j=1 to 8;
      do k=1 to 5;
         _row_='work'||put(j,1.)||put(k,1.);
         _type_='eq';
         _col_='_RHS_';
         _coef_=1;
         output;
         _coef_=1;
         _type_=' ';
         do i=1 to 4;
            _col_='x'||put(i,1.)||put(j,1.)||put(k,1.);
            output;
         end;
      end;
   end;

   /* each person has a lunch */
   do i=1 to 4;
      do k=1 to 5;
         _row_='lunch'||put(i,1.)||put(k,1.);
         _type_='le';
         _col_='_RHS_';
         _coef_=1;
         output;
         _coef_=1;
         _type_=' ';
         _col_='x'||put(i,1.)||'4'||put(k,1.);
         output;
         _col_='x'||put(i,1.)||'5'||put(k,1.);
         output;
      end;
   end;

   /* work at most 2 slots in a row */
   do i=1 to 4;
```

```
            do k=1 to 5;
               do l=1 to 6;
               _row_='seq'||put(i,1.)||put(k,1.)||put(l,1.);
               _type_='le';
               _col_='_RHS_';
               _coef_=2;
                output;
               _coef_=1;
               _type_=' ';
                  do j=0 to 2;
                     _col_='x'||put(i,1.)||put(l+j,1.)||put(k,1.);
                     output;
                  end;
               end;
            end;
         end;

         /* work at most n hours in a week */
         do i=1 to 4;
            _row_='capacit'||put(i,1.);
            _type_='le';
            _col_='_RHS_';
            _coef_=hours{i};
            output;
            _coef_=1;
            _type_=' ';
            do j=1 to 8;
               do k=1 to 5;
                  _col_='x'||put(i,1.)||put(j,1.)||put(k,1.);
                  output;
               end;
            end;
         end;
      end;
   run;
```

Next, this SAS data set is converted to an MPS-format data table by establishing the structure of the MPS format and through very minor conversions of the data.

```
   /* the following code transforms the above sparse data set */
   /* into an MPS-format data set                              */

   /* generate the header of the MPS-format data set */
   data mps0;
      format field1 field2 field3 $10.;
      format field4 10.;
      format field5 $10.;
      format field6 10.;
      field1 = 'NAME';
      field2 = '       ';
      field3 = 'PROBLEM';
      field4 = .;
      field5 = '       ';
      field6 = .;
```

```
   output;
   field1 = 'ROWS';
   field3 = '';
   output;
   field1 = 'MAX';
   field2 = 'object';
   field3 = '';
   output;
run;

/* generate rows */
proc sql;
   create table mps1 as
      select _type_ as field1, _row_ as field2 from model
         where _row_ eq 'object' and _type_ ne '' union
      select 'E' as field1, _row_ as field2 from model
         where _type_ eq 'eq' union
      select 'L' as field1, _row_ as field2 from model
         where _type_ eq 'le' union
      select 'G' as field1, _row_ as field2 from model
         where _type_ eq 'ge';
quit;

/* indicate start of columns section and declare type of all */
/* variables as integer                                      */
data mps2;
   format field1 field2 field3  $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   field1 = 'COLUMNS';
   field2 = '         ';
   field3 = '         ';
   field4 = .;
   field5 = '         ';
   field6 = .;
   output;
   field1 = '         ';
   field2 = '.MARK0';
   field3 = "'MARKER'";
   field4 = .;
   field5 = "'INTORG'";
   field6 = .;
   output;
run;

/* generate columns */
data mps3;
   set model;
   format field1 field2 field3 $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
```

```
   keep field1-field6;
   field1 = '      ';
   field2 = _col_;
   field3 = _row_;
   field4 = _coef_;
   field5 = '      ';
   field6 = .;
   if field2 ne '_RHS_' then output;
run;

/* sort columns by variable names */
proc sort data=mps3;
   by field2;
run;

/* indicate the end of the columns section */
data mps4;
   format field1 field2 field3  $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   field1 = '         ';
   field2 = '.MARK1';
   field3 = "'MARKER'";
   field4 = .;
   field5 = "'INTEND'";
   field6 = .;
   output;
run;

/* indicate the start of the RHS section */
data mps5;
   format field1 field2 field3  $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   field1 = 'RHS';
run;

/* generate RHS entries */
data mps6;
   set model;
   format field1 field2 field3 $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   keep field1-field6;
   field1 = '      ';
   field2 = _col_;
   field3 = _row_;
   field4 = _coef_;
   field5 = '      ';
   field6 = .;
   if field2 eq '_RHS_' then output;
```

```
run;

/* denote the end of the MPS-format data set */
data mps7;
   format field1 field2 field3  $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   field1 = 'ENDATA';
run;

/* merge all sections into an MPS-format data table */
data mycas.mps;
   format field1 field2 field3 $10.;
   format field4 10.;
   format field5 $10.;
   format field6 10.;
   set mps0 mps1 mps2 mps3 mps4 mps5 mps6 mps7;
   _id_ = _n_;
run;
```

The model is solved using the OPTMILP procedure. The option PRIMALOUT=SOLUTION causes PROC OPTMILP to save the primal solution in the data table named SOLUTION.

```
/* solve the binary program */
proc optmilp data=mycas.mps
   printlevel=0 loglevel=0
   primalout=mycas.solution maxtime=1000;
run;
```

The following DATA step takes the solution data table SOLUTION and generates a report data table named ASSIGNMENTS. It restores the original interpretation (person, shift, day) of the variable names x_{ijk} so that a more meaningful report can be written. Then a data step and PROC PRINT are used to display a schedule that shows how the eight time slots are covered for the week.

```
/* report the solution */
title 'Reported Solution';

data mycas.assignments;
   set mycas.solution;
   keep slot mon tue wed thu fri;
   if substr(_var_,1,1)='x' then do;
      if _value_>0 then do;
         n=input(substr(_var_,2,1), 8.);
         slot=input(substr(_var_,3,1), 8.);
         d=substr(_var_,4,1);
         if      d='1' then mon=n;
         else if d='2' then tue=n;
         else if d='3' then wed=n;
         else if d='4' then thu=n;
         else               fri=n;
         output;
      end;
   end;
```

```
run;

proc format;
   value namefmt 1='Marc' 2='Mike' 3='Bill' 4='Bob' .= ' ';
run;

data report;
   do until (last.slot);
      set mycas.assignments;
      by slot notsorted;
      if mon ne . then Monday = mon;
      if tue ne . then Tuesday = tue;
      if wed ne . then Wednesday = wed;
      if thu ne . then Thursday = thu;
      if fri ne . then Friday = fri;
   end;
   drop mon tue wed thu fri;
   format Monday Tuesday Wednesday Thursday Friday namefmt.;
run;

proc print data=report;
   id slot;
run;
```

Output 6.4.1 summarizes the schedule. Notice that the constraint that requires a person to be assigned to each possible time slot on each day is satisfied.

Output 6.4.1 A Scheduling Problem

Reported Solution

slot	Monday	Tuesday	Wednesday	Thursday	Friday
1	Marc	Marc	Marc	Marc	Marc
2	Mike	Marc	Marc	Marc	Marc
3	Mike	Mike	Mike	Bill	Bill
4	Bob	Mike	Mike	Mike	Mike
5	Marc	Marc	Marc	Marc	Marc
6	Marc	Mike	Mike	Mike	Mike
7	Mike	Mike	Mike	Mike	Mike
8	Marc	Bob	Bob	Bob	Bob

Recall that PROC OPTMILP puts a character string in the macro variable _OROPTMILP_ that describes the characteristics of the solution on termination. This string can be parsed using macro functions, and the information obtained can be used in report writing. The variable can be written to the log with the following command:

```
%put &_OROPTMILP_;
```

This command produces the output shown in Output 6.4.2.

Output 6.4.2 _OROPTMILP_ Macro Variable

```
STATUS=OK ALGORITHM=BAC SOLUTION_STATUS=OPTIMAL OBJECTIVE=211000 RELATIVE_GAP=0
ABSOLUTE_GAP=0 PRIMAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0
INTEGER_INFEASIBILITY=0 BEST_BOUND=211000 NODES=1 SOLUTIONS_FOUND=1
ITERATIONS=63 PRESOLVE_TIME=0.00 SOLUTION_TIME=0.01
```

From this output you learn, for example, that at termination the solution is integer-optimal and has an objective value of 211,000.

References

Achterberg, T., Koch, T., and Martin, A. (2003). "MIPLIB 2003." http://miplib2010.zib.de/miplib2003/index.php.

Achterberg, T., Koch, T., and Martin, A. (2005). "Branching Rules Revisited." *Operations Research Letters* 33:42–54.

Andersen, E. D., and Andersen, K. D. (1995). "Presolving in Linear Programming." *Mathematical Programming* 71:221–245.

Atamturk, A. (2004). "Sequence Independent Lifting for Mixed-Integer Programming." *Operations Research* 52:487–490.

Bixby, R. E., Ceria, S., McZeal, C. M., and Savelsbergh, M. W. P. (1998). "An Updated Mixed Integer Programming Library: MIPLIB 3.0." *Optima* 58:12–15.

Dantzig, G. B., Fulkerson, R., and Johnson, S. M. (1954). "Solution of a Large-Scale Traveling Salesman Problem." *Operations Research* 2:393–410.

Gondzio, J. (1997). "Presolve Analysis of Linear Programs Prior to Applying an Interior Point Method." *INFORMS Journal on Computing* 9:73–91.

Land, A. H., and Doig, A. G. (1960). "An Automatic Method for Solving Discrete Programming Problems." *Econometrica* 28:497–520.

Linderoth, J. T., and Savelsbergh, M. W. P. (1998). "A Computational Study of Search Strategies for Mixed Integer Programming." *INFORMS Journal on Computing* 11:173–187.

Marchand, H., Martin, A., Weismantel, R., and Wolsey, L. (1999). "Cutting Planes in Integer and Mixed Integer Programming." DP 9953, CORE, Université Catholique de Louvain.

Ostrowski, J. (2008). "Symmetry in Integer Programming." Ph.D. diss., Lehigh University.

Savelsbergh, M. W. P. (1994). "Preprocessing and Probing Techniques for Mixed Integer Programming Problems." *ORSA Journal on Computing* 6:445–454.

Chapter 7
The OPTQP Procedure

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Overview: OPTQP Procedure

The OPTQP procedure solves quadratic programs—problems with quadratic objective function and a collection of linear constraints, including lower or upper bounds (or both) on the decision variables.

Mathematically, a quadratic programming (QP) problem can be stated as follows:

$$\begin{aligned} \min \quad & \tfrac{1}{2}\,\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} \quad & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{aligned}$$

where

$\mathbf{Q}$	$\in$	$\mathbb{R}^{n\times n}$	is the quadratic (also known as Hessian) matrix
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the constraints matrix
$\mathbf{x}$	$\in$	$\mathbb{R}^{n}$	is the vector of decision variables
$\mathbf{c}$	$\in$	$\mathbb{R}^{n}$	is the vector of linear objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^{m}$	is the vector of constraints' right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^{n}$	is the vector of lower bounds on the decision variables
$\mathbf{u}$	$\in$	$\mathbb{R}^{n}$	is the vector of upper bounds on the decision variables

The quadratic matrix $\mathbf{Q}$ is assumed to be symmetric; that is,

$$q_{ij} = q_{ji}, \quad \forall i, j = 1, \ldots, n$$

Indeed, it is easy to show that even if $\mathbf{Q} \neq \mathbf{Q}^{\mathrm{T}}$, the simple modification

$$\tilde{\mathbf{Q}} = \frac{1}{2}(\mathbf{Q} + \mathbf{Q}^{\mathrm{T}})$$

produces an equivalent formulation $\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \equiv \mathbf{x}^{\mathrm{T}}\tilde{\mathbf{Q}}\mathbf{x}$; hence symmetry is assumed. When you specify a quadratic matrix, it suffices to list only lower triangular coefficients.

In addition to being symmetric, $\mathbf{Q}$ is also required to be positive semidefinite,

$$\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \geq 0, \quad \forall \mathbf{x} \in \mathbb{R}^{n}$$

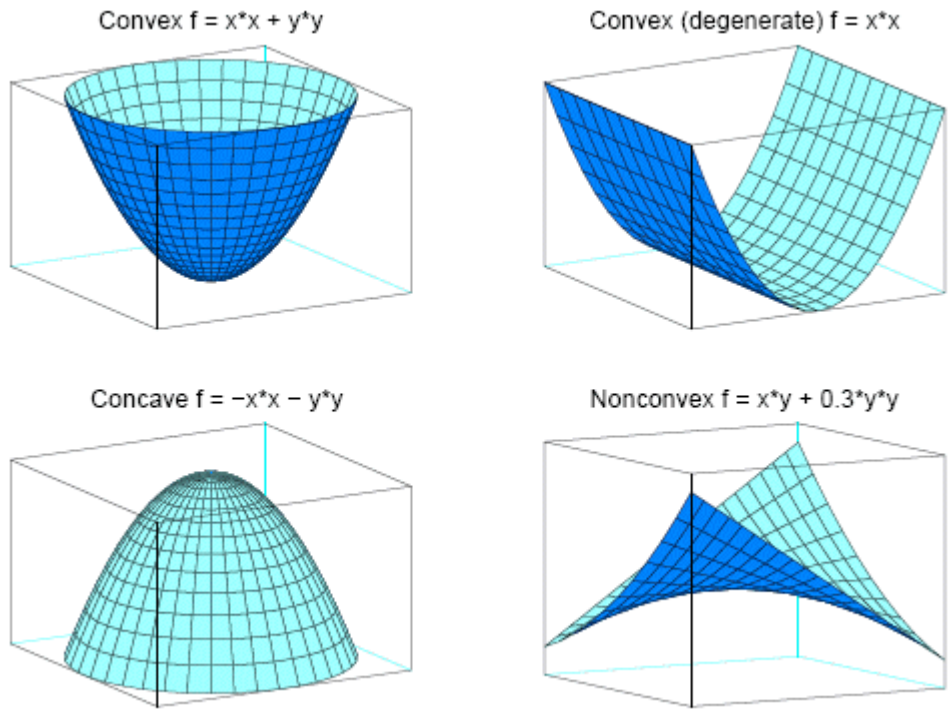
for minimization type of models; it is required to be negative semidefinite for the maximization type of models. Convexity can come as a result of a matrix-matrix multiplication

$$\mathbf{Q} = \mathbf{L}\mathbf{L}^{\mathrm{T}}$$

or as a consequence of physical laws, and so on. See Figure 7.1 for examples of convex, concave, and nonconvex objective functions.

The order of constraints is insignificant. Some or all components of $\mathbf{l}$ or $\mathbf{u}$ (lower and upper bounds, respectively) can be omitted.

Figure 7.1 Examples of Convex, Concave, and Nonconvex Objective Functions



Getting Started: OPTQP Procedure

Consider a small illustrative example. Suppose you want to minimize a two-variable quadratic function $f(x_1, x_2)$ on the nonnegative quadrant, subject to two constraints:

$$\begin{array}{rrcrcrcrcr} \min & 2x_1 & + & 3x_2 & + & x_1^2 & + & 10x_2^2 & + & 2.5x_1x_2 \\ \text{subject to} & x_1 & - & x_2 & \leq & 1 & & & & \\ & x_1 & + & 2x_2 & \geq & 100 & & & & \\ & x_1 & & & \geq & 0 & & & & \\ & & & x_2 & \geq & 0 & & & & \end{array}$$

The linear objective function coefficients, vector of right-hand sides, and lower and upper bounds are identified immediately as

$$\mathbf{c} = \begin{bmatrix} 2 \\ 3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 1 \\ 100 \end{bmatrix}, \quad \mathbf{l} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} +\infty \\ +\infty \end{bmatrix}$$

Carefully construct the quadratic matrix $\mathbf{Q}$. Observe that you can use symmetry to separate the main-diagonal and off-diagonal elements:

$$\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \equiv \frac{1}{2}\sum_{i,j=1}^{n} x_i\, q_{ij}\, x_j = \frac{1}{2}\sum_{i=1}^{n} q_{ii}\, x_i^2 + \sum_{i>j} x_i\, q_{ij}\, x_j$$

The first expression

$$\frac{1}{2}\sum_{i=1}^{n} q_{ii}\, x_i^2$$

sums the main-diagonal elements. Thus, in this case you have

$$q_{11} = 2, \quad q_{22} = 20$$

Notice that the main-diagonal values are doubled in order to accommodate the 1/2 factor. Now the second term

$$\sum_{i>j} x_i\, q_{ij}\, x_j$$

sums the off-diagonal elements in the strict lower triangular part of the matrix. The only off-diagonal ($x_i\, x_j,\ i \neq j$) term in the objective function is $2.5\, x_1\, x_2$, so you have

$$q_{21} = 2.5$$

Notice that you do not need to specify the upper triangular part of the quadratic matrix.

Finally, the matrix of constraints is as follows:

$$\mathbf{A} = \begin{bmatrix} 1 & -1 \\ 1 & 2 \end{bmatrix}$$

The input data table with a quadratic programming system (QPS) format for the preceding problem can be expressed in the following manner:

```
data gsdata;
   input field1 $ field2 $ field3 $ field4 field5 $ field6 @;
   datalines;
NAME      .       EXAMPLE     .            .          .
ROWS      .       .           .            .          .
N         OBJ     .           .            .          .
L         R1      .           .            .          .
G         R2      .           .            .          .
COLUMNS   .       .           .            .          .
.         X1      R1          1.0          R2         1.0
.         X1      OBJ         2.0          .          .
.         X2      R1         -1.0          R2         2.0
.         X2      OBJ         3.0          .          .
RHS       .       .           .            .          .
.         RHS     R1          1.0          .          .
.         RHS     R2          100          .          .
RANGES    .       .           .            .          .
BOUNDS    .       .           .            .          .
QUADOBJ   .       .           .            .          .
.         X1      X1          2.0          .          .
.         X1      X2          2.5          .          .
.         X2      X2          20           .          .
ENDATA    .       .           .            .          .
;
```

For more information about the QPS-format data table, see Chapter 8, "The MPS-Format Data Table."

Alternatively, if you have a QPS-format flat file named *gs.qps*, then the following call to the SAS macro %MPS2SASD translates that file into a SAS data set named gsdata:

```
%mps2sasd(mpsfile =gs.qps, outdata = gsdata);
```

NOTE: The SAS macro %MPS2SASD is provided in SAS optimization software. For more information, see the section "Converting an MPS/QPS-Format File: %MPS2SASD" on page 295.

To make the created data set available in the CAS server, you need to upload it as shown in the following DATA step. At the same time, you also need to add an _id_ column to ensure that the MPS reader can read the file in the correct order even if it is distributed across several machines and hence loses its original ordering. For more information about the MPS format, see Chapter 8, "The MPS-Format Data Table."

```
data mycas.gsdata;
   set gsdata;
   _id_ = _n_;
run;
```

Alternatively, you can create the MPS data table directly in CAS and include the _id_ column in the datalines input.

You can use the following call to PROC OPTQP:

```
proc optqp data = mycas.gsdata
   primalout = mycas.gspout
   dualout   = mycas.gsdout;
run;
```

The procedure output is displayed in Figure 7.2.

Figure 7.2 Procedure Output

The OPTQP Procedure

Problem Summary	
Problem Name	EXAMPLE
Objective Sense	Minimization
Objective Function	OBJ
RHS	RHS
Number of Variables	2
Bounded Above	0
Bounded Below	2
Bounded Above and Below	0
Free	0
Fixed	0
Number of Constraints	2
LE (<=)	1
EQ (=)	0
GE (>=)	1
Range	0
Constraint Coefficients	4
Hessian Diagonal Elements	2
Hessian Elements Below Diagonal	1

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	OBJ
Solution Status	Optimal
Objective Value	15018.000046
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	7.8497853E-9
Complementarity	0
Iterations	4
Presolve Time	0.00
Solution Time	0.00

Output CAS Tables

CAS Library	Name	Number of Rows	Number of Columns
CASUSERHDFS(tiarno)	**GSPOUT**	2	9
CASUSERHDFS(tiarno)	**GSDOUT**	2	10

The optimal primal solution is stored in the data table gspout and is displayed in Figure 7.3.

```
proc print data = mycas.gspout label;
run;
```

Figure 7.3 Optimal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Linear Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status
1	OBJ	RHS	X1	N	2	0	1.7977E308	34.0000	O
2	OBJ	RHS	X2	N	3	0	1.7977E308	33.0000	O

The SAS log shown in Figure 7.4 provides information about the problem, convergence information after each iteration, and the optimal objective value.

Figure 7.4 Iteration Log

```
NOTE: The problem EXAMPLE has 2 variables (0 free, 0 fixed).
NOTE: The problem has 2 constraints (1 LE, 0 EQ, 1 GE, 0 range).
NOTE: The problem has 4 constraint coefficients.
NOTE: The objective function has 2 Hessian diagonal elements and 1 Hessian
      elements above the diagonal.
NOTE: The QP presolver value AUTOMATIC is applied.
NOTE: The QP presolver removed 0 variables and 0 constraints.
NOTE: The QP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 2 variables, 2 constraints, and 4 constraint
      coefficients.
NOTE: The QP solver is called.
NOTE: The Interior Point algorithm is used.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Interior Point algorithm is using up to 32 threads.
                                        Primal       Bound        Dual
      Iter  Complement Duality Gap      Infeas      Infeas      Infeas   Time
         0  4.4604E+03  2.6380E-01  1.7962E-02  1.8143E+00  2.7770E-14      0
         1  1.2367E+02  7.8255E-03  1.7962E-04  1.8143E-02  1.9285E-14      0
         2  1.2365E+00  7.8496E-05  1.7973E-06  1.8154E-04  4.6816E-14      0
         3  1.2364E-02  7.8498E-07  1.7973E-08  1.8154E-06  1.9865E-14      0
         4  0.0000E+00  7.8498E-09  1.7861E-09  1.8154E-08  3.4973E-07      0
NOTE: Optimal.
NOTE: Objective = 15018.000046.
NOTE: The Interior Point solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.066678
      seconds.
NOTE: The data set MYCAS.GSPOUT has 2 observations and 9 variables.
NOTE: The data set MYCAS.GSDOUT has 2 observations and 10 variables.
```

See the section "Interior Point Algorithm: Overview" on page 264 and the section "Iteration Log for the OPTQP Procedure" on page 266 for more details about convergence information given by the iteration log.

Syntax: OPTQP Procedure

The following statements are available in the OPTQP procedure:

PROC OPTQP < *options* > **;**

Functional Summary

Table 7.1 outlines the options available for the OPTQP procedure classified by function.

Table 7.1 Options in the OPTQP Procedure

Description	Option
Data Table Options	
Specifies a QPS-format input data table	DATA=
Specifies a dual solution output data table	DUALOUT=
Specifies the constant part of the objective	OBJCONSTANT=
Specifies whether the QP model is a maximization or minimization problem	OBJSENSE=
Specifies the primal solution output data table	PRIMALOUT=
Solver Options	
Enables or disables IIS detection	IIS=
Control Options	
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Specifies the dual feasibility tolerance	DUALTOL=
Specifies how often to print the solution progress	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the maximum number of threads	NTHREADS=
Specifies the type of presolve	PRESOLVER=
Specifies the primal feasibility tolerance	PRIMALTOL=
Enables or disables printing summary	PRINTLEVEL=
Specifies units of CPU time or real time	TIMETYPE=

PROC OPTQP Statement

The following options can be specified in the PROC OPTQP statement.

DATA=*CAS-libref.data-table*

specifies the input data table. This data table can also be created from a QPS-format flat file by using the SAS macro %MPS2SASD. For more information, see Chapter 8, "The MPS-Format Data Table." If the DATA= option is not specified, PROC OPTQP uses the most recently created data table.

DUALITYGAP=δ

specifies the desired relative duality gap, $\delta \in$[1E–9, 1E–4]. This is the relative difference between the primal and dual objective function values and is the primary solution quality parameter. For more information, see the section "Interior Point Algorithm: Overview" on page 264. The default value is 1E–6.

DUALOUT=*CAS-libref.data-table*

DOUT=*CAS-libref.data-table*

specifies the output data table to contain the dual solution. For more information, see the section "Output Data Tables" on page 262.

DUALTOL=β

OPTTOL=β

specifies the maximum relative dual constraints violation, $\beta \in$[1E–9, 1E–4]. For more information, see the section "Interior Point Algorithm: Overview" on page 264. The default value is 1E–6.

IIS=FALSE | **TRUE**

specifies whether to attempt to identify a set of constraints and variables that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection.

If an IIS is found, information about infeasible constraints or variable bounds is written to the data tables that are specified in the DUALOUT= and PRIMALOUT= options. For more information, see the section "Irreducible Infeasible Set" on page 271. By default, IIS=FALSE.

LOGFREQ=*k*

PRINTFREQ=*k*

prints the solution progress to the iteration log after every k iterations, where k is an integer between 0 and the largest four-byte, signed integer, which is $2^{31} - 1$. The value $k = 0$ suppresses printing of the progress of the solution. By default, LOGFREQ=1.

LOGLEVEL=NONE | **BASIC** | **MODERATE** | **AGGRESSIVE**

PRINTLEVEL2=NONE | **BASIC** | **MODERATE** | **AGGRESSIVE**

controls the amount of information that the OPTQP procedure displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXITER=*k*

specifies the maximum number of predictor-corrector iterations performed by the interior point algorithm (see the section "Interior Point Algorithm: Overview" on page 264). The value *k* is an integer between 1 and the largest four-byte, signed integer, which is $2^{31} - 1$. If you do not specify this option, the procedure does not stop based on the number of iterations performed.

MAXTIME=*t*

specifies an upper limit of *t* seconds of time for reading in the data and performing the optimization process. The value of the TIMETYPE= option determines the type of units used. If you do not specify this option, the procedure does not stop based on the amount of time elapsed. The value of *t* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

NTHREADS=*k*

specifies the number of threads that PROC OPTQP can use, where *k* can be any integer between 1 and 256, inclusive. This option overrides the THREADS | NOTHREADS SAS system option. The default value of this option is the value of the CPUCOUNT= SAS system option.

Specifying *k* as a number greater than the actual number of available cores might result in reduced performance. Specifying a high value for *k* does not guarantee shorter solution time; the actual change in solution time depends on the computing hardware and the scalability of the underlying algorithms in PROC OPTQP. In some circumstances, PROC OPTQP might use fewer than *k* threads because the procedure's internal algorithms have determined that a smaller number is preferable.

OBJCONSTANT=*number*

OBJECTIVECONSTANT=*number*

specifies the constant part of the objective, where *number* can be any number. By default, OBJCONSTANT=0.

OBJSENSE=MIN | MAX

specifies whether the QP model is a minimization or maximization problem. You can specify the following values:

MIN treat the QP model as a minimization problem.

MAX treat the QP model as a maximization problem.

Alternatively, you can specify the objective sense in the input data table; for more information, see the section "ROWS Section" on page 287. This option supersedes any objective sense that is specified in the input data table. If the objective sense is not specified anywhere, then PROC OPTQP interprets and solves the quadratic program as a minimization problem.

PRESOLVER=AUTOMATIC | **NONE** | **BASIC** | **MODERATE** | **AGGRESSIVE**
PRESOL=AUTOMATIC | **NONE** | **BASIC** | **MODERATE** | **AGGRESSIVE**
specifies the presolve level. You can specify the following values:

AUTOMATIC applies the presolver by using default setting.

NONE disables the presolver.

BASIC applies the basic presolver.

MODERATE applies the moderate presolver.

AGGRESSIVE applies the aggressive presolver.

By default, PRESOLVER=AUTOMATIC.

PRIMALOUT=*CAS-libref.data-table*
POUT=*CAS-libref.data-table*
specifies the output data table to contain the primal solution. For more information, see the section "Output Data Tables" on page 262.

PRIMALTOL=α
FEASTOL=α
specifies the maximum relative bound and primal constraints violation, $\alpha \in$[1E–9, 1E–4]. For more information, see the section "Interior Point Algorithm: Overview" on page 264. The default value is 1E–6.

PRINTLEVEL=0 | **1** | **2**
specifies whether to print summary Output Delivery System (ODS) tables of the problem and solution. You can specify the following values:

0 does not produce or print any ODS tables.

1 produces and prints the following ODS tables: ProblemSummary, SolutionSummary, and optional OutputCasTables.

2 produces and prints the following ODS tables: ProblemSummary, SolutionSummary, ProblemStatistics, Timing, and optional OutputCasTables.

For more information about the ODS tables that PROC OPTQP creates, see the section "ODS Tables" on page 267. By default, PRINTLEVEL=1.

TIMETYPE=CPU | **REAL**
specifies whether CPU time or real time is used for the MAXTIME= option and the _OROPTQP_ macro variable in a PROC OPTQP call. You can specify the following values:

CPU specifies that units are in CPU time.

REAL specifies that units are in real time.

By default, TIMETYPE=REAL.

Details: OPTQP Procedure

Output Data Tables

This section describes the output data tables that are specified in the PRIMALOUT= and DUALOUT= options.

Definitions of Variables in the PRIMALOUT= Data Table

The PRIMALOUT= data table contains the primal solution to the quadratic programming (QP) model. The variables in the data table have the following names and meanings.

_OBJ_ID_
specifies the name of the objective function. Naming objective functions is particularly useful when there are multiple objective functions, in which case each objective function has a unique name. For more information, see the section "ROWS Section" on page 287.

NOTE: PROC OPTQP does not support simultaneous optimization of multiple objective functions in this release.

_RHS_ID_
specifies the name of the variable that contains the right-hand-side value of each constraint. For more information, see the section "RHS Section (Optional)" on page 289.

VAR
specifies the name of the decision variable.

TYPE
specifies the type of the decision variable. _TYPE_ can take one of the following values:

N nonnegative variable

D bounded variable (with both lower and upper bound)

F free variable

X fixed variable

O other (with either lower or upper bound)

OBJCOEF
specifies the coefficient of the decision variable in the linear component of the objective function.

LBOUND
specifies the lower bound on the decision variable.

UBOUND
specifies the upper bound on the decision variable.

VALUE
specifies the value of the decision variable.

STATUS
specifies the status of the decision variable. _STATUS_ can indicate one of the following two cases:

O The QP problem is optimal.

I The QP problem could be infeasible or unbounded, or PROC OPTQP was not able to solve the problem.

The following values can appear only if IIS=TRUE. For more information, see the section "Irreducible Infeasible Set" on page 271.

I_L The lower bound of the variable is needed for the IIS.

I_U The upper bound of the variable is needed for the IIS.

I_F Both bounds of the variable are needed for the IIS (the variable is fixed or has conflicting bounds).

Definitions of Variables in the DUALOUT= Data Table

The DUALOUT= data table contains the dual solution to the QP model. Information about the objective rows of the QP problems is not included. The variables in the data table have the following names and meanings.

_OBJ_ID_
specifies the name of the objective function. Naming objective functions is particularly useful when there are multiple objective functions, in which case each objective function has a unique name. For more information, see the section "ROWS Section" on page 287.

NOTE: PROC OPTQP does not support simultaneous optimization of multiple objective functions in this release.

_RHS_ID_
specifies the name of the variable that contains the right-hand-side value of each constraint. For more information, see the section "RHS Section (Optional)" on page 289.

ROW
specifies the name of the constraint. For more information, see the section "ROWS Section" on page 287.

TYPE
specifies the type of the constraint. _TYPE_ can take one of the following values:

L "less than or equals" constraint

E equality constraint

G "greater than or equals" constraint

R ranged constraint (both "less than or equals" and "greater than or equals")

For more information, see the sections "ROWS Section" on page 287 and "RANGES Section (Optional)" on page 290.

RHS
specifies the value of the right-hand side of the constraint. It takes a missing value for a ranged constraint.

_L_RHS_
specifies the lower bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

_U_RHS_
specifies the upper bound of a ranged constraint. It takes a missing value for a non-ranged constraint.

VALUE
specifies the value of the dual variable associated with the constraint.

STATUS
specifies the status of the constraint. _STATUS_ can indicate one of the following two cases:

O The QP problem is optimal.

I The QP problem could be infeasible or unbounded, or PROC OPTQP was not able to solve the problem.

The following values can appear only if option IIS=TRUE. For more information, see the section "Irreducible Infeasible Set" on page 271.

I_L The "GE" ($\geq$) condition of the constraint is needed for the IIS.

I_U The "LE" ($\leq$) condition of the constraint is needed for the IIS.

I_F Both conditions of the constraint are needed for the IIS (the constraint is an equality or a range constraint with conflicting bounds).

ACTIVITY
specifies the value of a constraint. In other words, the value of _ACTIVITY_ for the ith constraint is equal to $\mathbf{a}_i^{\mathrm{T}}\mathbf{x}$, where $\mathbf{a}_i$ refers to the ith row of the constraints matrix and $\mathbf{x}$ denotes the vector of current decision variable values.

Interior Point Algorithm: Overview

The interior point solver in PROC OPTQP implements an infeasible primal-dual predictor-corrector interior point algorithm. To illustrate the algorithm and the concepts of duality and dual infeasibility, consider the following QP formulation (the primal):

$$\begin{aligned} \min \quad & \tfrac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} \quad & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{aligned}$$

The corresponding dual is as follows:

$$\begin{array}{rrcrcrcl} \max & -\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} & + & \mathbf{b}^{\mathrm{T}}\mathbf{y} & & & & \\ \text{subject to} & -\mathbf{Q}\mathbf{x} & + & \mathbf{A}^{\mathrm{T}}\mathbf{y} & + & \mathbf{w} & = & \mathbf{c} \\ & & & & & \mathbf{y} & \geq & \mathbf{0} \\ & & & & & \mathbf{w} & \geq & \mathbf{0} \end{array}$$

where $\mathbf{y} \in \mathbb{R}^m$ refers to the vector of dual variables and $\mathbf{w} \in \mathbb{R}^n$ refers to the vector of slack variables in the dual problem.

The dual makes an important contribution to the certificate of optimality for the primal. The primal and dual constraints combined with complementarity conditions define the first-order optimality conditions, also known as KKT (Karush-Kuhn-Tucker) conditions, which can be stated as follows:

$$\begin{array}{rcll} \mathbf{A}\mathbf{x} - \mathbf{s} & = & \mathbf{b} & \text{(primal feasibility)} \\ -\mathbf{Q}\mathbf{x} + \mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{w} & = & \mathbf{c} & \text{(dual feasibility)} \\ \mathbf{W}\mathbf{X}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{S}\mathbf{Y}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{x},\ \mathbf{y},\ \mathbf{w},\ \mathbf{s} & \geq & \mathbf{0} & \end{array}$$

where $\mathbf{e} \equiv (1, \ldots, 1)^{\mathrm{T}}$ is of appropriate dimension and $\mathbf{s} \in \mathbb{R}^m$ is the vector of primal slack variables.

NOTE: Slack variables (the *s* vector) are automatically introduced by the solver when necessary; it is therefore recommended that you not introduce any slack variables explicitly. This enables the solver to handle slack variables much more efficiently.

The letters $\mathbf{X}$, $\mathbf{Y}$, $\mathbf{W}$, and $\mathbf{S}$ denote matrices with corresponding x, y, w, and s on the main diagonal and zero elsewhere, as in the following example:

$$\mathbf{X} \equiv \begin{bmatrix} x_1 & 0 & \cdots & 0 \\ 0 & x_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x_n \end{bmatrix}$$

If $(\mathbf{x}^*, \mathbf{y}^*, \mathbf{w}^*, \mathbf{s}^*)$ is a solution of the previously defined system of equations that represent the KKT conditions, then $\mathbf{x}^*$ is also an optimal solution to the original QP model.

At each iteration the interior point algorithm solves a large, sparse system of linear equations as follows:

$$\begin{bmatrix} \mathbf{Y}^{-1}\mathbf{S} & \mathbf{A} \\ \mathbf{A}^{\mathrm{T}} & -\mathbf{Q} - \mathbf{X}^{-1}\mathbf{W} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{y} \\ \Delta\mathbf{x} \end{bmatrix} = \begin{bmatrix} \Xi \\ \Theta \end{bmatrix}$$

where $\Delta\mathbf{x}$ and $\Delta\mathbf{y}$ denote the vector of *search directions* in the primal and dual spaces, respectively, and Θ and Ξ constitute the vector of the right-hand sides.

The preceding system is known as the reduced KKT system. PROC OPTQP uses a preconditioned quasi-minimum residual algorithm to solve this system of equations efficiently.

An important feature of the interior point solver is that it takes full advantage of the sparsity in the constraint and quadratic matrices, thereby enabling it to efficiently solve large-scale quadratic programs.

The interior point algorithm works simultaneously in the primal and dual spaces. It attains optimality when both primal and dual feasibility are achieved and when complementarity conditions hold. Therefore, it is of interest to observe the following four measures where $\|v\|_2$ is the Euclidean norm of the vector v:

- relative primal infeasibility measure α:

$$\alpha = \frac{\|\mathbf{Ax} - \mathbf{b} - \mathbf{s}\|_2}{\|\mathbf{b}\|_2 + 1}$$

- relative dual infeasibility measure β:

$$\beta = \frac{\|\mathbf{Qx} + \mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y} - \mathbf{w}\|_2}{\|\mathbf{c}\|_2 + 1}$$

- relative duality gap δ:

$$\delta = \frac{|\mathbf{x}^{\mathrm{T}}\mathbf{Qx} + \mathbf{c}^{\mathrm{T}}\mathbf{x} - \mathbf{b}^{\mathrm{T}}\mathbf{y}|}{|\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Qx} + \mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

- absolute complementarity γ:

$$\gamma = \sum_{i=1}^{n} x_i w_i + \sum_{i=1}^{m} y_i s_i$$

These measures are displayed in the iteration log.

Iteration Log for the OPTQP Procedure

The interior point solver in PROC OPTQP implements an infeasible primal-dual predictor-corrector interior point algorithm. The following information is displayed in the iteration log:

Iter	indicates the iteration number.
Complement	indicates the (absolute) complementarity.
Duality Gap	indicates the (relative) duality gap.
Primal Infeas	indicates the (relative) primal infeasibility measure.
Bound Infeas	indicates the (relative) bound infeasibility measure.
Dual Infeas	indicates the (relative) dual infeasibility measure.
Time	indicates the time elapsed (in seconds).

If the sequence of solutions converges to an optimal solution of the problem, you should see all columns in the iteration log converge to zero or very close to zero. Nonconvergence can be the result of insufficient iterations being performed to reach optimality. In this case, you might need to increase the value that you specify in the MAXITER= or MAXTIME= option. If the complementarity or the duality gap does not converge, the problem might be infeasible or unbounded. If the infeasibility columns do not converge, the problem might be infeasible.

ODS Tables

PROC OPTQP creates two Output Delivery System (ODS) tables by default: the ProblemSummary table is a summary of the input QP problem, and the SolutionSummary table is a brief summary of the solution status. If either or both of the PRIMALOUT= and DUALOUT= options are specified, then PROC OPTQP creates a third ODS table, OutputCasTables, which is the summary of output CAS table information. You can use ODS table names to select tables and create output data sets. For more information about ODS, see the *SAS Output Delivery System: User's Guide*.

If you specify PRINTLEVEL=2, then two additional ODS tables are produced: The Timing table, which is a summary of the time spent on different PROC OPTQP tasks, and the ProblemStatistics table, which contains information about the problem data. For more information about the ProblemStatistics table, see the section "Problem Statistics" on page 270.

Table 7.2 lists all the ODS tables that can be produced by the OPTQP procedure, along with the statement and option specifications required to produce each table.

Table 7.2 ODS Tables Produced by PROC OPTQP

ODS Table Name	Description	Statement	Option
ProblemSummary	Summary of the input QP problem	PROC OPTQP	PRINTLEVEL=1 (default)
SolutionSummary	Summary of the solution status	PROC OPTQP	PRINTLEVEL=1 (default)
OutputCasTables	A special ODS table that has information about all the CAS tables that are created during a CAS action execution	PROC OPTQP	PRINTLEVEL=1 (default); PRIMALOUT= or DUALOUT=
ProblemStatistics	Description of input problem data	PROC OPTQP	PRINTLEVEL=2
Timing	Summary of time consumption	PROC OPTQP	PRINTLEVEL=2

A typical output of PROC OPTQP is shown in Output 7.5.

Figure 7.5 Typical OPTQP Output

The OPTQP Procedure

Problem Summary	
Problem Name	BANDM
Objective Sense	Minimization
Objective Function	1
RHS	ZZZZ0001
Number of Variables	472
Bounded Above	0
Bounded Below	472
Bounded Above and Below	0
Free	0
Fixed	0
Number of Constraints	305
LE (<=)	0
EQ (=)	305
GE (>=)	0
Range	0
Constraint Coefficients	2494
Hessian Diagonal Elements	25
Hessian Elements Below Diagonal	16

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	1
Solution Status	Optimal
Objective Value	16352.342037
Primal Infeasibility	5.0289411E-8
Dual Infeasibility	1.935807E-12
Bound Infeasibility	0
Duality Gap	3.711993E-11
Complementarity	0
Iterations	23
Presolve Time	0.00
Solution Time	0.03

Output CAS Tables

CAS Library	Name	Number of Rows	Number of Columns
CASUSERHDFS(tiarno)	**P**	472	9
CASUSERHDFS(tiarno)	**D**	305	10

You can create output data sets from these tables by using the ODS OUTPUT statement. This can be useful, for example, when you want to create a report to summarize multiple PROC OPTQP runs. The output data sets that correspond to the preceding output are shown in Output 7.6, where you can also find (in the row following the heading of each data set in the display) the variable names that are used in the table definition (template) of each table.

Figure 7.6 ODS Output Data Sets

Problem Summary

Obs	Name1	Label1	cValue1	nValue1
1	problemName	Problem Name	BANDM	.
2	objectiveSense	Objective Sense	Minimization	.
3	objectiveName	Objective Function	1	.
4	rhs	RHS	ZZZZ0001	.
5				.
6	numVars	Number of Variables	472	472.000000
7	numBoundedAbove	Bounded Above	0	0
8	numBoundedBelow	Bounded Below	472	472.000000
9	numBounded	Bounded Above and Below	0	0
10	numFree	Free	0	0
11	numFixed	Fixed	0	0
12				.
13	numRows	Number of Constraints	305	305.000000
14	numLE	LE (<=)	0	0
15	numEQ	EQ (=)	305	305.000000
16	numGE	GE (>=)	0	0
17	numRange	Range	0	0
18				.
19	numElems	Constraint Coefficients	2494	2494.000000
20				.
21	numQDiagonal	Hessian Diagonal Elements	25	25.000000
22	numQAbove	Hessian Elements Below Diagonal	16	16.000000

Figure 7.6 *continued*

Solution Summary

Obs	Name1	Label1	cValue1	nValue1
1	solver	Solver	QP	.
2	algorithm	Algorithm	Interior Point	.
3	objectiveName	Objective Function	1	.
4	solStatus	Solution Status	Optimal	.
5	objective	Objective Value	16352.342037	16352
6				.
7	primalInfeasibility	Primal Infeasibility	5.0289411E-8	5.0289411E-8
8	dualInfeasibility	Dual Infeasibility	1.935807E-12	1.935807E-12
9	boundInfeasibility	Bound Infeasibility	0	0
10	dualityGap	Duality Gap	3.711993E-11	3.711993E-11
11	complementarity	Complementarity	0	0
12				.
13	iterations	Iterations	23	23.000000
14	presolveTime	Presolve Time	0.00	0
15	solutionTime	Solution Time	0.03	0.031318

Output CAS Tables

Obs	casLib	Name	Rows	Columns
1	CASUSERHDFS(tiarno)	P	472	9
2	CASUSERHDFS(tiarno)	D	305	10

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTQP procedure causes the ODS table ProblemStatistics to be generated. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Output 7.7 demonstrates the contents of the ODS table ProblemStatistics.

Figure 7.7 ODS Table ProblemStatistics

The OPTQP Procedure

Problem Statistics	
Number of Constraint Matrix Nonzeros	4
Maximum Constraint Matrix Coefficient	2
Minimum Constraint Matrix Coefficient	1
Average Constraint Matrix Coefficient	1.25
Number of Linear Objective Nonzeros	2
Maximum Linear Objective Coefficient	3
Minimum Linear Objective Coefficient	2
Average Linear Objective Coefficient	2.5
Number of Nonzeros Below Diagonal in the Hessian	1
Number of Diagonal Nonzeros in the Hessian	2
Maximum Hessian Coefficient	20
Minimum Hessian Coefficient	2
Average Hessian Coefficient	6.75
Number of RHS Nonzeros	2
Maximum RHS	100
Minimum RHS	1
Average RHS	50.5
Maximum Number of Nonzeros per Column	2
Minimum Number of Nonzeros per Column	2
Average Number of Nonzeros per Column	2.00
Maximum Number of Nonzeros per Row	2
Minimum Number of Nonzeros per Row	2
Average Number of Nonzeros per Row	2.00

Irreducible Infeasible Set

For a quadratic programming problem, an irreducible infeasible set (IIS) is an infeasible subset of constraints and variable bounds that becomes feasible if any single constraint or variable bound is removed. It is possible to have more than one IIS in an infeasible QP. Identifying an IIS can help isolate the structural infeasibility in a QP. The IIS=TRUE option directs the OPTQP procedure to search for an IIS in a specified QP.

Whether a quadratic programming problem is feasible or infeasible is determined by its constraints and variable bounds, which have nothing to do with its objective function. When you specify the IIS=TRUE option, the OPTQP procedure treats this problem as a linear programming problem by ignoring its objective function. Then finding IIS is the same as what PROC OPTLP does with the IIS=TRUE option. For more information about the irreducible infeasible set, see the section "Irreducible Infeasible Set" on page 150 in Chapter 5, "The OPTLP Procedure."

Macro Variable _OROPTQP_

The OPTQP procedure defines a macro variable named _OROPTQP_. This variable contains a character string that indicates the status of the OPTQP procedure upon termination. The various terms of the variable are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The procedure terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data were inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produced the solution data in the macro variable. This term appears only when STATUS=OK. It can take the following value:

IP	The interior point algorithm produced the solution data.
IIS	The IIS functionality produced the solution data.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The solution is optimal, but some infeasibilities (primal, dual or bound) exceed tolerances because of scaling or preprocessing.
FEASIBLE	The problem is feasible (IIS).
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
NONCONVEX	The quadratic matrix is nonconvex (minimization).
NONCONCAVE	The quadratic matrix is nonconcave (maximization).
ITERATION_LIMIT_REACHED	The maximum allowable number of iterations was reached.
TIME_LIMIT_REACHED	The maximum time limit was reached.
ABORTED	The solver was interrupted externally.
FAILED	The solver failed to converge, possibly because of numerical issues.

OBJECTIVE
indicates the objective value obtained by the solver at termination.

PRIMAL_INFEASIBILITY
indicates the (relative) infeasibility of the primal constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 264.

DUAL_INFEASIBILITY
indicates the (relative) infeasibility of the dual constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 264.

BOUND_INFEASIBILITY
indicates the (relative) violation by the solution of the lower or upper bounds (or both). For more information, see the section "Interior Point Algorithm: Overview" on page 264.

DUALITY_GAP
indicates the (relative) duality gap. For more information, see the section "Interior Point Algorithm: Overview" on page 264.

COMPLEMENTARITY
indicates the (absolute) complementarity at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 264.

ITERATIONS
indicates the number of iterations taken to solve the problem.

PRESOLVE_TIME
indicates the time (in seconds) taken for preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time that is reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

Examples: OPTQP Procedure

This section contains examples that illustrate the use of the OPTQP procedure. Example 7.1 illustrates how to model a linear least squares problem and solve it by using PROC OPTQP. Example 7.2 and Example 7.3 explain in detail how to model the portfolio optimization and selection problems.

Example 7.1: Linear Least Squares Problem

The linear least squares problem arises in the context of determining a solution to an overdetermined set of linear equations. In practice, these equations could arise in data fitting and estimation problems. An overdetermined system of linear equations can be defined as

$$\mathbf{Ax} = \mathbf{b}$$

where $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{x} \in \mathbb{R}^n$, $\mathbf{b} \in \mathbb{R}^m$, and $m > n$. Since this system usually does not have a solution, you need to be satisfied with some sort of approximate solution. The most widely used approximation is the least squares solution, which minimizes $\|\mathbf{Ax} - \mathbf{b}\|_2^2$.

This problem is called a least squares problem for the following reason. Let $\mathbf{A}$, $\mathbf{x}$, and $\mathbf{b}$ be defined as previously. Let $k_i(x)$ be the kth component of the vector $\mathbf{Ax} - \mathbf{b}$:

$$k_i(x) = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n - b_i, \; i = 1, 2, \ldots, m$$

By definition of the Euclidean norm, the objective function can be expressed as follows:

$$\|\mathbf{Ax} - \mathbf{b}\|_2^2 = \sum_{i=1}^{m} k_i(x)^2$$

Therefore, the function you minimize is the sum of squares of m terms $k_i(x)$; hence the term least squares. The following example is an illustration of the *linear* least squares problem; that is, each of the terms k_i is a linear function of x.function $\sum_{ij} a_{ij}x_j$ plus a constant, $-b_i$.

Consider the following least squares problem defined by

$$\mathbf{A} = \begin{bmatrix} 4 & 0 \\ -1 & 1 \\ 3 & 2 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

This translates to the following set of linear equations:

$$4x_1 = 1, \quad -x_1 + x_2 = 0, \quad 3x_1 + 2x_2 = 1$$

The corresponding least squares problem is

$$\text{minimize} \quad (4x_1 - 1)^2 + (-x_1 + x_2)^2 + (3x_1 + 2x_2 - 1)^2$$

The preceding objective function can be expanded to

$$\text{minimize} \quad 26x_1^2 + 5x_2^2 + 10x_1x_2 - 14x_1 - 4x_2 + 2$$

In addition, you impose the following constraint so that the equation $3x_1 + 2x_2 = 1$ is satisfied within a tolerance of 0.1:

$$0.9 \le 3x_1 + 2x_2 \le 1.1$$

You can create the QPS-format input data set by using the following SAS statements:

```
data mycas.lsdata;
   input _id_ field1 $ field2 $ field3 $ field4 field5 $ field6 @;
   datalines;
1  NAME     .      LEASTSQ     .          .        .
2  ROWS     .      .           .          .        .
3  N        OBJ    .           .          .        .
4  G        EQ3    .           .          .        .
5  COLUMNS  .      .           .          .        .
6  .        X1     OBJ        -14         EQ3      3
7  .        X2     OBJ        -4          EQ3      2
8  RHS      .      .           .          .        .
9  .        RHS    OBJ        -2          EQ3      0.9
10 RANGES   .      .           .          .        .
11 .        RNG    EQ3         0.2        .        .
12 BOUNDS   .      .           .          .        .
13 FR       BND1   X1          .          .        .
14 FR       BND1   X2          .          .        .
15 QUADOBJ  .      .           .          .        .
16 .        X1     X1          52         .        .
17 .        X1     X2          10         .        .
18 .        X2     X2          10         .        .
19 ENDATA   .      .           .          .        .
;
```

The decision variables x_1 and x_2 are free, so they have bound type FR in the BOUNDS section of the QPS-format data set.

You can use the following SAS statements to solve the least squares problem:

```
proc optqp data = mycas.lsdata
   printlevel = 0
   primalout = mycas.lspout;
run;
```

The optimal solution is displayed in Output 7.1.1.

Output 7.1.1 Solution to the Least Squares Problem

Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Linear Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status
1	OBJ	RHS	X1	F	-14	-1.7977E308	1.7977E308	0.23810	O
2	OBJ	RHS	X2	F	-4	-1.7977E308	1.7977E308	0.16190	O

The iteration log is shown in Output 7.1.2.

Output 7.1.2 Iteration Log

```
NOTE: The problem LEASTSQ has 2 variables (2 free, 0 fixed).
NOTE: The problem has 1 constraints (0 LE, 0 EQ, 0 GE, 1 range).
NOTE: The problem has 2 constraint coefficients.
NOTE: The objective function has 2 Hessian diagonal elements and 1 Hessian
      elements above the diagonal.
NOTE: The QP presolver value AUTOMATIC is applied.
NOTE: The QP presolver removed 0 variables and 0 constraints.
NOTE: The QP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 2 variables, 1 constraints, and 2 constraint
      coefficients.
NOTE: The QP solver is called.
NOTE: The Interior Point algorithm is used.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Interior Point algorithm is using up to 32 threads.
                                      Primal       Bound        Dual
      Iter  Complement Duality Gap      Infeas      Infeas      Infeas   Time
         0  4.4635E-02  7.3436E-03  1.2741E-12  1.1785E-01  4.8074E-14      0
         1  6.0753E-03  2.0093E-03  1.1909E-11  1.1785E-03  6.0126E-16      0
         2  2.0139E-04  6.7323E-05  1.1107E-10  2.4835E-05  3.9761E-18      0
         3  2.0978E-06  7.0148E-07  1.3759E-11  2.4976E-07  1.8591E-17      0
         4  1.8047E-06  5.5952E-07  1.3759E-11  2.1193E-07  1.3642E-07      0
         5  0.0000E+00  9.4234E-08  2.7308E-13  2.1193E-09  6.2902E-08      0
NOTE: Optimal.
NOTE: Objective = 0.0095238095.
NOTE: The Interior Point solve time is 0.00 seconds.
NOTE: The Cloud Analytic Services server processed the request in 0.058246
      seconds.
NOTE: The data set MYCAS.LSPOUT has 2 observations and 9 variables.
```

Example 7.2: Portfolio Optimization

Consider a portfolio optimization example. The two competing goals of investment are (1) long-term growth of capital and (2) low risk. A good portfolio grows steadily without wild fluctuations in value. The Markowitz model is an optimization model for balancing the return and risk of a portfolio. The decision variables are the amounts invested in each asset. The objective is to minimize the variance of the portfolio's total return, subject to the constraints that (1) the expected growth of the portfolio reaches at least some target level and (2) you do not invest more capital than you have.

Let $x_1, \ldots, x_n$ be the amount invested in each asset, $\mathcal{B}$ be the amount of capital you have, $\mathbf{R}$ be the random vector of asset returns over some period, and $\mathbf{r}$ be the expected value of $\mathbf{R}$. Let G be the minimum growth you hope to obtain, and $\mathcal{C}$ be the covariance matrix of $\mathbf{R}$. The objective function is $\mathrm{Var}\left(\sum_{i=1}^{n} x_i R_i\right)$, which

can be equivalently denoted as $\mathbf{x}^{\mathrm{T}}\mathcal{C}\mathbf{x}$.

Assume, for example, $n = 4$. Let $\mathcal{B} = 10{,}000$, $G = 1000$, $\mathbf{r} = [0.05, -0.2, 0.15, 0.30]$, and

$$\mathcal{C} = \begin{bmatrix} 0.08 & -0.05 & -0.05 & -0.05 \\ -0.05 & 0.16 & -0.02 & -0.02 \\ -0.05 & -0.02 & 0.35 & 0.06 \\ -0.05 & -0.02 & 0.06 & 0.35 \end{bmatrix}$$

The QP formulation can be written as follows:

$$\begin{aligned} \min \quad & 0.08x_1^2 - 0.1x_1x_2 - 0.1x_1x_3 - 0.1x_1x_4 + 0.16x_2^2 \\ & -0.04x_2x_3 - 0.04x_2x_4 + 0.35x_3^2 + 0.12x_3x_4 + 0.35x_4^2 \end{aligned}$$

$$\begin{array}{lrcl} \text{subject to} & & & \\ \text{(budget)} & x_1 + x_2 + x_3 + x_4 & \leq & 10000 \\ \text{(growth)} & 0.05x_1 - 0.2x_2 + 0.15x_3 + 0.30x_4 & \geq & 1000 \\ & x_1,\ x_2,\ x_3,\ x_4 & \geq & 0 \end{array}$$

The corresponding QPS-format input data set is as follows:

```
data portdata;
   input field1 $ field2 $ field3 $ field4 field5 $ field6 @;
datalines;
NAME   .         PORT     .          .         .
ROWS   .         .        .          .         .
N      OBJ.FUNC  .        .          .         .
L      BUDGET    .        .          .         .
G      GROWTH    .        .          .         .
COLUMNS .        .        .          .         .
.      X1        BUDGET   1.0        GROWTH    0.05
.      X2        BUDGET   1.0        GROWTH    -.20
.      X3        BUDGET   1.0        GROWTH    0.15
.      X4        BUDGET   1.0        GROWTH    0.30
RHS    .         .        .          .         .
.      RHS       BUDGET   10000      .         .
.      RHS       GROWTH   1000       .         .
RANGES .         .        .          .         .
BOUNDS .         .        .          .         .
QUADOBJ .         .       .           .        .
.      X1        X1       0.16       .         .
.      X1        X2       -.10       .         .
.      X1        X3       -.10       .         .
.      X1        X4       -.10       .         .
.      X2        X2       0.32       .         .
.      X2        X3       -.04       .         .
.      X2        X4       -.04       .         .
.      X3        X3       0.70       .         .
.      X3        X4       0.12       .         .
.      X4        X4       0.70       .         .
ENDATA .         .        .          .         .
;
```

Use the following SAS statements to solve the problem:

```
data mycas.portdata;
   set portdata;
   _id_ = _n_;
run;

proc optqp data = mycas.portdata
  printlevel = 0
  primalout = mycas.portpout
  dualout   = mycas.portdout;
run;
```

The optimal solution is shown in Output 7.2.1.

Output 7.2.1 Portfolio Optimization

The OPTQP Procedure
Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Linear Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status
1	OBJ.FUNC	RHS	X1	N	0	0	1.7977E308	3452.86	O
2	OBJ.FUNC	RHS	X2	N	0	0	1.7977E308	0.00	O
3	OBJ.FUNC	RHS	X3	N	0	0	1.7977E308	1068.81	O
4	OBJ.FUNC	RHS	X4	N	0	0	1.7977E308	2223.45	O

Thus, the minimum variance portfolio that earns an expected return of at least 10% is $x_1 = 3452.86$, $x_2 = 0$, $x_3 = 1068.81$, $x_4 = 2223.45$. Asset 2 gets nothing, because its expected return is -20% and its covariance with the other assets is not sufficiently negative for it to bring any diversification benefits. What if you drop the nonnegativity assumption? You need to update the BOUNDS section in the existing QPS-format data set to indicate that the decision variables are free.

```
...
RANGES .        .        .        .        .
BOUNDS .        .        .        .        .
FR     BND1     X1       .        .        .
FR     BND1     X2       .        .        .
FR     BND1     X3       .        .        .
FR     BND1     X4       .        .        .
QUADOBJ .        .       .        .        .
...
```

Financially, that means you are allowed to short-sell—that is, sell low-mean-return assets and use the proceeds to invest in high-mean-return assets. In other words, you put a negative portfolio weight in low-mean assets and "more than 100%" in high-mean assets. You can see in the optimal solution displayed in Output 7.2.2 that the decision variable x_2, denoting Asset 2, is equal to -1563.61, which means short sale of that asset.

Output 7.2.2 Portfolio Optimization with Short-Sale Option

The OPTQP Procedure
Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Linear Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status
1	OBJ.FUNC	RHS	X1	F	0	-1.7977E308	1.7977E308	1684.35	O
2	OBJ.FUNC	RHS	X2	F	0	-1.7977E308	1.7977E308	-1563.61	O
3	OBJ.FUNC	RHS	X3	F	0	-1.7977E308	1.7977E308	682.51	O
4	OBJ.FUNC	RHS	X4	F	0	-1.7977E308	1.7977E308	1668.95	O

Example 7.3: Portfolio Selection with Transactions

Consider a portfolio selection problem with a slight modification. You are now required to take into account the current position and transaction costs associated with buying and selling assets. The objective is to find the minimum variance portfolio. In order to understand the scenario better, consider the following data.

You are given three assets. The current holding of the three assets is denoted by the vector $\mathbf{c}$ = [200, 300, 500], the amount of asset bought and sold is denoted by b_i and s_i, respectively, and the net investment in each asset is denoted by x_i and is defined by the following relation:

$$x_i - b_i + s_i = c_i, \quad i = 1, 2, 3$$

Suppose you pay a transaction fee of 0.01 every time you buy or sell. Let the covariance matrix $\mathcal{C}$ be defined as

$$\mathcal{C} = \begin{bmatrix} 0.027489 & -0.00874 & -0.00015 \\ -0.00874 & 0.109449 & -0.00012 \\ -0.00015 & -0.00012 & 0.000766 \end{bmatrix}$$

Assume that you hope to obtain at least 12% growth. Let $\mathbf{r}$ = [1.109048, 1.169048, 1.074286] be the vector of expected return on the three assets, and let $\mathcal{B}$=1000 be the available funds. Mathematically, this problem can be written in the following manner:

$$\begin{aligned} \min \quad & 0.027489x_1^2 - 0.01748x_1x_2 - 0.0003x_1x_3 + 0.109449x_2^2 \\ & -0.00024x_2x_3 + 0.000766x_3^2 \end{aligned}$$

$$\begin{array}{lrcll} \text{subject to} & & & & \\ \text{(return)} & \sum_{i=1}^{3} r_i x_i & \geq & 1.12\mathcal{B} & \\ \text{(budget)} & \sum_{i=1}^{3} x_i + \sum_{i=1}^{3} 0.01(b_i + s_i) & = & \mathcal{B} & \\ \text{(balance)} & x_i - b_i + s_i & = & c_i, & i = 1, 2, 3 \\ & x_i,\, b_i,\, s_i & \geq & 0, & i = 1, 2, 3 \end{array}$$

The QPS-format input data set is as follows:

```
data potrdata;
   input field1 $ field2 $ field3 $ field4 field5 $ field6 @;
datalines;
NAME     .         POTRAN    .           .          .
ROWS     .         .         .           .          .
N        OBJ.FUNC  .         .           .          .
G        RETURN    .         .           .          .
E        BUDGET    .         .           .          .
E        BALANC1   .         .           .          .
E        BALANC2   .         .           .          .
E        BALANC3   .         .           .          .
COLUMNS  .         .         .           .          .
.        X1        RETURN    1.109048    BUDGET     1.0
.        X1        BALANC1   1.0         .          .
.        X2        RETURN    1.169048    BUDGET     1.0
.        X2        BALANC2   1.0         .          .
.        X3        RETURN    1.074286    BUDGET     1.0
.        X3        BALANC3   1.0         .          .
.        B1        BUDGET    .01         BALANC1   -1.0
.        B2        BUDGET    .01         BALANC2   -1.0
.        B3        BUDGET    .01         BALANC3   -1.0
.        S1        BUDGET    .01         BALANC1    1.0
.        S2        BUDGET    .01         BALANC2    1.0
.        S3        BUDGET    .01         BALANC3    1.0
RHS      .         .         .           .          .
.        RHS       RETURN    1120        .          .
.        RHS       BUDGET    1000        .          .
.        RHS       BALANC1   200         .          .
.        RHS       BALANC2   300         .          .
.        RHS       BALANC3   500         .          .
RANGES   .         .         .           .          .
BOUNDS   .         .         .           .          .
QUADOBJ  .         .         .           .          .
.        X1        X1        0.054978    .          .
.        X1        X2        -.01748     .          .
.        X1        X3        -.0003      .          .
.        X2        X2        0.218898    .          .
.        X2        X3        -.00024     .          .
.        X3        X3        0.001532    .          .
ENDATA   .         .         .           .          .
;
```

Use the following SAS statements to solve the problem:

```
data mycas.potrdata;
   set potrdata;
   _id_ = _n_;
run;

proc optqp data = mycas.potrdata
  printlevel = 0
  primalout = mycas.potrpout
  dualout   = mycas.potrdout;
```

```
run;
```

The optimal solution is displayed in Output 7.3.1.

Output 7.3.1 Portfolio Selection with Transactions

The OPTQP Procedure
Primal Solution

Obs	Objective Function ID	RHS ID	Variable Name	Variable Type	Linear Objective Coefficient	Lower Bound	Upper Bound	Variable Value	Variable Status
1	OBJ.FUNC	RHS	X1	N	0	0	1.7977E308	397.584	O
2	OBJ.FUNC	RHS	X2	N	0	0	1.7977E308	406.115	O
3	OBJ.FUNC	RHS	X3	N	0	0	1.7977E308	190.165	O
4	OBJ.FUNC	RHS	B1	N	0	0	1.7977E308	197.584	O
5	OBJ.FUNC	RHS	B2	N	0	0	1.7977E308	106.115	O
6	OBJ.FUNC	RHS	B3	N	0	0	1.7977E308	0.000	O
7	OBJ.FUNC	RHS	S1	N	0	0	1.7977E308	0.000	O
8	OBJ.FUNC	RHS	S2	N	0	0	1.7977E308	0.000	O
9	OBJ.FUNC	RHS	S3	N	0	0	1.7977E308	309.835	O

References

Freund, R. W. (1991). "On Polynomial Preconditioning and Asymptotic Convergence Factors for Indefinite Hermitian Matrices." *Linear Algebra and Its Applications* 154–156:259–288.

Freund, R. W., and Jarre, F. (1997). "A QMR-Based Interior Point Algorithm for Solving Linear Programs." *Mathematical Programming* 76:183–210.

Freund, R. W., and Nachtigal, N. M. (1996). "QMRPACK: A Package of QMR Algorithms." *ACM Transactions on Mathematical Software* 22:46–77.

Vanderbei, R. J. (1999). "LOQO: An Interior Point Code for Quadratic Programming." *Optimization Methods and Software* 11:451–484.

Wright, S. J. (1997). *Primal-Dual Interior-Point Methods*. Philadelphia: SIAM.

Chapter 8
The MPS-Format Data Table

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Overview: MPS-Format Data Table

The MPS file format is a format commonly used in industry to describe linear programming (LP) and mixed integer linear programming (MILP) problems (Murtagh 1981; IBM 1988). It can be extended to the QPS format (Maros and Mészáros 1999), which describes quadratic programming (QP) problems. MPS-format and QPS-format files are in text format and have specific conventions for the order in which the different pieces of the mathematical model are specified. The MPS-format data table corresponds closely to the format of an MPS-format or QPS-format file and is used to describe linear programming, mixed integer linear programming, and quadratic programming problems for SAS.

Observations

An MPS-format data table contains seven variables: _ID_, field1, field2, field3, field4, field5, and field6. The variables _ID_, field4, and field6 are numeric type; the others are character type. Among the character variables, only the value of field1 is case-insensitive and leading blanks are ignored. Values of field2, field3, and field5 are case-sensitive and leading blanks are NOT ignored. Not all variables are used in a particular observation.

Observations in an MPS-format data table are grouped into sections. Each section starts with an *indicator record*, followed by associated *data records*. Indicator records specify the names of sections and the format of the following data records. Data records contain the actual data values for a section.

The _ID_ variable maintains the order of the sections in the MPS-format data table on the CAS server. Hence it has to be an increasing index number, indicating an order of the observations that results in a valid MPS-format data table. If the _ID_ variable is omitted, you might get an error message that indicates that sections are not read in the expected order.

Order of Sections

Sections of an MPS-format data table must be specified in a *fixed* order, as indicated by the _ID_ variable.

Sections of linear programming problems are listed in the following order:

- NAME
- OBJSENSE (optional)
- ROWS
- COLUMNS
- RHS (optional)
- RANGES (optional)
- BOUNDS (optional)
- ENDATA

Sections of quadratic programming problems are listed in the following order:

- NAME
- OBJSENSE (optional)
- ROWS
- COLUMNS
- RHS (optional)
- RANGES (optional)
- BOUNDS (optional)
- QSECTION (optional)
- ENDATA

Sections of mixed integer linear programming problems are listed in the following order:

- NAME
- OBJSENSE (optional)
- ROWS
- COLUMNS
- RHS (optional)
- RANGES (optional)
- BOUNDS (optional)
- INDICATORS (optional)
- BRANCH (optional)
- ENDATA

Sections Format: MPS-Format Data Table

The following subsections describe the format of the records for each section of the MPS-format data table. Note that each section contains two types of records: an indicator record and multiple data records. The following subsections of this documentation describe the two different types of records for each section of the MPS data table.

NAME Section

The NAME section contains only a single record identifying the name of the problem.

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	NAME	Blank	Input model name	.	Blank or FREE or FIXED	.

OBJSENSE Section (Optional)

The OBJSENSE section contains the sense of the objective. The objective sense is specified by the indicator code in field2 as follows:

- **MIN**: minimization objective
- **MAX**: maximization objective

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	OBJSENSE	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	Objective sense	Blank	.	Blank	.

Notes:

- The objective sense that is specified in this section supersedes the objective sense that is set in the ROWS section, but the objective sense that is set using the OBJSENSE= option in the solver supersedes the objective sense that is set in the MPS-format data table.

ROWS Section

The ROWS section contains the name and type of the rows (linear constraints or objectives). The type of each row is specified by the indicator code in field1 as follows:

- **MIN**: minimization objective
- **MAX**: maximization objective
- **N**: objective
- **G**: $\geq$ constraint
- **L**: $\leq$ constraint
- **E**: = constraint

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	ROWS	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Indicator code	Row name	Blank	.	Blank	.

Notes:

1. At least one objective row should be specified in the ROWS section. It is possible to specify multiple objective rows. However, among all the data records indicating the objective, only the first one is regarded as the objective row, and the rest are ignored. If a type-N row is used as the objective row, minimization is assumed. The value of the solver's OBJSENSE= option supersedes the objective sense that is specified in this section.
2. Duplicate entries of field2 in the ROWS section are not allowed. In other words, row name is unique. The variable field2 in the ROWS section cannot take a missing value.

COLUMNS Section

The COLUMNS section defines the column (that is, variable or decision variable) names of the problem. It also specifies the coefficients of the columns for each row.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	COLUMNS	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	Column name (e.g., col)	Row name (e.g., rowi)	Matrix element in row rowi, column col	Row name (e.g., rowj)	Matrix element in row rowj, column col

Notes:

1. All elements belonging to one column must be grouped together.
2. A missing coefficient value is ignored. A data record with missing values in both field4 and field6 is ignored.
3. Duplicate entries in each pair of column and row are not allowed.
4. When a sequence of data records have an identical value in field2, you can specify the value in the first occurrence and omit the value by giving a missing value in the other records. The value in field2 of the first data record in the section cannot be missing.

Mixed Integer Linear Programs

Mixed integer linear programming (MILP) problems require you to specify which variables are constrained to be integers. Integer variables can be specified in the COLUMNS section with the use of special marker records in the following form:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	Marker name	‘MARKER’ (including the quotation marks)	.	‘INTORG’ or ‘INTEND’ (including the quotation marks)	.

A marker record with field5 that contains the value ‘INTORG’ indicates the start of integer variables. In the marker record that indicates the end of integer variables, field5 must be ‘INTEND’. An alternative way to

specify integer variables without using the marker records is described in the section "BOUNDS Section (Optional)" on page 291.

Notes:

1. INTORG and INTEND markers must appear in pairs in the COLUMNS section. The marker pairs can appear any number of times.
2. The marker name in field2 should be different from the preceding and following column names.
3. All variables between the INTORG and INTEND markers are assumed to be binary unless you specify a different lower bound and/or upper bound in the BOUNDS section.

RHS Section (Optional)

The RHS section specifies the right-hand-side value for the rows. Any row unspecified in this section is considered to have an RHS value of 0. Missing the entire RHS section implies that all RHS values are 0.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	RHS	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	RHS name	Row name (e.g., rowi)	RHS value for row rowi	Row name (e.g., rowj)	RHS value for row rowj

Notes:

1. The rows that have an RHS element defined in this section need not be specified in the same order in which the rows were specified in the ROWS section. However, a row in the RHS section should be defined in the ROWS section.
2. It is possible to specify multiple RHS vectors, which are labeled by different RHS names. The first RHS vector encountered in the RHS section is used, and all other RHS vectors are discarded. All the elements of the selected RHS vector must be specified before other RHS vectors are introduced. Within a specific RHS vector, for a given row, duplicate assignments of RHS values are not allowed.
3. An RHS value assigned to the objective row is used as the negative of the constant term of the objective function. The value of the solver's OBJCONSTANT= option supersedes the objective constant that is specified in Field4 or Field6 in the RHS section.
4. A missing value in field4 or field6 is ignored. A data record with missing values in both field4 and field6 is ignored.

5. When a sequence of data records have an identical value in field2, you can specify the value in the first occurrence and omit the value by giving a missing value in the other records. If the value in field2 of the first data record in the section is missing, it means the name of the first vector is the missing value.

RANGES Section (Optional)

The RANGES section specifies the range of the RHS value for the constraint rows. With range specification, a row can be constrained from above and below.

For a constraint row c, if b is the RHS value and r is the range for this row, then the equivalent constraints are given in Table 8.1, depending on the type of row and the sign of r.

Table 8.1 Range Effect

Type of Row	Sign of r	Equivalent Constraints
G	$\pm$	$b \le c \le b + \lvert r \rvert$
L	$\pm$	$b - \lvert r \rvert \le c \le b$
E	$+$	$b \le c \le b + r$
E	$-$	$b + r \le c \le b$

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	RANGES	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	Range name	Row name (e.g., rowi)	Range for RHS of row rowi	Row name (e.g., rowj)	Range for RHS of row rowj

Notes:

1. Range assignment for an objective row (that is, **MAX**, **MIN**, or **N** row) is not allowed.
2. The rows that have a range element defined in this section need not be specified in the same order in which the rows were specified in the ROWS or RHS section. However, a row in the RANGES section should be defined in the ROWS section.
3. It is possible to specify multiple range vectors, which are labeled by different range names. The first range vector encountered in the RANGES section is used, and all other range vectors are discarded. All the elements in a range vector must be specified before other range vectors are introduced. Within the specific range vector, for a given range, duplicate assignments of range values are not allowed.

4. A missing value in field4 or field6 is ignored. A data record with missing values in both field4 and field6 is ignored.
5. When a sequence of data records have an identical value in field2, you can specify the value in the first occurrence and omit the value by giving a missing value in the other records. If the value in field2 of the first data record in the section is missing, it means the name of the first vector is the missing value.

BOUNDS Section (Optional)

The BOUNDS section specifies bounds for the columns.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	BOUNDS	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Bound type	Bound name	Column name	Bound for the column	Blank	Blank

Notes:

1. If you do not specify any bound for a column, then the upper bound is $+\infty$ for a continuous variable, and 1 for an integer variable, that is specified in the COLUMNS section. The lower bound is 0 by default.
2. General bound types include **LO**, **UP**, **FX**, **FR**, **MI**, and **PL**. Suppose the bound for a column identified in field3 is specified as b in field4. Table 8.2 explains the effects of different bound types.

Table 8.2 Bound Type Rules

Bound Type	Ignore b	Resultant Lower Bound	Resultant Upper Bound
LO	No	b	Unspecified
UP	No	Unspecified	b
FX	No	b	b
FR	Yes	$-\infty$	$+\infty$
MI	Yes	$-\infty$	Unspecified
PL	Yes	Unspecified	$+\infty$

If a bound (lower or upper) is not explicitly specified, then it takes the default values according to Note 1. There is one exception: if the upper bound is specified as a negative value ($b < 0$) and the lower bound is unspecified, then the lower bound is set to $-\infty$.

Mixed integer linear programming problems can specify integer variables in the BOUNDS section. Table 8.3 shows bound types defined for MILP.

Table 8.3 Bound Type Rules

Bound Type	Ignore *b*	Variable Type	Resultant Lower Bound	Resultant Upper Bound
BV	Yes	Binary	0	1
LI	No	Integer	b	$+\infty$
UI	No	Integer	Unspecified	b

3. The columns that have bounds do not need to be specified in the same order in which the columns were specified in the COLUMNS section. However, all columns in the BOUNDS section should be defined in the COLUMNS section.

4. It is possible to specify multiple bound vectors, which are labeled by different bound names. The first bound vector encountered in the BOUNDS section is used, and all other bound vectors are discarded. All the elements of the selected bound vector must be specified before other bound vectors are introduced.

5. When data records in a sequence have an identical value in field2, you can specify the value in the first occurrence and omit the value by giving a missing value in the other records. If the value in field2 of the first data record in the section is missing, it means the name of the first vector is the missing value.

6. Within a particular BOUNDS vector, for a given column, if a bound (lower or upper) is explicitly specified by the bound type rules listed in Table 8.2, any other specification is considered to be an error.

7. If the value in field1 is **LO**, **UP**, **FX**, **LI**, or **UI**, then a data record with a missing value in field4 is ignored.

INDICATORS Section (Optional)

The INDICATORS section describes indicator constraints in the problem instance. For more information, see the section "Indicator Constraints" on page 417.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	INDICATO	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	IF	Row name (e.g., rowi)	Column name (e.g., colj)	Indicator value	Blank	.

Notes:

1. Historically, Field1 is eight characters wide in the MPS format, and that is how the MPS data tables are implemented in SAS. For this reason, the section indicator is INDICATO instead of INDICATORS.

2. The row that is identified by rowi is the consequent of the indicator constraint. The sense of this constraint as well as its coefficients, right-hand side, and possibly its range is specified in the ROWS, COLUMNS, RHS, and RANGES sections.

3. The column that is identified by colj is the indicator variable in the conditional of the indicator constraint.

4. In any feasible solution to the problem, if the value of the indicator variable is equal to the indicator value specified in field4, then the consequent must be satisfied; otherwise the consequent might or might not hold.

5. Variable colj must be binary, and the indicator value must be *0* or *1*.

BRANCH Section (Optional)

Sometimes you want to specify branching priorities or directions for integer variables to improve performance. Variables with higher priorities are branched on before variables with lower priorities. The branch direction is used to decide which branch to take first at each node. For more information, see the section "Branching Priorities" on page 207.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	BRANCH	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Branch direction	Blank	First column name	First column priority	Second column name	Second column priority

Notes:

1. Valid directions include **UP** (up branch), **DN** (down branch), **RD** (rounding), and **CB** (closest bound). If field1 is blank, the solver automatically decides the direction.

2. If field4 is missing, then the name defined in field3 is ignored. Similarly, if field6 is missing, then the name defined in field5 is ignored.

3. The priority value in field4 and field6 must be nonnegative. Zero is the lowest priority and is also the default.

QSECTION Section (Optional)

The QSECTION section is needed only to describe quadratic programming problems. It specifies the coefficients of the quadratic terms in the objective function.

- Indicator record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	QSECTION or QUADOBJ	Blank	Blank	.	Blank	.

- Data record:

_ID_	Field1	Field2	Field3	Field4	Field5	Field6
Number	Blank	Column name	Column name	Coefficient in objective function	Blank	.

Notes:

1. The QSECTION section can appear only in PROC OPTQP and should not appear in PROC OPTLP or PROC OPTMILP. For PROC OPTLP and PROC OPTMILP, an error is reported when the submitted data table contains a QSECTION section. For PROC OPTQP, if the QSECTION section is not specified, or if there is no valid data record in the QSECTION section, then the LP solver is used to solve the resulting linear programming problem.

2. The variables field2 and field3 contain the names of the columns that form a quadratic term in the objective function. They must have been defined in the COLUMNS section. They need not refer to the same column. Zero entries should not be specified.

3. Duplicate entries of a quadratic term are not allowed. This means the combination of (field2, field3) must be unique, where (k, j) and (j, k) are considered to be the same combination.

4. If field4 of one data record is missing or takes a value of zero, then this data record is ignored.

ENDATA Section

The ENDATA section simply declares the end of all records. It contains only one indicator record, where field1 takes the value ENDATA, _ID_ has a value larger than in all other observations, and the values of the remaining variables are blank or missing.

Details: MPS-Format Data Table

Converting an MPS/QPS-Format File: %MPS2SASD

As described in the section "Overview: MPS-Format Data Table" on page 284, the MPS or QPS format is a standard file format for describing linear, integer, and quadratic programming problems. The MPS/QPS format is defined for plain text files, whereas in the SAS System it is more convenient to read data from data sets or data tables. Therefore, a facility is required to convert MPS/QPS-format text files to MPS-format data sets or data tables. The SAS macro %MPS2SASD serves this purpose.

In the MPS/QPS-format text file, a record refers to a single line of text that is divided into six fields. MPS/QPS files can be read and printed in both *fixed* and *free* format. In fixed MPS/QPS format, each field of a data record must occur in specific columns:

Field	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6
Columns	2–3	5–12	15–22	25–36	40–47	50–61

In free format, fields of a record are separated by a space. Both fixed and free format have limitations. If users need to use row names or column names longer than 8 characters, then there is not enough space to hold them in fixed format. If users use a space as a part of a row name or column name, such as "ROW NAME", then free-format MPS format interprets this symbol as two fields, "ROW" and "NAME".

You can insert a comment record, denoted by an asterisk (*) in column 1, anywhere in an MPS/QPS file. Also, if a dollar sign ($) is the first character in field 3 or field 5 of any record, the information from that point to the end of the record is treated as a comment. All comments are ignored by the %MPS2SASD macro, which is described as follows.

%MPS2SASD Macro Parameters

%MPS2SASD(MPSFILE=*'infilename'*, **OUTDATA**=*mpsdata*, **MAXLEN**=*n*, **FORMAT**=**FIXED | FREE)**;

FORMAT=FIXED | FREE

specifies the format of the input MPS file. This parameter is optional. The default value is the one, if any, specified by the flat file, and FIXED otherwise. You can specify the following values:

FIXED specifies that each field of a data record occurs in specific columns.

FREE specifies that the fields of a data record are separated by a space.

MAXLEN=*n*
specifies length of the variables field2, field3, and field5 in the output MPS-format data table. This parameter is optional. By default, MAXLEN=8.

MPSFILE=*'infilename'*
specifies the path and name of the input MPS-format file. The input file is a plain text file, usually with either an ".mps" extension for linear programming problems or a ".qps" extension for quadratic programming problems. This parameter is required; there is no default value.

OUTDATA=*mpsdata*
specifies the name of the output MPS-format data table. If a CAS library reference is specified before the name, the output data are directly stored as a data table on the CAS server. This parameter is optional. By default, OUTDATA=MPSData.

Length of Variables

In an MPS-format data table, the variables field2, field3, and field5 hold the names of the rows and columns. The length of these character variables is limited to the maximum size of a SAS character variable. This enables you to use sufficiently long names for the rows and columns in your model.

In a data table generated by the %MPS2SASD macro, the length of the variables field2, field3, and field5 is fixed to be 8 ASCII characters by default. This length fits the fixed-format MPS/QPS file well because field 2, field 3, and field 5 are fixed at 8 characters. However, the free-format MPS/QPS files might have longer row names or longer column names. The %MPS2SASD macro provides a parameter MAXLEN=*n*. Using this parameter, you can set the variables field2, field3, and field5 to have a length of *n* characters in the output data table.

The parameter MAXLEN works only when the given MPS file is in free format. For a fixed-format MPS file, this parameter is ignored and the length of field2, field3, and field5 is 8 characters by default.

Examples: MPS-Format Data Table

Example 8.1: MPS-Format Data Table for a Product Mix Problem

Consider a simple product mix problem where a furniture company tries to find an optimal product mix of four items: a desk (x_1), a chair (x_2), a cabinet (x_3), and a bookcase (x_4). Each item is processed in a stamping department (STAMP), an assembly department (ASSEMB), and a finishing department (FINISH). The time each item requires in each department is given in the input data. Because of resource limitations, each department has an upper limit on the time available for processing. Also, because of labor constraints, the assembly department must work at least 300 hours. Finally, the marketing department tells you not to make more than 75 chairs and to make at least 50 bookcases.

This problem can be expressed as the following linear program:

$$
\begin{array}{rrcll}
\text{maximize} & 95x_1 + 41x_2 + 84x_3 + 76x_4 & & & \\
\text{subject to} & 3x_1 + 1.5x_2 + 2x_3 + 2x_4 & \leq & 800 & \text{(STAMP)} \\
 & 10x_1 + 6x_2 + 8x_3 + 7x_4 & \leq & 1200 & \text{(ASSEMB)} \\
 & 10x_1 + 6x_2 + 8x_3 + 7x_4 & \geq & 300 & \text{(ASSEMB)} \\
 & 10x_1 + 8x_2 + 8x_3 + 7x_4 & \leq & 800 & \text{(FINISH)} \\
 & x_2 & \leq & 75 & \\
 & x_4 & \geq & 50 & \\
 & x_i & \geq & 0 & i = 1, 2, 3
\end{array}
$$

The following DATA step saves the problem specification as an MPS-format data table:

```
data mycas.ProdMix;
   infile datalines;
   input field1 $ field2 $ field3$ field4 field5 $ field6 _ID_;
   datalines;
NAME        .          PROD_MIX        .    .            .     1
ROWS        .          .               .    .            .     2
MAX         PROFIT     .               .    .            .     3
L           STAMP      .               .    .            .     4
L           ASSEMB     .               .    .            .     5
L           FINISH     .               .    .            .     6
COLUMNS     .          .               .    .            .     7
.           DESK       STAMP         3.0    ASSEMB      10     8
.           DESK       FINISH       10.0    PROFIT      95     9
.           CHAIR      STAMP         1.5    ASSEMB       6    10
.           CHAIR      FINISH        8.0    PROFIT      41    11
.           CABINET    STAMP         2.0    ASSEMB       8    12
.           CABINET    FINISH        8.0    PROFIT      84    13
.           BOOKCSE    STAMP         2.0    ASSEMB       7    14
.           BOOKCSE    FINISH        7.0    PROFIT      76    15
RHS         .          .               .    .            .    16
.           TIME       STAMP       800.0    ASSEMB    1200    17
.           TIME       FINISH      800.0    .            .    18
RANGES      .          .               .    .            .    19
.           T1         ASSEMB      900.0    .            .    20
BOUNDS      .          .               .    .            .    21
UP          BND        CHAIR        75.0    .            .    22
LO          BND        BOOKCSE      50.0    .            .    23
ENDATA      .          .               .    .            .    24
;
```

Example 8.2: Fixed-MPS-Format File

The following file, example_fix.mps, contains the data from Example 8.1 in the form of a fixed-MPS-format file. The indicator codes MAX and MIN are not available for objective rows in fixed MPS format, so the PROFIT row is specified as type N. Minimization is assumed for type-N rows; for a maximization objective, the objective coefficients must be replaced with values of the opposite sign.

```
* THIS IS AN EXAMPLE FOR FIXED MPS FORMAT.
NAME          PROD_MIX
ROWS
 N  PROFIT
 L  STAMP
 L  ASSEMB
 L  FINISH
COLUMNS
    DESK      STAMP          3.00000   ASSEMB        10.00000
    DESK      FINISH        10.00000   PROFIT       -95.00000
    CHAIR     STAMP          1.50000   ASSEMB         6.00000
    CHAIR     FINISH         8.00000   PROFIT       -41.00000
    CABINET   STAMP          2.00000   ASSEMB         8.00000
    CABINET   FINISH         8.00000   PROFIT       -84.00000
    BOOKCSE   STAMP          2.00000   ASSEMB         7.00000
    BOOKCSE   FINISH         7.00000   PROFIT       -76.00000
RHS
    TIME      STAMP        800.00000   ASSEMB       1200.0000
    TIME      FINISH       800.00000
RANGES
    T1        ASSEMB       900.00000
BOUNDS
 UP BND       CHAIR         75.00000
 LO BND       BOOKCSE       50.00000
ENDATA
```

Example 8.3: Free-MPS-Format File

In free format, fields in data records other than the first record have no predefined positions. They can be written anywhere except column 1, with each field separated from the next by one or more blanks (a tab cannot be used as a field separator). However, the fields must appear in the same sequence as in the fixed format. The following file, example_free.mps, is an example. It describes the same problem as in Example 8.2.

```
* THIS IS AN EXAMPLE FOR FREE MPS FORMAT.
NAME          PROD_MIX  FREE
ROWS
 N  PROFIT
    L  STAMP
    L  ASSEMB
    L  FINISH
```

```
COLUMNS
 DESK       STAMP    3.00000   ASSEMB      10.00000
 DESK       FINISH   10.00000    PROFIT   -95.00000
    CHAIR   STAMP    1.50000   ASSEMB      6.00000
    CHAIR   FINISH   8.00000     PROFIT   -41.00000
 CABINET    STAMP    2.00000   ASSEMB      8.00000
 CABINET    FINISH   8.00000     PROFIT   -84.00000
    BOOKCSE STAMP    2.00000   ASSEMB      7.00000
    BOOKCSE FINISH   7.00000     PROFIT   -76.00000
RHS
    TIME STAMP   800.00000  ASSEMB 1200.0000
    TIME FINISH  800.00000
RANGES
    T1   ASSEMB   900.00000
BOUNDS
 UP BND     CHAIR 75.00000
 LO BND   BOOKCSE 50.00000
ENDATA
```

Example 8.4: Using the %MPS2SASD Macro

This example illustrates the use of the %MPS2SASD macro, assuming that the files example_fix.mps and example_free.mps are in your current SAS working directory.

The %MPS2SASD macro function has one required parameter, MPSFILE=*'infilename'*, which specifies the path and name of the MPS/QPS-format file. With this single parameter, the macro reads the file, converts the records, and saves the conversion to the default MPS-format data set MPSData. To save the conversion to a CAS library reference, the additional parameter OUTDATA= is required and needs to include a caslib in the name.

Running the following statements converts the fixed-format MPS file shown in Example 8.2 to the MPS-format data table ProdMix:

```
%mps2sasd(mpsfile='example_fix.mps', outdata=mycas.ProdMix);
proc print data=mycas.ProdMix noobs;
run;
```

Output 8.4.1 displays the MPS-format data table ProdMix.

Output 8.4.1 The MPS-Format Data Table ProdMix

field1	field2	field3	field4	field5	field6	_id_
NAME		PROD_MIX	.		.	2
L	STAMP		.		.	5
COLUMNS			.		.	8
	CHAIR	STAMP	1.5	ASSEMB	6	11
	CABINET	FINISH	8.0	PROFIT	-84	14
RHS			.		.	17
RANGES			.		.	20
UP	BND	CHAIR	75.0		.	23
ROWS			.		.	3
L	ASSEMB		.		.	6
	DESK	STAMP	3.0	ASSEMB	10	9
	CHAIR	FINISH	8.0	PROFIT	-41	12
	BOOKCSE	STAMP	2.0	ASSEMB	7	15
	TIME	STAMP	800.0	ASSEMB	1200	18
	T1	ASSEMB	900.0		.	21
LO	BND	BOOKCSE	50.0		.	24
N	PROFIT		.		.	4
L	FINISH		.		.	7
	DESK	FINISH	10.0	PROFIT	-95	10
	CABINET	STAMP	2.0	ASSEMB	8	13
	BOOKCSE	FINISH	7.0	PROFIT	-76	16
	TIME	FINISH	800.0		.	19
BOUNDS			.		.	22
ENDATA			.		.	25

Note that the _ID_ variable has been added automatically and its index is increasing. The order is not preserved on the CAS server, but sorting by _ID_ would put the rows in the correct order. It does not start at 1 because of the comment in the input file.

Running the following statement converts the free-format MPS file shown in Example 8.3 to the MPS-format data table ProdMix on the caslib mycas:

```
%mps2sasd(mpsfile='example_free.mps', outdata=mycas.ProdMix);
```

This data table is identical to the one shown in Output 8.4.1.

In the following statement, when the free-format MPS file is converted, the length of the variables field2, field3, and field5 in the data table ProdMix is explicitly set to 10 characters:

```
%mps2sasd(mpsfile='example_free.mps', outdata=mycas.ProdMix, maxlen=10, format=free);
```

References

IBM (1988). *Mathematical Programming System Extended/370 (MPSX/370) Version 2 Program Reference Manual.* Vol. SH19-6553-0. Armonk, NY: IBM.

Maros, I., and Mészáros, C. (1999). "A Repository of Convex Quadratic Programming Problems." *Optimization Methods and Software* 11–12:671–681.

Murtagh, B. A. (1981). *Advanced Linear Programming: Computation and Practice*. New York: McGraw-Hill.

Chapter 9
The OPTMODEL Procedure

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Overview: OPTMODEL Procedure

The OPTMODEL procedure includes the powerful OPTMODEL modeling language and state-of-the-art solvers for several classes of mathematical programming problems. The problems and their solvers are listed in Table 9.1.

Table 9.1 Solvers in PROC OPTMODEL

Problem	Solver
Black-box optimization	Black-box
Constraint programming	CLP
Conic optimization	Conic
Linear programming	LP
Mixed integer linear programming	MILP
Network algorithms	Network
General nonlinear programming	NLP
Quadratic programming	QP

The OPTMODEL modeling language provides a modeling environment tailored to building, solving, and maintaining optimization models. This makes the process of translating the symbolic formulation of an optimization model into OPTMODEL virtually transparent since the modeling language mimics the symbolic algebra of the formulation as closely as possible. The OPTMODEL language also streamlines and simplifies the critical process of populating optimization models with data from SAS data sets. All of this transparency produces models that are more easily inspected for completeness and correctness, more easily corrected, and more easily modified, whether through structural changes or through the substitution of new data for old.

In addition to invoking optimization solvers directly with PROC OPTMODEL as already mentioned, you can use the OPTMODEL language purely as a modeling facility. You can save optimization models built with the OPTMODEL language in SAS data sets that can be submitted to other SAS Optimization procedures. In general, the OPTMODEL language serves as a common point of access for many of the SAS Optimization capabilities, whether providing both modeling and solver access or acting as a modeling interface for other optimization procedures.

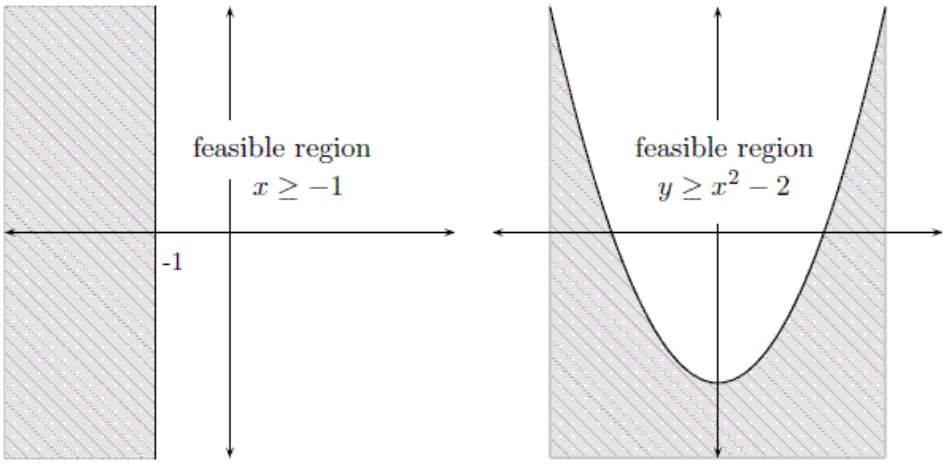
For details and examples of the problems addressed and corresponding solvers, please see the dedicated chapters in this book. This chapter aims to give you a comprehensive understanding of the OPTMODEL procedure by discussing the framework provided by the OPTMODEL modeling language. For additional examples that demonstrate the features of the OPTMODEL procedure, see *SAS/OR User's Guide: Mathematical Programming Examples*.

The OPTMODEL modeling language features automatic differentiation, advanced flow control, optimization-oriented syntax (parameters, variables, arrays, constraints, objective functions), dynamic model generation, model-data separation, and transparent access to SAS data sets.

Getting Started: OPTMODEL Procedure

Optimization or mathematical programming is a search for a maximum or minimum of an *objective function* (also called a *cost function*), where search variables are restricted to particular constraints. Constraints are said to define a *feasible region* (see Figure 9.1).

Figure 9.1 Examples of Feasible Regions



A more rigorous general formulation of such problems is as follows.

Let

$$f : S \to \mathbb{R}$$

be a real-valued function. Find x^* such that

- $x^* \in S$
- $f(x^*) \leq f(x), \quad \forall x \in S$

Note that the formulation is for the minimum of f and that the maximum of f is simply the negation of the minimum of $-f$.

Here, function f is the *objective function*, and the variable in the objective function is called the optimization variable (or decision variable). S is the *feasible region*. Typically S is a subset of the Euclidean space $\mathbb{R}^n$ specified by the set of *constraints*, which are often a set of equalities (=) or inequalities ($\leq, \geq$) that every element in S is required to satisfy simultaneously. For the special case where $S = \mathbb{R}^n$, the problem is an *unconstrained optimization*. An element x of S is called a *feasible solution* to the optimization problem, and the value $f(x)$ is called the *objective value*. A feasible solution x^* that minimizes the objective function is called an *optimal solution* to the optimization problem, and the corresponding objective value is called the *optimal value*.

In mathematics, special notation is used to denote an optimization problem. Generally, you can write an optimization problem as follows:

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & x \in S \end{array}$$

Normally, an empty body of constraint (the part after "subject to") implies that the optimization is unconstrained (that is, the feasible region is the whole space $\mathbb{R}^n$). The optimal solution (x^*) is denoted as

$$x^* = \underset{x \in S}{\operatorname{argmin}}\, f(x)$$

The optimal value ($f(x^*)$) is denoted as

$$f(x^*) = \min_{x \in S} f(x)$$

Optimization problems can be classified by the forms (linear, quadratic, nonlinear, and so on) of the functions in the objective and constraints. For example, a problem is said to be *linearly constrained* if the functions in the constraints are linear. A *linear programming* problem is a linearly constrained problem with a linear objective function. A nonlinear programming problem occurs where some function in the objective or constraints is nonlinear, and so on.

An Unconstrained Optimization Example

An unconstrained optimization problem formulation is simply

$$\text{minimize} \quad f(x)$$

For example, suppose you wanted to find the minimum value of this polynomial:

$$z(x, y) = x^2 - x - 2y - xy + y^2$$

You can compactly specify and solve the optimization problem by using the OPTMODEL modeling language. Here is the program:

```
/* invoke procedure */
proc optmodel;
   var x, y;  /* declare variables */

   /* objective function */
   min z=x**2 - x - 2*y - x*y + y**2;

   /* now run the solver */
   solve;

   print x y;
quit;
```

This program produces the output in Figure 9.2.

Figure 9.2 Optimizing a Simple Polynomial

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	z
Objective Type	Quadratic
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	0
Constraint Coefficients	0
Hessian Diagonal Elements	2
Hessian Elements Below Diagonal	1

Figure 9.2 *continued*

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	z
Solution Status	Optimal
Objective Value	-2.333333333
Primal Infeasibility	0
Dual Infeasibility	6.861556E-17
Bound Infeasibility	0
Duality Gap	0
Complementarity	0
Iterations	0
Presolve Time	0.00
Solution Time	0.03

x	y
1.3333	1.6667

In PROC OPTMODEL you specify the mathematical formulas that describe the behavior of the optimization problem that you want to solve. In the preceding example there were two independent variables in the polynomial, x and y. These are the *optimization variables* of the problem. In PROC OPTMODEL you declare optimization variables with the VAR statement. The formula that defines the quantity that you are seeking to optimize is called the *objective function*, or *objective*. The solver varies the values of the optimization variables when searching for an optimal value for the objective.

In the preceding example the objective function is named z, declared with the MIN statement. The keyword MIN is an abbreviation for MINIMIZE. The expression that follows the equal sign (=) in the MIN statement defines the function to be minimized in terms of the optimization variables.

The VAR and MIN statements are just two of the many available PROC OPTMODEL declaration and programming statements. PROC OPTMODEL processes all such statements interactively, meaning that each statement is processed as soon as it is complete.

After PROC OPTMODEL has completed processing of declaration and programming statements, it processes the SOLVE statement, which submits the problem to a solver and prints a summary of the results. The PRINT statement displays the optimal values of the optimization variables x and y found by the solver.

It is worth noting that PROC OPTMODEL does not use a RUN statement but instead operates on an interactive basis throughout. You can continue to interact with PROC OPTMODEL even after invoking a solver. For example, you could modify the problem and issue another SOLVE statement (see the section "Model Update" on page 450).

The Rosenbrock Problem

You can use parameters to produce a clear formulation of a problem. Consider the Rosenbrock problem,

$$\text{minimize} \;\; f(x_1, x_2) = \alpha\,(x_2 - x_1^2)^2 + (1 - x_1)^2$$

where $\alpha = 100$ is a parameter (constant), x_1 and x_2 are optimization variables (whose values are to be determined), and $f(x_1, x_2)$ is an objective function.

Here is a PROC OPTMODEL program that solves the Rosenbrock problem:

```
proc optmodel;
   number alpha = 100; /* declare parameter */
   var x {1..2};       /* declare variables */
   /* objective function */
   min f = alpha*(x[2] - x[1]**2)**2 +
           (1 - x[1])**2;
   /* now run the solver */
   solve;

   print x;
quit;
```

The PROC OPTMODEL output is shown in Figure 9.3.

Figure 9.3 Rosenbrock Function Results

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	0

Figure 9.3 *continued*

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	5.86569E-23
Optimality Error	2.319291E-10
Infeasibility	0
Iterations	15
Presolve Time	0.00
Solution Time	0.01

[1]	x
1	1
2	1

A Transportation Problem

You can easily translate the symbolic formulation of a problem into the OPTMODEL procedure. Consider the transportation problem, which is mathematically modeled as the following linear programming problem:

$$
\begin{array}{llllll}
\text{minimize} & \displaystyle\sum_{i\in O, j\in D} c_{ij}x_{ij} & & & & \\
\text{subject to} & \displaystyle\sum_{j\in D} x_{ij} & = & a_i, & \forall i \in O & \text{(SUPPLY)} \\
& \displaystyle\sum_{i\in O} x_{ij} & = & b_j, & \forall j \in D & \text{(DEMAND)} \\
& x_{ij} & \geq & 0, & \forall (i,j) \in O \times D &
\end{array}
$$

where O is the set of origins, D is the set of destinations, c_{ij} is the cost to transport one unit from i to j, a_i is the supply of origin i, b_j is the demand of destination j, and x_{ij} is the decision variable for the amount of shipment from i to j.

Here is a very simple example. The cities in the set O of origins are Detroit and Pittsburgh. The cities in the set D of destinations are Boston and New York. The cost matrix, supply, and demand are shown in Table 9.2.

Table 9.2 A Transportation Problem

	Boston	New York	Supply
Detroit	30	20	200
Pittsburgh	40	10	100
Demand	150	150	

The problem is compactly and clearly formulated and solved by using the OPTMODEL procedure with the following statements:

```
proc optmodel;
   /* specify parameters */
   set O={'Detroit','Pittsburgh'};
   set D={'Boston','New York'};
   number c{O,D}=[30 20
                  40 10];
   number a{O}=[200 100];
   number b{D}=[150 150];
   /* model description */
   var x{O,D} >= 0;
   min total_cost = sum{i in O, j in D}c[i,j]*x[i,j];
   constraint supply{i in O}: sum{j in D}x[i,j]=a[i];
   constraint demand{j in D}: sum{i in O}x[i,j]=b[j];
   /* solve and output */
   solve;
   print x;
```

The output is shown in Figure 9.4.

Figure 9.4 Solution to the Transportation Problem

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	total_cost
Objective Type	Linear
Number of Variables	4
Bounded Above	0
Bounded Below	4
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	0
Linear EQ (=)	4
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	8

Figure 9.4 *continued*

Solution Summary	
Solver	LP
Algorithm	Simplex
Objective Function	total_cost
Solution Status	Optimal
Objective Value	6500
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	0
Presolve Time	0.00
Solution Time	0.00

	x	
	Boston	**New York**
Detroit	150	50
Pittsburgh	0	100

Syntax: OPTMODEL Procedure

PROC OPTMODEL statements are divided into three categories: the PROC statement, the declaration statements, and the programming statements. The PROC statement invokes the procedure and sets initial option values. The declaration statements declare optimization model components. The programming statements read and write data, invoke the solver, and print results. In the following text, the statements are listed in the order in which they are grouped, with declaration statements first.

NOTE: Solver specific options are described in the individual chapters that correspond to the solvers.

PROC OPTMODEL *options* **;**

Declaration Statements:
CONSTRAINT *constraints* **;**
IMPVAR *optimization expression declarations* **;**
MAX *objective* **;**
MIN *objective* **;**
NUMBER *parameter declarations* **;**
PROBLEM *problem declaration* **;**
SET [**<** *types* **>**] *parameter declarations* **;**
STRING *parameter declarations* **;**
VAR *variable declarations* **;**

Programming Statements:
Assignment *parameter* = *expression* **;**
CALL *name* [**(** *expressions* **)**] **;**
CLOSEFILE *files* **;**
COFOR { *index-set* **}** *statement* **;**
CONTINUE ;
CREATE DATA *SAS-data-set* **FROM** *columns* **;**
DO ; *statements* **; END ;**
DO *variable* **=** *specifications* **;** *statements* **; END ;**
DO UNTIL (*logic* **) ;** *statements* **; END ;**
DO WHILE (*logic* **) ;** *statements* **; END ;**
DROP *constraint* **;**
END ;
ENDSOURCE ;
ENDSUBMIT ;
EXPAND *name* [/ *options*] **;**
FILE *file* **;**
FIX *variable* [**=** *expression*] **;**
FOR { *index-set* **}** *statement* **;**
IF *logic* **THEN** *statement* **;** [**ELSE** *statement*] **;**
LEAVE ;
Null **;**
PRINT *print items* **;**
PROFILE [*mode*] *options* **;**
PUT *put items* **;**
QUIT ;
READ DATA *SAS-data-set* **INTO** *columns* **;**
RESET OPTIONS *options* **;**
RESTORE *constraint* **;**
SAVE MPS *SAS-data-set* [**LINEARIZE**] [**OBJECTIVE** *name*] [**NOOBJECTIVE**] **;**
SAVE QPS *SAS-data-set* [**OBJECTIVE** *name*] [**NOOBJECTIVE**] **;**
SOLVE [**WITH** *solver*] [**CONIC**] [**LINEARIZE**] [**OBJECTIVE** *name*] [**NOOBJECTIVE**] [**RELAXINT**] [/ *options*] **;**
SOURCE *parameter* [**END=***keyword*] **;** *source-block* **; ENDSOURCE ;**
STOP ;
SUBMIT [*arguments*] [/ *options*] **;** *SAS-statements* **; ENDSUBMIT ;**
UNFIX *variable* [**=** *expression*] **;**
USE PROBLEM *problem* **;**

Functional Summary

The statements and options available with PROC OPTMODEL are summarized by purpose in Table 9.3.

Table 9.3 PROC OPTMODEL Functional Summary

Description	Statement	Option
Declaration Statements		
Declares a constraint	CONSTRAINT	
Declares optimization expressions	IMPVAR	
Declares a maximization objective	MAX	
Declares a minimization objective	MIN	
Declares a number type parameter	NUMBER	
Declares a problem	PROBLEM	
Declares a set type parameter	SET	
Declares a string type parameter	STRING	
Declares optimization variables	VAR	
Programming Statements		
Assigns a value to a variable or parameter	=	
Invokes a library subroutine	CALL	
Closes the opened file	CLOSEFILE	
Executes the statement repeatedly with support for concurrent solver invocations	COFOR	
Terminates one iteration of a loop statement	CONTINUE	
Creates a new SAS data set and copies data into it from PROC OPTMODEL parameters and variables	CREATE DATA	
Groups a sequence of statements together as a single statement	DO	
Executes statements repeatedly	DO (iterative)	
Executes statements repeatedly until some condition is satisfied	DO UNTIL	
Executes statements repeatedly as long as some condition is satisfied	DO WHILE	
Ignores the specified constraint	DROP	
Marks the end of a DO statement list	END	
Marks the end of a SOURCE block	ENDSOURCE	
Marks the end of a SUBMIT block	ENDSUBMIT	
Prints the specified constraint, variable, or objective declaration expressions after expanding aggregation operators, and so on	EXPAND	
Selects a file for the PUT statement	FILE	
Treats a variable as fixed in value	FIX	
Executes the statement repeatedly	FOR	
Executes the statement conditionally	IF	

Table 9.3 *continued*

Description	Statement	Option
Terminates the execution of the entire loop body	LEAVE	
Null statement	;	
Outputs string and numeric data	PRINT	
Provides timing and execution count information for statements and declarations	PROFILE	
Writes text data to the current output file	PUT	
Terminates the PROC OPTMODEL session	QUIT	
Reads data from a SAS data set into PROC OPTMODEL parameters and variables	READ DATA	
Sets PROC OPTMODEL option values or restores them to their defaults	RESET OPTIONS	
Adds a constraint that was previously dropped back into the model	RESTORE	
Saves the structure and coefficients for a linear programming model into a SAS data set	SAVE MPS	
Saves the structure and coefficients for a quadratic programming model into a SAS data set	SAVE QPS	
Invokes a PROC OPTMODEL solver	SOLVE	
Assigns a source text block to a string parameter	SOURCE	
Halts the execution of all statements that contain it	STOP	
Submits SAS code for execution	SUBMIT	
Reverses the effect of FIX statement	UNFIX	
Selects the current problem	USE PROBLEM	
PROC OPTMODEL Options		
Specifies the accuracy for nonlinear constraints	PROC OPTMODEL	CDIGITS=
Specifies the maximum number of error messages displayed	PROC OPTMODEL	ERRORLIMIT=
Specifies the method used to approximate numeric derivatives	PROC OPTMODEL	FD=
Specifies the accuracy for the objective function	PROC OPTMODEL	FDIGITS=
Forces finite differences to be used for nonlinear expressions	PROC OPTMODEL	FORCEFD=
Enables the OPTMODEL presolver for the CLP, conic, LP, MILP, and QP solvers	PROC OPTMODEL	FORCEPRESOLVE=
Passes initial values for variables to the solver	PROC OPTMODEL	INITVAR=
Specifies the tolerance for rounding the bounds on integer and binary variables	PROC OPTMODEL	INTFUZZ=
Specifies the maximum length for MPS row and column labels	PROC OPTMODEL	MAXLABLEN=
Checks missing values	PROC OPTMODEL	MISSCHECK=
Specifies the maximum number of non-error messages displayed	PROC OPTMODEL	MSGLIMIT=

Table 9.3 *continued*

Description	Statement	Option
Specifies the number for threads to use for threaded processing	PROC OPTMODEL	NTHREADS=
Specifies the number of digits to display	PROC OPTMODEL	PDIGITS=
Adjusts how two-dimensional array is displayed	PROC OPTMODEL	PMATRIX=
Specifies the type of presolve performed by the PROC OPTMODEL presolver	PROC OPTMODEL	PRESOLVER=
Specifies the tolerance, enabling the PROC OPTMODEL presolver to remove slightly infeasible constraints	PROC OPTMODEL	PRESTOL=
Enables or disables printing summary	PROC OPTMODEL	PRINTLEVEL=
Specifies the width to display numeric columns	PROC OPTMODEL	PWIDTH=
Specifies the CAS session name	PROC OPTMODEL	SESSREF=
Specifies the CAS session UUID	PROC OPTMODEL	SESSUUID=
Specifies the smallest difference that is permitted by the PROC OPTMODEL presolver between the upper and lower bounds of an unfixed variable	PROC OPTMODEL	VARFUZZ=

PROC OPTMODEL Statement

PROC OPTMODEL [*options*] **;**

The PROC OPTMODEL statement invokes the OPTMODEL procedure. You can specify options to control how the optimization model is processed and how results are displayed. You can specify the following *options* (these options can also be specified in the RESET OPTIONS statement).

CDIGITS=*number*

NLCDIGITS=*number*

specifies the expected number of decimal digits of accuracy for nonlinear constraints, where *number* is any positive number, including fractions. PROC OPTMODEL uses this option to choose a step length when numeric derivative approximations are required to evaluate the Jacobian of nonlinear constraints. The default value depends on your operating environment. It is assumed that constraint values are accurate to the limits of machine precision.

For more information about numeric derivative approximations, see the section "Automatic Differentiation" on page 458.

ERRORLIMIT=*number* | **NONE**

specifies the maximum number of error messages that can be displayed during SOLVE statement processing. Specifying a value of *number* in the range 1 to $2^{31} - 1$ sets a specific limit. Specifying ERRORLIMIT=NONE removes any existing limit. The default value is 10.

NOTE: Some errors abort processing immediately.

FD=FORWARD | CENTRAL

FINITEDIFF=FORWARD | CENTRAL

specifies the method to use to approximate numeric derivatives when analytic derivatives are unavailable. Most solvers require the derivatives of the objective and constraints. You can specify the following values:

FORWARD uses forward differences.

CENTRAL uses central differences.

By default, FD=FORWARD. For more information about numeric derivative approximations, see the section "Automatic Differentiation" on page 458.

FDIGITS=*number*

OBJDIGITS=*number*

specifies the expected number of decimal digits of accuracy for the objective function, where *number* is any positive number, including fractions. PROC OPTMODEL uses this option to choose a step length when numeric derivatives are required. The default value depends on your operating environment. It is assumed that objective function values are accurate to the limits of machine precision.

For more information about numeric derivative approximations, see the section "Automatic Differentiation" on page 458.

FORCEFD=NONE | OBJ | CON | ALL

FORCEFINITEDIFF=NONE | OBJ | CON | ALL

forces PROC OPTMODEL to use finite differences instead of analytic derivatives for the specified set of nonlinear expressions. This option can be useful with FCMP functions to provide more control over derivative computation. You can specify the following values:

ALL restricts all derivative computations to use finite differences.

CON restricts derivative computations for the nonlinear constraint expressions and any IMPVAR expressions they reference to use finite differences.

NONE requests analytic derivatives where they are available.

OBJ restricts derivative computations for the objective and any IMPVAR expressions it references to use finite differences.

By default, FORCEFD=NONE.

FORCEPRESOLVE=*number* | *string*

specifies whether PROC OPTMODEL can use the OPTMODEL presolver with the CLP, conic, LP, MILP, and QP solvers. By default, the OPTMODEL presolver is disabled when PROC OPTMODEL solves linear problems or problems with predicates, or when you specify the CLP, conic, LP, MILP, or QP solver in the SOLVE statement. Table 9.4 shows the valid values for this option.

Table 9.4 Values for the FORCEPRESOLVE= Option

number	*string*	**Description**
0	FALSE	Restores the default behavior
1	TRUE	Enables PROC OPTMODEL to use the OPTMODEL presolver when the CLP, conic, LP, MILP, or QP solver is specified in the SOLVE statement

By default, FORCEPRESOLVE=0.

INITVAR

is equivalent to INITVAR=TRUE.

INITVAR=TRUE | FALSE

specifies whether to pass initial values for variables to the solver when the SOLVE statement is executed. The CLP, conic, LP, and QP solvers always ignore initial values. The NLP solver attempts to use specified initial values. The black-box and MILP solvers use initial values only if you specify the PRIMALIN option.

You can specify the following values:

TRUE passes the current variable values.

FALSE invokes the solver without any specific initial values for variables.

By default, INITVAR=TRUE.

INTFUZZ=*number*

specifies the tolerance for rounding the bounds on integer and binary variables to integer values. Bounds that differ from an integer by at most *number* are rounded to that integer. Otherwise, lower bounds are rounded up to the next greater integer and upper bounds are rounded down to the next lesser integer. The value of *number* can range between 0 and 0.5. The default value is 0.00001.

MAXLABLEN=*number*

MAXLABELLEN=*number*

specifies the maximum length for MPS row and column labels, where *number* is an integer from 8 to 256, inclusive. This option can also be used to control the length of row and column names that are displayed by solvers, such as those found in the LP solver iteration log. See also the description of the .label suffix in the section "Suffixes" on page 420. By default, MAXLABLEN=32.

MISSCHECK

is equivalent to MISSCHECK=TRUE.

MISSCHECK=TRUE | FALSE

specifies whether to perform detailed checking of missing values in expressions. You can specify the following values:

TRUE — produces a message each time PROC OPTMODEL evaluates an arithmetic operation or function that has missing value operands (except when the operation or function specifically supports missing values). This value can increase processing time.

FALSE — turns off the detailed reporting.

By default, MISSCHECK=FALSE.

MSGLIMIT=*number* | NONE

MESSAGELIMIT=*number* | NONE

specifies the maximum number of messages about certain issues that can be displayed during processing of a single top-level statement, such as a SOLVE or FOR statement. Specifying a value of *number* in the range 0 to $2^{31} - 1$ sets a specific limit. Specifying MSGLIMIT=NONE removes any existing limit. The default value is 25.

The limit is applied to notes and warnings for the following issues:

- arithmetic evaluation issues, such as division by zero
- function evaluation issues, such as invalid arguments
- problem generation and PROC OPTMODEL presolver issues
- duplicate members in set constructor and literal expressions
- string concatenation results truncated to the maximum string length
- duplicate READ DATA keys
- truncated data set column labels for the CREATE DATA statement
- misspelled keywords for an option value specified using a string expression
- unrecognized file specifications in the CLOSEFILE statement

NOTE: Because of complications of concurrent execution, PROC OPTMODEL might display more or fewer messages than the limit when you use a COFOR statement.

NLCDIGITS=*number*

is an alias for the CDIGITS= option.

NOINITVAR

is equivalent to INITVAR=FALSE.

NOMISSCHECK

is equivalent to MISSCHECK=FALSE.

NTHREADS=*number*

NUMTHREADS=*number*

specifies the maximum number of threads to use for threaded processing, where *number* must be an integer between 1 and 256, inclusive. Problem generation and many of the solvers can take advantage of threaded processing. The default depends on the execution environment. When the distributed computing environment is used, the default is the maximum number of threads that are allowed on each computing node. Otherwise the default depends on the SAS system options CPUCOUNT= and THREADS. For more information, see the section "Threaded and Distributed Processing" on page 465.

OBJDIGITS=*number*

is an alias for the FDIGITS= option.

PDIGITS=*number*

PRINTDIGITS=*number*

requests that the PRINT statement display *number* significant digits for numeric columns for which no format is specified. The value can range from 1 to 9. By default, PDIGITS=5.

PMATRIX=*number*

PRINTMATRIX=*number*

adjusts the density evaluation of a two-dimensional array to affect how it is displayed, where *number* can be any nonnegative value. The value *number* scales the total number of nonempty array elements and is used by the PRINT statement to evaluate whether a two-dimensional array is "sparse" or "dense." Tables that contain a single two-dimensional array are printed in list form if they are sparse and in matrix form if they are dense. If *number* < 1, the list form is used in more cases. If *number* > 1, the matrix form to be used in more cases. If *number* = 0, the list form is always used. For more information, see the section "PRINT Statement" on page 355. By default, PMATRIX=1.

PRESOLVER=*number* | *string*

specifies the type of presolve that the OPTMODEL presolver performs. Table 9.5 shows the valid values of this option.

Table 9.5 Values for the PRESOLVER= Option

number	*string*	**Description**
–1	AUTOMATIC	Applies presolver using default setting
0	NONE	Disables presolver
1	BASIC	Performs minimal processing, only substituting fixed variables and removing empty feasible constraints
2	MODERATE	Applies a higher level of presolve processing
3	AGGRESSIVE	Applies the highest level of presolve processing

The OPTMODEL presolver tightens variable bounds and eliminates redundant constraints. In general, this tightening improves the performance of any solver. Higher levels of presolve processing allow more tightening and substitution passes, but might take more time to execute. The AUTOMATIC option is intermediate between the MODERATE and AGGRESSIVE levels.

NOTE: The OPTMODEL presolver is normally bypassed when PROC OPTMODEL uses the CLP,

conic, LP, MILP, network, or QP solver and when the SAVE MPS and SAVE QPS statements are executed. The FORCEPRESOLVE= option enables the OPTMODEL presolver to be used with the CLP, conic, LP, MILP, and QP solvers. PROC OPTMODEL always bypasses the OPTMODEL presolver when you specify certain solver options. For more information, see the chapter for the relevant solver in this book.

PRESTOL=*number*

PRESOLVETOL=*number*

specifies a tolerance (where *number* can range between 0 and 0.1) so that slightly infeasible constraints can be eliminated by the PROC OPTMODEL presolver. If the magnitude of the infeasibility is no greater than num($|X| + 1$), where X is the value of the original bound, then the empty constraint is removed from the presolved problem. PROC OPTMODEL's presolver does not print messages about infeasible constraints and variable bounds when the infeasibility is within the tolerance that is specified by *number*. The default value is 1E–12.

PRINTLEVEL=*number*

controls the level of listing output during a SOLVE or COFOR command. The Output Delivery System (ODS) tables printed at each level are listed in Table 9.6. Some solvers can produce additional tables; see the individual solver chapters for more information.

Table 9.6 Values for the PRINTLEVEL= Option

number	**Description**
0	Disables all tables
1	Prints Problem Summary and Solution Summary
2	Prints Problem Summary, Solution Summary, Methods of Derivative Computation (for NLP solvers), Solver Options, Optimization Statistics, Timing, and solver-specific ODS tables

For more information about the ODS tables produced by PROC OPTMODEL, see the section "ODS Table and Variable Names" on page 408.

PWIDTH=*number*

PRINTWIDTH=*number*

sets the width that is used by the PRINT statement to display numeric columns when no format is specified. The smallest value *number* can take is the value of the PDIGITS= option plus 7; the largest value *number* can take is 16. The default value is equal to the value of the PDIGITS= option plus 7.

SESSREF=*string* | "*string*"

specifies the name of the CAS session to use for distributed computing. The *string* specifies a session name defined by the SAS CAS statement. You must specify either the SESSREF= or SESSUUID= option in order to use distributed computing.

SESSUUID="*string*"
specifies the universal unique identifier (UUID) of the CAS session to use for distributed computing. The *string* specifies the UUID text. The UUID for a CAS session can be determined through various methods, such as using the LISTSESSIONS option of the SAS CAS statement. You must specify either the SESSUUID= or SESSREF= option in order to use distributed computing.

VARFUZZ=*number*
specifies the smallest difference that is permitted by the OPTMODEL presolver between the upper and lower bounds of an unfixed variable. If the difference is smaller than *number*, then the variable is fixed to the average of the upper and lower bounds before it is presented to the solver. Any nonnegative value can be assigned to *number*; the default value is 0.

Declaration Statements

The declaration statements define the parameters, variables, constraints, and objectives that describe a PROC OPTMODEL optimization model. Declarations in the PROC OPTMODEL input are saved for later use. Unlike programming statements, declarations cannot be nested in other statements. Declaration statements are terminated by a semicolon.

Many declaration attributes, such as variable bounds, are defined using expressions. Expressions in declarations are handled symbolically and are resolved as needed. In particular, expressions are generally reevaluated when one of the parameter values they use has been changed.

CONSTRAINT Declaration

CONSTRAINT *constraint* [**,** *. . . constraint*] **;**

CON *constraint* [**,** *. . . constraint*] **;**

The constraint declaration defines one or more constraints on expressions in terms of the optimization variables. You can specify multiple constraint declaration statements.

Constraints can have an upper bound, a lower bound, or both bounds. The allowed forms are as follows:

[*name* [**{** *index-set* **}**] **:**] *expression relation expression* [**SUFFIXES=(** *values* **)**]
declares a constraint (or, when an *index-set* is specified, a family of constraints) that specifies the relation between two expressions. The *relation* operator is one =, ∼=, <=, <, >=, or >. When *relation* is the = (∼=, <=, <, >=, >) operator, the solver tries to assign optimization variable values so that the value of the left *expression* is equal to (not equal to, less than or equal to, less than, greater than or equal to, greater than) the value of the right *expression*.

The CLP solver must be used when you specify the ∼=, <, or > operator.

[*name* [**{** *index-set* **}**] **:**] *bound relation body relation bound* [**SUFFIXES=(** *values* **)**]
declares an inequality constraint that is bounded on both sides, called a range constraint. The *index-set* declares a family of range constraints. Both *relation* operators are one of <=, <, >=, or >, and they must match in direction. If the <= or < operator is used in the first position, then a <= or < operator must be used in the second position. If the >= or > operator is used in the first position, then a >= or > operator must be used in the second position. The first *bound* expression defines the lower bound (if the <= or < operator is used) or the upper bound (if the >= or > operator is used). The second *bound* defines the

upper bound (if the <= or < operator is used) or the lower bound (if the >= or > operator is used). The solver tries to assign optimization variables so that the value of the *body* expression is in the range between the upper and lower bounds.

The CLP solver must be used when you specify the < or > operator.

[*name* [**{** *index-set* **}**] **:**] *predicate* [**SUFFIXES=(** *values* **)**]

declares a predicate constraint for the CLP or conic solver. See the section "Predicates" on page 578 in Chapter 12, "The Constraint Programming Solver," for a description of the syntax and meaning of CLP *predicates*. See the section "Predicates" on page 552 in Chapter 11, "The Conic Optimization Solver," for a description of the syntax and meaning of conic *predicates*. The NLP and black-box solvers handle conic predicates as quadratic constraints by using the standard mathematical form.

[*name* [**{** *index-set* **}**] **:**] *variable* **=** *value* **IMPLIES** *expression relation expression* [**SUFFIXES=(** *values* **)**]

[*name* [**{** *index-set* **}**] **:**] *variable* **=** *value* **IMPLIES** *bound relation body relation bound* [**SUFFIXES=(** *values* **)**]

declares an indicator constraint, which extends the first two constraint forms. An indicator constraint conditions the enforcement of a regular constraint on the value of a binary variable. See the section "Indicator Constraints" on page 417 for a detailed description.

NOTE: You can use the alternate forms from Table 9.10 for the relational operators.

The *name* defines the name for the constraint. Use the name to reference constraint attributes, such as the bounds, elsewhere in the PROC OPTMODEL model. If no name is provided, then a default name is created of the form _ACON_[*n*], where *n* is an integer. See the section "Constraints" on page 413 for more information.

The SUFFIXES=() clause enables you to specify certain auxiliary values in the constraint declaration. (For more information, see the section "Suffixes" on page 420.) Dummy parameters that you declare in an *index-set* specification after the constraint *name* can be used in *value* expressions.

Here is a simple example that defines a constraint with a lower bound:

```
proc optmodel;
   var x, y;
   number low;
   con a: x+y >= low;
```

The following example adds an upper bound:

```
   var x, y;
   number low;
   con a: low <= x+y <= low+10;
```

Indexed families of constraints can be defined by specifying an *index-set* after the name. Any dummy parameters that are declared in the *index-set* can be referenced in the expressions that define the constraint. A particular member of an indexed family can be specified by using an *identifier-expression* with a bracketed index list, in the same fashion as array parameters and variables. For example, the following statements create an indexed family of constraints named incr:

```
proc optmodel;
   number n;
   var x{1..n}
   /* require nondecreasing x values */
   con incr{i in 1..n-1}: x[i+1] >= x[i];
```

The CON statement in the example creates constraints incr[1] through incr[n–1].

Constraint expressions cannot be defined using functions that return different values each time they are called. See the section "Indexing" on page 377 for more information.

IMPVAR Declaration

IMPVAR *impvar-decl* [**,** . . . *impvar-decl*] **;**

The IMPVAR declaration specifies one or more names that refer to optimization expressions in the model. The declared name is called an implicit variable. An implicit variable is useful for structuring models so that complex expressions do not need to be repeated each time they are used. The value of an implicit variable needs to be computed only once instead of at each place where the original expression is used, which helps reduce computational overhead. Implicit variables are evaluated without intervention from the solver.

Multiple IMPVAR declarations are allowed. The names of implicit variables must be distinct from other model declarations, such as variables and constraints. Implicit variables can be used in model expressions in the same places where ordinary variables are allowed. When the defining expression does not depend on optimization variables, you can also use implicit variables in constant expressions.

This is the syntax for an *impvar-decl*:

name [**{** *index-set* **}**] **=** *expression*

Each *impvar-decl* declares a name for an implicit variable. The name can be followed by an *index-set* specification to declare a family of implicit variables. The *expression* that the name refers to follows. Dummy parameters that are declared in the *index-set* specification can be used in the expression. The *expression* can refer to other model components, including variables, the current implicit variable, and other implicit variables.

As an example, in the following model statements the implicit variable total_weight is used in multiple constraints to set a limit on various product quantities, represented by locations in array x:

```
impvar total_weight = sum{p in PRODUCTS} Weight[p]*x[p];

con prod1_limit: Weight['Prod1'] * x['Prod1'] <= 0.3 * total_weight;
con prod2_limit: Weight['Prod2'] * x['Prod2'] <= 0.25 * total_weight;
```

MAX and MIN Objective Declarations

MAX *name* [**{** *index-set* **}**] **=** *expression* [**SUFFIXES=(** *values* **)**] **;**

MIN *name* [**{** *index-set* **}**] **=** *expression* [**SUFFIXES=(** *values* **)**] **;**

The MAX or MIN declaration specifies an objective for the solver. The *name* names the objective function for later reference. When an objective declaration is read, the declaration is added to the current problem. The solver maximizes an objective that is specified with the MAX keyword and minimizes an objective that is specified with the MIN keyword. An objective is not allowed to have the same name as a parameter or

variable. Multiple objectives are permitted, but only the black-box solver can process more than one objective at a time. Other solvers consider only the last objective that is added after array objectives are expanded.

The *expression* specifies the numeric function to maximize or minimize in terms of the optimization variables. Specify an *index-set* to declare a family of objectives. Dummy parameters that you declare in the *index-set* specification can be used in the *expression* and *values* that follow it. The SUFFIXES=() clause enables you to specify certain auxiliary values in the objective declaration. For more information, see the section "Suffixes" on page 420.

Objectives can also be used as implicit variables. When used in an expression, an objective name refers to the current value of the named objective function. The value of an unsuffixed objective name can depend on the value of optimization variables, so objective names cannot be used in constant expressions such as variable bounds. You can reference objective names in objective or constraint expressions. For example, the following statements declare two objective names, q and l, which are immediately referred to in the objective declaration of z and the declarations of the constraints:

```
proc optmodel;
   var x, y;
   min q=(x+y)**2;
   max l=x+2*y;
   min z=q+l;
   con c1: q<=4;
   con c2: l>=2;
```

Objectives cannot be defined using functions that return different values each time they are called. See the section "Indexing" on page 377 for details.

NUMBER, STRING, and SET Parameter Declarations

NUMBER *parameter-decl* [**,** . . . *parameter-decl*] **;**

STRING *parameter-decl* [**,** . . . *parameter-decl*] **;**

SET [**<** *scalar-type*, . . . *scalar-type* **>**] *parameter-decl* [**,** . . . *parameter-decl*] **;**

Parameters provide names for constants. Parameters are declared by specifying the parameter type followed by a list of parameter names. Declarations of parameters that have NUMBER or STRING types start with a *scalar-type* specification:

NUMBER | NUM ;

STRING | STR ;

The NUM and STR keywords are abbreviations for the NUMBER and STRING keywords, respectively.

The declaration of a parameter that has the set type begins with a *set-type* specification:

SET [**<** *scalar-type*, . . . *scalar-type* **>**] **;**

In a *set-type* declaration, the SET keyword is followed by a list of *scalar-type* items that specify the member type. A set with scalar members is specified with a single *scalar-type* item. A set with tuple members has a *scalar-type* item for each tuple element. The *scalar-type* items specify the types of the elements at each tuple position.

If the SET keyword is not followed by a list of *scalar-type* items, then the set type is determined from the type of the initialization expression. The declared type defaults to SET<NUMBER> if no initialization expression is given or if the expression type cannot be determined.

For any parameter type, the type declaration is followed by a list of *parameter-decl* items that specify the names of the parameters to declare. In a *parameter-decl* item the parameter name can be followed by an optional index specification and any necessary options, as follows:

name [**{** *index-set* **}**] [*parameter-options*]

The parameter *name* and *index-set* can be followed by a list of *parameter-options*. Dummy parameters declared in the *index-set* can be used in the *parameter-options*. The parameter options can be specified with the following forms:

= *expression*
: provides an explicit value for each parameter location. In this case the parameter acts like an alias for the *expression* value.

INIT *expression*
: specifies a default value that is used when a parameter value is required but no other value has been supplied. For example:

```
number n init 1;
set s init {'a', 'b', 'c'};
```

PROC OPTMODEL evaluates the expression for each parameter location the first time the parameter needs to be resolved. The expression is not used when the parameter already has a value.

= [*initializers* **]**
: provides a compact means to define the values for an array, in which each array location value can be individually specified by the *initializers*.

INIT [*initializers* **]**
: provides a compact means to define multiple default values for an array. Each array location value can be individually specified by the *initializers*. With this option the array values can still be updated outside the declaration.

The =*expression* parameter option defines a parameter value by using a formula. The formula can refer to other parameters. The parameter value is updated when the referenced parameters change. The following example shows the effects of the update:

```
proc optmodel;
   number n;
   set<number> s = 1..n;
   number a{s};
   n = 3;
   a[1] = 2;    /* OK */
   a[7] = 19;   /* error, 7 is not in s */
   n = 10;
   a[7] = 19;   /* OK now */
```

In the preceding example the value of set s is resolved for each use of array a that has an index. For the first use of a[7], the value 7 is not a member of the set s. However, the value 7 is a member of s at the second use of a[7].

The INIT *expression* parameter option specifies a default value for a parameter. The following example shows the usage of this option:

```
proc optmodel;
   num a{i in 1..2} init i**2;
   a[1] = 2;
   put a[*]=;
```

When the value of a parameter is needed but no other value has been supplied, the default value specified by INIT *expression* is used, as shown in Figure 9.5.

Figure 9.5 INIT Option: Output

```
a[1]=2 a[2]=4
```

NOTE: Parameter values can also be read from files or specified with assignment statements. However, the value of a parameter that is assigned with the =*expression* or =[*initializers*] forms can be changed only by modifying the parameters used in the defining expressions. Parameter values specified by the INIT option can be reassigned freely.

Initializing Arrays

Arrays can be initialized with the =[*initializers*] or INIT [*initializers*] forms. These forms are convenient when array location values need to be individually specified. The forms behave the same way, except that the INIT [*initializers*] form allows the array values to be modified after the declaration. These forms of initialization are used in the following statements:

```
proc optmodel;
   number a{1..3} = [5 4 7];
   number b{1..3} INIT [5 4 7];
   put a[*]=;
   b[1] = 1;
   put b[*]=;
```

Each array location receives a different value, as shown in Figure 9.6. The displayed values for b are a combination of the default values from the declaration and the assigned value in the statements.

Figure 9.6 Array Initialization

```
a[1]=5 a[2]=4 a[3]=7
b[1]=1 b[2]=4 b[3]=7
```

Each *initializer* takes the following form:

[**[** *index* **]**] *value*

The *value* specifies the value of an array location and can be a numeric or string constant, a set literal, or an expression enclosed in parentheses.

In array initializers, string constants can be specified using quoted strings. When the string text follows the rules for a SAS name, the text can also be specified without quotation marks. String constants that begin with a digit, contain blanks, or contain other special characters must be specified with a quoted string.

As an example, the following statements define an array parameter that could be used to map numeric days of the week to text strings:

```
proc optmodel;
   string dn{1..5} =
          [Monday Tuesday Wednesday Thursday Friday];
```

The optional *index* in square brackets specifies the index of the array location to initialize. The index specifies one or more numeric or string subscripts. The subscripts allow the same syntactic forms as the *value* items. Commas can be used to separate index subscripts. For example, location a[1,'abc'] of an array a could be specified with the index [1 abc]. The following example initializes just the diagonal locations in a square array:

```
proc optmodel;
   number m{1..3,1..3} = [[1 1] 0.1 [2 2] 0.2 [3 3] 0.3];
```

An index does not need to specify all the subscripts of an array location. If the index begins with a comma, then only the rightmost subscripts of the index need to be specified. The preceding subscripts are supplied from the index that was used by the preceding *initializer*. This can simplify the initialization of arrays that are indexed by multiple subscripts. For example, you can add new entries to the matrix of the previous example by using the following statements:

```
proc optmodel;
   number m{1..3,1..3} = [[1 1] 0.1            [,3] 1
                                     [2 2] 0.2  [,3] 2
                                               [3 3] 0.3];
```

The spacing shows the layout of the example array. The previous example was updated by initializing two more values at m[1,3] and m[2,3].

If an index is omitted, then the next location in the order of the array's index set is initialized. If the index set has multiple *index-set-items*, then the rightmost indices are updated before indices to the left are updated. At the beginning of the initializer list, the rightmost index is the first member of the index set. The index set must use a range expression to avoid unpredictable results when an index value is omitted.

The initializers can be followed by commas. The use of commas has no effect on the initialization. The comma can be used to clarify layout. For example, the comma could separate rows in a matrix.

Not every array location needs to be initialized. The locations without an explicit initializer are set to missing for numeric arrays, set to an empty string for string arrays, and set to an empty set for set arrays. You can also specify a different default value in the last initializer by using an asterisk (*) in place of the *index*. For example:

```
proc optmodel;
   /* initialize to [2 7 30 40] */
   number a{i in 1..4} = [2 7 [*] (i*10)];
```

NOTE: An array location must not be initialized more than once during the processing of the initializer list.

PROBLEM Declaration

PROBLEM *name* [**{** *index-set* **}**] [**FROM** *problem-id*] [**INCLUDE** *problem-items*] [**SUFFIXES=(** *values* **)**] **;**

Problems are declared with the PROBLEM declaration. Problem declarations track objectives, a set of included variables and constraints, and some status information that is associated with the variables and constraints. The problem name can optionally be followed by an *index-set* to create a family of problems. When a problem is first used (via the USE PROBLEM statement), the specifications from the optional FROM and INCLUDE clauses create the initial set of included variables, constraints, and the problem objectives. An empty problem is created if neither clause is specified.

The FROM clause specifies an existing problem from which to copy the set of included symbols. The *problem-id* is an *identifier expression*. The dropped and fixed status for these symbols in the specified problem is also copied. Subsequent changes to the FROM problem via the DROP, FIX, RESTORE, and UNFIX statements do not affect the new problem status.

The INCLUDE clause specifies a list of variables, constraints, and objectives to include in the problem. These items are included with default status (unfixed and undropped) which overrides the status from the FROM clause, if it exists. Each item is specified with one of the following forms:

identifier-expression
: includes the specified items in the problem. The *identifier-expression* can be a symbol name or an array symbol with explicit index. If an array symbol is used without an index, then all array elements are included.

{ *index-set* **}** *identifier-expression*
: includes the specified subset of items in the problem. The item specified by the *identifier-expression* is added to the problem for each member of the *index-set*. The dummy parameters from the *index-set* can be used in the indexing of the *identifier-expression*. If the *identifier-expression* is an array symbol without indexing, then the *index-set* provides the indices for the included locations.

The set of elements that are included by an INCLUDE clause is updated when array indexing for the *identifier-expression* changes or when parameters referenced in the INCLUDE clause change. However, status changes from the DROP, FIX, RESTORE, and UNFIX statements override INCLUDE clauses, including clauses that are inherited from a FROM problem.

You can use the FROM and INCLUDE clauses to designate the objectives for a problem. The objectives are copied from the problem that is designated by the FROM clause, if present. Then the INCLUDE clause, if any, is applied. The black-box solver can process multiple objectives. Other solvers use only the last objective that is specified.

The SUFFIXES=() clause enables you to specify certain auxiliary values in the problem declaration. (For more information, see the section "Suffixes" on page 420.) Dummy parameters that you declare in an *index-set* specification for the problem *name* can be used in the *value* expressions.

The following statements declare some problems with a variable x and different objectives to illustrate some of the ways of including model components. Note that the statements use the predeclared problem _START_ to avoid resetting the objective in prob2 when the objective z3 is declared.

```
proc optmodel;
   problem prob1;
   use problem prob1;
   var x >= 0;              /* included in prob1 */
   min z1 = (x-1)**2;       /* included in prob1 */
   expand;                  /* prob1 contains x, z1 */

   problem prob2 from prob1;
   use problem prob2;       /* includes x, z1 */
   min z2 = (x-2)**2;       /* included in prob2 */
   expand;                  /* prob2 contains x, z1, z2 */
                            /* note z1 is not expanded */

   use problem _start_;     /* don't modify prob2 */
   min z3 = (x-3)**2;
   problem prob3 include x z3;
   use problem prob3;
   expand;                  /* prob3 contains x, z3 */
```

See the section "Multiple Subproblems" on page 454 for more details about problem processing.

VAR Declaration

VAR *var-decl* [**,** . . . *var-decl*] **;**

The VAR statement declares one or more optimization variables. Multiple VAR statements are permitted. A variable is not allowed to have the same name as a parameter or constraint.

Each *var-decl* specifies a variable name. The name can be followed by an array *index-set* specification and then variable options. Dummy parameters declared in the index set specification can be used in the following variable options.

Here is the syntax for a *var-decl*:

name [**{** *index-set* **}**] [*var-options*] [**SUFFIXES=(** *values* **)**]

For example, the following statements declare a group of 100 variables, x[1]–x[100]:

```
proc optmodel;
   var x{1..100};
```

Here are the available variable options:

INIT *expression*
: sets an initial value for the variable. The expression is used only the first time the value is required. If no initial value is specified, then 0 is used by default.

>= *expression*
: sets a lower bound for the variable value. The default lower bound is $-\infty$, or 0 if the BINARY option is used.

<= *expression*
sets an upper bound for the variable value. The default upper bound is ∞, or 1 if the BINARY option is used.

INTEGER
requests that the solver assign the variable an integer value.

BINARY
requests that the solver assign the variable an integer value within default bounds of 0 to 1.

Dummy parameters that you declare in an *index-set* specification for the variable *name* can be used in the variable declaration expressions, including the SUFFIXES=() clause. The SUFFIXES=() clause enables you to specify certain auxiliary values in the declaration. For more information, see the section "Suffixes" on page 420.

For example, the following statements declare a variable that has an initial value of 0.5. The variable is bounded by 0 and 1:

```
proc optmodel;
   var x init 0.5 >= 0 <= 1;
```

The values of the bounds can be determined later by using suffixed references to the variable. For example, the upper bound for variable x can be referred to as x.ub. In addition, the bounds options can be overridden by explicit assignment to the suffixed variable name. Suffixes are described further in the section "Suffixes" on page 420. Note that the bounds for integer and binary variables are rounded to integers according to the value that you specify in the PROC OPTMODEL option INTFUZZ=.

When used in an expression, an unsuffixed variable name refers to the current value of the variable. Unsuffixed variables are not allowed in the expressions for options that define variable bounds or initial values. Such expressions have values that must be fixed during execution of the solver.

Programming Statements

PROC OPTMODEL supports several programming statements. You can perform various actions with these statements, such as reading or writing data sets, setting parameter values, generating text output, or invoking a solver.

Statements are read from the input and are executed immediately when complete. Certain statements can contain one or more substatements. The execution of substatements is held until the statements that contain them are submitted. Parameter values that are used by expressions in programming statements are resolved when the statement is executed; this resolution might cause errors to be detected. For example, the use of undefined parameters is detected during resolution of the symbolic expressions from declarations.

A statement is terminated by a semicolon. The positions at which semicolons are placed are shown explicitly in the following statement syntax descriptions.

The programming statements can be grouped into the categories shown in Table 9.7.

Table 9.7 Types of Programming Statements in PROC OPTMODEL

Control	Looping	General	Input/Output	Model
DO	COFOR	Assignment	CLOSEFILE	DROP
END	CONTINUE	CALL	CREATE DATA	EXPAND
IF	DO Iterative	ENDSOURCE	FILE	FIX
Null (;)	DO UNTIL	ENDSUBMIT	PRINT	RESTORE
QUIT	DO WHILE	PROFILE	PUT	SOLVE
STOP	FOR	RESET OPTIONS	READ DATA	UNFIX
	LEAVE	SOURCE	SAVE MPS	USE PROBLEM
		SUBMIT	SAVE QPS	

Assignment Statement

identifier-expression = *expression* **;**

The assignment statement assigns a variable or parameter value. The type of the target *identifier-expression* must match the type of the right-hand-side expression.

For example, the following statements set the current value for variable x to 3:

```
proc optmodel;
   var x;
   x = 3;
```

NOTE: Parameters that were declared with the equal sign (=) initialization forms must not be reassigned a value with an assignment statement. If this occurs, PROC OPTMODEL reports an error.

CALL Statement

CALL *name* **(** *argument-1* [**,** . . . *argument-n*] **) ;**

The CALL statement invokes the named library subroutine. The values that are determined for each argument expression are passed to the subroutine when the subroutine is invoked. The subroutine can update the values of PROC OPTMODEL parameters and variables when an argument is an *identifier-expression* (see the section "Identifier Expressions" on page 383). For example, the following statements set the parameter array a to a random permutation of 1 to 4:

```
proc optmodel;
   number a{i in 1..4} init i;
   number seed init -1;
   call ranperm(seed, a[1], a[2], a[3], a[4]);
```

NOTE: The maximum length of the string value returned from an output argument is equal to the character length of the argument before the call. An undefined STRING parameter that is used as an output argument has a character length of 8.

For a list of CALL routines, see *SAS Functions and CALL Routines: Reference*. You can also call subroutines that are compiled by the FCMP procedure. For more information, see the section "FCMP Routines" on page 461.

CLOSEFILE Statement

CLOSEFILE *file-specifications* **;**

The CLOSEFILE statement closes files that were opened by the FILE statement. Each file is specified by a logical name, a physical file name in quotation marks, or an expression enclosed in parentheses that evaluates to a physical file name. See the section "FILE Statement" on page 350 for more information about file specifications.

The following example shows how the CLOSEFILE statement is used with a logical file name:

```
filename greet 'hello.txt';
proc optmodel;
   file greet;
   put 'Hi!';
   closefile greet;
```

Generally you must close a file with a CLOSEFILE statement before external programs can access the file. However, any open files are automatically closed when PROC OPTMODEL terminates.

COFOR Statement

COFOR { *index-set* **}** *statement* **;**

The COFOR statement executes its *statement* for each member of the specified *index-set*, similar to how the FOR statement executes. However, in a COFOR statement, PROC OPTMODEL can execute the SOLVE statement concurrently with other statements. The execution of the COFOR substatement is interleaved between loop iterations so that other iterations can be processed while an iteration waits for a SOLVE statement to complete. Multiple solvers can run concurrently. This interleaving is managed so that in many cases a FOR loop can be replaced by a COFOR loop to achieve concurrency with minimal or no other changes to the code.

The following code shows a simple example:

```
proc optmodel printlevel=0 sessref=mysess;
   var x {1..6} >= 0;

   minimize z = sum {j in 1..6} x[j];

   con a1: x[1] + x[2] + x[3]                      <= 4;
   con a2:                     x[4] + x[5] + x[6] <= 6;
   con a3: x[1] +              x[4]               >= 5;
   con a4:        x[2] +               x[5]        >= 2;
   con a5:               x[3] +               x[6] >= 3;

   cofor{i in 3..5} do;
      fix x[1]=i;
      solve;
      put i= x[1]= _solution_status_=;
   end;
```

Figure 9.7 shows the PROC OPTMODEL output. The order of the output from different iterations can vary between runs, depending on the order in which the SOLVE statements complete. Because the SESSREF= option is used, the solvers execute in the distributed computing environment. A FOR statement could have been used instead of COFOR; the FOR statement would produce a consistent output order but only one solver

would be executed at a time. Note that because the solver execution in this example is trivial, the benefits from concurrency are limited.

Figure 9.7 A Simple COFOR Loop

```
i=4 x[1]=4 _SOLUTION_STATUS_=OPTIMAL
i=5 x[1]=5 _SOLUTION_STATUS_=INFEASIBLE
i=3 x[1]=3 _SOLUTION_STATUS_=OPTIMAL
```

A COFOR statement can contain other control and looping statements, including nested COFOR loops. The maximum number of threads that can be used is controlled by the PROC OPTMODEL and SAS options that are in effect when the outermost COFOR loop is entered, as described in the section "Threaded and Distributed Processing" on page 465. The outermost COFOR statement allocates threads for execution on the computer that is running PROC OPTMODEL. When you use a SESSREF= or SESSUUID= option to request distributed computing, the outermost COFOR statement also creates a distributed execution environment. Solvers within the COFOR loop can then run remotely in single-machine mode on the compute nodes (as shown in the solver output).

The COFOR statement supports simultaneous processing of several SOLVE statements. Processing proceeds through the iteration body statements as it would through a FOR loop until a SOLVE statement is executed. After the problem is generated, the solver starts processing in a background thread (or remote computing node in the distributed case) and the COFOR loop switches execution to another iteration of the loop, assuming enough threads and iterations are available. (Note that you need at least two threads on the computer that is running the COFOR loop to enable overlap of statement execution with solver execution.) Execution could switch to an existing iteration where the solver has completed. Alternatively, a new iteration of a COFOR loop could be started. All output from an iteration, except within a SUBMIT block, is displayed together after the iteration has completed. Output from a SUBMIT block is displayed as the block is executed.

You can change the NTHREADS= option value within a COFOR loop by using the RESET OPTIONS statement. The new value affects SOLVE statements that are executed subsequently in the same iteration but not those in other iterations. When a COFOR statement is running in distributed mode, the default value of the NTHREADS= option is the number of threads per compute node, as determined when the outermost COFOR loop starts. Otherwise the default value of the NTHREADS= option is 1. Executing SOLVE statements in the background by using a single thread usually provides the best performance on a single computer.

The order in which the solvers complete is unpredictable. So it is usually not useful for a problem that is solved within an iteration to depend on the results of SOLVE statements that are executed in other iterations of the COFOR loop. It is advisable to limit global parameter updates to operations where order is not important, such as accumulating counts, sums, or unions or writing mutually exclusive subsets of an array. It is possible to execute multiple SOLVE statements within a loop iteration, and subsequent solver invocations within an iteration can use results from prior solvers in the same iteration.

In many cases, a COFOR loop iteration solves a specialized version of a common problem structure. This requires it to modify problem attributes that are also used in other iterations, such as coefficient values or the fixed status of variables. Changes to problem attributes are not made visible to other iterations of a COFOR loop in order to avoid confusing behavior due to interleaved execution. For example, the value printed for x[1] in Figure 9.7 is the local value for the iteration, not the most recent global value. Changes to these attributes create or update a copy of the value that is local to the iteration. These attribute values along with the local dummy parameters provide a local context for the iteration.

The following problem attributes are automatically made local to the modifying iteration when they are changed within a COFOR loop:

- the current problem, selected by USE PROBLEM
- the value of variables and their suffix values
- the fixed status of variables
- the constraint suffix values
- the dropped status of constraints
- the .LABEL suffix
- NUMBER, STRING, and SET parameters that determine values that are used in the bounds or body expressions of problem declarations (CONSTRAINT, IMPVAR, MIN, MAX, or VAR)
- NUMBER, STRING, and SET parameters that determine values that are used in solver arguments within the same outermost COFOR loop
- the predeclared string parameters _SOLVER_OPTIONS_ and _*solver*_OPTIONS_ (for each solver)

To illustrate these rules, consider the following code, which uses the NLP solver to solve a MINLP portfolio optimization problem by selecting random subsets of the assets to optimize:

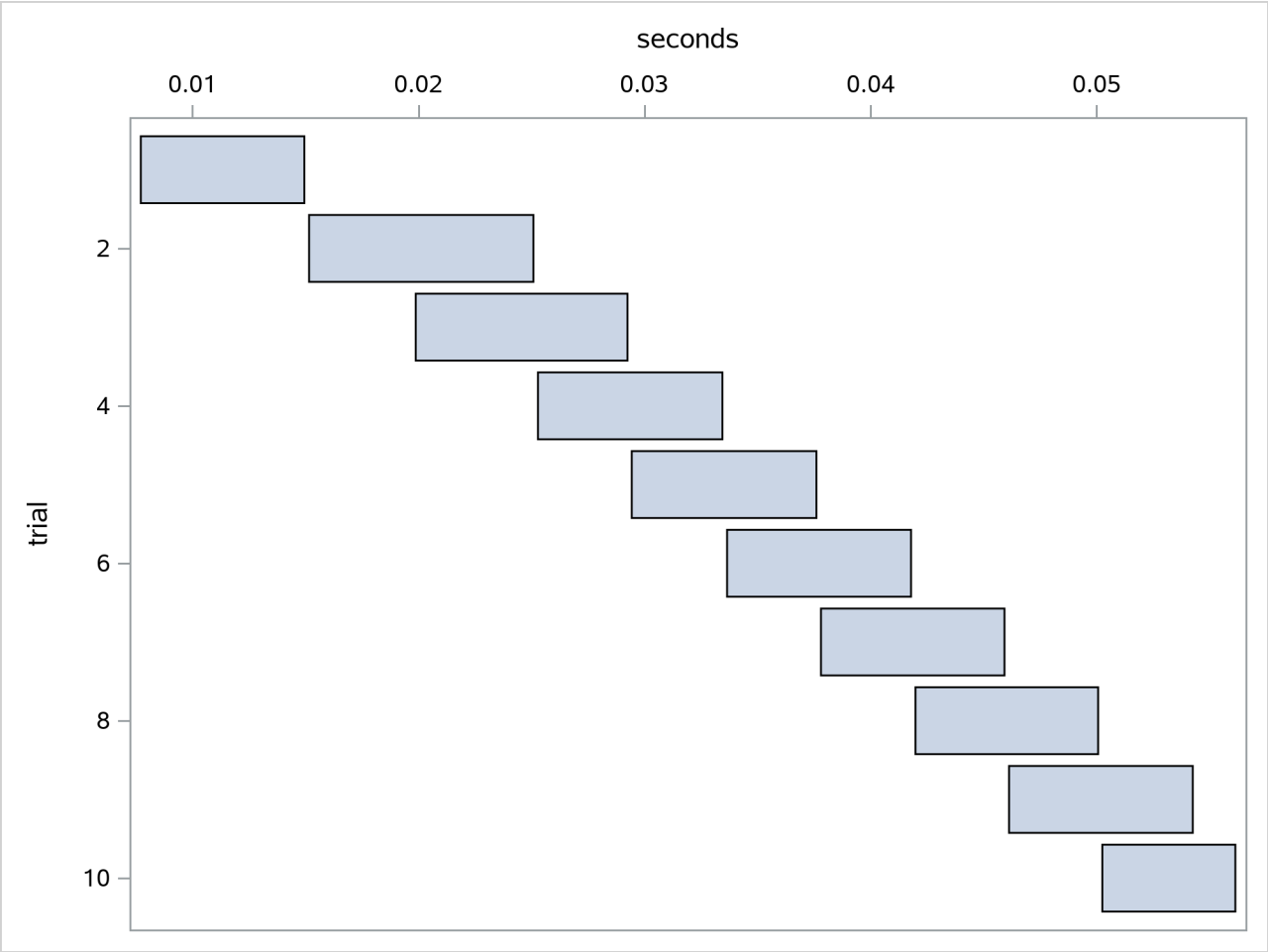
```
proc optmodel printlevel=0 nthreads=4;
   /* assets and related parameters */
   set ASSETS;
   num return {ASSETS};
   num cov {ASSETS, ASSETS} init 0;
   read data means into ASSETS=[_n_] return;
   read data covdata into [asset1 asset2] cov cov[asset2,asset1]=cov;
   num riskLimit init 0.00025;
   num minThreshold init 0.1;
   num numTrials = 10;

   /* number of random trials */
   set TRIALS = 1..numTrials;

   /* declare NLP problem for fixed set of assets */
   set ASSETS_THIS;
   var AssetPropVar {ASSETS} >= minThreshold <= 1;
   max ExpectedReturn = sum {i in ASSETS} return[i] * AssetPropVar[i];
   con RiskBound:
      sum {i in ASSETS_THIS, j in ASSETS_THIS}
          cov[i,j] * AssetPropVar[i] * AssetPropVar[j] <= riskLimit;
   con TotalPortfolio:
      sum {asset in ASSETS} AssetPropVar[asset] = 1;

   /* parameters to track best solution */
   num infinity = constant('BIG');
   num best_objective init -infinity;
   set INCUMBENT;

   /* iterate over trials */
   num start  {TRIALS};
```

```
   num finish {TRIALS};
   num overall_start;
   overall_start = time();
   call streaminit(1);
   cofor {trial in TRIALS} do;
      start[trial] = time() - overall_start;
      put;
      put trial=;
      ASSETS_THIS = {i in ASSETS: rand('UNIFORM') < 0.5};
      put ASSETS_THIS=;
      for {i in ASSETS diff ASSETS_THIS}
         fix AssetPropVar[i] = 0;
      solve with NLP / logfreq=0;
      put _solution_status_=;
      if _solution_status_ ne 'INFEASIBLE' then do;
         if best_objective < ExpectedReturn then do;
            best_objective = ExpectedReturn;
            INCUMBENT = ASSETS_THIS;
         end;
      end;
      finish[trial] = time() - overall_start;
   end;

   put best_objective= INCUMBENT=;
   create data plotdata from [trial] start finish;

proc sgplot data=plotdata;
   highlow y=trial low=start high=finish / type=bar x2axis;
   yaxis reverse;
   x2axis label="seconds";
run;
```

All the COFOR loop iterations use the same problem, _START_. However, the changes to the problem are local to the iteration that makes them. For example, the FIX statement does not affect variables in other iterations. The value of the ASSETS_THIS parameter is used by the RiskBound constraint, so the change to it is local. Because AssetPropVar is a VAR, the changes to its value are also local.

On the other hand, the values of the best_objective and INCUMBENT parameters do not affect any problem declarations. Therefore, their global values are used, enabling the code in the COFOR loop to select and save the best result. Similarly, the start and finish parameters are not used in the problem and allow the overlapping of iterations to be illustrated. Figure 9.8 from the SGPLOT procedure shows how the iterations have overlapped execution times.

Figure 9.8 Overlapped COFOR Iterations



Changes to problem attributes from completed iterations are made visible after the loop is finished. They appear in the context that contained the COFOR statement. If multiple iterations modify the same problem attribute value, then the value from the iteration that completed last is the one made visible.

The LEAVE statement can be used to terminate execution of a COFOR loop. This completes the current iteration of the COFOR loop. The currently active solvers for the COFOR loop are terminated, and the output of the incomplete iterations is discarded. The CONTINUE statement within a COFOR loop can also be used to complete the current iteration, but it has no effect on other iterations.

Using the LEAVE statement to terminate is useful, for example, when a sufficiently good solution is found for a problem. The preceding code has been modified as follows to keep generating solutions until a time limit is reached. The code sets a time limit and then executes the LEAVE statement to stop processing when the limit is exceeded. The COFOR loop uses a very large iteration range to allow it to run indefinitely.

```
proc optmodel printlevel=0;
   set ASSETS;
   num return {ASSETS};
   num cov {ASSETS, ASSETS} init 0;
   read data means into ASSETS=[_n_] return;
   read data covdata into [asset1 asset2] cov cov[asset2,asset1]=cov;
```

```
   num riskLimit init 0.00025;
   num minThreshold init 0.1;

   /* declare NLP problem for fixed set of assets */
   set ASSETS_THIS;
   var AssetPropVar {ASSETS} >= minThreshold <= 1;
   max ExpectedReturn = sum {i in ASSETS} return[i] * AssetPropVar[i];
   con RiskBound:
      sum {i in ASSETS_THIS, j in ASSETS_THIS}
          cov[i,j] * AssetPropVar[i] * AssetPropVar[j] <= riskLimit;
   con TotalPortfolio:
      sum {asset in ASSETS} AssetPropVar[asset] = 1;

   num infinity = constant('BIG');
   num best_objective init -infinity;
   set INCUMBENT;

   /* run for 30 seconds */
   num last_time;
   last_time = time() + 30;
   num n_trials init 0;
   call streaminit(1);
   cofor {trial in 1..1e9} do;
      put;
      put trial=;
      ASSETS_THIS = {i in ASSETS: rand('UNIFORM') < 0.5};
      put ASSETS_THIS=;
      for {i in ASSETS diff ASSETS_THIS} fix AssetPropVar[i] = 0;
      solve with NLP / logfreq=0;
      put _solution_status_=;
      if _solution_status_ ne 'INFEASIBLE' then do;
         if best_objective < ExpectedReturn then do;
            best_objective = ExpectedReturn;
            INCUMBENT = ASSETS_THIS;
         end;
      end;
      n_trials = n_trials + 1;
      if time() >= last_time then leave;
   end;

   put n_trials=;
   put best_objective= INCUMBENT=;
quit;
```

CONTINUE Statement

CONTINUE ;

The CONTINUE statement terminates the current iteration of the loop statement (iterative DO, DO UNTIL, DO WHILE, FOR, or COFOR) that immediately contains the CONTINUE statement. Execution resumes at the start of the loop after checking WHILE or UNTIL tests. The FOR, COFOR, or iterative DO loops apply new iteration values.

CREATE DATA Statement

CREATE DATA *SAS-data-set* **FROM** [**[** *key-columns* **]** [**=** *key-set*]] *columns* **;**

The CREATE DATA statement creates a new SAS data set and copies data into it from PROC OPTMODEL parameters and variables. The CREATE DATA statement can create a data set with a single observation or a data set with observations for every location in one or more arrays. The data set is closed after the execution of the CREATE DATA statement.

NOTE: Currently, the source data are always located on the client.

The arguments to the CREATE DATA statement are as follows:

SAS-data-set
: specifies the output data set name and options. You can specify the data set name and options directly or as the string value of an expression enclosed in parentheses.

key-columns
: declares index values and their corresponding data set variables. The values are used to index array locations in *columns*.

key-set
: specifies a set of index values for the *key-columns*.

columns
: specifies data set variables as well as the PROC OPTMODEL source data for the variables.

Each *column* or *key-column* defines output data set variables and a data source for a column. For example, the following statement generates the output SAS data set resdata from the PROC OPTMODEL array opt, which is indexed by the set indset:

```
create data resdata from [solns]=indset opt;
```

The output data set variable solns contains the index elements in indset.

Columns

Columns can have the following forms:

identifier-expression [/ *options*]
: transfers data from the PROC OPTMODEL parameter or variable specified by the *identifier-expression*. The output data set variable has the same name as the *name* part of the *identifier-expression* (see the section "Identifier Expressions" on page 383). If the *identifier-expression* refers to an array, then the index can be omitted when it matches the *key-columns*. The *options* enable formats and labels to be associated with the data set variable. See the section "Column Options" on page 341 for more information. The following example creates a data set with the variables m and n:

```
proc optmodel;
   number m = 7, n = 5;
   create data example from m n;
```

name **=** *expression* [/ *options*]

transfers the value of a PROC OPTMODEL expression to the output data set variable *name*. The *expression* is reevaluated for each observation. If the *expression* contains any operators or function calls, then it must be enclosed in parentheses. If the *expression* is an *identifier-expression* that refers to an array, then the index can be omitted if it matches the *key-columns*. The *options* enable formats and labels to be associated with the data set variable. See the section "Column Options" on page 341 for more information. The following example creates a data set with the variable ratio:

```
proc optmodel;
   number m = 7, n = 5;
   create data example from ratio=(m/n);
```

COL(*name-expression***) =** *expression* [/ *options*]

transfers the value of a PROC OPTMODEL expression to the output data set variable named by the string expression *name-expression*. The PROC OPTMODEL expression is reevaluated for each observation. If this expression contains any operators or function calls, then it must be enclosed in parentheses. If the PROC OPTMODEL *expression* is an *identifier-expression* that refers to an array, then the index can be omitted if it matches the *key-columns*. The *options* enable formats and labels to be associated with the data set variable. See the section "Column Options" on page 341 for more information. The following example uses the COL expression to form the variable s5:

```
proc optmodel;
   number m = 7, n = 5;
   create data example from col("s"||n)=(m+n);
```

{ *index-set* **}** **<** *columns* **>**

performs the transfers by iterating each column specified by **<** *columns* **>** for each member of the *index set*. If there are n columns and m index set members, then $n \times m$ columns are generated. The dummy parameters from the index set can be used in the columns to generate distinct output data set variable names in the iterated columns, using COL expressions. The columns are expanded when the CREATE DATA statement is executed, before any output is performed. This form of *columns* cannot be nested. In other words, the following form of *columns* is NOT allowed:

{ *index-set* **}** **<** **{** *index-set* **}** **<** *columns* **>** **>**

The following example demonstrates the use of the iterated *columns* form:

```
proc optmodel;
   set<string> alph = {'a', 'b', 'c'};
   var x{1..3, alph} init 2;
   create data example from [i]=(1..3)
      {j in alph}<col("x"||j)=x[i,j]>;
```

The data set created by these statements is shown in Figure 9.9.

Figure 9.9 CREATE DATA with COL Expression

Obs	i	xa	xb	xc
1	1	2	2	2
2	2	2	2	2
3	3	2	2	2

NOTE: When no *key-columns* are specified, the output data set has a single observation.

The following statements incorporate several of the preceding examples to create and print a data set by using PROC OPTMODEL parameters:

```
proc optmodel;
   number m = 7, n = 5;
   create data example from m n ratio=(m/n) col("s"||n)=(m+n);

proc print;
run;
```

The output from the PRINT procedure is shown in Figure 9.10.

Figure 9.10 CREATE DATA for Single Observation

Obs	m	n	ratio	s5
1	7	5	1.4	12

Column Options

Each *column* or *key-column* that defines a data set variable can be followed by zero or more of the following modifiers:

FIXED [**=***length*]
stores a character column with fixed length even when the data set engine supports VARCHAR. The optional *length* argument specifies a byte length for the column. The length can be specified by a numeric constant or an expression in parentheses. The value of *length* can be between 1 and 32,767.

FORMAT=*format.*
associates a format with the current column.

INFORMAT=*informat.*
associates an informat with the current column.

LABEL='*label*'
associates a label with the current column. The label can be specified by a quoted string or an expression in parentheses.

LENGTH=*length*
specifies a length for the current column. The length can be specified by a numeric constant or a parenthesized expression. For character columns, the length specifies a character length. The character length is used to determine a byte length for the column so that any character string of the specified length can be represented in the output encoding. For example, specifying LENGTH=5 with UTF-8 encoding produces a byte length of 20, whereas a single-byte encoding produces a byte length of 5.

For character columns, the minimum length is 1, and the maximum length depends on the data set engine. Output to fixed CHAR variables is limited to 32,767 bytes, but VARCHAR output can use up to $2^{31} - 1$ bytes. For numeric columns, the length specifies a byte length for the output variable. The range for numeric variables depends on the operating environment and has a minimum of 2 or 3.

TRANSCODE=YES | NO
specifies whether character variables can be transcoded. The default value is YES. See the TRANSCODE=option of the ATTRIB statement in *SAS DATA Step Statements: Reference* for more information.

The following statements demonstrate the use of column options, including the use of multiple options for a single column:

```
proc optmodel;
   num sq{i in 1..10} = i*i;
   create data squares from [i/format=hex2./length=3] sq/format=6.2;

proc print;
run;
```

The output from the PRINT procedure is shown in Figure 9.11.

Figure 9.11 CREATE DATA with Column Options

Obs	i	sq
1	01	1.00
2	02	4.00
3	03	9.00
4	04	16.00
5	05	25.00
6	06	36.00
7	07	49.00
8	08	64.00
9	09	81.00
10	0A	100.00

Key Columns

Key-columns declare index values that enable multiple observations to be written from array *columns*. An observation is created for each unique index value combination. The index values supply the index for array *columns* that do not have an explicit index.

Key-columns define the data set variables where the index value elements are written. They can also declare local dummy parameters for use in expressions in the *columns*. *Key-columns* are syntactically similar to *columns*, but are more restricted in form. The following forms of *key-columns* are allowed:

name [/ *options*]
transfers an index element value to the data set variable *name*. A local dummy parameter, *name*, is declared to hold the index element value. The *options* enable formats and labels to be associated with the data set variable. See the section "Column Options" on page 341 for more information.

COL(*name-expression***)** [**=** *index-name*] [/ *options*]
transfers an index element value to the data set variable named by the string-valued *name-expression*. The argument *index-name* optionally declares a local dummy parameter to hold the index element value. The *options* enable formats and labels to be associated with the data set variable. See the section "Column Options" on page 341 for more information.

A *key-set* in the CREATE DATA statement explicitly specifies the set of index values. You can specify *key-set* as an identifier expression, an index set expression, a set constructor expression, or an arbitrary set expression enclosed in parentheses. When you specify *key-set* as an index set expression, the *index-set* dummy parameters remain visible in *columns* and override dummy parameters that are declared in the *key-columns* items with the same name.

The following statements create a data set from the PROC OPTMODEL parameter m, a matrix whose only nonzero entries are located at (1, 1) and (4, 1):

```
proc optmodel;
   number m{1..5, 1..3} = [[1 1] 1 [4 1] 1 [*] 0];
   set ISET = setof{i in 1..2} i**2;
   create data example
      from [i j] = {i in ISET, {1, 2}} m;

proc print data=example noobs;
run;
```

The dummy parameter i in the *key-set* expression takes precedence over the dummy parameter i declared in the *key-columns* item. The output from these statements is shown in Figure 9.12.

Figure 9.12 CREATE: *key-set* with SETOF Aggregation Expression

i	j	m
1	1	1
1	2	0
4	1	1
4	2	0

If no *key-set* is specified, then the set of index values is formed from the union of the index sets of the implicitly indexed *columns*. The number of index elements for each implicitly indexed array must match the number of *key-columns*. The type of each index element (string versus numeric) must match the element of the same position in other implicit indices.

The arrays for implicitly indexed columns in a CREATE DATA statement do not need to have identical index sets. A missing value is supplied for the value of an implicitly indexed array location when the implied index value is not in the array's index set.

In the following statements, the *key-set* is unspecified. The set of index values is $\{1, 2, 3\}$, which is the union of the index sets of x and y. These index sets are not identical, so missing values are supplied when necessary. The results of these statements are shown in Figure 9.13.

```
proc optmodel;
   number x{1..2} init 2;
   var y{2..3} init 3;
   create data exdata from [keycol] x y;
```

```
proc print;
run;
```

Figure 9.13 CREATE: Unspecified *key-set*

Obs	keycol	x	y
1	1	2	.
2	2	2	3
3	3	.	3

The types of the output data set variables match the types of the source values. The output variable type for a *key-columns* value matches the corresponding element type in the index value tuple. A numeric element matches a numeric data set variable, and a string element matches a character variable. For regular *columns*, the source expression type determines the output data set variable type. A numeric expression produces a numeric variable, and a string expression produces a character variable. Character variables that do not include a FIXED= column option are stored in VARCHAR form when the data set engine supports that form. Otherwise, character variables are stored in fixed CHAR form.

Lengths of character variables in the output data set are determined automatically when the LENGTH= column option is not specified. The length is set to accommodate the longest string value output in that column.

You can use the iterated *columns* form to output selected rows of multiple arrays, assigning a different data set variable to each column. For example, the following statements output the last two rows of the two-dimensional array, a, along with corresponding elements of the one-dimensional array, b:

```
proc optmodel;
   num m = 3;  /* number of rows/observations */
   num n = 4;  /* number of columns in a */
   num a{i in 1..m, j in 1..n} = i*j;  /* compute a */
   num b{i in 1..m} = i**2;  /* compute b */
   set<num> subset = 2..m;  /* used to omit first row */
   create data out
          from [i]=subset {j in 1..n}<col("a"||j)=a[i,j]> b;
```

The preceding statements create a data set out, which has $m - 1$ observations and $n + 2$ variables. The variables are named i, a1 through an, and b, as shown in Figure 9.14.

Figure 9.14 CREATE DATA Set: The Iterated Column Form

Obs	i	a1	a2	a3	a4	b
1	2	2	4	6	8	4
2	3	3	6	9	12	9

See the section "Data Set Input/Output" on page 401 for more examples of using the CREATE DATA statement.

DO Statement

DO ; *statements* **; END ;**

The DO statement groups a sequence of statements together as a single statement. Each statement within the list is executed sequentially. The DO statement can be used for grouping with the IF, FOR, and COFOR statements.

DO Statement, Iterative

DO *name* **=** *specification-1* [**,** *. . . specification-n*] **;** *statements* **; END ;**

The iterative DO statement assigns the values from the sequence of *specification* items to a previously declared parameter or variable, *name*. The specified statement sequence is executed after each assignment. This statement corresponds to the iterative DO statement of the DATA step.

Each *specification* provides either a single number or a single string value, or a sequence of such values. Each *specification* takes the following form:

expression [**WHILE(** *logic-expression* **)** | **UNTIL(** *logic-expression* **)**]

The *expression* in the *specification* provides a single value or set of values to assign to the target *name*. Multiple values can be provided for the loop by giving multiple *specification* items that are separated by commas. For example, the following statements output the values 1, 3, and 5:

```
proc optmodel;
   number i;
   do i=1,3,5;
      put i;
   end;
```

In this case, the same effect can be achieved with a single range expression in place of the explicit list of values, as in the following statements:

```
proc optmodel;
   number i;
   do i=1 to 5 by 2;
      put 'value of i assigned by the DO loop = ' i;
      i=i**2;
      put 'value of i assigned in the body of the loop = ' i;
   end;
```

The output of these statements is shown in Figure 9.15.

Figure 9.15 DO Loop: Name Parameter Unaffected

```
value of i assigned by the DO loop = 1
value of i assigned in the body of the loop = 1
value of i assigned by the DO loop = 3
value of i assigned in the body of the loop = 9
value of i assigned by the DO loop = 5
value of i assigned in the body of the loop = 25
```

Unlike the DATA step, a range expression requires the limit to be specified. Additionally the BY part, if any, must follow the limit expression. Moreover, although the *name* parameter can be reassigned in the body of

the loop, the sequence of values that is assigned by the DO loop is unaffected.

The argument *expression* can also be an expression that returns a set of numbers or strings. For example, the following statements produce the same sequence of values for i as the previous statements but use a set parameter value:

```
proc optmodel;
   set s = {1,3,5};
   number i;
   do i = s;
      put i;
   end;
```

Each *specification* can include a WHILE or UNTIL clause. A WHILE or UNTIL clause applies to the *expression* that immediately precedes the clause. The sequence that is specified by an *expression* can be terminated early by a WHILE or UNTIL clause. A WHILE *logic-expression* is evaluated for each sequence value before the nested *statements*. If the *logic-expression* returns a false (zero or missing) value, then the current sequence is terminated immediately. An UNTIL *logic-expression* is evaluated for each sequence value after the nested *statements*. The sequence from the current *specification* is terminated if the *logic-expression* returns a true value (nonzero and nonmissing). After early termination of a sequence due to a WHILE or UNTIL expression, the DO loop execution continues with the next *specification*, if any.

To demonstrate use of the WHILE clause, the following statements output the values 1, 2, and 3. In this case the sequence of values from the set s is stopped when the value of i reaches 4.

```
proc optmodel;
   set s = {1,2,3,4,5};
   number i;
   do i = s while(i NE 4);
      put i;
   end;
```

DO UNTIL Statement

DO UNTIL (*logic-expression* **) ;** *statements* **; END ;**

The DO UNTIL loop executes the specified sequence of statements repeatedly until the *logic-expression*, evaluated after the *statements*, returns true (a nonmissing nonzero value).

For example, the following statements output the values 1 and 2:

```
proc optmodel;
   number i;
   i = 1;
   do until (i=3);
      put i;
      i=i+1;
   end;
```

Multiple criteria can be introduced using expression operators, as in the following example:

```
do until (i=3 and j=7);
```

For a list of expression operators, see Table 9.10.

DO WHILE Statement

DO WHILE (*logic-expression* **) ;** *statements* **; END ;**

The DO WHILE loop executes the specified sequence of statements repeatedly as long as the *logic-expression*, evaluated before the *statements*, returns true (a nonmissing nonzero value).

For example, the following statements output the values 1 and 2:

```
proc optmodel;
   number i;
   i = 1;
   do while (i<3);
      put i;
      i=i+1;
   end;
```

Multiple criteria can be introduced using expression operators, as in the following example:

```
do while (i<3 and j<7);
```

For a list of expression operators, see Table 9.10.

DROP Statement

DROP *constraint-list* **;**

The DROP statement causes the solver to ignore a list of constraints, constraint arrays, or constraint array locations. The space-delimited *constraint-list* specifies the names of the dropped constraints. Each constraint, constraint array, or constraint array location is named by an *identifier-expression*. An entire constraint array is dropped if an *identifier-expression* omits the index for an array name. Each *identifier-expression* can be prefixed by an indexing set to specify the constraint indices.

The following example statements use the DROP statement:

```
proc optmodel;
   var x{1..10};
   con c1: x[1] + x[2] <= 3;
   con disp{i in 1..9}: x[i+1] >= x[i] + 0.1;

   drop c1;        /* drops the c1 constraint */
   drop disp[5];   /* drops just disp[5] */
   drop {i in 1..3} disp;  /* drops disp[1] disp[2] disp[3] */
   drop disp;      /* drops all disp constraints */
```

The following line drops both the c1 and disp[5] constraints:

```
drop c1 disp[5];
```

Constraints can be added back to the model by using the RESTORE statement.

END Statement

END ;

The END statement marks the end of the list of statements that are executed by a DO group statement, iterative DO statement, DO UNTIL statement, or DO WHILE statement.

ENDSOURCE Statement

ENDSOURCE ;

The ENDSOURCE statement is the default marker for the end of a SOURCE block that begins with a SOURCE statement.

ENDSUBMIT Statement

ENDSUBMIT ;

The ENDSUBMIT statement marks the end of the SAS code block that begins with a SUBMIT statement.

EXPAND Statement

EXPAND [*identifier-expression*] [/ *options*] **;**

The EXPAND statement prints the specified constraint, variable, implicit variable, or objective declaration expressions in the current problem after expanding aggregation operators, substituting the current value for parameters and indices, and resolving constant subexpressions. *identifier-expression* is the name of a variable, objective, or constraint. If the name is omitted and no *options* are specified, then all variables, the last objective, used implicit variables, and undropped constraints in the current problem are printed. The following statements show an example EXPAND statement:

```
proc optmodel;
   number n=2;
   var x{1..n};
   min z1=sum{i in 1..n}(x[i]-i)**2;
   max z2=sum{i in 1..n}(i-x[i])**3;
   con c{i in 1..n}: x[i]>=0;
   fix x[2]=3;
   expand;
```

These statements produce the output in Figure 9.16.

Figure 9.16 EXPAND Statement Output

```
Var x[1]
Fix x[2] = 3
Maximize z2=(-x[1] + 1)**3 + (-x[2] + 2)**3
Constraint c[1]: x[1] >= 0
Constraint c[2]: x[2] >= 0
```

Specifying an *identifier-expression* restricts output to the specified declaration. A non-array name prints only the specified item. If an array name is used with a specific index, then information for the specified array location is output. Using an array name without an index restricts output to all locations in the array.

You can use the following *options* to further control the EXPAND statement output:

SOLVE

causes the EXPAND statement to print the variables, objectives, and constraints in the same form that would be seen by the solver if a SOLVE statement were executed. This includes any transformations by the PROC OPTMODEL presolver (see the section "Presolver" on page 432). In this form any fixed variables are replaced by their values. Unless an *identifier-expression* specifies a particular non-array item or array location, the EXPAND output is restricted to only the variables, the constraints, and the current problem objective.

The following options restrict the types of declarations output when no specific non-array item or array location is requested. By default, variables, implicit variables, the current objective, and constraints are output. Only the requested declaration types are output when one or more of the following options are used.

ALL

requests the output of all declaration types. This includes the complete list of problem objectives, not just the current objective.

ALLOBJ

requests the output of all objectives that are used in the current problem. This includes the complete list of problem objectives and any objectives that are referenced as implicit variables.

CONIC

transforms objectives and constraints for processing by the conic solver, where possible. PROC OPTMODEL replaces suitable nonlinear subexpressions by using added variables, linear constraints, and second-order cone constraints. See the section "Conic Transformation" on page 442 for a description of the supported transformations.

CONSTRAINT | CON

requests the output of undropped constraints.

FIX

requests the output of fixed variables. These variables might have been fixed by the FIX statement (or by the presolver if the SOLVE option is specified). The FIX option can also be used in combination with the name of a variable array to display just the fixed elements of the array.

IIS

restricts the display to items that are found in the irreducible infeasible set (IIS) after the most recent SOLVE that was performed by the LP, MILP, NLP, or QP solver with the IIS=TRUE option. The IIS option for the EXPAND statement can also be used in combination with the name of a variable or constraint array to display only the elements of the array in the IIS. For more information, see the section "Irreducible Infeasible Set" on page 655 (LP), "Irreducible Infeasible Set" on page 733 (MILP), "Example 16.8: Finding an Irreducible Infeasible Set" on page 998 (NLP), or "Irreducible Infeasible Set" on page 1019 (QP).

IMPVAR

requests the output of nonconstant implicit variables referenced in the current problem.

LINEARIZE
transforms objectives and constraints into linear form where possible. PROC OPTMODEL replaces certain nonlinear subexpressions with linear equivalents, using added variables and constraints. See the section "Linearization" on page 433 for a description of the supported transformations.

OBJECTIVE | OBJ
requests the output of objectives that are used in the current problem. This includes the current problem objective and any objectives referenced as implicit variables.

OMITTED
requests the output of variables that are referenced by problem formulas but are not included in the current USE PROBLEM instance. The OPTMODEL procedure omits these variables from the generated problem.

VAR
requests the output of unfixed variables. The VAR option can also be used in combination with the name of a variable array to display just the unfixed elements of the array.

For example, you can see the effect of a FIX statement on the problem that is presented to the solver by using the SOLVE option. You can modify the previous example as follows:

```
proc optmodel;
   number n=2;
   var x{1..n};
   min z1=sum{i in 1..n}(x[i]-i)**2;
   max z2=sum{i in 1..n}(i-x[i])**3;
   con c{i in 1..n}: x[i]>=0;
   fix x[2]=3;
   expand / solve;
```

These statements produce the output in Figure 9.17.

Figure 9.17 Expansion with Fixed Variable

```
Var x[1] >= 0
Fix x[2] = 3
Maximize z2=(-x[1] + 1)**3 - 1
```

Compare the results in Figure 9.17 to those in Figure 9.16. The constraint c[1] has been converted to a variable bound. The subexpression that uses the fixed variable has been resolved to a constant.

FILE Statement

FILE *file-specification* [**LRECL=***value*] **;**

The FILE statement selects the current output file for the PUT statement. By default PUT output is sent to the SAS log. Use the FILE statement to manage a group of output files. The specified file is opened for output if it is not already open. The output file remains open until it is closed with the CLOSEFILE statement.

The *file-specification* names the output file. It can use any of the following forms:

'*external-file*'
specifies the physical name of an external file in quotation marks. The interpretation of the file name depends on the operating environment.

file-name
specifies the logical name associated with a file by the FILENAME statement or by the operating environment. The names PRINT and LOG are reserved to refer to the SAS listing and log files, respectively.

NOTE: Details about the FILENAME statement can be found in *SAS Global Statements: Reference*.

(*expression* **)**
specifies an expression that evaluates to a string that contains the physical name of an external file.

The LRECL= option sets the line length of the output file. The LRECL= option is ignored if the file is already open or if the PRINT or LOG file is specified.

The LRECL= *value* can be specified in these forms:

integer
specifies the desired line length.

identifier-expression
specifies the name of a numeric parameter that contains the length.

(*expression* **)**
specifies a numeric expression in parentheses that returns the line length.

The LRECL= *value* cannot exceed the largest four-byte signed integer, which is $2^{31} - 1$.

The following example shows how to use the FILE statement to handle multiple files:

```
proc optmodel;
   file 'file.txt' lrecl=80;   /* opens file.txt     */
   put 'This is line 1 of file.txt.';
   file print;                  /* selects the listing */
   put 'This goes to the listing.';
   file 'file.txt';            /* reselects file.txt */
   put 'This is line 2 of file.txt.';
   closefile 'file.txt';       /* closes file.txt    */
   file log;                    /* selects the SAS log */
   put 'This goes to the log.';

   /* using expression to open and write a collection of files */
   str ofile;
   num i;
   num l = 40;
   do i = 1 to 3;
      ofile = ('file' || i || '.txt');
      file (ofile) lrecl=(l*i);
      put ('This goes to ' || ofile);
      closefile (ofile);
   end;
```

The following statements illustrate the usefulness of using a logical name associated with a file by FILENAME statement:

```
proc optmodel;
   /* assigns a logical name to file.txt */
   /* see FILENAME statement in        */
   /* SAS Global Statements: Reference */
   filename myfile 'file.txt' mod;

   file myfile;
   put 'This is line 3 of file.txt.';
   closefile myfile;
   file myfile;
   put 'This is line 4 of file.txt.';
   closefile myfile;
```

Notice that the FILENAME statement opens the file referenced for append. Therefore, new data are appended to the end every time the logical name, myfile, is used in the FILE statement.

FIX Statement

FIX *variable-list* [**=** *expression*] **;**

The FIX statement causes the solver to treat a list of variables, variable arrays, or variable array locations as fixed in value. The *variable-list* consists of one or more variable names separated by spaces. Each member of the *variable-list* is fixed to the same *expression*. For example, the following statements fix the variables x and y to 3:

```
proc optmodel;
   var x, y;
   num a = 2;
   fix x y=a+1;
```

A variable is specified with an *identifier-expression* (see the section "Identifier Expressions" on page 383). An entire variable array is fixed if the *identifier-expression* names an array without providing an index. Each *identifier-expression* can be prefixed by an indexing set to specify the variable indices.

You can specify a new value for the variables by using the *expression*. If a single *identifier-expression* is specified, prefixed by an indexing set, then the *expression* is evaluated for each element in the indexing set. Otherwise the *expression* is evaluated exactly once. For example, the following statements fix all locations in array x to 0 except x[10], which is fixed to 1:

```
proc optmodel;
   var x{1..10};
   fix x = 0;
   fix x[10] = 1;
```

The same effect can be achieved using a single statement:

```
   fix {i in 1..10} x[i] = if i eq 10 then 1 else 0;
```

If *expression* is omitted, the variable is fixed at its current value. For example, you can fix some variables to be their optimal values after the SOLVE statement is invoked. **NOTE:** The fixed value is equal to the current value for a fixed variable. The fixed value is updated if a new value is assigned to a fixed variable.

The effect of FIX can be reversed by using the UNFIX statement.

FOR Statement

FOR { *index-set* **}** *statement* **;**

The FOR statement executes its substatement for each member of the specified *index-set*. The index set can declare local dummy parameters. You can reference the value of these parameters in the substatement. For example, consider the following statements:

```
proc optmodel;
   for {i in 1..2, j in {'a', 'b'}} put i= j=;
```

These statements produce the output in Figure 9.18.

Figure 9.18 FOR Statement Output

```
i=1 j=a
i=1 j=b
i=2 j=a
i=2 j=b
```

As another example, the following statements set the current values for variable x to random values between 0 and 1:

```
proc optmodel;
   var x{1..10};
   for {i in 1..10}
      x[i] = ranuni(-1);
```

Multiple statements can be controlled by specifying a DO statement group for the substatement.

CAUTION: Avoid modifying the parameters that are used by the FOR or COFOR statement index set from within the substatement. The set value that is used for the left-most index set item is not affected by such changes. However, the effect of parameter changes on later index set items cannot be predicted.

IF Statement

IF *logic-expression* **THEN** *statement* [**ELSE** *statement*] **;**

The IF statement evaluates the logical expression and then conditionally executes the THEN or ELSE substatements. The substatement that follows the THEN keyword is executed when the logical expression result is nonmissing and nonzero. The ELSE substatement, if any, is executed when the logical expression result is a missing value or zero. The ELSE part is optional and must immediately follow the THEN substatement. When IF statements are nested, an ELSE is always matched to the nearest incomplete unmatched IF-THEN. Multiple statements can be controlled by using DO statements with the THEN or ELSE substatements.

NOTE: When an IF-THEN statement is used **without** an ELSE substatement, substatements of the IF statement are executed when possible as they are entered. Under certain circumstances, such as when an IF statement is nested in a FOR loop, the statement is not executed during interactive input until the next statement is seen. By following the IF-THEN statement with an extra semicolon, you can cause it to be executed upon submission, since the extra semicolon is handled as a null statement.

LEAVE Statement

LEAVE ;

The LEAVE statement terminates the execution of the entire loop body (iterative DO, DO UNTIL, DO WHILE, FOR, or COFOR) that immediately contains the LEAVE statement. Execution resumes at the statement that follows the loop. The following example demonstrates a simple use of the LEAVE statement:

```
proc optmodel;
   number i, j;
   do i = 1..5;
      do j = 1..4;
         if i >= 3 and j = 2 then leave;
      end;
      print i j;
   end;
```

The results from these statements are displayed in Figure 9.19.

Figure 9.19 LEAVE Statement Output

i	j
1	4

i	j
2	4

i	j
3	2

i	j
4	2

i	j
5	2

For values of i equal to 1 or 2, the inner loop continues uninterrupted, leaving j with a value of 4. For values of i equal to 3, 4, or 5, the inner loop terminates early, leaving j with a value of 2.

Null Statement

;

The null statement is treated as a statement in the PROC OPTMODEL syntax, but its execution has no effect. It can be used as a placeholder statement.

PRINT Statement

PRINT *print-items* **;**

The PRINT statement outputs string and numeric data in tabular form. The statement specifies a list of arrays or other data items to print. Multiple items can be output together as data columns in the same table.

If no format is specified, the PRINT statement handles the details of formatting automatically (see the section "Formatted Output" on page 405 for details). The default format for a numerical column is the fixed-point format (*w.d* format), which is chosen based on the values of the PDIGITS= and PWIDTH= options (see the section "PROC OPTMODEL Statement" on page 316) and on the values in the column. The PRINT statement uses scientific notation (the E*w.* format) when a value is too large or too small to display in fixed format. The default format for a character column is the $*w.* format, where the width is set to be the length of the longest string (ignoring trailing blanks) in the column.

print-item can be specified in the following forms:

identifier-expression [*format*]
: specifies a data item to output. *identifier-expression* can name an array. In that case all defined array locations are output. *format* specifies a SAS format that overrides the default format.

(*expression* **)** [*format*]
: specifies a data value to output. *format* specifies a SAS format that overrides the default format.

{ *index-set* **}** *identifier-expression* [*format*]
: specifies a data item to output under the control of an *index set*. The item is printed as if it were an array with the specified set of indices. This form can be used to print a subset of the locations in an array, such as a single column. If the *identifier-expression* names an array, then the indices of the array must match the indices of the *index-set*. The *format* argument specifies a SAS format that overrides the default format.

{ *index-set* **}** **(** *expression* **)** [*format*]
: specifies a data item to output under the control of an *index set*. The item is printed as if it were an array with the specified set of indices. In this form the *expression* is evaluated for each member of the *index-set* to create the array values for output. *format* specifies a SAS format that overrides the default format.

'*string*'
: specifies a string value to print.

PAGE
: specifies a page break.

The following example demonstrates the use of several *print-item* forms:

```
proc optmodel;
   num x = 4.3;
   var y{j in 1..4} init j*3.68;
   print y; /* identifier-expression */
   print (x * .265) dollar6.2; /* (expression) [format] */
   print {i in 2..4} y; /* {index-set} identifier-expression */
   print {i in 1..3}(i + i*.2345692) best7.;
                              /* {index-set} (expression) [format] */
```

```
print "Line 1"; /* string */
```

The output is displayed in Figure 9.20.

Figure 9.20 *Print-item* Forms

[1]	y
1	3.68
2	7.36
3	11.04
4	14.72

$1.14

[1]	y
2	7.36
3	11.04
4	14.72

[1]	
1	1.23457
2	2.46914
3	3.70371

Line 1

Adjacent print items that have similar indexing are grouped together and output in the same table. Items have similar indexing if they specify arrays that have the same number of indices and have matching index types (numeric versus string). Nonarray items are considered to have the same indexing as other nonarray items. The resulting table has a column for each array index followed by a column for each print item value. This format is called *list form*. For example, the following statements produce a list form table:

```
proc optmodel;
   num a{i in 1..3} = i*i;
   num b{i in 3..5} = 4*i;
   print a b;
```

These statements produce the listing output in Figure 9.21.

Figure 9.21 List Form PRINT Table

[1]	a	b
1	1	
2	4	
3	9	12
4		16
5		20

The array index columns show the set of valid index values for the print items in the table. The array index column for the ith index is labeled [i]. There is a row for each combination of index values that was used. The index values are displayed in sorted ascending order.

The data columns show the array values that correspond to the index values in each row. If a particular array index is invalid or the array location is undefined, then the corresponding table entry is displayed as blank for numeric arrays and as an empty string for string arrays. If the print items are scalar, then the table has a single row and no array index columns.

If a table contains a single array print item, the array is two-dimensional (has two indices), and the array is dense enough, then the array is shown in *matrix form*. In this format there is a single index column that contains the row index values. The label of this column is blank. This column is followed by a column for every unique column index value for the array. The latter columns are labeled by the column value. These columns contain the array values for that particular array column. Table entries that correspond to array locations that have invalid or undefined combinations of row and column indices are blank or (for strings) printed as an empty string.

The following statements generate a simple example of matrix output:

```
proc optmodel;
   print {i in 1..6, j in i..6} (i*10+j);
```

The PRINT statement produces the output in Figure 9.22.

Figure 9.22 Matrix Form PRINT Table

	1	2	3	4	5	6
1	11	12	13	14	15	16
2		22	23	24	25	26
3			33	34	35	36
4				44	45	46
5					55	56
6						66

The PRINT statement prints single two-dimensional arrays in the form that uses fewer table cells (headings are ignored). Sparse arrays are normally printed in list form, and dense arrays are normally printed in matrix form. In a PROC OPTMODEL statement, the PMATRIX= option enables you to tune how the PRINT statement displays a two-dimensional array. The value of this option scales the total number of nonempty array elements, which is used to compute the tables cells needed for list form display. Specifying values for the PMATRIX= option less than 1 causes the list form to be used in more cases, while specifying values greater than 1 causes the matrix form to be used in more cases. If the value is 0, then the list form is always used. The default value of the PMATRIX= option is 1. Changing the default can be done with the RESET OPTIONS statement.

The following statements illustrate how the PMATRIX= option affects the display of the PRINT statement:

```
proc optmodel;
   num a{i in 1..6, i..i} = i;
   num b{i in 1..3, j in 1..3} = i*j;
   print a;
   print b;
   reset options pmatrix=3;
   print a;
   reset options pmatrix=0.5;
   print b;
```

The output is shown in Figure 9.23.

Figure 9.23 PRINT Statement: Effects of PMATRIX= Option

[1]	[2]	a
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6

	b		
	1	2	3
1	1	2	3
2	2	4	6
3	3	6	9

	a					
	1	2	3	4	5	6
1	1					
2		2				
3			3			
4				4		
5					5	
6						6

[1]	[2]	b
1	1	1
1	2	2
1	3	3
2	1	2
2	2	4
2	3	6
3	1	3
3	2	6
3	3	9

From Figure 9.23, you can see that, by default, the PRINT statement tries to make the display compact. However, you can change the default by using the PMATRIX= option.

PROFILE Statement

PROFILE [*mode*] *options* **;**

The PROFILE statement controls the PROC OPTMODEL profiler, which enables you to collect and display timing and execution count information for PROC OPTMODEL processing. The profiler can be very useful for finding bottlenecks during execution, such as constraints that require large amounts of time during problem generation. When the profiler is enabled, PROC OPTMODEL records the time for processing a declaration, the time for executing statements, and the number of times that statements are executed. See "Example 9.7: Sparse Modeling" on page 488 for an example use of the PROFILE statement.

The *mode* argument specifies the action that the PROFILE statement performs. You can use the following values for *mode*:

ON
enables the profiler. Data are collected until the profiler is disabled or PROC OPTMODEL terminates. The profiler is also enabled when no *mode* is specified in a PROFILE statement.

OFF
disables the profiler. Note that the profiler is disabled when PROC OPTMODEL begins execution.

PRINT
prints the current accumulated profiler data. Items for declarations and statements are displayed in a table in descending order of their net time. Accumulated data are printed automatically when PROC OPTMODEL terminates.

The *options* control how PROC OPTMODEL collects and displays profiler information. You can specify the following options:

MEMORY | NOMEMORY
specifies whether to add the memory requirements for declarations to the output for the PROFILE PRINT action. The MemSize column of the ProfileInfo ODS table contains the approximate memory requirements in bytes when the table is displayed. The memory that is used by shared values, such as strings and sets, is divided among the declarations that reference the values. NOMEMORY is the default.

PERCENT=*number*
restricts the output for PROFILE PRINT to items whose net times account for at least the specified percentage of total profiled time, $\text{total time} \cdot \text{number}/100$. Items that have smaller times are aggregated into a single item at the end of the table. You can set this option before the display of profile data, and it does not affect the data collection. The value of *number* can range from 0 to 100. The default value is 1.

RESET
discards accumulated profiler data when the PROFILE statement completes execution. Accumulated data are retained until they are explicitly reset.

STMTDEPTH=*number* **| ALL**
allows collection of profiler data for nested statements. With the default option, STMTDEPTH=1, profiler data are collected only for top-level statements. The elapsed time for nested statement timing is included in the top-level statement timing. For example, time for a top-level FOR statement would include the execution of its substatement. Use the STMTDEPTH= option to profile the nested statements individually. The value *number* specifies the maximum nesting depth at which to profile statements individually. The nesting depth of a top-level statement is 1. Otherwise the nesting depth of a statement is one more than the nesting depth of the statement that encloses it, such as a DO, IF, or FOR statement.

For a PROFILE statement within a DO block or DO loop, the statement depth value is interpreted relative to the enclosing DO statement. For example, specifying STMTDEPTH=1 within a DO block causes the top-level statements of the DO block to be profiled. The STMTDEPTH= option is reset to its previous value when the enclosing DO statement completes execution.

The value of *number* can be an integer between 1 and 32,767. Using the ALL keyword is equivalent to specifying 32,767. Note that profiler timing can add significant overhead. Use a small *number* to minimize overhead.

The elapsed time that is required to process an item includes the processing of other profiled items that it depends on. For example, the processing of a constraint during problem generation might require the evaluation of parameter values. The PROFILE statement reports net time so that the total of profiled times represents actual processing time.

The equation that is used to compute net time is

$$\text{net time} = \text{elapsed time} - \text{nested time} - \text{wait time}$$

Elapsed time is the elapsed clock time this is required for processing an item. Nested time is the total of the elapsed times that are spent within the same thread to process other profiled items, such as substatements or declaration values. Wait time represents the time that a single thread is allocated but idle because it is waiting for other threads to perform the required processing. The total of net times can exceed the elapsed wall clock time when multiple threads are used.

PUT Statement

PUT [*put-items*] [@ | @@] **;**

The PUT statement writes text data to the current output file. The syntax of the PUT statement in PROC OPTMODEL is similar to the syntax of the PROC IML and DATA step PUT statements. The PUT statement contains a list of items that specify data for output and provide instructions for formatting the data.

The current output file is initially the SAS log. This can be overridden with the FILE statement. An output file can be closed with the CLOSEFILE statement.

Normally the PUT statement outputs the current line after processing all items. Final @ or @@ operators suppress this automatic line output and cause the current column position to be retained for use in the next PUT statement.

put-item can take any of the following forms.

identifier-expression [**=**] [*format*]

outputs the value of the parameter or variable that is specified by the *identifier-expression*. The equal sign (=) causes a name for the location to be printed before each location value. If the *identifier-expression* uses a suffix that can be followed by a solution index, you can use an asterisk (*) instead of the index *expression* to display all saved solution values.

Normally each item value is printed in a default format. Any leading and trailing blanks in the formatted value are removed, and the value is followed by a blank space. When an explicit format is specified, the value is printed within the width determined by the format.

*name***[*]** [**.***suffix* [**[** *expression* | ***]**]] [**=**] [*format*]

outputs each defined location value for an array parameter. The array name is specified as in the *identifier-expression* form except that the index list is replaced by an asterisk (*). The equal sign (=) causes a name for the location to be printed before each location value along with the actual index values to be substituted for the asterisk. If the *suffix* can be followed by a solution index, you can use an asterisk (*) instead of the index *expression* to display all saved solution values.

Each item value normally prints in a default format. Any leading and trailing blanks in the formatted value are removed, and the value is followed by a blank space. When an explicit format is specified, the value is printed within the width determined by the format.

(*expression* **)** [**=**] [*format*]
outputs the value of the expression enclosed in parentheses. This produces similar results to the *identifier-expression* form except that the equal sign (=) uses the expression to form the name.

'*string*'
copies the string to the output file.

@*integer* | *identifier-expression* | **(** *expression* **)**
sets the absolute column position within the current line. The literal or expression value determines the new column position.

+*integer* | *identifier-expression* | **(** *expression* **)**
sets the relative column position within the current line. The literal or expression value determines the amount to update the column position.

/
outputs the current line and moves to the first column of the next line.

PAGE
outputs any pending line data and moves to the top of the next page.

QUIT Statement

QUIT ;

The QUIT statement terminates the OPTMODEL execution. The statement is executed immediately, so it cannot be a nested statement. A QUIT statement is implied when a DATA or PROC statement is read.

READ DATA Statement

READ DATA *SAS-data-set* [**NOMISS**] **INTO** [[*set-name* **=**] **[** *read-key-columns* **]**] [*read-columns*] **;**

The READ DATA statement reads data from a SAS data set into PROC OPTMODEL parameter and variable locations. The arguments to the READ DATA statement are as follows:

SAS-data-set
specifies the input data set name and options. You can specify the data set name and options directly or as the string value of an expression enclosed in parentheses.

set-name
specifies a set parameter in which to save the set of observation key values read from the input data set.

read-key-columns
provide the index values for array destinations.

read-columns
specify the data values to read and the destination locations.

NOTE: Currently, the data are always saved on the client. Transferring large data sets from a CAS libref can have significant network overhead and require a large amount of client memory.

The following example uses the READ DATA statement to copy data set variables j and k from the SAS data set indata into parameters of the same name. The READ= data set option specifies a password.

```
proc optmodel;
   number j, k;
   read data indata(read=secret) into j k;
```

Key Columns

If any *read-key-columns* are specified, then the READ DATA statement reads all observations from the input data set. If no *read-key-columns* are specified, then only the first observation of the data set is read. The data set is closed after reading the requested information.

Each *read-key-column* specifies a data set variable that supplies the column value. The values of the specified data set variables from each observation are combined into a key tuple. This combination is known as the *observation key*. The observation key is used to index array locations specified by the *read-columns* items. The observation key is expected to be unique for each observation read from the data set.

The syntax for a *read-key-column* is as follows:

[*name* **=**] *source-name* [/ *trim-option*]

Each *read-key-column* specifies an element of the observation key tuple. The *source-name* specifies the data set variable name, either as a *name* or by using a COL expression (as described later for *read-columns*). Use the special data set variable name _N_ to refer to the observation's iteration number, starting at 1.

A local dummy parameter can be created for each *read-key-column*. You can use the dummy parameter to reference the key tuple element value in subsequent *read-columns* items. A dummy parameter is created when the *read-key-column* specifies a *name* preceding the equal sign (=). The dummy parameter has the specified name. Also, a dummy parameter is created when the *source-name* is a nonliteral *name* and no alternate name has been specified using the equal sign. In this case, the dummy parameter has the same name as the data set variable.

You can specify a *set-name* to save the set of observation keys into a set parameter. If the observation key consists of a single scalar value, then the set member type must match the scalar type. Otherwise the set member type must be a tuple with element types that match the corresponding observation key element types.

The READ DATA statement initially assigns an empty set to the target *set-name* parameter. As observations are read, a tuple for each observation key is added to the set. A set used to index an array destination in the *read-columns* can be read at the same time as the array values. Consider a data set, invdata, created by the following statements:

```
data invdata;
   input item $ invcount;
   datalines;
table 100
sofa  250
chair 80
;
```

The following statements read the data set invdata, which has two variables, item and invcount. The READ DATA statement constructs a set of inventory items, Items. At the same time, the parameter location invcount[item] is assigned the value of the data set variable invcount in the corresponding observation.

```
proc optmodel;
   set<string> Items;
   number invcount{Items};
   read data invdata into Items=[item] invcount;
   print invcount;
```

The output of these statements is shown in Figure 9.24.

Figure 9.24 READ DATA Statement: Key Column

[1]	invcount
chair	80
sofa	250
table	100

When observations are read, the values of data set variables are copied to parameter locations. Numeric values are copied unchanged. For character values, *trim-option* controls how leading and trailing blanks are processed. *trim-option* is ignored when the value type is numeric. Specify any of the following keywords for *trim-option*:

TRIM | **TR**
removes leading and trailing blanks from the data set value. This is the default behavior.

LTRIM | **LT**
removes only leading blanks from the data set value.

RTRIM | **RT**
removes only trailing blanks from the data set value.

NOTRIM | **NT**
copies the data set value with no changes.

Columns

read-columns specify data set variables to read and PROC OPTMODEL parameter locations to which to assign the values. The types of the input data set variables must match the types of the parameters. Array parameters can be implicitly or explicitly indexed by the observation key values.

Normally, missing values from the data set are assigned to the parameters that are specified in the *read-columns*. The NOMISS keyword suppresses the assignment of missing values, leaving the corresponding parameter locations unchanged. Note that the parameter location does not need to have a valid index in this case. This permits a single statement to read data into multiple arrays that have different index sets.

read-columns have the following forms:

identifier-expression [**=** *name* | **COL(** *name-expression* **)**] [/ *trim-option*]

transfers an input data set variable to a target parameter or variable. *identifier-expression* specifies the target. If the *identifier-expression* specifies an array without an explicit index, then the observation key provides an implicit index. The name of the input data set variable can be specified with a *name* or a COL expression. Otherwise the data set variable name is given by the *name* part of the *identifier-expression*. For COL expressions, the string-valued *name-expression* is evaluated to determine the data set variable name. *trim-option* controls removal of leading and trailing blanks in the incoming data. For example, the following statements read the data set variables column1 and column2 from the data set exdata into the PROC OPTMODEL parameters p and q, respectively. The observation numbers in exdata are read into the set indx, which indexes p and q.

```
data exdata;
   input column1 column2;
   datalines;
1 2
3 4
;


proc optmodel;
   number n init 2;
   set<num> indx;
   number p{indx}, q{indx};
   read data exdata into
      indx=[_N_] p=column1 q=col("column"||n);
   print p q;
```

The output is shown in Figure 9.25.

Figure 9.25 READ DATA Statement: Identifier Expressions

[1]	p	q
1	1	2
2	3	4

{ *index-set* **}** **<** *read-columns* **>**

performs the transfers by iterating each column specified by *<read-columns>* for each member of the *index-set*. If there are n columns and m index set members, then $n \times m$ columns are generated. The dummy parameters from the index set can be used in the columns to generate distinct input data set variable names in the iterated columns, using COL expressions. The columns are expanded when the READ DATA statement is executed, before any observations are read. This form of *read-columns* cannot be nested. In other words, the following form of *read-columns* is NOT allowed:

{ *index-set* **}** **<** **{** *index-set* **}** **<** *read-columns* **>** **>**

An example that demonstrates the use of the iterated column *read-option* follows.

You can use an iterated column *read-option* to read multiple data set variables into the same array. For example, a data set might store an entire row of array data in a group of data set variables. The following statements demonstrate how to read a data set that contains demand data divided by day:

```
data dmnd;
   input loc $ day1 day2 day3 day4 day5;
   datalines;
East 1.1 2.3 1.3 3.6 4.7
West 7.0 2.1 6.1 5.8 3.2
;

proc optmodel;
   set DOW = 1..5;  /* days of week, 1=Monday, 5=Friday */
   set<string> LOCS; /* locations */
   number demand{LOCS, DOW};
   read data dmnd
        into LOCS=[loc]
        {d in DOW} < demand[loc, d]=col("day"||d) >;
   print demand;
```

These statements read a set of demand variables named DAY1–DAY5 from each observation, filling in the two-dimensional array demand. The output is shown in Figure 9.26.

Figure 9.26 Demand Data

	demand				
	1	2	3	4	5
East	1.1	2.3	1.3	3.6	4.7
West	7.0	2.1	6.1	5.8	3.2

RESET OPTIONS Statement

RESET OPTIONS *options* **;**

RESET OPTION *options* **;**

The RESET OPTIONS statement sets PROC OPTMODEL option values or restores them to their defaults. Options can be specified by using the same syntax as in the PROC OPTMODEL statement. The RESET OPTIONS statement provides two extensions to the option syntax. If an option normally requires a value (specified with an equal sign (=) operator), then specifying the option name alone resets it to its default value. You can also specify an expression enclosed in parentheses in place of a literal value. See the section "OPTMODEL Options" on page 458 for an example.

The RESET OPTIONS statement can be placed inside loops or conditional statements. The statement is applied each time it is executed.

RESTORE Statement

RESTORE *constraint-list* **;**

The RESTORE statement adds a list of constraints, constraint arrays, or constraint array locations that were dropped by the DROP statement back into the solver model, or includes constraints in a problem where they were not previously present. The space-delimited *constraint-list* specifies the names of the constraints. Each constraint, constraint array, or constraint array location is named by an *identifier-expression*. An entire constraint array is restored if an *identifier-expression* omits the index from an array name. Each *identifier-expression* can be prefixed by an indexing set to specify the constraint indices.

For example, the following statements declare a constraint array and then drop it:

```
con c{i in 1..4}: x[i] + y[i] <=1;
drop c;
```

The following statement restores the first constraint:

```
restore c[1];
```

The following statement restores the second and third constraints:

```
restore {i in 2..3} c[i]; /* like "restore c[2] c[3];" */
```

If you want to restore all of the constraints, you can submit the following statement:

```
restore c;
```

SAVE MPS Statement

SAVE MPS *SAS-data-set* [**LINEARIZE**] [**(OBJECTIVE** | **OBJ)** *name*] [**(NOOBJECTIVE** | **NOOBJ)**] **;**

The SAVE MPS statement saves the structure and coefficients for a linear programming model into a SAS data set. This data set can be used as input data for the OPTLP or OPTMILP procedure.

NOTE: The OPTMODEL presolver (see the section "Presolver" on page 432) is automatically bypassed so that the statement saves the original model *without* eliminating fixed variables, tightening bounds, and so on.

The *SAS-data-set* argument specifies the output data set name and options. You can specify the data set name and options directly or as the string value of an expression enclosed in parentheses. The output data set uses the MPS format described in Chapter 8, "The MPS-Format Data Table." An _ID_ column is automatically added to the data set when it is created using a CAS engine libref. The generated data set contains observations that define different parts of the linear program.

Variables, constraints, and objectives are referenced in the data set by using label text from the corresponding .label suffix value. The default text is based on the name in the model. See the section "Suffixes" on page 420 for more details. Labels are limited by default to 32 characters and are abbreviated to fit. You can change the maximum length for labels by using the MAXLABLEN= option. When needed, a programmatically generated number is added to labels to avoid duplication.

The LINEARIZE keyword transforms objectives and constraints into linear form where possible. PROC OPTMODEL replaces certain nonlinear subexpressions with linear equivalents, using added variables and constraints. See the section "Linearization" on page 433 for a description of the supported transformations.

If the OBJECTIVE keyword is used, the objective *name* becomes the current problem objective. If the NOOBJECTIVE keyword is used or the current problem does not have an objective, then the data set includes a default constant zero objective. Otherwise, the current problem objective is included in the data set.

When an integer variable has been assigned a nondefault branching priority or direction, the MPS data set includes a BRANCH section. See Chapter 8, "The MPS-Format Data Table," for more details.

The following statements show an example of the SAVE MPS statement. The LIBNAME statement for the mycas libref allows the creation of CAS tables. The model is specified using the OPTMODEL procedure. Then it is saved as the MPS data set mycas.MPSData, as shown in Figure 9.27. Next, PROC OPTLP is used to solve the resulting linear program.

```
libname mycas cas sessref=mysess datalimit=all;
proc optmodel;
   var x >= 0, y >= 0;
   con c: x >= y;
   con bx: x <= 2;
   con by: y <= 1;
   min obj=0.5*x-y;
   save mps mycas.MPSData;
quit;

proc optlp data=mycas.MPSData pout=mycas.PrimalOut dout=mycas.DualOut;
run;
```

Figure 9.27 The MPS Data Set Generated by SAVE MPS Statement

FIELD1	FIELD2	FIELD3	FIELD4	FIELD5	FIELD6	_ID_
NAME		MPSData	.		.	1
ROWS			.		.	2
N	obj		.		.	3
G	c		.		.	4
L	bx		.		.	5
L	by		.		.	6
COLUMNS			.		.	7
	x	obj	0.5	c	1	8
	x	bx	1.0		.	9
	y	obj	-1.0	c	-1	10
	y	by	1.0		.	11
RHS			.		.	12
	.RHS.	bx	2.0		.	13
	.RHS.	by	1.0		.	14
ENDATA			.		.	15

SAVE QPS Statement

SAVE QPS *SAS-data-set* [**(OBJECTIVE** | **OBJ)** *name*] [**(NOOBJECTIVE** | **NOOBJ)**] **;**

The SAVE QPS statement saves the structure and coefficients for a quadratic programming model into a SAS data set. This data set can be used as input data for the OPTQP procedure.

NOTE: The OPTMODEL presolver (see the section "Presolver" on page 432) is automatically bypassed so that the statement saves the original model *without* eliminating fixed variables, tightening bounds, and so on.

The *SAS-data-set* argument specifies the output data set name and options. You can specify the data set name and options directly or as the string value of an expression enclosed in parentheses. The output data set uses the QPS format described in Chapter 8. An _ID_ column is automatically added to the data set when it is created using a CAS engine libref. The generated data set contains observations that define different parts of the quadratic program.

Variables, constraints, and objectives are referenced in the data set by using label text from the corresponding .label suffix value. The default text is based on the name in the model. See the section "Suffixes" on page 420 for more details. Labels are limited by default to 32 characters and are abbreviated to fit. You can change

the maximum length for labels by using the MAXLABLEN= option. When needed, a programmatically generated number is added to labels to avoid duplication.

If the OBJECTIVE keyword is used, the objective *name* becomes the current problem objective. If the NOOBJECTIVE keyword is used or the current problem does not have an objective, then the data set includes a default constant zero objective. Otherwise, the current problem objective is included in the data set. The quadratic coefficients of the objective function appear in the QSECTION section of the output data set.

The following statements show an example of the SAVE QPS statement. The LIBNAME statement for the mycas libref allows the creation of CAS tables. The model is specified using the OPTMODEL procedure. Then it is saved as the QPS data set mycas.QPSData, as shown in Figure 9.28. Next, PROC OPTQP is used to solve the resulting quadratic program.

```
libname mycas cas sessref=mysess datalimit=all;
proc optmodel;
   var x{1..2} >= 0;
   min z = 2*x[1] + 3 * x[2] + x[1]**2 + 10*x[2]**2
                  + 2.5*x[1]*x[2];
   con c1: x[1] - x[2] <= 1;
   con c2: x[1] + 2*x[2] >= 100;
   save qps mycas.QPSData;
quit;

proc optqp data=mycas.QPSData pout=mycas.PrimalOut dout=mycas.DualOut;
run;
```

Figure 9.28 QPS Data Set Generated by the SAVE QPS Statement

FIELD1	FIELD2	FIELD3	FIELD4	FIELD5	FIELD6	_ID_
NAME		QPSData	.		.	1
ROWS			.		.	2
N	z		.		.	3
L	c1		.		.	4
G	c2		.		.	5
COLUMNS			.		.	6
	x[1]	z	2.0	c1	1	7
	x[1]	c2	1.0		.	8
	x[2]	z	3.0	c1	-1	9
	x[2]	c2	2.0		.	10
RHS			.		.	11
	.RHS.	c1	1.0		.	12
	.RHS.	c2	100.0		.	13
QSECTION			.		.	14
	x[1]	x[1]	2.0		.	15
	x[1]	x[2]	2.5		.	16
	x[2]	x[2]	20.0		.	17
ENDATA			.		.	18

SOLVE Statement

SOLVE [**WITH** *solver*] [**CONIC**] [**LINEARIZE**] [**(OBJECTIVE** | **OBJ)** *name*] [**(NOOBJECTIVE** | **NOOBJ)**] [**RELAXINT**] [/ *options*] **;**

The SOLVE statement invokes a PROC OPTMODEL solver. The current model is first resolved to the numeric form that is required by the solver. The resolved model and possibly the current values of any optimization variables are passed to the solver. The solver is executed in the distributed computing environment when you specify the SESSREF= or SESSUUID= option. After the solver finishes executing, the SOLVE statement prints a short table that shows a summary of results from the solver (see the section "ODS Table and Variable Names" on page 408) and updates the _OROPTMODEL_ macro variable.

Here are the arguments to the SOLVE statement:

solver

selects the named solver: BLACKBOX, CLP, CONIC, LP, MILP, NETWORK, NLP, or QP (see corresponding chapters in this book for details). If you do not specify a WITH clause, PROC OPTMODEL chooses a solver that depends on the problem type. Table 9.8 lists the default solver for each problem type.[1]

Table 9.8 Default Solvers and Algorithms in PROC OPTMODEL

Problem	Solver	Algorithm
Constraint programming	CLP	Constraint propagation and backtracking search
Conic optimization	Conic	Interior point conic
Linear programming	LP	Simplex
Mixed integer linear programming	MILP	Branch-and-cut
General nonlinear programming	NLP	Interior point NLP
Quadratic programming	QP	Interior point QP

CONIC

transforms objectives and constraints for processing by the conic solver, where possible. PROC OPTMODEL replaces suitable nonlinear subexpressions by using added variables, linear constraints, and second-order cone constraints. See the section "Conic Transformation" on page 442 for a description of the supported transformations.

LINEARIZE

transforms objectives and constraints into linear form where possible. PROC OPTMODEL replaces certain nonlinear subexpressions with linear equivalents, using added variables and constraints. See the section "Linearization" on page 433 for a description of the supported transformations.

[1] The OPTMODEL procedure never uses the black-box or network solver as a default. If the QP solver detects nonconvexity (nonconcavity) for a minimization (maximization) problem, then PROC OPTMODEL calls the NLP solver instead.

name
specifies the objective to use. This resets the objective list for the problem. You can abbreviate the OBJECTIVE keyword as OBJ. If you do not specify this argument, then the problem objectives are unchanged. You can also specify multiple objectives for the black-box solver by using a list in parentheses of *names*, separated by spaces, in place of *name*. Within this list, you can prefix each *name* by using an indexing set to specify a group of objectives.

NOOBJECTIVE
requests that the solver ignore the objectives for the problem and use a constant zero objective instead. This keyword enables the solver to process the current model as a feasibility problem. You can abbreviate the NOOBJECTIVE keyword as NOOBJ.

RELAXINT
requests that any integral variables be relaxed to be continuous. RELAXINT can be used with linear and nonlinear problems in addition to any solver.

options
specifies solver options. You can specify solver options directly only when you use the WITH clause. A list of the options available with the solver is provided in the individual chapters that describe each solver. Table 9.9 lists the available option types. You can use an expression in parentheses in place of a literal option value for numeric and keyword options. A string expression is matched to a keyword. OPTMODEL parameters that are changed by the solver must be specified by a parameter or array option.

Table 9.9 Solver Option Types

Type	Syntax	Example
Boolean	*option* | NO*option*	**solve with nlp / NOMULTISTART;**
Keyword	*option=name*	**solve with lp / ALGORITHM=PS;**
Numeric	*option=number*	**solve with nlp / OPTTOL=1E–4;**
Parameter	*option=identifier-expression*	**solve with network / links=(INCLUDE=LINKS) concomp;**
Array	*option=array-name* [*.suffix*]	**solve with network / links=(WEIGHT=WEIGHT) tsp;**

The SOLVE statement uses the value of the predeclared _SOLVER_OPTIONS_ and _*solver*_OPTIONS_ string parameters to provide default solver options. Any options that are specified by these parameters are added before options that are specified in the SOLVE statement, with options from _SOLVER_OPTIONS_ appearing first. These options are included even when the SOLVE statement does not contain a WITH clause to specify a solver; in this case, *solver* is the name of the default solver as shown in Table 9.8.

Initially the predeclared string parameters _SOLVER_OPTIONS_ and _*solver*_OPTIONS_ (for each solver) are empty strings, but you can assign them. You must use keywords or literal values to specify option values in these strings. Redundant white space is allowed. For example, the following statements set up some simple defaults:

```
_SOLVER_OPTIONS_ = "MAXTIME = 600"; /* options for all solvers */
_LP_OPTIONS_ = "PRESOLVER=AGGRESSIVE"; /* options for LP solver */
```

Optimization techniques that use initial values obtain them from the current values of the optimization variables unless the NOINITVAR option is specified. When the solver finishes executing, the current value of each optimization variable is replaced by the optimal value found by the solver. These values can then be used as the initial values for subsequent solver invocations.

NOTE: If a solver fails, any currently pending statement is stopped and processing continues with the next complete statement read from the input. For example, if a SOLVE statement that is enclosed in a DO group (see the section "DO Statement" on page 345) fails, then the subsequent statements in the group are not executed and processing resumes at the point immediately following the DO group. Neither an infeasible result, an unbounded result, nor reaching an iteration limit is considered to be a solver failure.

NOTE: The information that appears in the macro variable _OROPTMODEL_ (see the section "Macro Variable _OROPTMODEL_" on page 466) varies by solver.

NOTE: The RELAXINT keyword is applied immediately before the problem is passed to the solver, after any processing by the PROC OPTMODEL presolver. So the problem presented to the solver might not be equivalent to the one produced by setting the .RELAX suffix of all variables to a nonzero value. In particular, the bounds of integer variables are still adjusted to be integral, and PROC OPTMODEL's presolver might use integrality to tighten bounds further.

SOURCE Statement

SOURCE *identifier-expression* [**END=***keyword*] **;**

source-block **;**

ENDSOURCE | *keyword* **;**

The SOURCE statement assigns the text of the *source-block* as a string value to the parameter location that is specified by *identifier-expression*. You can use the SOURCE statement to save source code blocks for later processing, as an alternative to quoted SAS strings. In contrast with quoted strings, line breaks are preserved and nested quotes are specified normally. SOURCE statements can be read from SAS macros. Macros and SAS global statements are processed when the source block is read.

The END= option specifies that the source block is terminated by an alternative to the default keyword, ENDSOURCE. You can use this option to nest SOURCE blocks.

The following code demonstrates how to use the SOURCE statement with the SUBMIT statement inside a macro definition:

```
%macro submit_test;
proc optmodel;
   string testCode;
   %do i=1 %to 3;
      source testCode end=endsrc;
         data _null_;
            i = &i;
            put i=;
         run;
      endsrc;
```

```
      submit / code=testCode;
   %end;
quit;
%mend submit_test;
%submit_test;
```

STOP Statement

STOP ;

The STOP statement halts the execution of all statements that contain it, including DO statements and other control or looping statements. Execution continues with the next top-level source statement. The following statements demonstrate a simple use of the STOP statement:

```
proc optmodel;
   number i, j;
   do i = 1..5;
      do j = 1..4;
         if i = 3 and j = 2 then stop;
      end;
   end;
   print i j;
```

The output is shown in Figure 9.29.

Figure 9.29 STOP Statement: Output

i	j
3	2

When the counters i and j reach 3 and 2, respectively, the STOP statement terminates both loops. Execution continues with the PRINT statement.

SUBMIT Statement

SUBMIT [*arguments*] [/ *options*] **;**

SAS statements **;**

ENDSUBMIT ;

The SUBMIT statement allows SAS code to be executed before PROC OPTMODEL processing continues. For example, you can use the SUBMIT statement to invoke other SAS procedures to perform analysis or to display results. The following statements use PROC SORT to order a list of nodes by decreasing priority; the nodes can be used for further processing:

```
proc optmodel;
   set<str> NODES;
   num priority{NODES};

   /* set up priority data... */

   /* sort nodes by descending priority */
   create data temppri from [id] priority;
```

```
submit;
   proc sort;
      by descending priority;
   run;
endsubmit;

/* load nodes by priority */
str nodesByPri{i in 1..card(NODES)};
read data temppri into [_n_] nodesByPri=id;

/* use the sorted list... */
```

The SUBMIT statement must appear as the last or only statement on a line, unless you specify the CODE= option in the *options* list. The SUBMIT statement is followed by lines of SAS statements, terminated by the ENDSUBMIT statement on a line of its own. The SAS statements between the SUBMIT and ENDSUBMIT statements are referred to as a *SUBMIT block*. The SUBMIT block is sent to the SAS language processor each time the SUBMIT statement is executed.

When you specify the CODE= option in *options*, the SUBMIT block is specified by the string value of the option. The ENDSUBMIT statement is not used in this case.

The SUBMIT block can include SAS global statements and procedure and invocations. Macros are not expanded until the SUBMIT block is executed. So you can change macro variables to modify the behavior of the SUBMIT block each time it is processed.

The *arguments* list specifies macro variables to initialize before the SUBMIT block is executed. List items are separated by spaces. Each of the *arguments* takes one of the following forms:

name
: copies the value of the PROC OPTMODEL parameter *name* to the macro variable that has the same name.

name=*identifier-expression*
: copies the value of the PROC OPTMODEL parameter specified by *identifier-expression* to the macro variable *name*.

name=*number* | '*string*'
: copies the value of the specified *number* or string constant to the macro variable *name*.

name=(*expression*)
: copies the result of evaluating *expression* to the macro variable *name*.

The following statements use a SUBMIT argument to modify the output each time the SUBMIT block is invoked:

```
for {i in 1..5} do;
   submit a=i;
      %put Value of a is &a..;
   endsubmit;
end;
```

The *options* in the SUBMIT statement are used to specify a SUBMIT block or to retrieve status information after a SUBMIT block is executed. Each item in the space-delimited *options* list has one of the following forms:

CODE=*identifier-expression* | '*string*' | **(** *expression* **)**
specifies a string value that evaluates to the text of the SUBMIT block to execute, in place of specifying the SUBMIT block and ENDSUBMIT statement following the SUBMIT statement. The string value can be created dynamically during program execution.

OK=*identifier-expression*
specifies a PROC OPTMODEL numeric parameter location, *identifier-expression*, that is updated to indicate the success of the SUBMIT block execution. The location is set to 1 if execution is successful or 0 if errors are detected. PROC OPTMODEL continues execution when the SUBMIT block encounters errors only if the OK= option is specified.

OUT [**=**] *output-argument*
specifies a single *output-argument* for retrieving macro variable values after each execution of the block.

OUT [**=**] **(** *output-arguments* **)**
specifies a list of space-delimited *output-arguments* for retrieving macro variable values after the block is executed.

Each *output-argument* item specifies a macro variable to copy after the block is executed. Each item takes one of the following two forms:

identifier-expression
copies the macro variable specified by the *name* portion of the *identifier-expression* into the PROC OPTMODEL parameter location specified by *identifier-expression*.

identifier-expression **=** *name*
copies the macro variable specified by *name* into the PROC OPTMODEL parameter location specified by *identifier-expression*.

The following statements show how to use the *options* in the SUBMIT statement to retrieve the result of a SUBMIT block execution:

```
proc optmodel;
   num success, syscc;
   submit / OK = success out syscc;
      data example;
         set notfound;
         j = i*i;
      run;
   endsubmit;
   print success syscc;
```

The DATA step fails, so the success parameter is set to 0 and syscc is set to the error code in the &SYSCC macro variable. The output is shown in Figure 9.30.

Figure 9.30 SUBMIT Statement Error Handling

success	syscc
0	1012

NOTE: The SUBMIT block runs in the same environment that the OPTMODEL procedure is running in. The

SUBMIT block can change the values for options, LIBNAME librefs, FILENAME filerefs, titles, footnotes, and macro variables. The OPTMODEL procedure sees these changes but might not process them until the next top-level source statement is read.

NOTE: A SUBMIT block can reset the ODS environment of the OPTMODEL procedure. For example, the ODS SELECT and EXCLUDE lists could be cleared after the SUBMIT block executes.

NOTE: A SUBMIT statement can appear only in open code unless you specify the CODE= option. An error message is displayed if the SUBMIT statement is read from a macro. You can avoid this limitation by using a SOURCE statement to specify the SUBMIT block. Specify the CODE= option with the parameter location of the saved block. Otherwise, you can place the SUBMIT statement, SUBMIT block, and ENDSUBMIT in a separate file and use the %INCLUDE statement to include the file in the macro.

UNFIX Statement

UNFIX *variable-list* [**=** *expression*] **;**

The UNFIX statement reverses the effect of FIX statements. The solver can vary the specified variables, variable arrays, or variable array locations specified by *variable-list*. The *variable-list* consists of one or more variable names separated by spaces.

Each variable name in the *variable-list* is an *identifier expression* (see the section "Identifier Expressions" on page 383). The UNFIX statement affects an entire variable array if the identifier expression omits the index from an array name. Each *identifier-expression* can be prefixed by an indexing set to specify the variable indices.

The *expression* specifies a new initial value that is stored in each element of the *variable-list*. If a single *identifier-expression* is specified, prefixed by an indexing set, then the *expression* is evaluated for each element in the indexing set. Otherwise the *expression* is evaluated exactly once.

The following example demonstrates the UNFIX command:

```
proc optmodel;
   var x{1..3};
   fix x;       /* fixes entire array to 0 */
   unfix x[1];  /* x[1] can now be varied again */
   unfix x[2] = 2;  /* x[2] is given an initial value 2 */
                  /* and can be varied now */
   unfix x;  /* all x indices can now be varied */
```

After the following statements are executed, the variables x[1] and x[2] are not fixed. They each hold the value 4. The variable x[3] is fixed at a value of 2.

```
proc optmodel;
   var x{1..3} init 2;
   num a = 1;
   fix x;
   unfix x[1] x[2]=a+3;
   unfix {1..2} x = a+3;  /* equivalent to prior UNFIX statement */
```

USE PROBLEM Statement

USE PROBLEM *identifier-expression* **;**

The USE PROBLEM programming statement makes the problem specified by the *identifier-expression* be the current problem. If the problem has not been previously used, the problem is created using the PROBLEM declaration corresponding to the name. The problem must have been previously declared.

Details: OPTMODEL Procedure

Named Parameters

In the example described in the section "An Unconstrained Optimization Example" on page 307, all the numeric constants that describe the behavior of the objective function were specified directly in the objective expression. This is a valid way to formulate the objective expression. However, in many cases it is inconvenient to specify the numeric constants directly. Direct specification of numeric constants can also hide the structure of the problem that is being solved. The objective expression text would need to be modified when the numeric values in the problem change. This can be very inconvenient with large models.

In PROC OPTMODEL, you can create named numeric values that behave as constants in expressions. These named values are called *parameters*. You can write an expression by using mnemonic parameter names in place of numeric literals. This produces a clearer formulation of the optimization problem. You can easily modify the values of parameters, define them in terms of other parameters, or read them from a SAS data set.

The model from this same example can be reformulated in a more general polynomial form, as follows:

```
data coeff;
   input c_xx c_x c_y c_xy c_yy;
   datalines;
1 -1  -2 -1 1
;
proc optmodel;
   var x, y;
   number c_xx, c_x, c_y, c_xy, c_yy;
   read data coeff into c_xx c_x c_y c_xy c_yy;
   min z=c_xx*x**2 + c_x*x + c_y*y + c_xy*x*y + c_yy*y**2;
   solve;
```

These statements read the coefficients from a data set, COEFF. The NUMBER statement declares the parameters. The READ DATA statement reads the parameters from the data set. You can apply this model easily to coefficients that you have generated by various means.

Indexing

Many models have large numbers of variables or parameters that can be categorized into families of similar purpose or behavior. Such families of items can be compactly represented in PROC OPTMODEL by using indexing. You can use indexing to assign each item in such families to a separate value location.

PROC OPTMODEL indexing is similar to array indexing in the DATA step, but it is more flexible. Index values can be numbers or strings, and are not required to fit into some rigid sequence. PROC OPTMODEL indexing is based on index sets, described further in the section "Index Sets" on page 385. For example, the following statement declares an indexed parameter:

```
number p{1..3};
```

The construct that follows the parameter name p, "{1..3}," is a simple index set that uses a range expression (see "Range Expression" on page 392). The index set contains the numeric members 1, 2, and 3. The parameter has distinct value locations for each of the index set members. The first such location is referenced as p[1], the second as p[2], and the third as p[3].

The following statements show an example of indexing:

```
proc optmodel;
   number p{1..3};
   p[1]=5;
   p[2]=7;
   p[3]=9;
   put p[*]=;
```

The preceding statements produce a line such as the one shown in Figure 9.31 in the log.

Figure 9.31 Indexed Parameter Output

```
p[1]=5 p[2]=7 p[3]=9
```

Index sets can also specify local dummy parameters. A dummy parameter can be used as an operand in the expressions that are controlled by the index set. For example, the assignment statements in the preceding statements could be replaced by an initialization in the parameter declaration, as follows:

```
number p{i in 1..3} init 3 + 2*i;
```

The initialization value of the parameter location p[1] is evaluated with the value of the local dummy parameter i equal to 1. So the initialization expression 3 + 2*i evaluates to 5. Similarly for location p[2], the value of i is 2 and the initialization expression evaluates to 7.

The OPTMODEL modeling language supports aggregation operators that combine values of an expression where a local dummy parameter (or parameters) ranges over the members of a set. For example, the SUM aggregation operator combines expression values by adding them together. The following statements output 21, since p[1] + p[2] + p[3] = 5 + 7 + 9 = 21:

```
proc optmodel;
   number p{i in 1..3} init 3 + 2*i;
   put (sum{i in 1..3} p[i]);
```

Aggregation operators like SUM are especially useful in objective expressions because they can combine a large number of similar expressions into a compact representation. As an example, the following statements define a trivial least squares problem:

```
proc optmodel;
   number n init 100000;
   var x{1..n};
   min z = sum{i in 1..n}(x[i] - log(i))**2;
   solve;
```

The objective function in this case is

$$z = \sum_{i=1}^{n} (x_i - \log i)^2$$

Effectively, the objective expression expands to the following large expression:

```
min z = (x[1] - log(1))**2
      + (x[2] - log(2))**2
      . . .
      + (x[99999] - log(99999))**2
      + (x[100000] - log(100000))**2;
```

Even though the problem has 100,000 variables, the aggregation operator SUM enables a compact objective expression.

NOTE: PROC OPTMODEL classifies as mathematically impure any function that returns a different value each time it is called. The RAND function, for example, falls into this category. PROC OPTMODEL disallows impure functions inside array index sets, objectives, and constraint expressions. The values of expressions that are specified in the declaration of a parameter are resolved in a nondeterministic order during threaded problem generation. Therefore, the values are also nondeterministic when these expressions use impure functions.

Types

In PROC OPTMODEL, parameters and expressions can have numeric or character values. These correspond to the elementary types named NUMBER and STRING, respectively. The NUMBER type is the same as the SAS data set numeric type. The NUMBER type includes support for missing values. The STRING type is like the SAS VARCHAR(*) character type, which allows lengths to vary as needed up to $2^{31} - 1$ bytes. However, string values are stored independently of parameters, and value references can be shared. The NUMBER and STRING types together are called the *scalar types*. You can abbreviate the type names as NUM and STR, respectively.

PROC OPTMODEL also supports set types for parameters and expressions. Sets represent collections of values of a member type, which can be a NUMBER, a STRING, or a vector of scalars (the latter is called a *tuple* and described in the following paragraphs). Members of a set all have the same member type. Members that have the same value are stored only once. For example, PROC OPTMODEL stores the set 2, 2, 2 as the set 2.

Specify a set of numbers with SET<NUMBER>. Similarly, specify a set of strings as SET<STRING>.

A set can also contain a collection of tuples, all of the same fixed length. A *tuple* is an ordered collection that contains a fixed number of elements. Each element in a tuple contains a scalar value. In PROC OPTMODEL, tuples of length 1 are equivalent to scalars. Two tuples have equal values if the elements at corresponding positions in each tuple have the same value. Within a set of tuples, the element type at a particular position in each tuple is the same for all set members. The element types are part of the set type. For example, the following statement declares parts as a set of tuples that have a string in the first element position and a number in the second element position and then initializes its elements to be <R 1>, <R 2>, <C 1>, and <C 2>.

```
set<string,number> parts = /<R 1> <R 2> <C 1> <C 2>/;
```

To create a compact model, use sets to take advantage of the structure of the problem being modeled. For example, a model might contain various values that specify attributes for each member of a group of suppliers. You could create a set that contains members that represent each supplier. You can then model the attribute values by using arrays that are indexed by members of the set.

The section "Parameters" on page 379 has more details and examples.

Names

Names are used in the OPTMODEL modeling language to refer to various entities such as parameters or variables. Names must follow the usual rules for SAS names. Names can be up to 32 bytes long and are not case sensitive. They must be declared before they are used.

Avoid declarations with names that begin with an underscore (_). These names can have special uses in PROC OPTMODEL.

Parameters

In the OPTMODEL modeling language, parameters are named locations that hold constant values. Parameter declarations specify the parameter type followed by a list of parameter names to declare. For example, the following statement declares numeric parameters named a and b:

```
number a, b;
```

Similarly, the following statements declare a set s of strings, a set n of numbers, and a set sn of tuples:

```
set<string> s;
set<number> n;
set<string, number> sn;
```

You can assign values to parameters in various ways. A parameter can be assigned a value with an assignment statement. For example, the following statements assign values to the parameter s, n, and sn in the preceding declaration:

```
s = {'a', 'b', 'c'};
n = {1, 2, 3};
sn = {<'a',1>, <'b',2>, <'c',3>};
```

Parameter values can also be assigned using a READ DATA statement (see the section "READ DATA Statement" on page 361).

A parameter declaration can provide an explicit value. To specify the value, follow the parameter name with an equal sign (=) and an expression. The value expression can be written in terms of other parameters. The declared parameter takes on a new value each time a parameter that is used in the expression changes. This automatic value update is shown in the following example:

```
proc optmodel;
   number pi=4*atan(1);
   number r;
   number circum=2*pi*r;
   r=1;
   put circum;       /* prints 6.2831853072 */
   r=2;
   put circum;       /* prints 12.566370614 */
```

The automatic update of parameter values makes it easy to perform "what if" analysis since, after the solver finds a solution, you can change parameters and reinvoke the solver. You can easily examine the effects of the changes on the optimal values.

If you declare a set parameter that has only the SET type specifier, then the element type is determined from the initialization expression. If the initialization expression is omitted or if the expression is an empty set, then the set type defaults to SET<NUMBER>. For example, the following statement implicitly declares s1 as a set of numbers:

```
set s1;
```

The following statement declares s2 as a set of strings:

```
set s2 = {'A'};
```

You can declare an array parameter by following the parameter name with an index set specification (see the section "Index Sets" on page 385). For example, declare an array of 10 numbers as follows:

```
number c{1..10};
```

Individual locations of a parameter array can be referred to with an indexing expression. For example, you can refer to the third location of parameter c as c[3]. Array index sets *cannot* be specified using a function such as RAND that returns a different value each time it is called.

Parameter names must be declared before they are used. Nonarray names become available at the end of the parameter declaration item. Array names become available after the index set specification. The latter case permits some forms of recursion in the optional initialization expression that can be supplied for a parameter.

You do not need to assign values to parameters before they are referenced. Most information in PROC OPTMODEL is stored symbolically and resolved when necessary. Values are resolved in certain statements. For example, PROC OPTMODEL resolves a parameter used in the objective during the execution of a SOLVE statement. If no value is available during resolution, then an error is diagnosed.

Expressions

Expressions are grouped into three categories based on the types of values they can produce: logical, set, and scalar (that is, numeric or character).

Logical expressions test for a Boolean (true or false) condition. As in the DATA step, logical operators produce a value equal to either 0 or 1. A value of 0 represents a false condition, while a value of 1 represents a true condition.

Logical expression operators are not allowed in certain contexts due to syntactic considerations. For example, in the VAR statement a logical operator might indicate the start of an option. Enclose a logical expression in parentheses to use it in such contexts. The difference is illustrated by the output (Figure 9.32) of the following statements, where two variables, x and y, are declared with initial values. The PRINT statement and the EXPAND statement are used to check the initial values and the variable bounds, respectively.

```
proc optmodel;
   var x init 0.5 >= 0 <= 1;
   var y init (0.5 >= 0) <= 1;
   print x y;
   expand;
```

Figure 9.32 Logical Expression in the VAR Statement

x	y
0.5	1

```
Var x >= 0 <= 1
Var y <= 1
```

Contexts that expect a logical expression also accept numeric expressions. In such cases zero or missing values are interpreted as false, and all nonzero nonmissing numeric values are interpreted as true.

Set expressions return a set value. PROC OPTMODEL supports a number of operators that create and manipulate sets. See the section "OPTMODEL Expression Extensions" on page 387 for a description of the various set expressions. Index-set syntax is described in the section "Index Sets" on page 385.

Scalar expressions are similar to the expressions in the DATA step except for PROC OPTMODEL extensions. PROC OPTMODEL provides an IF expression (described in the section "IF-THEN/ELSE Expression" on page 389). String lengths are assigned dynamically, so there is generally no padding or truncation of string values.

Table 9.10 shows the expression operators from lower to higher precedence (a higher precedence is given a larger number). Operators that have higher precedence are applied in compound expressions before operators that have lower precedence. The table also gives the order of evaluation that is applied when multiple operators of the same precedence are used together. Operators available in both PROC OPTMODEL and the DATA step have compatible precedences, except that in PROC OPTMODEL the NOT operator has a lower precedence than the relational operators. This means that, for example, `NOT 1 < 2` is equal to `NOT (1 < 2)` (which is 0), rather than `(NOT 1) < 2` (which is 1).

Table 9.10 Expression Operator Table

Precedence	Associativity	Operator	Alternates
Logic Expression Operators			
1	Left to right	OR	| !
2	Unary	OR{*index-set*}	
		AND{*index-set*}	
3	Left to right	AND	&
4	Unary	NOT	~ ^ ¬
5	Left to right	<	LT
		>	GT
		<=	LE
		>=	GE
		=	EQ
		~=	NE ^= ¬=
6	Left to right	IN	
		NOT IN	
7	Left to right	WITHIN	
		NOT WITHIN	
Set Expression Operators			
11		IF l THEN s1 ELSE s2	
12	Left to right	UNION	
		DIFF	
		SYMDIFF	
13	Unary	UNION{*index-set*}	
14	Left to right	INTER	
15	Unary	INTER{*index-set*}	
16	Left to right	CROSS	
17	Unary	SETOF{*index-set*}	
	Right to left	..	TO
		.. e BY	TO e BY
Scalar Expression Operators			
21		IF l THEN e	
		IF l THEN e1 ELSE e2	
22	Left to right	||	!!
23	Left to right	+ -	
24	Unary	SUM{*index-set*}	
		PROD{*index-set*}	
		MIN{*index-set*}	
		MAX{*index-set*}	
25	Left to right	* /	
26	Unary	+ -	
	Right to left	><	
		<>	
		**	^

Primary expressions are the individual operands that are combined using the expression operators. Simple primary expressions can represent constants or named parameter and variable values. More complex primary expressions can be used to call functions or construct sets.

Table 9.11 Primary Expression Table

Expression	Description
identifier-expression	Parameter/variable reference; see the section "Identifier Expressions" on page 383
name (*argument-list*)	Function call; *argument-list* is 0 or more expressions separated by commas
n	Numeric constant
. or **.***c*	Missing value constant
"*string*" or '*string*'	String constant
{ *member-list* **}**	Set constructor; *member-list* is 0 or more scalar expressions or tuple expressions separated by commas
{ *index-set* **}**	Index set expression; returns the set of all index set members
/ *members* /	Set literal expression; compactly specifies a simple set value
(*expression* **)**	Expression enclosed in parentheses
< *element-list* **>**	Tuple expression; used with set operations; contains one or more scalar expressions separated by commas

Identifier Expressions

Use an *identifier-expression* to refer to a variable, objective, constraint, parameter or problem location in expressions or initializations. This is the syntax for *identifier-expressions*:

name [**[** *expression-1* [**,** . . . *expression-n*] **]**] [**.** *suffix* [**[** *expression* **]**]]

To refer to a location in an array, follow the array *name* with a list of scalar expressions in square brackets ([ ]). The expression values are compared to the index set that was used to declare *name*. If there is more than one expression, then the values are formed into a tuple. The expression values for a valid array location must match a member of the array's index set. For example, the following statements define a parameter array A that has two valid indices that match the tuples <1,2> and <3,4>:

```
proc optmodel;
   set<number, number> ISET = {<1,2>, <3,4>};
   number A{ISET};
   a[1,2] = 0;  /* OK */
   a[3,2] = 0;  /* invalid index */
```

The first assignment is valid with this definition of the index set, but the second fails because <3,2> is not a member of the set parameter ISET.

Specify a *suffix* to refer to auxiliary locations for variables or objectives. For more information, see the section "Suffixes" on page 420. Certain suffixes can be followed by a numeric index *expression* that selects

a particular solution saved by the SOLVE statement. For more information about solution indices, see the section "Multiple Solutions" on page 455.

Function Expressions

Most functions that can be invoked from the DATA step or the %SYSFUNC macro can be used in PROC OPTMODEL expressions. Certain functions are specific to the DATA step and cannot be used in PROC OPTMODEL. Functions specific to the DATA step include these:

- functions in the LAG, DIF, and DIM families
- functions that access the DATA step program data vector
- functions that access symbol attributes

The CALL statement can invoke SAS library subroutines. These subroutines can read and update the values of the parameters and variables that are used as arguments. See the section "CALL Statement" on page 332 for an example.

OPTMODEL arrays can be passed to SAS library functions and subroutines using one of the following argument syntax forms:

OF *array-name***[*]** [**.** *suffix* [**[** *expression* | ***** **]**]]
OF *name* **.** *suffix* **[*]**
OF *array-name* **[** *expression-1* [**,** . . . *expression-n*] **]** **.** *suffix* **[*]**

The *array-name* is the name of an array symbol. The optional *suffix* allows auxiliary values to be referenced, as described in section "Suffixes" on page 420. You can also use an *identifier-expression* with a suffix that allows a solution index, specifying an asterisk (*) in place of the index *expression*.

The OF array form is a compact alternative to listing the array or solution elements explicitly. The OF argument form is resolved into a sequence of arguments, one for each index in the array or for each solution index. The array elements appear in order of the array's index set. Solutions appear in solution index order. If you use an asterisk for both the array and solution index lists, an argument appears for each combination of array and solution indices, and the solutions for each array index are placed in contiguous arguments.

As an example, the following statements use the CALL SORTN function to sort the elements of a numeric array:

```
proc optmodel;
   number original{i in 1..8} = sin(i);
   number sorted{i in 1..8} init original[i];
   call sortn(of sorted[*]);
   print original sorted;
```

The output is shown in Figure 9.33. Eight arguments are passed to the SORTN routine. The original column shows the original order, and the sorted column has the sorted order.

Figure 9.33 Sorting Using an OF Array Argument

[1]	original	sorted
1	0.84147	-0.95892
2	0.90930	-0.75680
3	0.14112	-0.27942
4	-0.75680	0.14112
5	-0.95892	0.65699
6	-0.27942	0.84147
7	0.65699	0.90930
8	0.98936	0.98936

Index Sets

An index set represents a set of combinations of members from the component set expressions. The index set notation is used in PROC OPTMODEL to describe collections of valid array indices and to specify sets of values with which to perform an operation. Index sets can declare local dummy parameters and can further restrict the set of combinations by a selection expression.

In an index-set specification, the index set consists of one or more *index-set-items* that are separated by commas. Each *index-set-item* can include local dummy parameter declarations. An optional selection expression follows the list of *index-set-items*. The following syntax, which describes an index set, usually appears in braces ({ }):

index-set-item [**,** . . . *index-set-item*] [**:** *logic-expression*]

index-set-item has these forms:

set-expression
name **IN** *set-expression*
< *name-1* [**,** . . . *name-n*] **>** **IN** *set-expression*

Names that precede the IN keyword in *index-set-items* declare local dummy parameter names. Dummy parameters correspond to the dummy index variables in mathematical expressions. For example, the following statements output the number 385:

```
proc optmodel;
   put (sum{i in 1..10} i**2);
```

The preceding statements evaluate this summation:

$$\sum_{i=1}^{10} i^2 = 385$$

In both the statements and the summation, the index name is i.

The last form of *index-set-item* in the list can be modified to use the SLICE expression implicitly. See the section "More on Index Sets" on page 464 for details.

Array index sets cannot be defined using functions that return different values each time the functions are called. See the section "Indexing" on page 377 for details.

Nil Values

The evaluation of certain PROC OPTMODEL expressions can produce a special value, the nil value, that is distinct from any other value of the expression's type. A nil value represents the lack of any ordinary value. You can use nil values to check for undefined parameters or to reset the effects of previous assignments or initializations.

Nil values are allowed for the following expressions:

- the operands of an equality comparison operator, = or ~=. Nil values are equal only to nil values.
- the second and third operands of an IF-THEN/ELSE expression
- the right-hand-side expression of an assignment statement. Assigning a nil value resets the effect of previous initializations or assignments of the target location.
- a parenthesized value expression for a PUT statement. Nil values are skipped on output.
- a parenthesized value expression for a PRINT statement. Nil values create an empty cell in the output.

NOTE: The *initializers* list from the INIT [*initializers*] clause for an array parameter declaration is evaluated at most once, except for any default element value. If an array element is assigned a nil value after the *initializers* are evaluated, then the default element value is used.

The _NIL_ keyword evaluates to a nil value in expressions. Nil values can also be generated when an *identifier expression* references an undefined parameter value. An *identifier expression* evaluates to a nil value instead of reporting an error when it is used as the operand of an equality comparison or as the right-hand-side expression of an assignment statement with a NUMBER, STRING, or SET parameter target. The nil value is generated when the *identifier expression* is used either directly or via the second or third operand of an IF-THEN/ELSE expression.

NOTE: Undefined parameter values are treated as errors when an *identifier expression* is used as the operand of a compound comparison (like b in (0 ~= b <= 10)) where one of the operators that are using the value is not an equality comparison.

The following code demonstrates some uses of nil values:

```
proc optmodel;
   num a{1..2};
   a[1] = 1;
   put (a[1] = _nil_)=; /* false, defined */
   put (a[2] = _nil_)=; /* true, undefined */
   put ((if a[1] then _nil_ else 2) = a[1])= /* false */;
   put ((if a[1] then _nil_ else 2) = a[2])= /* true */;
   a[1] = a[2]; /* now a[1] is undefined */
   put (a[1] = _nil_)=; /* true, undefined */

   /* array initialization list is evaluated at most once */
   num b{1..3} init [1 2 3 [*] 7];
   put b[*];     /* evaluates the initialization list */
   b[1] = _nil_; /* reset b[1] */
   put b[*];     /* b[1] replaced by the default value */
```

```
var x init (rand('UNIFORM')) >= 0 <= 10;
put x=;       /* initialized to a random value */
x = _nil_;    /* discard the current value */
put x=;       /* initialized to a new random value */
put x.ub=;    /* the declared bound */
x.ub = 1;     /* override the declared bound */
put x.ub=;    /* the overridden bound */
x.ub = _nil_; /* reverse the override */
put x.ub=;    /* the declared bound again */

/* nil values print as empty cells */
print {i in 1..3, j in 1..3}(if i+j-1=3 then _nil_ else 1/(i+j-1));
```

This code produces the output in Figure 9.34.

Figure 9.34 Nil Values

```
a[1] = _NIL_=0
a[2] = _NIL_=1
IF a[1] THEN _NIL_ ELSE 2 = a[1]=0
IF a[1] THEN _NIL_ ELSE 2 = a[2]=1
a[1] = _NIL_=1
1 2 3
7 2 3
x=0.5832970655
x=0.9936253726
x.UB=10
x.UB=1
x.UB=10
```

	1	2	3
1	1.00	0.50	
2	0.50		0.25
3		0.25	0.20

OPTMODEL Expression Extensions

PROC OPTMODEL defines several new types of expressions for the manipulation of sets. Aggregation operators combine values of an expression that is evaluated over the members of an index set. Other operators create new sets by combining existing sets, or they test relationships between sets. PROC OPTMODEL also supports an IF expression operator that can conditionally evaluate expressions. These and other such expressions are described in this section.

AND Aggregation Expression

AND { *index-set* **}** *logic-expression*

The AND aggregation operator evaluates the logical expression *logic-expression* jointly for each member of the index set *index-set*. The index set enumeration finishes early if the *logic-expression* evaluation produces a false value (zero or missing). The expression returns 0 if a false value is found or returns 1 otherwise. The following statements demonstrate both a true and a false result:

```
proc optmodel;
   put (and{i in 1..5} i < 10); /* returns 1 */
   put (and{i in 1..5} i NE 3); /* returns 0 */
```

CARD Function

CARD (*set-expression*)

The CARD function returns the number of members of its set operand. For example, the following statements produce the output 3 since the set has 3 members:

```
proc optmodel;
   put (card(1..3));
```

CROSS Expression

set-expression-1 **CROSS** *set-expression-2*

The CROSS expression returns the crossproduct of its set operands. The result is the set of tuples formed by concatenating the tuple value of each member of the left operand with the tuple value of each member of the right operand. Scalar set members are treated as tuples of length 1. The following statements demonstrate the CROSS operator:

```
proc optmodel;
   set s1 = 1..2;
   set<string> s2 = {'a', 'b'};
   set<number, string> s3=s1 cross s2;
   put 's3 is ' s3;
   set<number, string, number> s4 = s3 cross 4..5;
   put 's4 is ' s4;
```

This code produces the output in Figure 9.35.

Figure 9.35 CROSS Expression Output

```
s3 is {<1,'a'>,<1,'b'>,<2,'a'>,<2,'b'>}
s4 is {<1,'a',4>,<1,'a',5>,<1,'b',4>,<1,'b',5>,<2,'a',4>,<2,'a',5>,<2,'b',4>,<2,
'b',5>}
```

DIFF Expression

set-expression-1 **DIFF** *set-expression-2*

The DIFF operator returns a set that contains the set difference of the left and right operands. The result set contains values that are members of the left operand but not members of the right operand. The operands must have compatible set types. The following statements evaluate and print a set difference:

```
proc optmodel;
   put ({1,3} diff {2,3}); /* outputs {1} */
```

Equality Expression

set-expression-1 **=** *set-expression-2*

set-expression-1 ~**=** *set-expression-2*

The equality comparison operators are extended to support the comparison of sets. Sets are considered equal if they have the same members. The following code demonstrates set comparison:

```
proc optmodel;
   put (/a b/ = /a b/);  /* true */
   put (/a b/ = /a/);    /* false */
   put ({} = /a b/);     /* false */
   put (1..3 = {1,3,2}); /* true, ignores order */
```

IF-THEN/ELSE Expression

IF *logic-expression* **THEN** *expression-2* [**ELSE** *expression-3*]

The IF-THEN/ELSE expression evaluates the logical expression *logic-expression* and returns the result of evaluating the second or third operand expression according to the logical test result. If the *logic-expression* is true (nonzero and nonmissing), then the result of evaluating *expression-2* is returned. If the *logic-expression* is false (zero or missing), then the result of evaluating *expression-3* is returned. The other subexpression that is not selected is not evaluated.

An ELSE clause is matched during parsing with the nearest IF-THEN clause that does not have a matching ELSE. The ELSE clause can be omitted for numeric expressions; the resulting IF-THEN is handled as if a default ELSE 0 clause were supplied.

Use the IF-THEN/ELSE expression to handle special cases in models. For example, an inventory model based on discrete time periods might require special handling for the first or last period. In the following example the initial inventory for the first period is assumed to be fixed:

```
proc optmodel;
   number T;
   var inv{1..T}, order{1..T};
   number sell{1..T};
   number inv0;
   . . .
   /* balance inventory flow */
   con iflow{i in 1..T}:
       inv[i] = order[i] - sell[i] +
       if i=1 then inv0 else inv[i-1];
   . . .
```

The IF-THEN/ELSE expression in the example models the initial inventory for a time period *i*. Usually the inventory value is the inventory at the end of the previous period, but for the first time period the inventory value is given by the inv0 parameter. The iflow constraints are linear because the IF-THEN/ELSE test subexpression does not depend on variables and the other subexpressions are linear.

IF-THEN/ELSE can be used as either a set expression or a scalar expression. The type of expression depends on the subexpression between the THEN and ELSE keywords. The type used affects the parsing of the subexpression that follows the ELSE keyword because the set form has a lower operator precedence. For example, the following two expressions are equivalent because the numeric IF-THEN/ELSE has a higher precedence than the range operator (..):

```
IF logic THEN 1 ELSE 2 .. 3

(IF logic THEN 1 ELSE 2) .. 3
```

But the set form of IF-THEN/ELSE has lower precedence than the range expression operator. So the following two expressions are equivalent:

```
IF logic THEN 1 .. 2 ELSE 3 .. 4

IF logic THEN (1 .. 2) ELSE (3 .. 4)
```

The IF-THEN and IF-THEN/ELSE operators always have higher precedence than the logic operators. So, for example, the following two expressions are equivalent:

```
IF logic THEN numeric1 < numeric2

(IF logic THEN numeric1) < numeric2
```

It is best to use parentheses when in doubt about precedence.

IN Expression

expression **IN** *set-expression*

expression **NOT IN** *set-expression*

The IN expression returns 1 if the value of the left operand is a member of the right operand set. Otherwise, the IN expression returns 0. The NOT IN operator logically negates the returned value. Unlike the DATA step, the right operand is an arbitrary set expression. The left operand can be a tuple expression. The following example demonstrates the IN and NOT IN operators:

```
proc optmodel;
   set s = 1..10;
   put (5 in s);          /* outputs 1 */
   put (-1 not in s);     /* outputs 1 */
   set<num, str> t = {<1,'a'>, <2,'b'>, <2,'c'>};
   put (<2, 'b'> in t);    /* outputs 1 */
   put (<1, 'b'> in t);  /* outputs 0 */
```

Index Set Expression

{ *index-set* **}**

The index set expression returns the set of members of an index set. This expression is distinguished from a set constructor (see the section "Set Constructor Expression" on page 393) because it contains a list of set expressions.

The following statements use an index set with a selection expression that excludes the value 3:

```
proc optmodel;
   put ({i in 1..5 : i NE 3}); /* outputs {1,2,4,5} */
```

INTER Expression

set-expression-1 **INTER** *set-expression-2*

The INTER operator returns a set that contains the intersection of the left and right operands. This is the set that contains values that are members of both operand sets. The operands must have compatible set types.

The following statements evaluate and print a set intersection:

```
proc optmodel;
   put ({1,3} inter {2,3}); /* outputs {3} */
```

INTER Aggregation Expression

INTER { *index-set* **}** *set-expression*

The INTER aggregation operator evaluates the *set-expression* for each member of the index set *index-set*. The result is the set that contains the intersection of the set of values that were returned by the *set-expression* for each member of the index set. An empty index set causes an expression evaluation error.

The following statements use the INTER aggregation operator to compute the value of $\{1,2,3,4\} \cap \{2,3,4,5\} \cap \{3,4,5,6\}$:

```
proc optmodel;
   put (inter{i in 1..3} i..i+3); /* outputs {3,4} */
```

MAX Aggregation Expression

MAX { *index-set* **}** *expression*

The MAX aggregation operator evaluates the scalar-valued expression *expression* for each member of the index set *index-set*. The result is the maximum of the values that are returned by the *expression*. Missing numeric values are handled with the SAS numeric sort order; a missing value is treated as smaller than any nonmissing numeric value. If the index set is empty and the *expression* is numeric, then the result is the negative number that has the largest absolute value representable on the machine. Expression evaluation produces an error if the index set is empty and the *expression* has a string value.

The following example produces the outputs `0.5` and `*****`:

```
proc optmodel;
   put (max{i in 2..5} 1/i);
   put (max{i in 2..5} repeat('*',i-1));
```

MIN Aggregation Expression

MIN { *index-set* **}** *expression*

The MIN aggregation operator evaluates the scalar-valued expression *expression* for each member of the index set *index-set*. The result is the minimum of the values that are returned by the *expression*. Missing numeric values are handled with the SAS numeric sort order; a missing value is treated as smaller than any nonmissing numeric value. If the index set is empty and the *expression* is numeric, then the result is the largest positive number representable on the machine. Expression evaluation produces an error if the index set is empty and the *expression* has a string value.

The following example produces the outputs `0.2` and `**`:

```
proc optmodel;
   put (min{i in 2..5} 1/i);
   put (min{i in 2..5} repeat('*',i-1));
```

Nil Constant Expression

NIL

The _NIL_ keyword evaluates to a nil value. For more information about nil values, see the section "Nil Values" on page 386.

OR Aggregation Expression

OR { *index-set* **}** *logic-expression*

The OR aggregation operator evaluates the logical expression *logic-expression* for each member of the index set *index-set*. The index set enumeration finishes early if the *logic-expression* evaluation produces a true value (nonzero and nonmissing). The result is 1 if a true value is found, or 0 otherwise. The following statements demonstrate both a true and a false result:

```
proc optmodel;
   put (or{i in 1..5} i = 2); /* returns 1 */
   put (or{i in 1..5} i = 7); /* returns 0 */
```

PROD Aggregation Expression

PROD { *index-set* **}** *expression*

The PROD aggregation operator evaluates the numeric expression *expression* for each member of the index set *index-set*. The result is the product of the values that are returned by the *expression*. This operator is analogous to the $\prod$ operator used in mathematical notation. If the index set is empty, then the result is 1.

The following example uses the PROD operator to evaluate a factorial:

```
proc optmodel;
   number n = 5;
   put (prod{i in 1..n} i); /* outputs 120 */
```

Range Expression

expression-1 .. *expression-n* [**BY** *expression*]

The range expression returns the set of numbers from the specified arithmetic progression. The sequence proceeds from the left operand value up to the right operand limit. The increment between numbers is 1 unless a different value is specified with a BY clause. If the increment is negative, then the progression is from the left operand down to the right operand limit. The result can be an empty set.

For compatibility with the DATA step iterative DO loop construct, the keyword TO can substitute for the range (..) operator.

The limit value is not included in the resulting set unless it belongs in the arithmetic progression. For example, the following range expression does not include 30:

```
proc optmodel;
   put (10..30 by 7); /* outputs {10,17,24} */
```

The actual numbers that the range expression "f..l by i" produces are in the arithmetic sequence

$$f, f+i, f+2i, \ldots, f+ni$$

where

$$n = \left\lfloor \frac{l-f}{i} + \sqrt{\epsilon} \right\rfloor$$

and ϵ represents the relative machine precision. The limit is adjusted to avoid arithmetic roundoff errors.

PROC OPTMODEL represents the set specified by a range expression compactly when the value is stored in a parameter location, used as a set operand of an IN or NOT IN expression, used by an iterative DO loop, or used in an index set. For example, the following expression is evaluated efficiently:

```
999998.5 IN 1..1000000000
```

Set Constructor Expression

{ [*expression-1* [**,** . . . *expression-n*]] **}**

The set constructor expression returns the set of the expressions in the member list. Duplicated values are added to the set only once. A warning message is produced when duplicates are detected. The constructor expression consists of zero or more subexpressions of the same scalar type or of tuple expressions that match in length and in element types.

The following statements output a three-member set and warn about the duplicated value 2:

```
proc optmodel;
   put ({1,2,3,2}); /* outputs {1,2,3} */
```

The following example produces a three-member set of tuples, using PROC OPTMODEL parameters and variables. The output is displayed in Figure 9.36.

```
proc optmodel;
   number m = 3, n = 4;
   var x{1..4} init 1;
   string y = 'c';
   put ({<'a', x[3]>, <'b', m>, <y, m/n>});
```

Figure 9.36 Set Constructor Expression Output

```
{<'a',1>,<'b',3>,<'c',0.75>}
```

Set Literal Expression

/ members /

The set literal expression provides compact specification of simple set values. It is equivalent in function to the set constructor expression but minimizes typing for sets that contain numeric and string constant values. The set members are specified by *members*, which are literal values. As with the set constructor expression, each member must have the same type.

The following statement specifies a simple numeric set:

```
/1 2.5 4/
```

The set contains the members `1`, `2.5`, and `4`. A string set could be specified as follows:

```
/Miami 'San Francisco' Seattle 'Washington, D.C.'/
```

This set contains the strings `'Miami'`, `'San Francisco'`, `'Seattle'`, and `'Washington, D.C.'`. You can specify string values in set literals without quotation marks when the text follows the rules for a SAS name. Strings that begin with a digit or contain blanks or other special characters must be specified with quotation marks.

Specify tuple members of a set by enclosing the tuple elements within angle brackets (<*elements*>). The tuple elements can be specified with numeric and string literals. The following example includes the tuple elements `<'New York', 4.5>` and `<'Chicago', -5.7>`:

```
/<'New York' 4.5> <Chicago -5.7>/
```

SETOF Aggregation Expression

SETOF { *index-set* **}** *expression*

The SETOF aggregation operator evaluates the expression *expression* for each member of the index set *index-set*. The result is the set that is formed by collecting the values returned by the operand expression. The operand can be a tuple expression. For example, the following statements produce a set of tuples of numbers with their squared and cubed values:

```
proc optmodel;
   put (setof{i in 1..3}<i, i*i, i**3>);
```

Figure 9.37 shows the displayed output.

Figure 9.37 SETOF Aggregation Expression Output

```
{<1,1,1>,<2,4,8>,<3,9,27>}
```

SLICE Expression

SLICE (**<** *element-1*, . . . *element-n* **>** , *set-expression* **)**

The SLICE expression produces a new set by selecting members in the operand set that match a pattern tuple. The pattern tuple is specified by the element list in angle brackets. Each *element* in the pattern tuple must specify a numeric or string expression. The expressions are used to match the values of the corresponding elements in the operand set member tuples. You can also specify an *element* by using an asterisk (*). The

sequence of element values that correspond to asterisk positions in each matching tuple is combined into a tuple of the result set. At least one asterisk *element* must be specified.

The following statements demonstrate the SLICE expression:

```
proc optmodel;
   put (slice(<1,*>, {<1,3>, <1,0>, <3,1>}));
   put (slice(<*,2,*>, {<1,2,3>, <2,4,3>, <2,2,5>}));
```

These statements produce the output in Figure 9.38.

Figure 9.38 SLICE Expression Output

```
{3,0}
{<1,3>,<2,5>}
```

For the first PUT statement, <1,*> matches set members <1,3> and <1,0> but not <3,1>. The second element of each matching set tuple, corresponding to the asterisk element, becomes the value of the resulting set member. In the second PUT statement, the values of the first and third elements of the operand set member tuple are combined into a two-position tuple in the result set.

The following statements use the SLICE expression to help compute the transitive closure of a set of tuples representing a relation by using Warshall's algorithm. In these statements the set parameter dep represents a direct dependency relation.

```
proc optmodel;
   set<str,str> dep = {<'B','A'>, <'C','B'>, <'D','C'>};
   set<str,str> cl;
   set<str> cn;
   cl = dep;
   cn =  (setof{<i,j> in dep} i) inter (setof{<i,j> in dep} j);
   for {node in cn}
       cl = cl union (slice(<*,node>,cl) cross slice(<node,*>,cl));
   put cl;
```

The local dummy parameter node in the FOR statement iterates over the set cn of possible intermediate nodes that can connect relations transitively. At the end of each FOR iteration, the set parameter cl contains all tuples from the original set in addition to all transitive tuples found in the current or previous iterations.

The output in Figure 9.39 includes the indirect and direct transitive dependencies from the set dep.

Figure 9.39 Warshall's Algorithm Output

```
{<'B','A'>,<'C','B'>,<'D','C'>,<'C','A'>,<'D','B'>,<'D','A'>}
```

A special form of *index-set-item* uses the SLICE expression implicitly. See the section "More on Index Sets" on page 464 for details.

SUM Aggregation Expression

SUM { *index-set* **}** *expression*

The SUM aggregation operator evaluates the numeric expression *expression* for each member in the index set *index-set*. The result is the sum of the values that are returned by the *expression*. If the index set is empty, then the result is 0. This operator is analogous to the $\sum$ operator that is used in mathematical notation. The following statements demonstrate the use of the SUM aggregation operator:

```
proc optmodel;
   put (sum {i in 1..10} i);  /* outputs 55 */
```

SYMDIFF Expression

set-expression-1 **SYMDIFF** *set-expression-2*

The SYMDIFF expression returns the symmetric set difference of the left and right operands. The result set contains values that are members of either the left or right operand but are not members of both operands. The operands must have compatible set types.

The following example demonstrates a symmetric difference:

```
proc optmodel;
   put ({1,3} symdiff {2,3}); /* outputs {1,2} */
```

Tuple Expression

< *expression-1* [**,** . . . *expression-n*] **>**

A tuple expression represents the value of a member in a set of tuples. Each scalar subexpression inside the angle brackets represents the value of a tuple element. This form is used only with IN, SETOF, set constructor, and relational expressions.

The following statements demonstrate the tuple expression:

```
proc optmodel;
   put (<1,2,3> in setof{i in 1..2}<i,i+1,i+2>);
   put ({<1,'a'>, <2,'b'>} cross {<3,'c'>, <4,'d'>});
```

The first PUT statement checks whether the tuple <1, 2, 3> is a member of a set of tuples. The second PUT statement outputs the crossproduct of two sets of tuples that are constructed by the set constructor.

These statements produce the output in Figure 9.40.

Figure 9.40 Tuple Expression Output

```
1
{<1,'a',3,'c'>,<1,'a',4,'d'>,<2,'b',3,'c'>,<2,'b',4,'d'>}
```

You can specify tuple expressions as operands of the relational operators. For the equality operators (= and ~=), tuples are equal if their corresponding elements are equal. Ordering operators (<, <=, >, and >=) compare tuples lexicographically. That is, the corresponding tuple elements are compared left to right, and the leftmost pair of unequal elements determines the result of the comparison.

The following code demonstrates tuple comparison:

```
proc optmodel;
   put (<1,'a'> = <1,'a'>)=;  /* true, all elements equal */
   put (<1,'a'> = <1,'b'>)=;  /* false, at least one element unequal */
   put (<1,'a'> ~= <1,'b'>)=; /* true, at least one element unequal */
   put (<1,2,5> < <1,3,4>)=;  /* true, compared left to right, 2 < 3 */
```

These statements produce the output in Figure 9.41.

Figure 9.41 Tuple Comparison Output

```
<1,'a'> = <1,'a'>=1
<1,'a'> = <1,'b'>=0
<1,'a'> ~= <1,'b'>=1
<1,2,5> < <1,3,4>=1
```

UNION Expression

set-expression-1 **UNION** *set-expression-2*

The UNION expression returns the set union of the left and right operands. The result set contains values that are members of either the left or right operand. The operands must have compatible set types. The following example performs a set union:

```
proc optmodel;
   put ({1,3} union {2,3}); /* outputs {1,3,2} */
```

UNION Aggregation Expression

UNION { *index-set* **}** *set-expression*

The UNION aggregation expression evaluates the *set-expression* for each member of the index set *index-set*. The result is the set union of the values that are returned by the *set-expression*. If the index set is empty, then the result is an empty set.

The following statements demonstrate a UNION aggregation. The output is the value of $\{1,2,3,4\} \cup \{2,3,4,5\} \cup \{3,4,5,6\}$.

```
proc optmodel;
   put (union{i in 1..3} i..i+3); /* outputs {1,2,3,4,5,6} */
```

WITHIN Expression

set-expression-1 **WITHIN** *set-expression-2*

set-expression **NOT WITHIN** *set-expression*

The WITHIN expression returns 1 if the left operand set is a subset of the right operand set and returns 0 otherwise. (That is, the operator returns true if every member of the left operand set is a member of the right operand set.) The NOT WITHIN form logically negates the result value. The following statements demonstrate the WITHIN and NOT WITHIN operators:

```
proc optmodel;
   put ({1,3} within {2,3});     /* outputs 0 */
   put ({1,3} not within {2,3}); /* outputs 1 */
   put ({1,3} within {1,2,3});   /* outputs 1 */
```

Conditions of Optimality

Linear Programming

A standard linear program has the following formulation:

$$\begin{array}{ll} \text{minimize} & \mathbf{c}^T\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\ & \mathbf{x} \geq 0 \end{array}$$

where

$\mathbf{x}$	$\in$	$\mathbb{R}^n$	is the vector of decision variables
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the matrix of constraints
$\mathbf{c}$	$\in$	$\mathbb{R}^n$	is the vector of objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^m$	is the vector of constraints right-hand sides (RHS)

This formulation is called the primal problem. The corresponding dual problem (see the section "Dual Values" on page 425) is

$$\begin{array}{ll} \text{maximize} & \mathbf{b}^T\mathbf{y} \\ \text{subject to} & \mathbf{A}^T\mathbf{y} \leq \mathbf{c} \\ & \mathbf{y} \geq 0 \end{array}$$

where $\mathbf{y} \in \mathbb{R}^m$ is the vector of dual variables.

The vectors $\mathbf{x}$ and $\mathbf{y}$ are optimal to the primal and dual problems, respectively, only if there exist primal slack variables $\mathbf{s} = \mathbf{A}\mathbf{x} - \mathbf{b}$ and dual slack variables $\mathbf{w} = \mathbf{A}^T\mathbf{y} - \mathbf{c}$ such that the following *Karush-Kuhn-Tucker (KKT) conditions* are satisfied:

$$\begin{array}{rcl} \mathbf{A}\mathbf{x} + \mathbf{s} & = & \mathbf{b}, \quad \mathbf{x} \geq 0, \quad \mathbf{s} \geq 0 \\ \mathbf{A}^T\mathbf{y} + \mathbf{w} & = & \mathbf{c}, \quad \mathbf{y} \geq 0, \quad \mathbf{w} \geq 0 \\ \mathbf{s}^T\mathbf{y} & = & 0 \\ \mathbf{w}^T\mathbf{x} & = & 0 \end{array}$$

The first line of equations defines primal feasibility, the second line of equations defines dual feasibility, and the last two equations are called the complementary slackness conditions.

Nonlinear Programming

To facilitate discussion of optimality conditions in nonlinear programming, you write the general form of nonlinear optimization problems by grouping the equality constraints and inequality constraints. You also write all the general nonlinear inequality constraints and bound constraints in one form as "$\geq$" inequality constraints. Thus, you have the following formulation:

$$\begin{array}{ll} \underset{x \in \mathbb{R}^n}{\text{minimize}} & f(x) \\ \text{subject to} & c_i(x) = 0, \quad i \in \mathcal{E} \\ & c_i(x) \geq 0, \quad i \in \mathcal{I} \end{array}$$

where $\mathcal{E}$ is the set of indices of the equality constraints, $\mathcal{I}$ is the set of indices of the inequality constraints, and $m = |\mathcal{E}| + |\mathcal{I}|$.

A point x is *feasible* if it satisfies all the constraints $c_i(x) = 0, i \in \mathcal{E}$ and $c_i(x) \geq 0, i \in \mathcal{I}$. The feasible region $\mathcal{F}$ consists of all the feasible points. In unconstrained cases, the feasible region $\mathcal{F}$ is the entire $\mathbb{R}^n$ space.

A feasible point x^* is a *local solution* of the problem if there exists a neighborhood $\mathcal{N}$ of x^* such that

$$f(x) \geq f(x^*) \text{ for all } x \in \mathcal{N} \cap \mathcal{F}$$

Further, a feasible point x^* is a *strict local solution* if strict inequality holds in the preceding case; that is,

$$f(x) > f(x^*) \text{ for all } x \in \mathcal{N} \cap \mathcal{F}$$

A feasible point x^* is a *global solution* of the problem if no point in $\mathcal{F}$ has a smaller function value than $f(x^*)$; that is,

$$f(x) \geq f(x^*) \text{ for all } x \in \mathcal{F}$$

Unconstrained Optimization

The following conditions hold true for unconstrained optimization problems:

- **First-order necessary conditions**: If x^* is a local solution and $f(x)$ is continuously differentiable in some neighborhood of x^*, then

  $$\nabla f(x^*) = 0$$

- **Second-order necessary conditions**: If x^* is a local solution and $f(x)$ is twice continuously differentiable in some neighborhood of x^*, then $\nabla^2 f(x^*)$ is positive semidefinite.

- **Second-order sufficient conditions**: If $f(x)$ is twice continuously differentiable in some neighborhood of x^*, $\nabla f(x^*) = 0$, and $\nabla^2 f(x^*)$ is positive definite, then x^* is a strict local solution.

Constrained Optimization

For constrained optimization problems, the *Lagrangian function* is defined as follows:

$$L(x, \lambda) = f(x) - \sum_{i \in \mathcal{E} \cup \mathcal{I}} \lambda_i c_i(x)$$

where $\lambda_i, i \in \mathcal{E} \cup \mathcal{I}$, are called *Lagrange multipliers*. $\nabla_x L(x, \lambda)$ is used to denote the gradient of the Lagrangian function with respect to x, and $\nabla_x^2 L(x, \lambda)$ is used to denote the Hessian of the Lagrangian function with respect to x. The active set at a feasible point x is defined as

$$\mathcal{A}(x) = \mathcal{E} \cup \{i \in \mathcal{I} : c_i(x) = 0\}$$

You also need the following definition before you can state the first-order and second-order necessary conditions:

- **Linear independence constraint qualification and regular point**: A point x is said to satisfy the *linear independence constraint qualification* if the gradients of active constraints

  $$\nabla c_i(x), \quad i \in \mathcal{A}(x)$$

  are linearly independent. Such a point x is called a *regular point*.

You now state the theorems that are essential in the analysis and design of algorithms for constrained optimization:

- **First-order necessary conditions**: Suppose that x^* is a local minimum and also a regular point. If $f(x)$ and $c_i(x), i \in \mathcal{E} \cup \mathcal{I}$, are continuously differentiable, there exist Lagrange multipliers $\lambda^* \in \mathbb{R}^m$ such that the following conditions hold:

  $$\nabla_x L(x^*, \lambda^*) = \nabla f(x^*) - \sum_{i \in \mathcal{E} \cup \mathcal{I}} \lambda_i^* \nabla c_i(x^*) = 0$$

  $$\begin{aligned} c_i(x^*) &= 0, \quad i \in \mathcal{E} \\ c_i(x^*) &\geq 0, \quad i \in \mathcal{I} \\ \lambda_i^* &\geq 0, \quad i \in \mathcal{I} \\ \lambda_i^* c_i(x^*) &= 0, \quad i \in \mathcal{I} \end{aligned}$$

  The preceding conditions are often known as the *Karush-Kuhn-Tucker conditions*, or *KKT conditions* for short.

- **Second-order necessary conditions**: Suppose that x^* is a local minimum and also a regular point. Let λ^* be the Lagrange multipliers that satisfy the KKT conditions. If $f(x)$ and $c_i(x), i \in \mathcal{E} \cup \mathcal{I}$, are twice continuously differentiable, the following conditions hold:

  $$z^T \nabla_x^2 L(x^*, \lambda^*) z \geq 0$$

  for all $z \in \mathbb{R}^n$ that satisfy

  $$\nabla c_i(x^*)^T z = 0, \quad i \in \mathcal{A}(x^*)$$

- **Second-order sufficient conditions**: Suppose there exist a point x^* and some Lagrange multipliers λ^* such that the KKT conditions are satisfied. If

  $$z^T \nabla_x^2 L(x^*, \lambda^*) z > 0$$

  for all $z \in \mathbb{R}^n$ that satisfy

  $$\nabla c_i(x^*)^T z = 0, \quad i \in \mathcal{A}(x^*)$$

  then x^* is a strict local solution.

  Note that the set of all such z's forms the null space of the matrix $\left[\nabla c_i(x^*)^T\right]_{i \in \mathcal{A}(x^*)}$. Thus, you can search for strict local solutions by numerically checking the Hessian of the Lagrangian function projected onto the null space. For a rigorous treatment of the optimality conditions, see Fletcher (1987) and Nocedal and Wright (1999).

Data Set Input/Output

You can use the CREATE DATA and READ DATA statements to exchange PROC OPTMODEL data with SAS data sets. The statements can move data into and out of PROC OPTMODEL parameters and variables. For example, the following statements use a CREATE DATA statement to save the results from an optimization into a data set:

```
proc optmodel;
   var x;
   min z = (x-5)**2;
   solve;
   create data optdata from xopt=x z;
```

These statements write a single observation into the data set OPTDATA. The data set contains two variables, xopt and z, and the values contain the optimized values of the PROC OPTMODEL variable x and objective z, respectively. The statement "xopt=x" renames the variable x to xopt.

The group of values held by a data set variable in different observations of a data set is referred to as a *column*. The READ DATA and CREATE DATA statements specify a set of columns for a data set and define how data are to be transferred between the columns and PROC OPTMODEL parameters.

Columns in square brackets ([ ]) are handled specially. Such columns are called *key columns*. Key columns specify element values that provide an implicit index for subsequent array columns. The following example uses key columns with the CREATE DATA statement to write out variable values from an array:

```
proc optmodel;
   set LOCS = {'New York', 'Washington', 'Boston'};  /* locations */
   set DOW = 1..7;  /* day of week */
   var s{LOCS, DOW} init 1;
   create data soldata from [location day_of_week]={LOCS, DOW} sale=s;
```

In this case the optimization variable s is initialized to a value of 1 and is indexed by values from the set parameters LOCS and DOW. The output data set contains an observation for each combination of values in these sets. The output data set contains three variables, location, day_of_week, and sale. The data set variables location and day_of_week save the index element values for the optimization variable s that is written in each observation. The data set created is shown in Figure 9.42.

Figure 9.42 Data Sets Created

Data Set: SOLDATA

Obs	location	day_of_week	sale
1	New York	1	1
2	New York	2	1
3	New York	3	1
4	New York	4	1
5	New York	5	1
6	New York	6	1
7	New York	7	1
8	Washington	1	1
9	Washington	2	1
10	Washington	3	1
11	Washington	4	1
12	Washington	5	1
13	Washington	6	1
14	Washington	7	1
15	Boston	1	1
16	Boston	2	1
17	Boston	3	1
18	Boston	4	1
19	Boston	5	1
20	Boston	6	1
21	Boston	7	1

Note that the key columns in the preceding example do not name existing PROC OPTMODEL variables. They create new local dummy parameters, location and day_of_week, in the same manner as dummy parameters in index sets. These local parameters can be used in subsequent columns. For example, the following statements demonstrate how to use a key column value in an expression for a later column value:

```
proc optmodel;
   create data tab
          from [i]=(1..10)
          Square=(i*i) Cube=(i*i*i);
```

These statements create a data set that has 10 observations that hold squares and cubes of the numbers from 1 to 10. The key column variable here is named i and is explicitly assigned the values from 1 to 10, while the data set variables Square and Cube hold the square and cube, respectively, of the corresponding value of i.

In the preceding example the key column values are simply the numbers from 1 to 10. The value is the same as the observation number, so the variable i is redundant. You can remove the data set variable for a key column via the DROP data set option, as follows:

```
proc optmodel;
   create data tab2 (drop=i)
          from [i] =(1..10)
          Square=(i*i) Cube=(i*i*i);
```

The local parameters declared by key columns receive their values in various ways. For a READ DATA statement, the key column values come from the data set variables for the column. In a CREATE DATA

statement, the values can be defined explicitly, as shown in the previous example. Otherwise, the CREATE DATA statement generates a set of values that combines the index sets of array columns that need implicit indexing. The statements that produce the output in Figure 9.42 demonstrate implicit indexing.

Use a suffix ("Suffixes" on page 420) to read or write auxiliary values, such as variable bounds or constraint duals. For example, consider the following statements:

```
data pdat;
   input p $ maxprod cost;
   datalines;
ABQ    12  0.7
MIA     9  0.6
CHI    14  0.5
;

proc optmodel;
   set<string> plants;
   var prod{plants} >= 0;
   number cost{plants};
   read data pdat into plants=[p] prod.ub=maxprod cost;
```

The statement "plants=[p]" in the READ DATA statement declares p as a key column and instructs PROC OPTMODEL to store the set of plant names from the data set variable p into the set parameter plants. The statement assigns the upper bound for the variable prod indexed by p to be the value of the data set variable maxprod. The cost parameter location indexed by p is also assigned to be the value of the data set variable cost.

The target variables prod and cost in the preceding example use implicit indexing. Indexing can also be performed explicitly. The following version of the READ DATA statement makes the indices explicit:

```
read data pdat into plants=[p] prod[p].ub=maxprod cost[p];
```

Explicit indexing is useful when array indices need to be transformed from the key column values in the data set. For example, the following statements reverse the order in which elements from the data set are stored in an array:

```
data abcd;
   input letter $ @@;
   datalines;
a b c d
;

proc optmodel;
   set<num> subscripts=1..4;
   string  letter{subscripts};
   read data abcd into [_N_] letter[5-_N_];
   print letter;
```

The output from this example appears in Figure 9.43.

Figure 9.43 READ DATA Statement: Explicit Indexing

[1]	letter
1	d
2	c
3	b
4	a

The following example demonstrates the use of explicit indexing to save sequential subsets of an array in individual data sets:

```
data revdata;
   input month rev @@;
   datalines;
1 200 2 345 3 362 4 958
5 659 6 804 7 487 8 146
9 683 10 732 11 652 12 469
;

proc optmodel;
   set m = 1..3;
   var revenue{1..12};
   read data revdata into [_N_] revenue=rev;
   create data qtr1 from [month]=m revenue[month];
   create data qtr2 from [month]=m revenue[month+3];
   create data qtr3 from [month]=m revenue[month+6];
   create data qtr4 from [month]=m revenue[month+9];
```

Each CREATE DATA statement generates a data set that represents one quarter of the year. Each data set contains the variables month and revenue. The data set qtr2 is shown in Figure 9.44.

Figure 9.44 CREATE DATA Statement: Explicit Indexing

Obs	month	revenue
1	1	958
2	2	659
3	3	804

Data set names and options that are used in PROC OPTMODEL statements can also be generated dynamically, by using an expression in parentheses to specify the name and options. The expression must evaluate to a string value with the following form:

[*libref* **.**] *member* [**(** *options* **)**]

Dynamic data set names are useful for processing data sets inside looping statements such as a FOR statement, particularly when the loop contains a SOLVE statement. You can replace the multiple CREATE DATA statements in the previous example with a single statement in a loop:

```
proc optmodel;
   set m = 1..3;
   var revenue{1..12};
   read data revdata into [_N_] revenue=rev;
   for {q in 1..4}
```

```
create data ("qtr" || q)
       from [month]=m revenue[month+(q-1)*3];
```

Control Flow

Most of the control flow statements in PROC OPTMODEL are familiar to users of the DATA step or the IML procedure. PROC OPTMODEL supports the IF statement, DO blocks, the iterative DO statement, the DO WHILE statement, and the DO UNTIL statement. You can also use the CONTINUE, LEAVE, and STOP statements to modify control flow.

PROC OPTMODEL adds the FOR statement. This statement is similar in operation to an iterative DO loop. However, the iteration is performed over the members of an index set. This form is convenient for iteration over all the locations in an array, since the valid array indices are also defined using an index set. For example, the following statements initialize the array parameter A, indexed by i and j, to random values sampled from a normal distribution with mean 0 and variance 1:

```
proc optmodel;
   set R=1..10;
   set C=1..5;
   number A{R, C};
   for {i in R, j in C}
      A[i, j]=rand('NORMAL');
```

The FOR statement provides a convenient way to perform a statement such as the preceding assignment statement for each member of a set.

Formatted Output

PROC OPTMODEL provides two primary means of producing formatted output. The PUT statement provides output of data values with detailed format control. The PRINT statement handles arrays and produces formatted output in tabular form.

The PUT statement is similar in syntax to the PUT statement in the DATA step and in PROC IML. The PUT statement can output data to the SAS log, the SAS listing, or an external file. Arguments to the PUT statement specify the data to output and provide instructions for formatting. The PUT statement provides enough control to create reports within PROC OPTMODEL. However, typically the PUT statement is used to produce output for debugging or to quickly check data values.

The following example demonstrates some features of the PUT statement:

```
proc optmodel;
   number a=1.7, b=2.8;
   set s={a,b};
   put a b;        /* list output */
   put a= b=;      /* named output */
   put 'Value A: ' a 8.1 @30 'Value B: ' b 8.; /* formatted */
   string str='Ratio (A/B) is:';
   put str (a/b);  /* strings and expressions */
   put s=;         /* named set output */
```

These statements produce the output in Figure 9.45.

Figure 9.45 PUT Statement Output

```
1.7 2.8
a=1.7 b=2.8
Value A:      1.7            Value B:        3
Ratio (A/B) is: 0.6071428571
s={1.7,2.8}
```

The first PUT statement demonstrates list output. The numeric data values are output in a default format, BEST12., with leading and trailing blanks removed. A blank space is inserted after each data value is output. The second PUT statement uses the equal sign (=) to request that the variable name be output along with the regular list output.

The third PUT statement demonstrates formatted output. It uses the @ operator to position the output in a specific column. This style of output can be used in report generation. The format specification "8." causes the displayed value of parameter b to be rounded.

The fourth PUT statement shows the output of a string value, str. It also outputs the value of an expression enclosed in parentheses. The final PUT statement outputs a set along with its name.

The default destination for PUT statement output is the SAS log. The FILE and CLOSEFILE statements can be used to send output to the SAS listing or to an external data file. Multiple files can be open at the same time. The FILE statement selects the current destination for PUT statement output, and the CLOSEFILE statement closes the corresponding file. See the section "FILE Statement" on page 350 for more details.

The PRINT statement is designed to output numeric and string data in the form of tables. The PRINT statement handles the details of formatting automatically. However, the output format can be overridden by PROC OPTMODEL options and through Output Delivery System (ODS) facilities.

The PRINT statement can output array data in a table form that contains a row for each combination of array index values. This form uses columns to display the array index values for each row and uses other columns to display the value of each requested data item. The following statements demonstrate the table form:

```
proc optmodel;
   number square{i in 0..5} = i*i;
   number recip{i in 1..5} = 1/i;
   print square recip;
```

The PRINT statement produces the output in Figure 9.46.

Figure 9.46 PRINT Statement Output (List Form)

[1]	square	recip
0	0	
1	1	1.00000
2	4	0.50000
3	9	0.33333
4	16	0.25000
5	25	0.20000

The first table column, labeled "[1]," contains the index values for the parameters square and recip. The

columns that are labeled square and recip contain the parameter values for each array index. For example, the last row corresponds to the index 5 and the value in the last column is 0.2, which is the value of recip[5].

Note that the first row of the table contains no value in the recip column. Parameter location recip[0] does not have a valid index, so no value is printed. The PRINT statement does not display variables that are undefined or have invalid indices. This permits arrays that have similar indexing to be printed together. The sets of defined indices in the arrays are combined to generate the set of indices shown in the table.

Also note that the PRINT statement has assigned formats and widths that differ between the square and recip columns. The PRINT statement assigns a default fixed-point format to produce the best overall output for each data column. The format that is selected depends on the PDIGITS= and PWIDTH= options.

The PDIGITS= and PWIDTH= options specify the desired significant digits and formatted width, respectively. If the range of magnitudes is large enough that no suitable format can be found, then the data item is displayed in scientific format. The table in the preceding example displays the last column with five decimal places in order to display the five significant digits that were requested by the default PDIGITS= value. The square column, on the other hand, does not need any decimal places.

The PRINT statement can also display two-dimensional arrays in matrix form. If the list following the PRINT statement contains only a single array that has two index elements, then the array is displayed in matrix form when it is sufficiently dense (otherwise the display is in table form). In this form the left-most column contains the values of the first index element. The remaining columns correspond to and are labeled by the values of the second index element. The following statements print an example of matrix form:

```
proc optmodel;
   set R=1..6;
   set C=1..4;
   number a{i in R, j in C} = 10*i+j;
   print a;
```

The PRINT statement produces the output in Figure 9.47.

Figure 9.47 PRINT Statement Output (Matrix Form)

	a			
	1	**2**	**3**	**4**
1	11	12	13	14
2	21	22	23	24
3	31	32	33	34
4	41	42	43	44
5	51	52	53	54
6	61	62	63	64

In the example the first index element ranges from 1 to 6 and corresponds to the table rows. The second index element ranges from 1 to 4 and corresponds to the table columns. Array values can be found based on the row and column values. For example, the value of parameter a[3,2] is 32. This location is found in the table in the row labeled “3” and the column labeled “2.”

ODS Table and Variable Names

PROC OPTMODEL assigns a name to each table it creates. You can use these names to reference the table when you use the Output Delivery System (ODS) to select tables and create output data sets. The names of tables common to all solvers are listed in Table 9.12. Some solvers can generate additional tables; see the individual solver chapters for more information. For more information about ODS, see *SAS Output Delivery System: User's Guide*.

Table 9.12 ODS Tables Produced in PROC OPTMODEL

ODS Table Name	Description	Statement/Option
DerivMethods	List of derivatives used by the solver, including the method of computation	SOLVE
OptStatistics	Solver-dependent description of the resources required for solution, including function evaluations and solver time	SOLVE
PrintTable	Specified parameter or variable values	PRINT
ProblemSummary	Description of objective, variables, and constraints	SOLVE
ProfileInfo	Detailed timing of statements and declarations	PROFILE
SolutionSummary	Overview of solution, including solver-dependent solution quality values	SOLVE
SolverOptions	List of solver options and their values	SOLVE
Timing	Detailed solution timing	SOLVE

To guarantee that ODS output data sets contain information from all executed statements, use the PERSIST= option in the ODS OUTPUT statement. For details, see *SAS Output Delivery System: User's Guide*.
NOTE: The SUBMIT statement resets ODS SELECT and EXCLUDE lists.

Table 9.13 lists the variable names of the preceding tables used in the ODS template of the OPTMODEL procedure.

Table 9.13 Variable Names for the ODS Tables Produced in PROC OPTMODEL

ODS Table Name	Variables
DerivMethods	Label1, cValue1, and nValue1
OptStatistics	Label1, cValue1, and nValue1
PrintTable (matrix form)	ROW, COL1 – COL*n*
PrintTable (table form)	COL1 – COL*n*, *identifier-expression(_suffix)*
ProblemSummary	Label1, cValue1, and nValue1
ProfileInfo	Item, Line, Column, Count, MemSize (optional), NetTime, WaitTime, and PctTime
SolutionSummary	Label1, cValue1, and nValue1
SolverOptions	Label1, cValue1, nValue1, cValue2, and nValue2
Timing	Label1, cValue1, nValue1, cValue2, and nValue2

The PRINT statement produces an ODS table named PrintTable. The variable names that are used depend on the display format used. See the section "Formatted Output" on page 405 for details about choosing the display format.

For the PRINT statement with table format, the columns that display array indices are named COL1–COL*n*, where *n* is the number of index elements. Columns that display values from identifier expressions are named using the expression's name and suffix. The identifier name becomes the output variable name if no suffix is used. Otherwise the variable name is formed by appending an underscore (_) and the suffix to the identifier name. Columns that display the value of expressions are named COL*n*, where *n* is the column number in the table.

For the PRINT statement with matrix format, the first column has the variable name ROW. The remaining columns are named COL1–COL*n*, where *n* is the number of distinct column indices. When an ODS table displays values from identifier expressions, a label is generated based on the expression's name and suffix, as described for column names in the case of table format.

The PRINTLEVEL= option controls the ODS tables produced by the SOLVE and COFOR statements. When PRINTLEVEL=0, the statements produce no ODS tables. When PRINTLEVEL=1, the SOLVE statement produces the ODS tables ProblemSummary and SolutionSummary. When PRINTLEVEL=2, the SOLVE statement produces the ODS tables ProblemSummary, SolverOptions, DerivMethods, SolutionSummary, OptStatistics, and Timing.

The following statements generate several ODS tables and write each table to a SAS data set:

```
proc optmodel printlevel=2;
   ods output PrintTable=expt ProblemSummary=exps DerivMethods=exdm
              SolverOptions=exso SolutionSummary=exss OptStatistics=exos
              Timing=exti;
   var x{1..2} >= 0;
   min z = 2*x[1] + 3 * x[2] + x[1]**2 + 10*x[2]**2
           + 2.5*x[1]*x[2] + x[1]**3;
   con c1: x[1] - x[2] <= 1;
   con c2: x[1] + 2*x[2] >= 100;
   solve;
   print x;
```

The data set expt contains the PrintTable table and is shown in Figure 9.48. The variable names are COL1 and x.

Figure 9.48 PrintTable ODS Table

PrintTable

Obs	COL1	x
1	1	10.448
2	2	44.776

The data set exps contains the ProblemSummary table and is shown in Figure 9.49. The variable names are Label1, cValue1, and nValue1. The rows describe the instance, and the description depends on the form of the problem. In most solvers, the rows describe the objective function, variables, and constraints. In the network solver, the rows describe the number of nodes, the number of edges, the directedness of the graph, and the type of problem solved over the graph.

Figure 9.49 ProblemSummary ODS Table

ProblemSummary

Obs	Label1	cValue1	nValue1
1	Objective Sense	Minimization	.
2	Objective Function	z	.
3	Objective Type	Nonlinear	.
4			.
5	Number of Variables	2	2.000000
6	Bounded Above	0	0
7	Bounded Below	2	2.000000
8	Bounded Below and Above	0	0
9	Free	0	0
10	Fixed	0	0
11			.
12	Number of Constraints	2	2.000000
13	Linear LE (<=)	1	1.000000
14	Linear EQ (=)	0	0
15	Linear GE (>=)	1	1.000000
16	Linear Range	0	0

The data set exso contains the SolverOptions table and is shown in Figure 9.50. The variable names are Label1, cValue1, nValue1, cValue2, and nValue2. The rows, which depend on the solver called by PROC OPTMODEL, list the values taken by each of the solver options. The presence of an asterisk (*) next to an option indicates that a value has been specified for that option.

Figure 9.50 SolverOptions ODS Table

SolverOptions

Obs	Label1	cValue1	nValue1	cValue2	nValue2
1	ALGORITHM	IPDIRECT	.		.
2	FEASTOL	1E-6	0.000001000		.
3	HESSTYPE	FULL	.		.
4	INITDUAL	FALSE	.		.
5	LOGFREQ	1	1.000000		.
6	MAXITER	5000	5000.000000		.
7	MAXTIME	I	I		.
8	NLPTHREADS	(DEFAULT)	.		.
9	NTHREADS	12	12.000000		.
10	OBJLIMIT	1E20	1E20		.
11	OPTTOL	1E-6	0.000001000		.
12	PRESERVEINIT	OFF	.		.
13	SOLTYPE	1	1.000000		.
14	TIMETYPE	REAL	.		.

The data set exdm contains the DerivMethods table, which displays the methods of derivative computation, and is shown in Figure 9.51. The variable names are Label1, cValue1, and nValue1. The rows, which depend on the derivatives used by the solver, specify the method used to calculate each derivative.

Figure 9.51 DerivMethods ODS Table

DerivMethods

Obs	Label1	cValue1	nValue1
1	Objective Gradient	Analytic Formulas	.
2	Objective Hessian	Analytic Formulas	.

The data set exss contains the SolutionSummary table and is shown in Figure 9.52. The variable names are Label1, cValue1, and nValue1. The rows give an overview of the solution, including the solver chosen, the objective value, and the solution status. Depending on the values returned by the solver, the SolutionSummary table might also include some solution quality values such as optimality error and infeasibility. The values in the SolutionSummary table appear in the _OROPTMODEL_ macro variable; each solver chapter has a section that describes the solver's contribution to this macro variable.

Figure 9.52 SolutionSummary ODS Table

SolutionSummary

Obs	Label1	cValue1	nValue1
1	Solver	NLP	.
2	Algorithm	Interior Point Direct	.
3	Objective Function	z	.
4	Solution Status	Optimal	.
5	Objective Value	22623.346621	22623
6			.
7	Optimality Error	1.844916E-8	1.844916E-8
8	Infeasibility	0	0
9			.
10	Iterations	12	12.000000
11	Presolve Time	0.00	0.000121
12	Solution Time	0.00	0.001430

The data set exos contains the OptStatistics table, which displays the optimization statistics, and is shown in Figure 9.53. The variable names are Label1, cValue1, and nValue1. The rows, which depend on the solver called by PROC OPTMODEL, describe the amount of time and the function evaluations that are used by the solver and associated processing. Times are displayed in seconds of clock or CPU time according to the value of the TIMETYPE= option that is used by the solver.

Figure 9.53 OptStatistics ODS Table

OptStatistics

Obs	Label1	cValue1	nValue1
1	Function Evaluations	13	13.000000
2	Gradient Evaluations	14	14.000000
3	Hessian Evaluations	12	12.000000
4	Problem Generation Time	0.00	0.000484
5	Code Generation Time	0.01	0.005485
6	Presolve Time	0.00	0.000121
7	Solution Time	0.00	0.001430
8	Total Time	0.03	0.026680

Problem generation is the process of combining the model with the data into a format that solvers can use. This includes computing expression coefficients, but it does not include reading data or evaluating other programming statements. Code generation compiles code for nonlinear expressions in the model and performs other analysis that is needed prior to solver evaluations. The time that is required for problem generation is negligible if the model contains only linear expressions. The presolve time in this table includes the time used by the PROC OPTMODEL presolver and any presolver that is part of the solver. Solution time is the sum of the times used by the presolvers and the solver. The presolve and solution times also appear in the SolutionSummary table. The OptStatistics table includes a total time, which is the sum of times for problem generation, code generation, solution, and overhead in the SOLVE statement. Overhead includes solver setup, postprocessing, and ODS table output.

The Timing table provides an alternate breakdown of SOLVE statement timing. Times in this table are shown in seconds of clock time. The data set exti, which is shown in Figure 9.54, contains the Timing table data and statistics. The variable names are Label1, cValue1, nValue1, cValue2, and nValue2. The values present depend on the solver and on the context of the SOLVE statement.

Figure 9.54 Timing ODS Table

Timing

Obs	Label1	cValue1	nValue1	cValue2	nValue2
1	Problem Generation	0.0004839897	0.00	0.0207979018	2.08%
2	OPTMODEL Presolver	0.0001208782	0.00	0.0051943528	0.52%
3	Solver Initialization	0.0156400204	0.02	0.6720795853	67.21%
4	Code Generation	0.0054850578	0.01	0.2357027232	23.57%
5	Solver	0.001308918	0.00	0.0562465422	5.62%
6	Solver Postprocessing	0.0002322197	0.00	0.0099788947	1.00%

Some of the Timing table values have already been described for the OptStatistics table. Solver initialization time is overhead in the SOLVE statement before the solver starts. Solver time includes execution of the solver and its associated preprocessor, if any. Solver postprocessing time is overhead in the SOLVE statement after the solver has completed. Several table values appear only for a SOLVE statement called within a COFOR loop. These values are shown in Table 9.14.

Table 9.14 Solver Timing Values for COFOR Loops

Label	Description
Waiting for Multiple Threads	Time waiting for the required number of threads to become available on the client machine when NTHREADS > 1
Waiting for Grid	Time waiting for the distributed computing environment to become ready to accept a new problem
Sending to Grid	Time to transmit a solver problem description to the distributed computing environment
Receiving from Grid	Time to receive solver results from the distributed computing environment
Waiting after Solver	Time between solver completion and the resumption of the SOLVE statement for processing the results
Grid Overhead	Time required for processing in the distributed computing environment that is not included in the preceding times

Constraints

You can add constraints to a PROC OPTMODEL model. The solver tries to satisfy the specified constraints while minimizing or maximizing the objective.

Constraints in PROC OPTMODEL have names. By using the name, you can examine various attributes of the constraint, such as the dual value that is returned by the solver (see the section "Suffixes" on page 420 for details). A constraint is not allowed to have the same name as any other model component.

PROC OPTMODEL provides a default name if none is supplied by the constraint declaration. The predefined array _ACON_ provides names for otherwise anonymous constraints. The predefined numeric parameter _NACON_ contains the number of such constraints. The constraints are assigned integer indices in sequence, so _ACON_[1] refers to the first unnamed constraint declared, while _ACON_[_NACON_] refers to the newest.

Consider the following example of a simple model that has a constraint:

```
proc optmodel;
   var x, y;
   min r = x**2 + y**2;
   con c: x+y >= 1;
   solve;
   print x y;
```

Without the constraint named c, the solver would find the point $x = y = 0$ that has an objective value of 0. However, the constraint makes this point infeasible. The resulting output is shown in Figure 9.55.

Figure 9.55 Constrained Model Solution

Problem Summary	
Objective Sense	Minimization
Objective Function	r
Objective Type	Linear Least Squares
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	2
Least Squares Matrix Rows	2

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	r
Solution Status	Optimal
Objective Value	0.5000000365
Primal Infeasibility	0
Dual Infeasibility	2.3570225E-9
Bound Infeasibility	0
Duality Gap	2.5463909E-8
Complementarity	0
Iterations	5
Presolve Time	0.00
Solution Time	0.01

x	y
0.5	0.5

The solver has found the point where the objective function is minimized in the region $x + y \geq 1$. This is actually on the border of the region: the constraint c is active (see the section "Dual Values" on page 425 for details).

In the preceding example the constraint c had only a lower bound. You can specify constraints that have both upper and lower bounds. For example, replacing the constraint c in the previous example would further

restrict the feasible region:

```
con c: 3 >= x+y >= 1;
```

PROC OPTMODEL standardizes constraints to collect the expression terms that depend on variables and to separate the expression terms that are constant. When there is a single equality or inequality operator, the separable constant terms are moved to the right operand while the variable terms are moved to the left operand. For range constraints, the separable constant terms from the middle expression are subtracted from the lower and upper bounds. You can see the standardized constraints with the use of the EXPAND statement in the following example. Consider the following PROC OPTMODEL statements:

```
proc optmodel;
   var x{1..3};
   con b: sum{i in 1..3}(x[i] - i) = 0;
   expand b;
```

These statements produce an optimization problem with the following constraint:

```
(x[1] - 1) + (x[2] - 2) + (x[3] - 3) = 0
```

The EXPAND statement produces the output in Figure 9.56.

Figure 9.56 Expansion of a Standardized Constraint

```
Constraint b: x[1] + x[2] + x[3] = 6
```

Here the i separable constant terms in the operand of the SUM operation were moved to the right-hand side of the constraint. The sum of these i values is 6.

After standardization the constraint expression that contains all the variables is called the *body* of the constraint. You can reference the current value of the body expression by attaching the .body suffix to the constraint name. Similarly, the upper and lower bound expressions can be referenced by using the .ub and .lb suffixes, respectively. (See the section "Suffixes" on page 420 for more information.)

As a result of standardization, the value of a body expression depends on how the corresponding constraint is entered. The following example demonstrates how using equivalent relational syntax can result in different .body values:

```
proc optmodel;
    var x init 1;
    con c1: x**2 <= 5;
    con c2: 5 >= x**2;
    con c3: -x**2 >= -5;
    con c4: -5 <= -x**2;
    expand;
    print c1.body c2.body c3.body c4.body;
```

The EXPAND and PRINT statements produce the output in Figure 9.57.

Figure 9.57 Expansion and Body Values of Standardized Constraints

```
Var x
Constraint c1: x**2 <= 5
Constraint c2: -x**2 >= -5
Constraint c3: -x**2 >= -5
Constraint c4: --x**2 <= 5
```

c1.BODY	c2.BODY	c3.BODY	c4.BODY
1	-1	-1	1

CAUTION: Each constraint has an associated *dual value* (see "Dual Values" on page 425). As a result of standardization, the sign of a dual value depends in some instances on the way in which the corresponding constraint is entered into PROC OPTMODEL. In the case of a minimization objective with one-sided constraint $g(x) \geq L$, avoid entering the constraint as $L \leq g(x)$. For example, the following statements produce a value of 2:

```
proc optmodel;
   var x;
   min o1 = x**2;
   con c1: x >= 1;
   solve;
   print (c1.dual);
```

Replacing the constraint as follows results in a value of –2:

```
   con c1: 1 <= x;
```

In the case of a maximization objective with the one-sided constraint $g(x) \leq U$, avoid entering the constraint as $U \geq g(x)$.

When a constraint has variables on both sides, the sign of the dual value depends on the direction of the inequality. For example, you can enter the following constraint:

```
   con c1: x**5 - y + 8 <= 5*x + y**2;
```

This is a $\leq$ constraint, so c1.dual is nonpositive. If you enter the same constraint as follows, then c1.dual is nonnegative:

```
   con c1: 5*x + y**2 >= x**5 - y + 8;
```

It is also important to note that the signs of the dual values are negated in the case of maximization. The following statements output a value of 2:

```
proc optmodel;
   var x;
   min o1 = x**2;
   con c1: 1 <= x <= 2;
   solve;
   print (c1.dual);
```

Changing the objective function as follows yields the same value of x, but c1.dual now holds the value –2:

```
max o2 = -x**2;
solve;
print (c1.dual);
```

NOTE: A simple bound constraint on a decision variable x can be entered either by using a CONSTRAINT declaration or by assigning values to x.lb and x.ub. If you require dual values for simple bound constraints, use the CONSTRAINT declaration.

Constraints that are specified using relational operators can be linear or nonlinear. PROC OPTMODEL determines the type of constraint automatically by examining the form of the body expression. Subexpressions that do not involve variables are treated as constants. Constant subexpressions that are multiplied by or added to linear subexpressions produce new linear subexpressions. For example, constraint A in the following statements is linear:

```
proc optmodel;
   var x{1..3};
   con A: 0.5*(x[1]-x[2]) + x[3] >= 0;
```

Indicator Constraints

An indicator constraint conditions the enforcement of a constraint on the value of a binary variable. For example, the indicator constraint

```
con indcon: y=0 IMPLIES sum{i in 1..10} (a[i] * x[i]) >= l;
```

means that if in a solution y is equal to 0, then the constraint $\sum_{i=1}^{10} a_i x_i \geq l$ must be satisfied, and if in a solution y is equal to 1, then the constraint $\sum_{i=1}^{10} a_i x_i \geq l$ might or might not be violated. The part of the indicator constraint that precedes IMPLIES is also known as the *conditional* of the indicator constraint, and the part that follows IMPLIES is the *consequent*. The binary variable in the conditional is the *indicator variable*.

When an indicator constraint is present in the model, first its consequent must be linearized if it is not already linear. After that, the presolver applies a *big-M transformation*, and the resulting linear constraint(s) is passed on to the solver.

For example, consider the indicator constraint that is mentioned earlier. If $\sum_{i=1}^{10} a_i x_i$ is bounded from below, then using $M = l - \min(\sum_{i=1}^{10} a_i x_i)$ in the constraint $\sum_{i=1}^{10} a_i x_i + My \geq l$ enforces the consequent if $y = 0$. On the other hand, if $y = 1$, then this constraint is satisfied for any x; thus the consequent is not enforced. This is the big-M transformation of the indicator constraint. The presolver uses the best big-M value that it can for every indicator constraint.

NOTE: If there is no provably correct big-M value, or if the value would be so big as to be likely to cause numerical difficulties, the presolver issues a warning and uses a value that is still likely to provide a useful solution at the end.

NOTE: Because there is a binary variable in an indicator constraint, the solver that you use must be able to handle integrality restrictions. By default, the MILP solver is used when indicator constraints are present.

NOTE: Because the consequent of an indicator constraint must be linear, the LINEARIZE option is automatically set when the SOLVE or SAVE MPS statement is executed in the presence of indicator constraints. When the EXPAND statement is executed together with the LINEARIZE option, indicator constraints undergo a

big-M transformation. When the EXPAND statement is executed without the LINEARIZE option, indicator constraints are displayed in their original form.

Here is an example of a more complex indicator constraint:

```
proc optmodel;
   var x binary;
   var y >= 0;
   var z >= 1 <= 100;
   var u binary;
   con c0: x=0 implies y <= 10;
   con c1: x=1 implies u*z = 50;
   print "===== expand =====";
   expand;
   print "===== expand/linearize =====";
   expand / linearize;
```

The EXPAND statements produce the output in Figure 9.58.

Figure 9.58 Expansion of Indicator Constraints

```
===== expand =====

Var x BINARY
Var y >= 0
Var z >= 1 <= 100
Var u BINARY
Constraint c0: x = 0 IMPLIES y <= 10
Constraint c1: x = 1 IMPLIES u*z = 50

===== expand/linearize =====

Var x BINARY
Var y >= 0
Var z >= 1 <= 100
Var u BINARY
Var _ADDED_VAR_[1] >= 0 <= 100
Constraint c0: y - 100000*x <= 10
Constraint c1: _ADDED_VAR_[1] - 50*x >= 0
Constraint _ADDED_CON_[1]: _ADDED_VAR_[1] - z - u <= -1
Constraint _ADDED_CON_[2]: _ADDED_VAR_[1] - z - 100*u >= -100
Constraint _ADDED_CON_[3]: _ADDED_VAR_[1] - 100*u <= 0
Constraint _ADDED_CON_[4]: _ADDED_VAR_[1] - u >= 0
Constraint _ADDED_CON_[5]: _ADDED_VAR_[1] + 50*x <= 100
```

You can see that without the LINEARIZE option, the EXPAND statement simply displays the indicator constraints as they are specified.

In the linearized version, x has a large coefficient in constraint c0. This is the big-M value that is used here, even though in theory infinity is the only “correct” big-M value. The log file displays a warning about this:

```
WARNING: The big-M value (1.797693E308) generated for indicator constraint 'c0'
         was lowered (to 100000) to avoid serious numerical difficulties. This
         might affect the optimal solution and value. To avoid numerical issues,
         you can bound the variables as much as reasonable or use the INTTOL=
```

```
option to decrease the integrality tolerance.
```

You can avoid this warning and help set a smaller big-M value by setting an upper bound on y.

Then you can see that the product u*z has been linearized using the constraints _ADDED_CON_[1] through _ADDED_CON_[4] and u*z has been replaced by _ADDED_VAR_[1] in indicator constraint c1. Afterward the indicator constraint itself is linearized using two linear constraints: c1 and _ADDED_CON_[5]. Two constraints are needed, because the big-M transformation must be applied to the equality in both directions—that is, as ≤ 50 and as ≥ 50.

Linearization of nonlinear expressions can add indicator constraints to the updated model. The big-M transformation can produce large values when it is applied to these constraints, if the variables that the nonlinear expressions use are not suitably bounded. The following code shows an example that produces large big-M values:

```
proc optmodel;
   var x >= -100;
   max obj = abs(x);
   expand / linearize;
```

The EXPAND statement produces the output in Figure 9.59. The constraints _ADDED_CON_[3] and _ADDED_CON_[4] have large big-M values that you can reduce by supplying a suitable upper bound for the variable x.

Figure 9.59 Linearization with Indicator Constraints

```
Var x >= -100
Var _ADDED_VAR_[1]
Var _ADDED_VAR_[2] BINARY
Maximize obj=_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: x - _ADDED_VAR_[1] <= 0
Constraint _ADDED_CON_[2]: x + _ADDED_VAR_[1] >= 0
Constraint _ADDED_CON_[3]: x - _ADDED_VAR_[1] + 100000*_ADDED_VAR_[2] >= 0
Constraint _ADDED_CON_[4]: x + _ADDED_VAR_[1] + 100000*_ADDED_VAR_[2] <= 100000
```

The log file displays a warning when large big-M values are detected in added indicator constraints:

```
WARNING: Linearization of the expression for 'obj' produced big-M values that
         were lowered to avoid serious numerical difficulties. This might
         affect the optimal solution and value. To avoid numerical issues,
         you can bound the variables as much as reasonable or use the INTTOL=
         option to decrease the integrality tolerance.
```

Suffixes

You can use suffixes with *identifier-expressions* to retrieve and modify various auxiliary values maintained by the solver. The values of the suffixes can come from expressions in the declaration of the name that is suffixed. For example, the following declaration of variable v provides the values of several suffixes of v at the same time:

```
var v >= 0 <= 2 init 1 suffixes=(label='X0000000' status init 'L');
```

The preceding example sets the lower and upper bounds for variable v (that is, v.lb and v.ub, respectively) to 0 and 2. The solver label (v.label) is set to the string 'X0000000', and the initial solver status (v.status) is 'L'. The initial value of v is also set to 1. You can use more complex expressions in a declaration, as shown in the following example:

```
num ubound{1..N} init 2;
var x{i in 1..N} >= 0 <= ubound[i] suffixes=(label='X'||put(i,z7.));
```

The preceding declaration makes the upper bound value for each element of x equal to the value of the element in the ubound array with a corresponding index. That is, for each *i* in 1 to N, x[*i*].ub is equal to ubound[*i*]. Similarly, the declaration provides a distinct .label value for each element of the x array.

The CONSTRAINT, MAX, MIN, PROBLEM, and VAR statements support a SUFFIXES=() clause that allows values for existing, modifiable suffixes (other than .lb and .ub) to be specified with each declaration. This is the syntax for a SUFFIXES=() clause:

SUFFIXES=(*values* **)**

Each *value* specifies a suffix value. The following forms are allowed:

name **=** *expression*
: provides an explicit value for the suffix *name*. In this case the suffix acts like an alias for the *expression* value. When you use this form, the suffix value cannot be modified directly, such as by an assignment statement. Suffixes that are updated by the SOLVE statement, such as .status, cannot be specified using this form.

name **INIT** *expression*
: specifies a default value when the suffix *name* is first used but no other value has been supplied.

The values of the suffixes also come from the solver or from values assigned by assignment, READ DATA, or other statements (see an example in the section "Data Set Input/Output" on page 401). Note that PROC OPTMODEL allows the .lb and .ub suffixes to be assigned after the declaration even when the declaration provides a value with an expression following >= or <=.

You must use suffixes with names of the appropriate type. For example, the .dual suffix cannot be used with the name of an objective. In particular, local dummy parameter names cannot have suffixes.

Table 9.15 shows the names of the available suffixes.

Table 9.15 Suffix Names

Name Type	Suffix	Modifiable	Description
any	.name	No	Name text for any non-dummy symbol
Constraint	.active	No	Active status in the current problem
Constraint	.block	Yes	Block ID for decomposition
Constraint	.body	No	Current constraint body value
Constraint	.dual	Yes	Dual value from the solver
Constraint	.label	Yes	Label text for the solver
Constraint	.lb	Yes	Current lower bound
Constraint	.lbmax	No	Largest value of the stability interval for the lower bound in sensitivity analysis
Constraint	.lbmin	No	Smallest value of the stability interval for the lower bound in sensitivity analysis
Constraint	.status	Yes	Status information from the solver
Constraint	.ub	Yes	Current upper bound
Constraint	.ubmax	No	Largest value of the stability interval for the upper bound in sensitivity analysis
Constraint	.ubmin	No	Smallest value of the stability interval for the upper bound in sensitivity analysis
Implicit variable	.sol	No	Current solution value
Objective	.active	No	Active status in the current problem
Objective	.sol	No	Current objective value
Objective	.label	Yes	Label text for the solver
Problem	.active	No	Active status of the problem
Problem	.label	Yes	Label text for the solver
Variable	.active	No	Active status in the current problem
Variable	.dcone	No	Dual value for a cone constraint
Variable	.direction	Yes	Branching direction for MILP
Variable	.dual	Yes	Alias for .rc
Variable	.fixed	No	Fixed status
Variable	.label	Yes	Label text for the solver
Variable	.lb	Yes	Lower bound
Variable	.lbmax	No	Largest value of the stability interval for the lower bound in sensitivity analysis
Variable	.lbmin	No	Smallest value of the stability interval for the lower bound in sensitivity analysis
Variable	.msinit	No	Numeric value at the best starting point reported by the multistart solver
Variable	.objmax	No	Largest value of the stability interval for the objective coefficient in sensitivity analysis
Variable	.objmin	No	Smallest value of the stability interval for the objective coefficient in sensitivity analysis
Variable	.priority	Yes	Branching priority for MILP and CLP

Table 9.15 *continued*

Name Type	Suffix	Modifiable	Description
Variable	.rc	Yes	Reduced cost (LP) or gradient of the Lagrangian function
Variable	.relax	Yes	Relaxation of integrality restriction
Variable	.sol	No	Current variable value
Variable	.sol[*i*]	Yes	Saved solution value
Variable	.status	Yes	Status information from the solver
Variable	.ub	Yes	Upper bound
Variable	.ubmax	No	Largest value of the stability interval for the upper bound in sensitivity analysis
Variable	.ubmin	No	Smallest value of the stability interval for the upper bound in sensitivity analysis

The .sol suffix for a variable, implicit variable, or objective can be used within a declaration to reference the current value of the symbol. It is treated as a constant in such cases. The value is independent of the current problem. When the OPTMODEL procedure processes a SOLVE statement, the value is fixed at the start of the SOLVE statement. The .sol suffix can be followed by a positive integer solution index to refer to a particular solution that the SOLVE statement returns. See the section "Multiple Solutions" on page 455 for more information about accessing multiple solutions from the solver. Each problem tracks saved solution values separately. Outside of declarations, a variable, implicit variable, or objective name with the .sol suffix and no solution index is equivalent to the unsuffixed name.

The .status suffix reports status information from the solver. Currently, the LP, MILP, NLP, and QP solvers provide status information. For other solvers, the .status values default to a single blank character.

For the LP solver, the .status suffix takes the same character values that are found in the _STATUS_ variable of the PRIMALOUT= and DUALOUT= data sets for the OPTLP procedure, including the values specific to the IIS=TRUE option. The MILP, NLP, and QP solvers provide status information only when the IIS=TRUE option is specified. The NLP and QP solvers use the same status values as the LP solver for items that are in the irreducible infeasible set (IIS); the .status value for items not in an IIS is a single blank character. For more information that applies to the LP, NLP, and QP solvers, see the section "Variable and Constraint Status" on page 654 and the section "Irreducible Infeasible Set" on page 655, both in Chapter 13, "The Linear Programming Solver." For more information that applies to the MILP solver, see the section "Variable and Constraint Status" on page 732 and the section "Irreducible Infeasible Set" on page 733, both in Chapter 14, "The Mixed Integer Linear Programming Solver."

If you choose to modify the .status suffix for a variable or constraint, the assigned suffix value can be a single character or an empty string. The LP solver rejects invalid status characters. Blank or empty strings are treated as new row or column entries for the purpose of "warm starting" the solver.

The .active suffix reports the current activity status for names in the problem. The value is 1 if the element is active or 0 otherwise. A PROBLEM name is considered active if it is the current problem (that is, it was selected by the most recent USE PROBLEM statement). A constraint is considered active if it is included in the current problem and not dropped. An objective is considered active if it is the last objective that is added to the current problem. A variable is considered active if it is included in the current problem, independent of the fixed status.

The .fixed suffix reports the fixed status of a variable. The value is 1 if the variable is fixed using the FIX statement for the current problem or 0 otherwise. Variables that are not included in the current problem are treated as unfixed.

The .msinit suffix reports the numeric value of a variable at the best starting point, as reported by the NLP solver when the MULTISTART option is specified. If the solver does not report a best starting point, then the value is missing. The value is tracked independently for each problem to support multiple subproblems. See the section "Multistart" on page 970 in Chapter 16, "The Nonlinear Programming Solver," for more information.

The .block suffix identifies the subproblem for constraints when used with the METHOD=USER option of the decomposition algorithm. The value must be numeric and is initially assigned a missing value. A constraint with a missing value for the .block suffix is part of the master problem. Otherwise constraints belong to the same subproblem if and only if they have the same .block suffix values. See Chapter 18, "The Decomposition Algorithm," for more information.

The .label suffix represents the text passed to the solver to identify a variable, constraint, or objective. Some solvers can display this label in their output. The maximum text length passed to the solver is controlled by the MAXLABLEN= option. The default text is based on the name in the model, abbreviated to fit within MAXLABLEN. For example, a model variable x[1] would be labeled "x[1]". This label text can be reassigned. The .label suffix value is also used to create MPS labels stored in the output data set for the SAVE MPS and SAVE QPS statements.

The .name suffix represents the name of a symbol as a text string. The .name suffix can be used with any declared name except for local dummy parameters. This suffix is primarily useful when applied to problem symbols (see the section "Problem Symbols" on page 456), since the .name suffix returns the name of the referenced symbol, not the problem symbol name. The name text is based on the name in the model, abbreviated to fit in 256 characters.

Suffixed names can be used wherever a parameter name is accepted, provided only the value is required. However, you are not allowed to change the value of certain suffixes. Table 9.15 marks these suffixes as not modifiable. Suffixed names that are used as a target in an assignment or READ DATA statement must be modifiable.

The following statements formulate a trivial linear programming problem. The objective value is unbounded, which is reported after the execution of the SOLVE statement. The PRINT statements illustrate the corresponding default auxiliary values. This is shown in Figure 9.60.

```
proc optmodel;
   var x, y;
   min z = x + y;
   con c: x + 2*y <= 3;
   solve;
   print x.lb x.ub x.status x.sol;
   print y.lb y.ub y.status y.sol;
   print c.lb c.ub c.body c.dual;
```

Figure 9.60 Using a Suffix: Retrieving Auxiliary Values

x.LB	x.UB	x.STATUS	x.SOL
-1.7977E+308	1.7977E+308	I	0

Figure 9.60 *continued*

y.LB	y.UB	y.STATUS	y.SOL
-1.7977E+308	1.7977E+308	I	0

c.LB	c.UB	c.BODY	c.DUAL
-1.7977E+308	3	0	.

Next, continue to submit the following statements to change the default bounds and solve again. The output is shown in Figure 9.61.

```
x.lb=0;
y.lb=0;
c.lb=1;
solve;
print x.lb x.ub x.status x.sol;
print y.lb y.ub y.status y.sol;
print c.lb c.ub c.body c.dual;
```

Figure 9.61 Using a Suffix: Modifying Auxiliary Values

x.LB	x.UB	x.STATUS	x.SOL
0	1.7977E+308	L	0

y.LB	y.UB	y.STATUS	y.SOL
0	1.7977E+308	B	0.5

c.LB	c.UB	c.BODY	c.DUAL
1	3	1	0.5

NOTE: Spaces are significant. The form NAME.␣TAG is treated as a SAS format name followed by the tag name, not as a suffixed identifier. The forms NAME.TAG, NAME␣.␣TAG, and NAME␣.TAG (note the location of spaces) are interpreted as suffixed references.

Integer Variable Suffixes

The suffixes .relax, .priority, and .direction are applicable to integer variables.

For an integer variable x, setting x.relax to a nonzero, nonmissing value relaxes the integrality restriction. The value of x.relax is read as either 1 or 0, depending on whether or not integrality is relaxed. This suffix is ignored for noninteger variables.

The value that is contained in x.priority sets the priority of an integer variable x for use with branching in the MILP solver or selection in the CLP solvers. This value can be any nonnegative, nonmissing number. The default value is 0, which indicates default branching priority. Variables with positive .priority values are assigned greater priority than the default. Variables with the highest .priority values are assigned the highest priority. Variables with the same .priority value are assigned the same branching priority.

The value of x.direction assigns a branching direction to an integer variable x. This value should be an integer in the range –1 to 3. A noninteger value in this range is rounded on assignment. The default value is 0. The

significance of each integer is found in Table 9.16.

Table 9.16 Branching Directions

Value	Direction
–1	Round down to nearest integer
0	Default
1	Round up to nearest integer
2	Round to nearest integer
3	Round to closest presolved bound

Suppose the solver branches next on an integer variable x whose last LP relaxation solution is 3.3. Suppose also that after passing through the presolver, the lower bound of x is 0 and the upper bound of x is 10. If the value in x.direction is –1 or 2, then the solver sets x to 3 for the next iteration. If the value in x.direction is 1, then the solver sets x to 4. If the value in x.direction is 3, then the solver sets x to 0.

The MPS data set created by the SAVE MPS statement ("SAVE MPS Statement" on page 366) includes a BRANCH section if any nondefault .priority or .direction values have been specified for integer variables.

Dual Values

A dual value is associated with each constraint. To access the dual value of a constraint, use the constraint name followed by the suffix .dual.

For linear programming problems, the dual value associated with a constraint is also known as the dual price (also called the shadow price). The shadow price is usually interpreted economically as the rate at which the optimal value changes with respect to a change in some right-hand side that represents a resource supply or demand requirement.

For nonlinear programming problems, the dual values correspond to the values of the optimal Lagrange multipliers. For more details about duality in nonlinear programming, see Bazaraa, Sherali, and Shetty (1993).

From the dual value associated with the constraint, you can also tell whether the constraint is active or not. A constraint is said to be active (tight at a point) if it holds with equality at that point. It can be informative to identify active constraints at the optimal point and check their corresponding dual values. Relaxing the active constraints might improve the objective value.

Background on Duality in Mathematical Programming

For a minimization problem, there exists an associated problem with the following property: any feasible solution to the associated problem provides a lower bound for the original problem, and conversely any feasible solution to the original problem provides an upper bound for the associated problem. The original and the associated problems are referred to as the primal and the dual problem, respectively. More specifically,

consider the primal problem,

$$\begin{array}{ll} \underset{x}{\text{minimize}} & f(x) \\ \text{subject to} & c_i(x) = 0, \quad i \in \mathcal{E} \\ & c_i(x) \le 0, \quad i \in \mathcal{L} \\ & c_i(x) \ge 0, \quad i \in \mathcal{G} \end{array}$$

where $\mathcal{E}$, $\mathcal{L}$, and $\mathcal{G}$ denote the sets of equality, $\le$ inequality, and $\ge$ inequality constraints, respectively. Variables $x \in \mathbb{R}^n$ are called the primal variables. The Lagrangian function of the primal problem is defined as

$$L(x, \lambda, \mu, \nu) = f(x) - \sum_{i \in \mathcal{E}} \lambda_i c_i(x) - \sum_{i \in \mathcal{L}} \mu_i c_i(x) - \sum_{i \in \mathcal{G}} \nu_i c_i(x)$$

where $\lambda_i \in \mathbb{R}$, $\mu_i \le 0$, and $\nu_i \ge 0$. By convention, the Lagrange multipliers for inequality constraints have to be nonnegative. Hence λ, $-\mu$, and ν correspond to the Lagrange multipliers in the preceding Lagrangian function. It can be seen that the Lagrangian function is a linear combination of the objective function and constraints of the primal problem.

The Lagrangian function plays a fundamental role in nonlinear programming. It is used to define the optimality conditions that characterize a local minimum of the primal problem. It is also used to formulate the dual problem of the preceding primal problem. To this end, consider the following *dual* function:

$$d(\lambda, \mu, \nu) = \inf_x \; L(x, \lambda, \mu, \nu)$$

The dual problem is defined as

$$\begin{array}{ll} \underset{\lambda,\mu,\nu}{\text{maximize}} & d(\lambda, \mu, \nu) \\ \text{subject to} & \mu \le 0 \\ & \nu \ge 0. \end{array}$$

The variables λ, μ, and ν are called the dual variables. Note that the dual variables associated with the equality constraints (λ) are free, whereas those associated with $\le$ inequality constraints (μ) have to be nonpositive and those associated with $\ge$ inequality constraints (ν) have to be nonnegative.

The relation between the primal and the dual problems provides a nice connection between the optimal solutions of the problems. Suppose x^* is an optimal solution of the primal problem and $(\lambda^*, \mu^*, \nu^*)$ is an optimal solution of the dual problem. The difference between the objective values of the primal and dual problems, $\delta = f(x^*) - d(\lambda^*, \mu^*, \nu^*) \ge 0$, is called the duality gap. For some restricted class of convex nonlinear programming problems, both the primal and the dual problems have an optimal solution and the optimal objective values are equal—that is, the duality gap $\delta = 0$. In such cases, the optimal values of the dual variables correspond to the optimal Lagrange multipliers of the primal problem with the correct signs.

A maximization problem is treated analogously to a minimization problem. For the maximization problem

$$\begin{array}{ll} \underset{x}{\text{maximize}} & f(x) \\ \text{subject to} & c_i(x) = 0, \quad i \in \mathcal{E} \\ & c_i(x) \le 0, \quad i \in \mathcal{L} \\ & c_i(x) \ge 0, \quad i \in \mathcal{G}, \end{array}$$

the dual problem is

$$\begin{array}{ll} \underset{\lambda,\mu,\nu}{\text{minimize}} & d(\lambda, \mu, \nu) \\ \text{subject to} & \mu \ge 0 \\ & \nu \le 0. \end{array}$$

where the dual function is defined as $d(\lambda, \mu, \nu) = \sup_x L(x, \lambda, \mu, \nu)$ and the Lagrangian function $L(x, \lambda, \mu, \nu)$ is defined the same as earlier. In this case, λ, μ, and $-\nu$ correspond to the Lagrange multipliers in $L(x, \lambda, \mu, \nu)$.

Minimization Problems

For inequality constraints in minimization problems, a positive optimal dual value indicates that the associated $\geq$ inequality constraint is active at the solution, and a negative optimal dual value indicates that the associated $\leq$ inequality constraint is active at the solution. In PROC OPTMODEL, the optimal dual value for a *range constraint* (a constraint with both upper and lower bounds) is the sum of the dual values associated with the upper and lower inequalities. Since only one of the two inequalities can be active, the sign of the optimal dual value, if nonzero, identifies which one is active.

For equality constraints in minimization problems, the optimal dual values are unrestricted in sign. A positive optimal dual value for an equality constraint implies that, starting close enough to the primal solution, the same optimum could be found if the equality constraint were replaced with a $\geq$ inequality constraint. A negative optimal dual value for an equality constraint implies that the same optimum could be found if the equality constraint were replaced with a $\leq$ inequality constraint.

The following is an example where simple linear programming is considered:

```
proc optmodel;
   var x, y;
   min z = 6*x + 7*y;
   con
      4*x +   y >=  5,
       -x - 3*y <= -4,
        x +   y <=  4;
   solve;
   print x y;
   expand _ACON_ ;
   print _ACON_.dual _ACON_.body;
```

The PRINT statements generate the output shown in Figure 9.62.

Figure 9.62 Dual Values in Minimization Problem: Display

Problem Summary	
Objective Sense	Minimization
Objective Function	z
Objective Type	Linear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	3
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	6

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	z
Solution Status	Optimal
Objective Value	13
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	4
Presolve Time	0.00
Solution Time	0.00

x	y
1	1

```
Constraint _ACON_[1]: 4*x + y >= 5
Constraint _ACON_[2]: - x - 3*y <= -4
Constraint _ACON_[3]: x + y <= 4
```

[1]	_ACON_.DUAL	_ACON_.BODY
1	1	5
2	-2	-4
3	0	2

It can be seen that the first and second constraints are active, with dual values 1 and –2. Continue to submit the following statements. Notice how the objective value is changed in Figure 9.63.

```
_ACON_[1].lb = _ACON_[1].lb - 1;
solve;
_ACON_[2].ub = _ACON_[2].ub + 1;
solve;
```

Figure 9.63 Dual Values in Minimization Problem: Interpretation

Problem Summary	
Objective Sense	Minimization
Objective Function	z
Objective Type	Linear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	3
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	6

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	z
Solution Status	Optimal
Objective Value	12
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	4
Presolve Time	0.00
Solution Time	0.00

Figure 9.63 *continued*

Problem Summary	
Objective Sense	Minimization
Objective Function	z
Objective Type	Linear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	3
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	6

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	z
Solution Status	Optimal
Objective Value	10
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	4
Presolve Time	0.00
Solution Time	0.00

The change is just as the dual values imply. After the first constraint is relaxed by one unit, the objective value is improved by one unit. For the second constraint, the relaxation and improvement are one unit and two units, respectively.

NOTE: The signs of dual values produced by PROC OPTMODEL depend, in some instances, on the way in which the corresponding constraints are entered. See the section "Constraints" on page 413 for details.

Maximization Problems

For inequality constraints in maximization problems, a positive optimal dual value indicates that the associated $\leq$ inequality constraint is active at the solution, and a negative optimal dual value indicates that the associated $\geq$ inequality constraint is active at the solution. The optimal dual value for a range constraint is the sum of the dual values associated with the upper and lower inequalities. The sign of the optimal dual value identifies which inequality is active.

For equality constraints in maximization problems, the optimal dual values are unrestricted in sign. A positive optimal dual value for an equality constraint implies that, starting close enough to the primal solution, the same optimum could be found if the equality constraint were replaced with a $\leq$ inequality constraint. A negative optimal dual value for an equality constraint implies that the same optimum could be found if the equality constraint were replaced with a $\geq$ inequality constraint.

CAUTION: The signs of dual values produced by PROC OPTMODEL depend, in some instances, on the way in which the corresponding constraints are entered. See the section "Constraints" on page 413 for details.

Reduced Costs

In linear programming problems, each variable has a corresponding reduced cost. To access the reduced cost of a variable, add the suffix .rc or .dual to the variable name. These two suffixes are interchangeable.

The reduced cost of a variable is the rate at which the objective value changes when the value of that variable changes. At optimality, basic variables have a reduced cost of zero; a nonbasic variable with zero reduced cost indicates the existence of multiple optimal solutions.

In nonlinear programming problems, the reduced cost interpretation does not apply. The .dual and .rc variable suffixes represent the gradient of the Lagrangian function, computed using the values returned by the solver.

The following example illustrates the use of the .rc suffix:

```
proc optmodel;
   var x >= 0, y >= 0, z >= 0;
   max cost = 4*x + 3*y - 5*z;
   con
      -x + y + 5*z <= 15,
      3*x - 2*y - z <= 12,
      2*x + 4*y + 2*z <= 16;
   solve;
   print x y z;
   print x.rc y.rc z.rc;
```

The PRINT statements generate the output shown in Figure 9.64.

Figure 9.64 Reduced Cost in Maximization Problem: Display

x	y	z
5	1.5	0

x.RC	y.RC	z.RC
0	0	-6.5

In this example, x and y are basic variables, while z is nonbasic. The reduced cost of z is –6.5, which implies that increasing z from 0 to 1 decreases the optimal value from 24.5 to 18.

Presolver

PROC OPTMODEL includes a simple presolver that processes linear constraints to produce tighter bounds on variables. The presolver can reduce the number of variables and constraints that are presented to the solver. These changes can result in reduced solution times.

Linear constraints that involve only a single variable are converted into variable bounds. The presolver then eliminates redundant linear constraints for which variable bounds force the constraint to always be satisfied. Tightly bounded variables where upper and lower bounds are within the range specified by the VARFUZZ= option (see the section "PROC OPTMODEL Statement" on page 316) are automatically fixed to the average of the bounds. The presolver also eliminates variables that are fixed by the user or by the presolver.

The presolver can infer tighter variable bounds from linear constraints when all variables in the constraint or all but one variable have known bounds. For example, when given the following PROC OPTMODEL declarations, the presolver can use the inferred bounds $x \leq 7$ and $y \leq 4$ to remove the constraint c2:

```
proc optmodel;
   var x >= 3;
   var y >= 0;
   con c: x + y <= 7;
   con c2: x + 2*y <= 15; /* redundant */
```

The presolver makes multiple passes and rechecks linear constraints after bounds are tightened for the referenced variables. The number of passes is controlled by the PRESOLVER= option. After the passes are finished, the presolver attempts to fix the value of all variables that are not used in the updated objective and constraints. The current value of such a variable is used if the value lies between the variable's upper and lower bounds. Otherwise, the value is adjusted to the nearer bound. The value of an integer variable is rounded before being checked against its bounds.

The presolver uses the tightened variable bounds to infer the range of values for nonlinear constraint bodies. In some cases, the presolver can determine that a nonlinear constraint is infeasible. The presolver can also remove a constraint that does not restrict the feasible region of the problem.

In some cases the solver might perform better without the presolve transformations, so almost all such transformations are unavailable when the option PRESOLVER=BASIC is specified. However, the presolver still eliminates variables that have values that have been fixed by the FIX statement. To disable the OPTMODEL presolver entirely, use PRESOLVER=NONE. The solver assigns values to any unused, unfixed variables when the option PRESOLVER=NONE is specified.

Linearization

PROC OPTMODEL supports the transformation of certain nonlinear expressions in objectives and constraints into equivalent linear forms. This enables the processing of some MINLP formulations by using the MILP solver. Use the LINEARIZE option with the EXPAND, SAVE MPS, or SOLVE statement to request the linearization transformations.

Linearization examines each nonlinear objective, constraint, or IMPVAR expression, replacing nonlinear subexpressions with equivalent linear subexpressions. Fixed variables are treated as constants to enable more opportunities for linearization. The transformations might require the creation of additional variables and constraints. For example, the product of binary variables can be replaced by a new binary variable, with added constraints to relate the new variable value to the original variable values.

The added variables are elements of the predefined array _ADDED_VAR_, which has an integer index that starts from 1. Added constraints are elements of the predefined array _ADDED_CON_, which has an integer index that starts from 1. You can specify the name _ADDED_VAR_ or _ADDED_CON_ in the EXPAND statement with the LINEARIZE option to examine the added variables or constraints in the transformed problem.

When the problem is updated, added variables and constraints are re-created during problem generation. The optimal values for added variables from one SOLVE statement might not be meaningful in the next SOLVE statement, so the values that are assigned to the variables are ignored when PROC OPTMODEL determines initial values for the solver. The procedure attempts to determine initial values that are consistent with the values of the user-defined variables.

The LINEARIZE option is most often used with the MILP solver, although it can be used with other solvers. The MILP solver does not support dual values and reduced costs. PROC OPTMODEL does not attempt to recover the dual values and reduced costs of a problem that has been transformed by linearization, and it reports missing values.

The following types of subexpressions can be transformed:

- binary-binary products
- binary-bounded products
- polynomials with binary and bounded variables
- MIN/MAX/ABS function calls, <> expressions, and >< expressions
- linear ratio constraint bodies

Problem generation fails if linearization is unable to transform a nonlinear subexpression or if the required linear coefficients are out of range or undefined.

Binary-Binary Products

The product of two or more binary variables can be replaced by a new binary variable in combination with added constraints. For example, the product of binary variables x_i for indices i in a set S can be replaced by a new binary variable z, with the following constraints:

$$\begin{aligned} z &\leq x_i && \text{for all } i \in S \\ z &\geq \sum_{i \in S} x_i - |S| + 1 \end{aligned}$$

The first set of constraints ensures that z is 0 when any x_i is 0. The last constraint ensures that z is 1 when all x_i are 1. This covers all the possibilities, so z is constrained to equal the product.

The following code shows a simple example of the binary-binary product transformation:

```
proc optmodel;
   var x binary;
   var y binary;
   minimize obj = x*y + y*2*x;
   con c: x*y >= 1;
   expand / linearize;
   solve linearize;
   print x y;
```

The output is shown in Figure 9.65. PROC OPTMODEL recognizes that all the uses of xy are equivalent, and it reuses the same variable. The SOLVE statement invokes the MILP solver because the transformed problem uses binary variables. Note that the problem summary describes the problem before transformation.

Figure 9.65 Binary-Binary Products

```
Var x BINARY
Var y BINARY
Var _ADDED_VAR_[1] BINARY
Minimize obj=3*_ADDED_VAR_[1]
Constraint c: _ADDED_VAR_[1] >= 1
Constraint _ADDED_CON_[1]: _ADDED_VAR_[1] - x <= 0
Constraint _ADDED_CON_[2]: _ADDED_VAR_[1] - y <= 0
Constraint _ADDED_CON_[3]: - _ADDED_VAR_[1] + x + y <= 1
```

Figure 9.65 *continued*

Problem Summary	
Objective Sense	Minimization
Objective Function	obj
Objective Type	Quadratic
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2
Free	0
Fixed	0
Binary	2
Integer	0
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	0
Nonlinear GE (>=)	1
Nonlinear Range	0
Constraint Coefficients	0

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	obj
Solution Status	Optimal
Objective Value	3
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	3
Nodes	0
Solutions Found	2
Iterations	0
Presolve Time	0.00
Solution Time	0.01

x	y
1	1

Binary-Bounded Products

The product of a binary variable x and a bounded variable y can be replaced by a continuous variable, z, which is equal to 0 when x is 0 and equal to y when x is 1. You can also use a linearizable operand for y, such as an IMPVAR reference or a MIN/MAX/ABS function call, provided that the OPTMODEL presolver can determine the bounds for the operand. Let the lower bound for the value of y be L and the upper bound be U. Linearization adds the following constraints:

$$z \leq y - L(1 - x)$$
$$z \geq y - U(1 - x)$$
$$z \leq Ux$$
$$z \geq Lx$$

When x is 0, the second pair of constraints ensure that z is 0, and the first pair hold trivially, based on the bounds of y. When x is 1, the first pair of constraints ensure that $z = y$. The second pair of constraints hold trivially, based on the bounds of y.

The following code shows a simple example of the binary-bounded transformation:

```
proc optmodel;
   var x binary;
   var y >=1 <=2;
   minimize obj1 = x*y;
   expand / linearize;
```

The output is shown in Figure 9.66.

Figure 9.66 Binary-Bounded Products

```
Var x BINARY
Var y >= 1 <= 2
Var _ADDED_VAR_[1] >= 0 <= 2
Minimize obj1=_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: _ADDED_VAR_[1] - y - x <= -1
Constraint _ADDED_CON_[2]: _ADDED_VAR_[1] - y - 2*x >= -2
Constraint _ADDED_CON_[3]: _ADDED_VAR_[1] - 2*x <= 0
Constraint _ADDED_CON_[4]: _ADDED_VAR_[1] - x >= 0
```

Polynomials with Binary and Bounded Variables

More complex expressions, including linearizable subexpressions that are raised to constant nonnegative integer powers, are handled by expansion into a sum of product terms. Each expanded product term can include zero or more binary variables in combination with an optional bounded operand or a general variable. These terms are then linearized, if necessary, using the binary-binary and binary-bounded product transformations. An expanded term that contains multiple variables and includes either a general variable or multiple bounded nonbinary variables cannot be linearized.

When processing products, PROC OPTMODEL recognizes that an operand like $C - Cx$, where C is a constant and x is a binary variable, is a scaled version of the complement of x, $C(1 - x)$. The expansion into product terms uses the rule $x(1 - x) = 0$ to remove unneeded product terms.

The value of 0^0 is not defined, so a linear subexpression $a(x)^0$ is not linearized (as 1) unless PROC OPTMODEL can determine that the value of $a(x)$ cannot be 0. A linear subexpression $a(x)^1$ is treated as $a(x)$.

The following code shows an example of the polynomial transformation:

```
proc optmodel;
   var x {1..4} binary;
   minimize obj = (x[1] + x[2]) * (x[3] + x[4]);
   con c: (x[1] + x[2] + x[3]) * x[4]**3 >= 1;
   expand / linearize;
```

The output is shown in Figure 9.67.

Figure 9.67 Polynomial Linearization

```
Var x[1] BINARY
Var x[2] BINARY
Var x[3] BINARY
Var x[4] BINARY
Var _ADDED_VAR_[1] BINARY
Var _ADDED_VAR_[2] BINARY
Var _ADDED_VAR_[3] BINARY
Var _ADDED_VAR_[4] BINARY
Var _ADDED_VAR_[5] BINARY
Minimize obj=_ADDED_VAR_[4] + _ADDED_VAR_[1] + _ADDED_VAR_[5] + _ADDED_VAR_[2]
Constraint c: _ADDED_VAR_[1] + _ADDED_VAR_[2] + _ADDED_VAR_[3] >= 1
Constraint _ADDED_CON_[1]: _ADDED_VAR_[1] - x[1] <= 0
Constraint _ADDED_CON_[2]: _ADDED_VAR_[1] - x[4] <= 0
Constraint _ADDED_CON_[3]: - _ADDED_VAR_[1] + x[1] + x[4] <= 1
Constraint _ADDED_CON_[4]: _ADDED_VAR_[2] - x[2] <= 0
Constraint _ADDED_CON_[5]: _ADDED_VAR_[2] - x[4] <= 0
Constraint _ADDED_CON_[6]: - _ADDED_VAR_[2] + x[2] + x[4] <= 1
Constraint _ADDED_CON_[7]: _ADDED_VAR_[3] - x[3] <= 0
Constraint _ADDED_CON_[8]: _ADDED_VAR_[3] - x[4] <= 0
Constraint _ADDED_CON_[9]: - _ADDED_VAR_[3] + x[3] + x[4] <= 1
Constraint _ADDED_CON_[10]: _ADDED_VAR_[4] - x[1] <= 0
Constraint _ADDED_CON_[11]: _ADDED_VAR_[4] - x[3] <= 0
Constraint _ADDED_CON_[12]: - _ADDED_VAR_[4] + x[1] + x[3] <= 1
Constraint _ADDED_CON_[13]: _ADDED_VAR_[5] - x[2] <= 0
Constraint _ADDED_CON_[14]: _ADDED_VAR_[5] - x[3] <= 0
Constraint _ADDED_CON_[15]: - _ADDED_VAR_[5] + x[2] + x[3] <= 1
```

MIN/MAX/ABS Function Calls, <> Expressions, and >< Expressions

Subexpressions that call the MIN, MAX, and ABS functions or use the <> (maximum) and >< (minimum) operators can be linearized. When the function or operator is a convex term in the containing objective or constraint, PROC OPTMODEL can linearize the value by using a simplified transformation, adding one constraint for each argument and a single variable for the result term. For nonconvex terms, the transformation requires additional binary variables and constraints.

The function or operator is a convex term if it is used with a constant linear coefficient of the correct sign in the containing objective or constraint. For the linearizable subexpressions $a_i(x)$ and $b(y)$, with positive

constant coefficient c and constant bound B, the following examples of objectives and constraints can be linearized by using the transformation for convex terms:

$$
\begin{array}{rll}
\text{minimize} & c \cdot \mathrm{MAX}(a_1(x), a_2(x), \ldots) + b(y) & \\
\text{maximize} & -c \cdot \mathrm{MAX}(a_1(x), a_2(x), \ldots) + b(y) & \\
 & c \cdot \mathrm{MAX}(a_1(x), a_2(x), \ldots) + b(y) & \leq B \\
 & -c \cdot \mathrm{MAX}(a_1(x), a_2(x), \ldots) + b(y) & \geq B \\
\text{minimize} & -c \cdot \mathrm{MIN}(a_1(x), a_2(x), \ldots) + b(y) & \\
\text{maximize} & c \cdot \mathrm{MIN}(a_1(x), a_2(x), \ldots) + b(y) & \\
 & -c \cdot \mathrm{MIN}(a_1(x), a_2(x), \ldots) + b(y) & \leq B \\
 & c \cdot \mathrm{MIN}(a_1(x), a_2(x), \ldots) + b(y) & \geq B \\
\text{minimize} & c \cdot \mathrm{ABS}(a_1(x)) + b(y) & \\
\text{maximize} & -c \cdot \mathrm{ABS}(a_1(x)) + b(y) & \\
 & c \cdot \mathrm{ABS}(a_1(x)) + b(y) & \leq B \\
 & -c \cdot \mathrm{ABS}(a_1(x)) + b(y) & \geq B \\
\text{minimize} & c \cdot (a_1(x) <> a_2(x)) + b(y) & \\
\text{maximize} & -c \cdot (a_1(x) <> a_2(x)) + b(y) & \\
 & c \cdot (a_1(x) <> a_2(x)) + b(y) & \leq B \\
 & -c \cdot (a_1(x) <> a_2(x)) + b(y) & \geq B \\
\text{minimize} & -c \cdot (a_1(x) >< a_2(x)) + b(y) & \\
\text{maximize} & c \cdot (a_1(x) >< a_2(x)) + b(y) & \\
 & -c \cdot (a_1(x) >< a_2(x)) + b(y) & \leq B \\
 & c \cdot (a_1(x) >< a_2(x)) + b(y) & \geq B
\end{array}
$$

As an example of the convex linearization transformation, consider the subexpression $\mathrm{MAX}(a_1(x), a_2(x))$ used with a positive coefficient in a minimization objective. The subexpression can be replaced by a new variable, z, with these added constraints:

$$
\begin{array}{l}
z \geq a_1(x) \\
z \geq a_2(x)
\end{array}
$$

Because the variable z is used with a positive coefficient in a minimization objective, the solver drives z toward $-\infty$, subject to the added constraints. This results in an optimal value, with z equal to the largest of the MAX arguments. If the original subexpression were used with a positive coefficient in a constraint that had an upper bound, then the optimal solution value of z might not be equal to any of the arguments. But the transformed constraint is feasible if and only if the original constraint is feasible.

The following code shows some examples of the convex transformation:

```
proc optmodel;
   var x;
   var y;
   minimize obj = 2*max(-x+1, x-1) + y;
   expand / linearize;
   fix y = 7;
   minimize obj2 = y*abs(x+1) + 3*abs( x );
   con c: min(x, 2*x-1) >= 0;
   expand / linearize;
```

The output from the two EXPAND statements is shown in Figure 9.68.

Figure 9.68 Convex MIN/MAX/ABS Linearization

```
Var x
Var y
Var _ADDED_VAR_[1]
Minimize obj=y + 2*_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: - x - _ADDED_VAR_[1] <= -1
Constraint _ADDED_CON_[2]: x - _ADDED_VAR_[1] <= 1

Var x
Fix y = 7
Var _ADDED_VAR_[1]
Var _ADDED_VAR_[2]
Var _ADDED_VAR_[3]
Minimize obj2=7*_ADDED_VAR_[2] + 3*_ADDED_VAR_[3]
Constraint c: _ADDED_VAR_[1] >= 0
Constraint _ADDED_CON_[1]: x - _ADDED_VAR_[1] >= 0
Constraint _ADDED_CON_[2]: 2*x - _ADDED_VAR_[1] >= 1
Constraint _ADDED_CON_[3]: x - _ADDED_VAR_[2] <= -1
Constraint _ADDED_CON_[4]: x + _ADDED_VAR_[2] >= -1
Constraint _ADDED_CON_[5]: x - _ADDED_VAR_[3] <= 0
Constraint _ADDED_CON_[6]: x + _ADDED_VAR_[3] >= 0
```

When the function or operator is a nonconvex term, linearization requires additional variables and constraints. Consider the subexpression $\mathrm{MAX}(a_1(x), a_2(x), a_3(x))$. The nonconvex transformation requires a new binary variable, w_i, for each argument. Linearization replaces the subexpression with a new variable, z, that has these added constraints:

$$
\begin{aligned}
z &\geq a_1(x) \\
z &\geq a_2(x) \\
z &\geq a_3(x) \\
w_1 = 1 \text{ implies } z &\leq a_1(x) \\
w_2 = 1 \text{ implies } z &\leq a_2(x) \\
w_3 = 1 \text{ implies } z &\leq a_3(x) \\
w_1 + w_2 + w_3 &= 1
\end{aligned}
$$

The first three constraints match the convex transformation. The next three indicator constraints require z to be at most (hence equal to) the $a_i(x)$ argument value when the corresponding w_i variable is true. The final constraint ensures that one of the indicator constraints is active. The active constraint must correspond to an argument that has the maximum value because of the first three constraints.

When MIN or MAX has two arguments, the nonconvex transformation requires a single binary variable in order to select the active argument. For example, linearization replaces the function $\mathrm{MAX}(a_1(x), a_2(x))$ with a new variable, z, that has these constraints:

$$
\begin{aligned}
z &\geq a_1(x) \\
z &\geq a_2(x) \\
w_1 = 0 \text{ implies } z &\leq a_1(x) \\
w_1 = 1 \text{ implies } z &\leq a_2(x)
\end{aligned}
$$

The new binary variable, w_1, selects an argument that has the maximum value.

The nonconvex transformation for $\mathrm{ABS}(a_1(x))$ is similar, because $\mathrm{ABS}(a_1(x)) = \mathrm{MAX}(a_1(x), -a_1(x))$:

$$
\begin{aligned}
z &\geq a_1(x) \\
z &\geq -a_1(x) \\
w_1 = 0 \text{ implies } z &\leq a_1(x) \\
w_1 = 1 \text{ implies } z &\leq -a_1(x)
\end{aligned}
$$

The following code shows some examples of the nonconvex transformation:

```
proc optmodel;
   var x{1..4} >= 0 <= 100;
   con c1: max(x[1], x[2]) >= 50;
   con c2: min(x[1], x[2]) <= 10;
   maximize obj = abs(x[3]-x[4]);
   expand / linearize;
```

The output from the EXPAND statement is shown in Figure 9.69. Note that a big-M transformation was applied to the indicator constraints.

Figure 9.69 Nonconvex MIN/MAX/ABS Linearization

```
Var x[1] >= 0 <= 100
Var x[2] >= 0 <= 100
Var x[3] >= 0 <= 100
Var x[4] >= 0 <= 100
Var _ADDED_VAR_[1]
Var _ADDED_VAR_[2] BINARY
Var _ADDED_VAR_[3]
Var _ADDED_VAR_[4] BINARY
Var _ADDED_VAR_[5]
Var _ADDED_VAR_[6] BINARY
Maximize obj=_ADDED_VAR_[5]
Constraint c1: _ADDED_VAR_[1] >= 50
Constraint c2: _ADDED_VAR_[3] <= 10
Constraint _ADDED_CON_[1]: x[1] - _ADDED_VAR_[1] <= 0
Constraint _ADDED_CON_[2]: x[2] - _ADDED_VAR_[1] <= 0
Constraint _ADDED_CON_[3]: x[1] - _ADDED_VAR_[1] + 100*_ADDED_VAR_[2] >= 0
Constraint _ADDED_CON_[4]: x[2] - _ADDED_VAR_[1] - 100*_ADDED_VAR_[2] >= -100
Constraint _ADDED_CON_[5]: x[1] - _ADDED_VAR_[3] >= 0
Constraint _ADDED_CON_[6]: x[2] - _ADDED_VAR_[3] >= 0
Constraint _ADDED_CON_[7]: x[1] - _ADDED_VAR_[3] - 100*_ADDED_VAR_[4] <= 0
Constraint _ADDED_CON_[8]: x[2] - _ADDED_VAR_[3] + 100*_ADDED_VAR_[4] <= 100
Constraint _ADDED_CON_[9]: x[3] - x[4] - _ADDED_VAR_[5] <= 0
Constraint _ADDED_CON_[10]: x[3] - x[4] + _ADDED_VAR_[5] >= 0
Constraint _ADDED_CON_[11]: x[3] - x[4] - _ADDED_VAR_[5] + 200*_ADDED_VAR_[6] >=
0
Constraint _ADDED_CON_[12]: x[3] - x[4] + _ADDED_VAR_[5] + 200*_ADDED_VAR_[6] <=
200
```

Linear Ratio Constraints

A singly bounded constraint on the ratio of linear expressions can be transformed into a linear constraint by multiplying the bound by the denominator, provided that the denominator cannot equal 0. For example, the ratio constraint with linearizable expressions $a(x)$ and $b(y)$ and bound B,

$$\frac{a(x)}{b(y)} \leq B$$

can be linearized (assuming $b(y) > 0$) as

$$a(x) \leq B \cdot b(y)$$

If $b(y) < 0$, then the bound is multiplied by $-b(y)$:

$$-a(x) \leq -B \cdot b(y)$$

To handle a range constraint with bounds L and U,

$$L \leq \frac{a(x)}{b(y)} \leq U$$

the original constraint is replaced by an equality constraint that introduces a new variable, z,

$$a(x) = z$$

and the following added constraints (assuming $b(y) > 0$):

$$z \geq L \cdot b(y)$$
$$z \leq U \cdot b(y)$$

Note that the body value for ratio constraints is not preserved by the transformation.

The following code shows examples of the linearization of ratio constraints:

```
proc optmodel;
   var x {1..4} >=1;
   minimize obj = sum {i in 1..4} x[i];
   con c1: (x[1] + x[2] + 1) / (x[3] + x[4]) = 4;
   con c2: (x[1] + x[3]) / (x[2] + x[4]) <= 0.8;
   con c3: 4*(x[1] - x[2]) / (-x[3] - x[4]) >= -1;
   con c4: 2 <= (x[1] + x[2] + 1) / (x[3] + x[4] + 1) <= 3;
   expand / linearize;
```

The output is shown in Figure 9.70.

Figure 9.70 Ratio Constraint Linearization

```
Var x[1] >= 1
Var x[2] >= 1
Var x[3] >= 1
Var x[4] >= 1
Var _ADDED_VAR_[1]
Minimize obj=x[1] + x[2] + x[3] + x[4]
Constraint c1: x[1] + x[2] - 4*x[3] - 4*x[4] = -1
Constraint c2: x[1] + x[3] - 0.8*x[2] - 0.8*x[4] <= 0
Constraint c3: - 4*x[1] + 4*x[2] + x[3] + x[4] >= 0
Constraint c4: x[1] + x[2] - _ADDED_VAR_[1] = -1
Constraint _ADDED_CON_[1]: _ADDED_VAR_[1] - 2*x[3] - 2*x[4] >= 2
Constraint _ADDED_CON_[2]: _ADDED_VAR_[1] - 3*x[3] - 3*x[4] <= 3
```

Conic Transformation

PROC OPTMODEL supports the transformation of certain nonlinear expressions in objectives and constraints into equivalent forms for use by the conic solver. Use the CONIC option with the EXPAND or SOLVE statement to request conic transformation. Conic transformations are applied automatically when you use the conic solver for a problem that has a nonlinear objective or constraint.

The conic solver supports a linear or quadratic objective, linear constraints, quadratic constraints, and second-order cone predicate constraints. Conic transformation examines each nonlinear problem expression, replacing nonlinear subexpressions with equivalent linear subexpressions. Fixed variables are treated as constants to enable more opportunities for transformation. The transformations generally require the creation of additional variables and constraints. For example, you could use conic transformation to replace the square of a variable with a new linear variable term, along with a second-order cone constraint and a variable fixed to an auxiliary constant. Here is an example:

```
proc optmodel;
   var x;
   min z = x^2;
   expand / conic;
```

The EXPAND statement output in Figure 9.71 shows the transformed objective expression along with the added constraints and variables.

Figure 9.71 Simple Constraint Transformation

```
Var x
Var _ADDED_VAR_[1] >= 0
Fix _ADDED_VAR_[2] = 0.5
Minimize z=_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: RSOC(_ADDED_VAR_[2], _ADDED_VAR_[1], x)
```

The added variables are elements of the predefined array _ADDED_VAR_, which has an integer index that starts from 1. Added constraints are elements of the predefined array _ADDED_CON_, which has an integer index that starts from 1. You can specify the name _ADDED_VAR_ or _ADDED_CON_ in the EXPAND statement with the CONIC option to examine the added variables or constraints in the transformed problem.

Dual values could be meaningless after conic transformations. For example, fixed variables are replaced by

constants that have no dual values. The SOLVE statement does not attempt to recover the dual values and reduced costs of a problem that has conic transformations. The statement returns missing values for them when conic transformation is applied.

You can transform the following types of nonlinear subexpressions:

- quadratic constraint bodies equivalent to cone predicates
- linear ratio constraint bodies
- convex MIN/MAX/ABS function calls, <> expressions, and >< expressions
- Euclidean norms
- quadratic-linear ratios
- powers and roots
- univariate rational functions
- generalized geometric means

Problem generation fails if transformation is unable to replace a nonlinear subexpression or if the required linear coefficients are out of range or undefined.

You can apply conic transformations only to convex terms in problem formulas. This means that each nonlinear term must be used with the appropriate optimization direction. For example, you can transform the term $\mathrm{MAX}(x, y)$ when it is used with a positive coefficient in a minimization context. If you use the term in a maximization context with a positive coefficient, then the term would be concave and the transformation could not be applied. Note that applying a positive scaling coefficient to a term does not change the convexity.

A term $f(x)$ with a positive coefficient that is convex for minimization is also convex for maximization with a negative coefficient. The same term can be convex when it appears in a single-sided constraint with a coefficient of the correct sign, as the following examples show:

$$\begin{array}{rrl} \text{minimize} & c \cdot f(x) + g(y) & \\ \text{maximize} & -c \cdot f(x) + g(y) & \\ & c \cdot f(x) + g(y) & \leq b \\ & -c \cdot f(x) + g(y) & \geq b \end{array}$$

In these examples, c is a positive coefficient, b is a constant bound, and $g(y)$ represents other terms that can be transformed.

Similarly, a term $f(x)$ with a positive coefficient that is convex for maximization is also convex when it appears in a minimization objective or a single-sided constraint with the correct coefficient sign:

$$\begin{array}{rrl} \text{maximize} & c \cdot f(x) + g(y) & \\ \text{minimize} & -c \cdot f(x) + g(y) & \\ & c \cdot f(x) + g(y) & \geq b \\ & -c \cdot f(x) + g(y) & \leq b \end{array}$$

In the following descriptions of the various conic transformations, the allowed contexts are summarized as either minimization or maximization, assuming a positive coefficient. The allowed contexts include the opposite objective sense with a negative coefficient and single-sided constraints with the correct sign.

Note that you cannot transform nonlinear terms in equality and range constraints, except for replacing linear ratio constraints. Nonlinear terms in IMPVAR or objective expressions can be transformed only if all their uses have a consistent optimization direction.

Quadratic Constraints Specifying Second-Order Cones

The conic solver supports two types of quadratic cone predicates, SOC and RSOC, which stand for standard and rotated second-order cones, respectively. Conic transformation converts quadratic constraints to the corresponding cone predicates when possible. The body of the quadratic constraint must be a sum of squared linear terms and possibly some linear terms or the product of two linear terms for the left-hand side (LHS) of a rotated cone. Note that the linear terms on the left-hand side of a second-order cone predicate must be nonnegative. The order of terms is flexible, and you can specify constant coefficients for the terms. Constant terms can be treated as squared terms for the right-hand side (RHS) of the cone or as linear terms for the left-hand side, depending on the sign.

The following code demonstrates various ways to specify a second-order cone by using quadratic constraints:

```
proc optmodel;
   var x{1..4};
   x[1].lb = 0;                                /* cone LHS must be nonnegative */
   x[2].lb = 0;
   con q1: x[1]^2 >= x[3]^2 + x[4]^2;          /* standard SOC */
   con q2: x[3]^2 + x[4]^2 <= x[1]^2;          /* equivalent to q1 */
   con q3: 25 >= x[3]^2 + x[4]^2;              /* constant on cone LHS */
   con q4: x[1]^2 >= x[3]^2 + 25;              /* constant on cone RHS */
   con q5: 2*x[1]*x[2] >= x[3]^2 + x[4]^2;     /* standard RSOC */
   con q6: x[1] + x[2] + 1 >= x[3]^2 + x[4]^2; /* linear LHS for RSOC */
   con q7: x[1]*x[1] >= 4*(x[2]+x[3])^2 + x[4]*x[4]*3; /* term variants */
   expand / conic;
```

The output in Figure 9.72 shows that the quadratic constraints are transformed into equivalent cone predicates by using added variables and constraints, if necessary, to represent linear equations or to rescale variables.

Figure 9.72 Quadratic Constraint Transformation

```
Var x[1] >= 0
Var x[2] >= 0
Var x[3]
Var x[4]
Fix _ADDED_VAR_[1] = 5
Fix _ADDED_VAR_[2] = 0.5
Var _ADDED_VAR_[3]
Var _ADDED_VAR_[4]
Var _ADDED_VAR_[5]
Constraint q1: SOC(x[1], x[3] x[4])
Constraint q2: SOC(x[1], x[3] x[4])
Constraint q3: SOC(_ADDED_VAR_[1], x[3] x[4])
Constraint q4: SOC(x[1], x[3] _ADDED_VAR_[1])
Constraint q5: RSOC(x[1], x[2], x[3] x[4])
Constraint q6: RSOC(_ADDED_VAR_[3], _ADDED_VAR_[2], x[3] x[4])
Constraint q7: SOC(x[1], _ADDED_VAR_[4] _ADDED_VAR_[5])
Constraint _ADDED_CON_[1]: - _ADDED_VAR_[3] + x[1] + x[2] = -1
Constraint _ADDED_CON_[2]: - _ADDED_VAR_[4] + 2*x[2] + 2*x[3] = 0
Constraint _ADDED_CON_[3]: - _ADDED_VAR_[5] + 1.7320508076*x[4] = 0
```

Linear Ratio Constraints

A constraint whose body is the ratio of linear expressions can be transformed into one or more linear constraints. The same transformation is provided by the LINEARIZE option. See the description of the linearization transformation for more information.

Convex MIN/MAX/ABS Function Calls, <> Expressions, and >< Expressions

Subexpressions that call the MIN, MAX, and ABS functions or use the <> (maximum) and >< (minimum) operators can be linearized when the function or operator is a convex term in the containing problem formula. The same transformation is provided by the LINEARIZE option for convex terms. See the description of the linearization transformation for more information.

You can also transform terms that use the MAX function and the <> operator if they have a positive coefficient and are part of a sum of squared linear terms, provided that the operands are also sums of squared linear terms. You can transform terms that use the MIN function and the >< operator when they appear on the left-hand side of a second-order cone that you specify via a quadratic constraint, provided that the operands can also be transformed into the left-hand side of a second-order cone.

The following code demonstrates the transformation of MIN and MAX terms in quadratic constraints:

```
proc optmodel;
   var x{1..4};
   x[1].lb = 0;                                  /* cone LHS must be nonnegative */
   x[2].lb = 0;
   con c1: x[1]^2 >= max(x[3]^2, x[4]^2);        /* MAX result is nonnegative */
   con c2: min(x[1]*x[2], x[1]+x[2]) >= x[3]^2 + x[4]^2;
   expand / conic;
```

The output in Figure 9.73 shows that the quadratic constraints are transformed into equivalent linear or cone constraints, with added variables and constraints to enforce the MIN and MAX logic.

Figure 9.73 Quadratic MIN/MAX Transformation

```
Var x[1] >= 0
Var x[2] >= 0
Var x[3]
Var x[4]
Var _ADDED_VAR_[1] >= 0
Var _ADDED_VAR_[2] >= 0
Var _ADDED_VAR_[3]
Fix _ADDED_VAR_[4] = 0.5
Var _ADDED_VAR_[5]
Constraint c1: _ADDED_VAR_[1] - x[1] <= 0
Constraint c2: SOC(_ADDED_VAR_[2], x[3] x[4])
Constraint _ADDED_CON_[1]: x[3] - _ADDED_VAR_[1] <= 0
Constraint _ADDED_CON_[2]: x[3] + _ADDED_VAR_[1] >= 0
Constraint _ADDED_CON_[3]: x[4] - _ADDED_VAR_[1] <= 0
Constraint _ADDED_CON_[4]: x[4] + _ADDED_VAR_[1] >= 0
Constraint _ADDED_CON_[5]: RSOC(_ADDED_VAR_[3], x[2], _ADDED_VAR_[2])
Constraint _ADDED_CON_[6]: RSOC(_ADDED_VAR_[5], _ADDED_VAR_[4], _ADDED_VAR_[2])
Constraint _ADDED_CON_[7]: - _ADDED_VAR_[3] + 0.5*x[1] = 0
Constraint _ADDED_CON_[8]: - _ADDED_VAR_[5] + x[1] + x[2] = 0
```

Euclidean Norms

The Euclidean norm of a vector $\mathbf{x} \in \mathbb{R}^n$ is defined as

$$\|\mathbf{x}\|_2 = \sqrt{x_1^2 + x_2^2 + \cdots + x_n^2}$$

You can express a Euclidean norm term in PROC OPTMODEL by using the SQRT function applied to a sum of positive squared linear terms. The coefficients of the squared terms must be positive. Instead of using SQRT, you could also raise the sum of squares to the 0.5th power. When you apply conic transformation, the Euclidean norm must appear in a minimization context.

The following code demonstrates the transformation of a Euclidean norm:

```
proc optmodel;
   var x{1..3};
   min obj = sqrt(sum{i in 1..3}(x[i] - i + 1)^2);
   expand / conic;
```

The output in Figure 9.74 shows that the norm is replaced by an added variable with an added second-order cone predicate.

Figure 9.74 Euclidean Norm Transformation

```
Var x[1]
Var x[2]
Var x[3]
Var _ADDED_VAR_[1] >= 0
Var _ADDED_VAR_[2]
Var _ADDED_VAR_[3]
Minimize obj=_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: SOC(_ADDED_VAR_[1], x[1] _ADDED_VAR_[2]
_ADDED_VAR_[3])
Constraint _ADDED_CON_[2]: - _ADDED_VAR_[2] + x[2] = 1
Constraint _ADDED_CON_[3]: - _ADDED_VAR_[3] + x[3] = 2
```

Quadratic-Linear Ratios

The ratio of a sum of squares (squared linear terms with positive coefficients) over a nonnegative linear subexpression can be transformed into a linear term when the ratio is minimized. The following code demonstrates the transformation:

```
proc optmodel;
   var x{1..2};
   x[2].lb = 0;                                  /* divisor >= 0 */
   min obj = (x[1]^2 + 4) / x[2];
   expand / conic;
```

The output in Figure 9.75 shows that the ratio is replaced by an added variable with an added second-order cone predicate. The positive constant 4 is treated as a squared term.

Figure 9.75 Quadratic-Linear Ratio Transformation

```
Var x[1]
Var x[2] >= 0
Var _ADDED_VAR_[1] >= 0
Fix _ADDED_VAR_[2] = 2
Minimize obj=2*_ADDED_VAR_[1]
Constraint _ADDED_CON_[1]: RSOC(_ADDED_VAR_[1], x[2], x[1] _ADDED_VAR_[2])
```

Powers and Roots

A linear base subexpression, x, that is raised to a rational constant exponent, a, can be transformed into a linear term in some cases. The transformation is related to the generalized geometric mean transformation that is described in Erickson and Fourer (2019). The base value x must be nonnegative unless the exponent is an integer. If the exponent is 1, then no transformation is needed. If the exponent is an even positive integer, then the base term is unrestricted. If the exponent is any other integer, then the base can be nonnegative or nonpositive. A nonpositive base is negated and the sign for the coefficient of the exponentiation is adjusted if necessary.

A subexpression in which a constant c is divided by an exponentiated term, c/x^a, is transformed in the same way as cx^{-a}. An exponentiated term can also be replaced by a product of identical linear terms, such as $x \cdot x$ for x^2.

You can transform the following cases:

$$\begin{array}{rlll} \text{minimize} & x^a, & a \le 0, & x \ge 0 \\ \text{maximize} & x^a, & a \in [0,1], & x \ge 0 \\ \text{maximize} & \sqrt{x}, & & x \ge 0 \\ \text{minimize} & x^a, & a \ge 1, & x \ge 0 \\ \text{minimize} & x^{2n}, & n \in \mathbb{N} & \end{array}$$

Conic transformation recognizes the floating-point approximations to rational numbers like $\frac{1}{3}$ or $\frac{17}{2}$ that are used as exponents. The complexity of the exponent fractions is limited. You can use fractions with denominators up to 1,414, provided that the numerators are reasonably sized. Some fractions with larger denominators, such as $\frac{1}{100000}$, are also recognized, although the transformed problem could be difficult to solve to sufficient accuracy.

The following example demonstrates solving with the power transformations:

```
proc optmodel printlevel=0;
   var x{1..5};
   for {i in 1..4} x[i].lb = 0; /* need a lower bound in most cases */
   con c1: x[1]^-2 <= 0.25;     /* minimize with exponent <= 0 */
   con c2: x[2]^(1/3) >= 2;     /* maximize with exponent in [0,1] */
   con c3: sqrt(x[3]) >= 3;     /* maximize square root */
   con c4: x[4]^1.5 <= 8;       /* minimize with exponent >= 1 */
   con c5: x[5]^4 <= 16;        /* minimize with even exponent > 0 */
   min obj = x[1] + x[2] + x[3] - x[4] - x[5];
   solve with conic;
   print x;
```

Because the conic solver is used and the problem has nonlinear constraints, the SOLVE statement applies conic transformations automatically. The objective ensures that the constraints hold with equality at the optimal solution. The output in Figure 9.76 shows the resulting values of x.

Figure 9.76 Power and Root Transformation

[1]	x
1	2
2	8
3	9
4	4
5	2

Univariate Rational Functions

Conic transformation attempts to rewrite an expression that depends on a single variable when it represents the ratio of two polynomials in that variable. The expression is rewritten into a weighted sum of integer powers of linear terms. The rewritten power terms are then linearized as described in the preceding section. For example, the expression $x/(x+1)$ can be rewritten as $1-(x+1)^{-1}$. These rewritten terms can be linearized when you use them in a maximization context and $x \geq -1$.

You can specify the rational function as a sequence of polynomial terms that are combined using multiplication and division operators, with exponents optionally applied to the polynomial terms. For example, you can specify the ratio $(x+2)/(x^2-2x+1)$ in various ways, as shown in the following code:

```
var x >= 1;
min z1 = (x + 2) / (x**2 - 2*x + 1);      /* direct */
min z2 = (x**2 - 2*x + 1)**-1 * (x + 2); /* rearranged */
min z3 = (x + 2) / (x - 1)**2;            /* factored */
```

Conic transformation first performs polynomial division on the numerator and denominator polynomials, producing quotient and remainder polynomials. When the remainder is not zero, the ratio of the remainder and the denominator polynomials is split into a sum of negative powers of linear terms by using partial fraction decomposition. The power terms from the quotient and decomposition can then be linearized if they satisfy the requirements for conic transformation that are described in the preceding section.

Partial fraction decomposition requires the factorization of the denominator into a product of linear terms. Factors for quadratic or higher-degree denominator polynomial terms must be determined numerically by computing the roots. Conic transformation retains the factors of the denominator when they are given explicitly. The transformation fails when the denominator polynomial has complex roots.

When partial fraction decomposition rewrites a ratio, the linear factors of the denominator polynomial provide the linear terms for the rewritten negative powers. For example, the ratio $x/((x-1)(x-2))$ is rewritten as

$$\frac{-1}{x-1}+\frac{2}{x-2}$$

This expression is convex for maximization when $1 \leq x \leq 2$, so the power terms can be transformed in the appropriate contexts when the variable x is restricted to that range.

Even when the denominator can be factored into linear terms, it might not be possible to transform a rational function into a that form that the conic solver accepts. For example, the partial fraction decomposition of

$x/((x-1)(x-2)(x-3))$ is

$$\frac{1}{2(x-1)} - \frac{2}{x-2} + \frac{3}{2(x-3)}$$

Because the signs of the terms alternate, there is no range for the variable x where the terms are all convex for either maximization or minimization. On the other hand, the similar ratio $(x-\frac{5}{2})/((x-1)(x-2)(x-3))$ decomposes into

$$\frac{-3}{4(x-1)} + \frac{1}{2(x-2)} + \frac{1}{4(x-3)}$$

All the terms are convex for maximization for $1 \le x \le 2$, so they can be transformed when x is restricted to that range.

Generalized Geometric Means

Conic transformation recognizes a generalized form of geometric mean (Erickson and Fourer 2019) that can be described mathematically as

$$\text{maximize} \quad \prod_{i=1}^{n} x_i^{a_i}, \quad x_i \ge 0, \quad a_i \in (0,1), \quad \sum_{i=1}^{n} a_i \le 1$$

The x_i terms must be linear. The a_i exponents must be rational, like the exponents for the power transformation. You can specify the generalized form by using exponentiation with a power between 0 and 1 applied to a product of linear terms (such as $(x_1x_2)^{0.5}$), as the product of linear terms with exponents (such as $\sqrt{x_1}x_2^{0.3}$), or as a mixed combination of products and exponentiation (such as $(x_1x_2x_3^{0.5})^{0.4}$). You can also use the SAS library function GEOMEAN with the x_i terms as arguments. In this case, the required exponent is determined from the number of nonmissing arguments.

You can use geometric mean to model optimization problems that contain the product of nonnegative variables. For example, a problem might have an objective with a product:

$$\text{maximize} \quad x_1x_2x_3$$

To permit conic transformation, you can replace this objective with

$$\text{maximize} \quad (x_1x_2x_3)^{1/3}$$

The new objective becomes linear after conic transformations. The objective value changes, but the optimal solution is unchanged.

The following code demonstrates the transformation of a geometric mean:

```
proc optmodel printlevel=0;
   var x{1..4} >= 0;
   max obj = prod{i in 1..4} x[i]^0.25;
   con c: sum{i in 1..4} i*x[i] <= 72;
   solve with conic;
   print x;
```

The output in Figure 9.77 shows the resulting values of x.

Figure 9.77 Geometric Mean Transformation

[1]	x
1	17.9987
2	8.9977
3	6.0010
4	4.5007

Model Update

The PROC OPTMODEL modeling language provides several means of modifying a model after it is first specified. You can change the parameter values of the model. You can add new model components. The FIX and UNFIX statements can fix variables to specified values or rescind previously fixed values. The DROP and RESTORE statements can deactivate and reactivate constraints. See also the section "Multiple Subproblems" on page 454 for information on how to maintain multiple models.

To illustrate how these statements work, reconsider the following example from the section "Constraints" on page 413:

```
proc optmodel;
   var x, y;
   min r = x**2 + y**2;
   con c: x+y >= 1;
   solve;
   print x y;
```

As described previously, the solver finds the optimal point x = y = 0.5 with r = 0.5. You can see the effect of the constraint c on the solution by temporarily removing it. You can add the following statements:

```
   drop c;
   solve;
   print x y;
```

This change produces the output in Figure 9.78.

Figure 9.78 Solution with Dropped Constraint

Problem Summary	
Objective Sense	Minimization
Objective Function	r
Objective Type	Linear Least Squares
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	0
Constraint Coefficients	0
Least Squares Matrix Rows	2

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	r
Solution Status	Optimal
Objective Value	0
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	0
Complementarity	0
Iterations	0
Presolve Time	0.00
Solution Time	0.00

x	y
0	0

The optimal point is $x = y = 0$, as expected.

You can restore the constraint c with the RESTORE statement, and you can also investigate the effect of forcing the value of variable x to 0.3. This requires the following statements:

```
restore c;
fix x=0.3;
solve;
print x y c.dual;
```

This produces the output in Figure 9.79.

Figure 9.79 Solution with Fixed Variable

Problem Summary	
Objective Sense	Minimization
Objective Function	r
Objective Type	Linear Least Squares
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	1
Fixed	1
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	2
Least Squares Matrix Rows	1

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	r
Solution Status	Optimal
Objective Value	0.58
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	0
Complementarity	0
Iterations	0
Presolve Time	0.00
Solution Time	0.00

x	y	c.DUAL
0.3	0.7	1.4

The variable x still has the value that was defined in the FIX statement. The objective value has increased by 0.08 from its constrained optimum 0.5 (see Figure 9.55). The constraint c is active, as confirmed by the positive dual value.

You can return to the original optimization problem by allowing the solver to vary variable x with the UNFIX statement, as follows:

```
unfix x;
solve;
print x y c.dual;
```

This produces the output in Figure 9.80. The model was returned to its original conditions.

Figure 9.80 Solution with Original Model

Problem Summary	
Objective Sense	Minimization
Objective Function	r
Objective Type	Linear Least Squares
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	2
Least Squares Matrix Rows	2

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	r
Solution Status	Optimal
Objective Value	0.5000000365
Primal Infeasibility	0
Dual Infeasibility	2.3570225E-9
Bound Infeasibility	0
Duality Gap	2.5463909E-8
Complementarity	0
Iterations	5
Presolve Time	0.00
Solution Time	0.00

x	y	c.DUAL
0.5	0.5	1

Multiple Subproblems

The OPTMODEL procedure enables multiple models to be manipulated easily by using named problems to switch the active model components. Problems keep track of an objective, a set of included variables and constraints, and some status information that is associated with the variables and constraints. Other data, such as parameter values, bounds, and the current value of variables, are shared by all problems.

Problems are declared with the PROBLEM declaration. You can easily switch between problems by using the USE PROBLEM statement. The USE PROBLEM statement makes the specified problem become the current problem. The various statements that generate problem data, such as SOLVE, EXPAND, and SAVE MPS, always operate using the model components included in the current problem.

A problem declaration can specify the problem's objectives by copying them from the problem that is named in a FROM clause or by including objective symbols. The objectives can be updated while the problem is current by declaring a new non-array objective or by executing programming statements that specify new objectives.

Variables can also be included when the problem is current by declaring them or by using the FIX or UNFIX statement. Similarly, constraints can be included when the problem is current by declaring them or by using the RESTORE or DROP statement. There is no way to exclude a variable or constraint item after it has been included in a problem, although the variable or constraint can be fixed or dropped.

Variables that are declared but not included in a problem are treated as constants when a problem is generated, while constraints that are declared but not included are ignored. The solver does not update the values and status for these model components.

A problem also tracks certain other status information that is associated with its included symbols, and this information can be changed without affecting other problems. This information includes the fixed status for variables, and the dropped status for constraints. The following additional data that are tracked by the problem are available through constraint, objective, and variable suffixes:

- *con*.ACTIVE
- *con*.BLOCK
- *con*.DUAL
- *con*.LBMAX
- *con*.LBMIN
- *con*.STATUS (including IIS status)
- *con*.UBMAX
- *con*.UBMIN
- *obj*.ACTIVE
- *var*.ACTIVE
- *var*.DUAL (alias of *var*.RC)

- *var*.FIXED
- *var*.LBMAX
- *var*.LBMIN
- *var*.MSINIT
- *var*.OBJMAX
- *var*.OBJMIN
- *var*.RC
- *var*.SOL[*i*] (for each solution *i*)
- *var*.STATUS (including IIS status)
- *var*.UBMAX
- *var*.UBMIN

The initial problem when OPTMODEL starts is predeclared with the name _START_. This problem can be reinstated again (after other USE PROBLEM statements) with the statement

```
use problem _start_;
```

See "Example 9.5: Multiple Subproblems" on page 480 for example statements that use multiple subproblems.

Multiple Solutions

When a solver finishes, it reports zero or more solutions for the optimization variables of the current problem. Each solution assigns a value to each of the variables in the problem. The SOLVE statement saves these solutions with the current problem. The first reported solution, if any, is also copied into the optimization variables. The number of solutions is available in the predeclared numeric parameter _NSOL_.

NOTE: The network solver does not require optimization variables and has its own conventions for returning multiple solutions.

You can access the solutions that are saved with the problem by adding a solution index to the .sol suffix of the variable name. For example, x.sol[2] would reference the second solution saved for variable x in the current problem. Both the variable name and the suffix can be indexed. For example, assign[3,7].sol[1] refers to the first solution for the array variable element assign[3,7]. The solution index must be an integer in the range 1 to _NSOL_.

The following example illustrates the processing of multiple solutions from the CLP solver:

```
proc optmodel printlevel=0;
   var x{1..2} integer >= 1 <= 3;
   con c: alldiff(x);
   solve with clp / allsolns;
   print _NSOL_;
   print {j in 1..2, i in 1..._NSOL_} x[j].sol[i];
```

```
create data solout from [sol]={i in 1.._NSOL_}
    {j in 1..2} <col("x"||j)=x[j].sol[i]> ;
```

This program produces the output in Figure 9.81. It also creates a data set, solout, which has each solution in a separate observation.

Figure 9.81 Processing Multiple Solutions

NSOL
6

x.SOL					
1	**2**	**3**	**4**	**5**	**6**
1	1	2	2	3	3
2	3	1	3	1	2

Problem Symbols

The OPTMODEL procedure declares a number of symbols that are aliases for model components in the current problem. These symbols allow the model components to be accessed uniformly. These symbols are described in Table 9.17.

Table 9.17 Problem Symbols

Symbol	Indexing	Description
NVAR		Number of variables
VAR	{1.._NVAR_}	Variable array
NCON		Number of constraints
CON	{1.._NCON_}	Constraint array
_S_NVAR_		Number of presolved variables
_S_VAR_	{1.._S_NVAR_}	Presolved variable array
_S_NCON_		Number of presolved constraints
_S_CON_	{1.._S_NCON_}	Presolved constraint array
NOBJ		Number of objectives
ALLOBJ	{1.._NOBJ_}	Objective array
OBJ		Current objective
PROBLEM		Current problem

If the table specifies indexing, then the corresponding symbol is accessed as an array. For example, if the problem includes two variables, x and y, then the value of _NVAR_ is 2 and the current variable values can be accessed as _var_[1] and _var_[2]. The problem variables prefixed with _S are restricted to model components in the problem after processing by the OPTMODEL presolver.

The following statements define a simple linear programming model and then use the problem symbols to print out some of the problem results. The .name suffix is used in the PRINT statements to display the actual variable and constraint names. Any of the suffixes that apply to a model component can be applied to the corresponding generic symbol.

```
proc optmodel printlevel=0;
   var x1 >= 0, x2 >= 0, x3 >= 0, x4 >= 0, x5 >= 0;

   minimize z = x1 + x2 + x3 + x4;

   con a1: x1 + x2 + x3          <= 4;
   con a2:               x4 + x5 <= 6;
   con a3: x1 +          x4      >= 5;
   con a4:      x2 +          x5 >= 2;
   con a5:           x3          >= 3;

   solve with lp;

   print _var_.name _var_ _var_.rc _var_.status;
   print _con_.name _con_.lb _con_.body _con_.ub _con_.dual _con_.status;
```

The PRINT statement output is shown in Figure 9.82.

Figure 9.82 Problem Symbol Output

[1]	_VAR_.NAME	_VAR_	_VAR_.RC	_VAR_.STATUS
1	x1	1	0	B
2	x2	0	1	L
3	x3	3	0	B
4	x4	4	0	B
5	x5	2	0	B

[1]	_CON_.NAME	_CON_.LB	_CON_.BODY	_CON_.UB	_CON_.DUAL	_CON_.STATUS
1	a1	-1.7977E308	4	4.0000E+00	0	B
2	a2	-1.7977E308	6	6.0000E+00	0	L
3	a3	5	5	1.7977E+308	1	U
4	a4	2	2	1.7977E+308	0	U
5	a5	3	3	1.7977E+308	1	U

OPTMODEL Options

All PROC OPTMODEL options can be specified in the PROC statement (see the section "PROC OPTMODEL Statement" on page 316 for more information). However, it is sometimes necessary to change options after other PROC OPTMODEL statements have been executed. For example, if an optimization technique had trouble with convergence, then it might be useful to vary the PRESOLVER= option value. This can be done with the RESET OPTIONS statement.

The RESET OPTIONS statement accepts options in the same form used by the PROC OPTMODEL statement. The RESET OPTIONS statement is also able to reset option values and to change options programmatically. For example, the following statements print the value of parameter n at various precisions:

```
proc optmodel;
   number n = 1/7;
   for {i in 1..9 by 4}
   do;
      reset options pdigits=(i);
      print n;
   end;
   reset options pdigits; /* reset to default */
```

The output generated is shown in Figure 9.83. The RESET OPTIONS statement in the DO loop sets the PDIGITS option to the value of i. The final RESET OPTIONS statement restores the default option value, because the value was omitted.

Figure 9.83 Changing the PDIGITS Option Value

n
0.1

n
0.14286

n
0.142857143

Automatic Differentiation

PROC OPTMODEL automatically generates statements to evaluate the derivatives for most objective expressions and nonlinear constraints. PROC OPTMODEL generates analytic derivatives for objective and constraint expressions written in terms of the procedure's mathematical operators and most standard SAS library functions.

NOTE: Some functions, such as ABS, FLOOR, and SIGN, and some operators, such as IF-THEN, <> (maximum operator), and >< (minimum operator), must be used carefully in modeling expressions because functions that include such components are not continuously differentiable or even continuous.

Expressions that reference user-defined functions or some SAS library functions might require numerical approximation of derivatives. PROC OPTMODEL uses either forward-difference approximation or central-

difference approximation as specified by the FD= option (see the section "PROC OPTMODEL Statement" on page 316).

NOTE: The numerical gradient approximations are significantly slower than automatically generated derivatives when the number of optimization variables is large.

Forward-Difference Approximations

The FD=FORWARD option requests the use of forward-difference derivative approximations. For a function f of n variables, the first-order derivatives are approximated by

$$g_i = \frac{\partial f}{\partial x_i} = \frac{f(x + e_i h_i) - f(x)}{h_i}$$

Notice that up to n additional function calls are needed here. The step lengths h_i, $i = 1, \ldots, n$, are based on the assumed function precision, *DIGITS*:

$$h_i = 10^{-DIGITS/2}(1 + |x_i|)$$

You can use the FDIGITS= option to specify the function precision, *DIGITS*, for the objective function. For constraints, use the CDIGITS= option.

The second-order derivatives are approximated by using up to $n(n + 3)/2$ extra function calls (Dennis and Schnabel 1983, pp. 80, 104):

$$\begin{aligned}
\frac{\partial^2 f}{\partial x_i^2} &= \frac{f(x + h_i e_i) - 2f(x) + f(x - h_i e_i)}{h_i^2} \\
\frac{\partial^2 f}{\partial x_i \partial x_j} &= \frac{f(x + h_i e_i + h_j e_j) - f(x + h_i e_i) - f(x + h_j e_j) + f(x)}{h_i h_j}
\end{aligned}$$

Notice that the diagonal of the Hessian uses a central-difference approximation (Abramowitz and Stegun 1972, p. 884). The step lengths are

$$h_i = 10^{-DIGITS/3}(1 + |x_i|)$$

Central-Difference Approximations

The FD=CENTRAL option requests the use of central-difference derivative approximations. Generally, central-difference approximations are more accurate than forward-difference approximations, but they require more function evaluations. For a function f of n variables, the first-order derivatives are approximated by

$$g_i = \frac{\partial f}{\partial x_i} = \frac{f(x + e_i h_i) - f(x - e_i h_i)}{2h_i}$$

Notice that up to $2n$ additional function calls are needed here. The step lengths h_i, $i = 1, \ldots, n$, are based on the assumed function precision, *DIGITS*:

$$h_i = 10^{-DIGITS/3}(1 + |x_i|)$$

You can use the FDIGITS= option to specify the function precision, *DIGITS*, for the objective function. For constraints, use the CDIGITS= option.

The second-order derivatives are approximated by using up to $2n(n + 1)$ extra function calls (Abramowitz and Stegun 1972, p. 884):

$$\begin{aligned}
\frac{\partial^2 f}{\partial x_i^2} &= \frac{-f(x + 2h_i e_i) + 16f(x + h_i e_i) - 30f(x) + 16f(x - h_i e_i) - f(x - 2h_i e_i)}{12h_i^2} \\
\frac{\partial^2 f}{\partial x_i \partial x_j} &= \frac{f(x + h_i e_i + h_j e_j) - f(x + h_i e_i - h_j e_j) - f(x - h_i e_i + h_j e_j) + f(x - h_i e_i - h_j e_j)}{4h_i h_j}
\end{aligned}$$

The step lengths are

$$h_i = 10^{-DIGITS/3}(1 + |x_i|)$$

Conversions

Numeric values are implicitly converted to strings when needed for function arguments or operands to the string concatenation operator (||). A warning message is generated when the conversion is applied to a function argument. The conversion uses BEST12. format. Unlike the DATA step, the conversion trims blanks.

Implicit conversion of strings to numbers is not permitted. Use the INPUT function to explicitly perform such conversions.

FCMP Routines

The OPTMODEL procedure can call functions and subroutines that are compiled by the FCMP procedure. You can use FCMP functions wherever a function expression is allowed in PROC OPTMODEL. Use the CALL statement to call FCMP subroutines. The following example defines a function in the FCMP procedure and calls it within PROC OPTMODEL:

```
proc fcmp outlib=work.funcs.test;
   /* arithmetic geometric mean */
   function agm(a0, b0);
      a = a0; b = b0;
      if a<=0 or b<=0 then return(0);
      do until( a - b < a/1e12 );
         a1 = 0.5*a + 0.5*b;
         b1 = sqrt(a*b);
         a = a1; b = b1;
      end;
      return(a);
   endsub;
run;

/* libraries must be specified with the CMPLIB option */
option cmplib=work.funcs;

proc optmodel;
   print (agm(1,2));

   /* find x where agm(1,x) == 23 */
   var x init 1;
   num c = 23;
   min z = (agm(1,x)-c)^2;
   solve;
   print x;
```

FCMP subroutines can return data by updating OPTMODEL numeric and string parameters, which are passed as arguments in a CALL statement. These arguments are declared using the OUTARGS statement in the PROC FCMP subroutine definition. The OPTMODEL argument must be specified with an identifier expression. The following code shows a simple example of output arguments. The maximum length of output strings from OUTARGS arguments is restricted to the argument length before the call, as described in the section "CALL Statement" on page 332.

```
proc fcmp outlib=work.funcs.test;
   subroutine do_sqr(x, sq, text $);
      outargs sq, text;
      sq = x*x;
      text = 'This is an example of output arguments';
   endsub;
run;

option cmplib=work.funcs;

proc optmodel;
   string s init repeat(' ', 79); /* reserve 80 bytes */
   number n;
   call do_sqr(7, n, s);
   print s n;
```

This code produces the output in Figure 9.84.

Figure 9.84 FCMP Output Arguments

s	n
This is an example of output arguments	49

You can pass OPTMODEL arrays to FCMP functions and subroutines that accept matrix arguments. The array must match the type and dimensions of the FCMP argument declaration. The argument in the OPTMODEL CALL statement must be specified using the following syntax:

array-name [. *suffix*]

The following code passes a constant matrix to an FCMP function. The array coeff contains the coefficients of a polynomial, which in this case defines a simple quadratic formula, $x^2 - 2x + 1$.

```
proc fcmp outlib=work.funcs.test;
   function evalpoly(x, coeff[*]);
      z = 0;
      do i = dim1(coeff) to 1 by -1;
         z = z * x + coeff[i];
      end;
      return (z);
   endsub;
run;

option cmplib=work.funcs;

proc optmodel;
   num coeff{1..3} = [1, -2, 1];
   var x;
   min z=evalpoly(x, coeff);
   solve;
   print x;
```

An array that is used as a matrix argument must be indexed like an FCMP matrix. In other words, the array index set must be specified as the crossproduct of one or more range expressions (such as 1..N) where the

lower bound and step size are 1. Set parameters that are used for indexing must contain a crossproduct of ranges, but the element order is not important. The following code shows some examples of suitable and unsuitable array declarations:

```
proc fcmp outlib=work.funcs.test;
   subroutine mattest(x[*]);
      put x[1]=;
   endsub;
   subroutine mattest2(x[*,*]);
      put x[1,1]=;
   endsub;
run;

option cmplib=work.funcs;

proc optmodel;
   /* the following arrays can be used as matrices */
   num N init 3;
   num mat1{1..N} init 0;
   call mattest(mat1);     /* OK */
   set S1 = 1..5;
   num mat2{S1} init 0;
   call mattest(mat2);     /* OK */
   set S2 = {S1,S1};
   num mat3{S2} init 0;
   call mattest2(mat3);    /* OK */
   num mat4{S1 cross S1} init 0;
   call mattest2(mat4);    /* OK */
   num L init 1;
   num mat5{L..N} init 0;
   call mattest(mat5);     /* OK */
   set S3 init S1;
   num mat6{S3} init 0;
   call mattest(mat6);     /* OK */

   /* some errors are detected at execution time */
   S3 = 2..5;
   call mattest(mat6);     /* ERROR: lower bound not 1 */
   S3 = {1, 3, 4, 5};
   call mattest(mat6);     /* ERROR: missing index 2 */
   L = 0;
   call mattest(mat5);     /* ERROR: lower bound not 1 */

   /* the following arrays cannot be used as matrices */
   num arr1{1..10 by 3};   /* step size is not 1 */
   call mattest(arr1);     /* ERROR */
   num arr2{i in 1..N, j in 1..N: j >= i}; /* selection expression used */
   call mattest2(arr2);    /* ERROR */
   num arr3{i in 1..N, j in 1..i};         /* index dependency on 'i' */
   call mattest2(arr3);    /* ERROR */
```

Not all PROC FCMP functionality is compatible with PROC OPTMODEL; in particular, the following FCMP functions are not supported and should not be called within your FCMP function definitions: READ_ARRAY, WRITE_ARRAY, RUN_MACRO, and RUN_SASFILE. In many cases, OPTMODEL capabilities can replace

these functions. Matrix arguments can be used in place of the READ_ARRAY function by using the READ DATA statement to load the matrix in PROC OPTMODEL. Similarly, you can replace the WRITE_ARRAY function in an FCMP subroutine by copying the matrix to an output argument and using the OPTMODEL procedure to write the matrix. You can use the SUBMIT statement in place of the RUN_MACRO and RUN_SASFILE functions.

The SAS CMPLIB= system option specifies where to look for previously compiled functions and subroutines. For more information about the CMPLIB= system option, see *SAS System Options: Reference*. FCMP functions can be used in distributed mode with the NLP multistart or black-box solver. The needed PROC FCMP compiled routines are automatically packaged and distributed. For more information about the multistart solver, see Chapter 16, "The Nonlinear Programming Solver," in this book.

PROC OPTMODEL uses derivatives values that are provided by FCMP when they are available. FCMP cannot provide derivatives with respect to array arguments, so PROC OPTMODEL must use finite differences to compute these derivatives. Also, if the CMPOPT= SAS system option specifies the FUNCDIFFERENCING value, then PROC OPTMODEL uses its own finite differencing for FCMP functions.

More on Index Sets

Dummy parameters behave like parameters but are assigned values only when an index set is evaluated. You can reference the declared dummy parameters from index set expressions that follow the index set item. You can also reference the dummy parameters in the expression or statement controlled by the index set. As the members of the set expression of an index set item are enumerated, the element values of the members are assigned to the local dummy parameters.

The number of names in a dummy parameter declaration must match the element length of the corresponding set expression in the index set item. A single name is allowed when the set member type is scalar (numeric or string). If the set members are tuples that have $n > 1$ elements, then n names are required between the angle brackets (< >) that precede the IN keyword.

Multiple index set items in an index set are nominally processed in a left-to-right order. That is, a set expression from an index set item is evaluated as though the index set items that precede it have already been evaluated. The left-hand index set items can assign values to local dummy parameters that are used by the set expressions that follow them. After each member from the set expression is enumerated, any index set items to the right are reevaluated as needed. The actual order in which index set items are evaluated can vary, if necessary, to allow more efficient enumeration. PROC OPTMODEL generates the same set of values in any case, although possibly in a different order than strict left-to-right evaluation.

You can view the element combinations that are generated from an index set as tuples. This is especially true for index set expressions (see the section "Index Set Expression" on page 390). However, in most cases no tuple set is actually formed, and the element values are assigned only to local dummy parameters.

You can specify a selection expression following a colon (:). The index set generates only those combinations of values for which the selection expression is true. For example, the following statements produce a set of upper triangular indices:

```
proc optmodel;
   put (setof {i in 1..3, j in 1..3 : j >= i} <i, j>);
```

These statements produce the output in Figure 9.85.

Figure 9.85 Upper Triangular Index Set

```
{<1,1>,<1,2>,<1,3>,<2,2>,<2,3>,<3,3>}
```

You can use the left-to-right evaluation of index set items to express the previous set more compactly. The following statements produce the same output as the previous statements:

```
proc optmodel;
   put ({i in 1..3, i..3});
```

In this example, the first time the second index set item is evaluated, the value of the dummy parameter i is 1, so the item produces the set {1,2,3}. At the second evaluation the value of i is 2, so the second item produces the set {2,3}. At the final evaluation the value of i is 3, so the second item produces the set {3}.

In many cases it is useful to combine the SLICE operator with index sets. A special form of index set item uses the SLICE operator implicitly. Normally an index set item that is applied to a set of tuples of length greater than one must be of the form

< *name-1* [**,** . . . *name-n*] **>** **IN** *set-expression*

In the special form, one or more of the name elements are replaced by expressions. The expressions select tuple elements by using the SLICE operator. An expression that consists of a single name must be enclosed in parentheses to distinguish it from a dummy parameter. The remaining names are the dummy parameters for the index set item that is applied to the SLICE result. The following example demonstrates the use of implicit set slicing:

```
proc optmodel;
   number N = 3;
   set<num,str> S = {<1,'a'>,<2,'b'>,<3,'a'>,<4,'b'>};
   put ({i in 1..N, <(i),j> in S});
   put ({i in 1..N, j in slice(<i,*>, S)});
```

The two PUT statements in this example are equivalent.

Threaded and Distributed Processing

The OPTMODEL procedure can take advantage of the multiple CPUs that are available in many computers. PROC OPTMODEL automatically uses multithreaded execution to divide problem generation among the multiple CPUs of the computer that is running the procedure. Hessian and Jacobian matrix evaluation is automatically parallelized across threads of execution on multiple CPUs. The COFOR statement enables solvers to concurrently execute in background threads on multiple CPUs, overlapping with PROC OPTMODEL statement processing. Parallel execution can decrease the amount of clock time required to perform a task, although the total CPU time required might increase.

Optimization solvers execute in the distributed computing environment when you specify the SESSREF= or SESSUUID= option. Distributed computing provides the most benefit when you can structure a computational process to include a large number of nontrivial subprocesses that can be executed independently. Solvers can run on the distributed computing environment by using one or more threads of a compute node. The COFOR statement allows concurrent processing by multiple solvers. Alternatively, some solvers can distribute their processing across multiple compute nodes.

When you do not request distributed computing, threaded processing is performed on the client. The NTHREADS= option controls the number of threads that are used for processing. When you do not specify the NTHREADS= option, threading in the OPTMODEL procedure is controlled by the following SAS system options:

CPUCOUNT=*number* **| ACTUAL**
specifies the maximum number of CPUs that can be used.

THREADS | NOTHREADS
enables or disables the use of threading.

Good performance is usually obtained with the default option settings (THREADS and CPUCOUNT=ACTUAL). See the option descriptions in *SAS System Options: Reference* for more details.

When distributed computing is used, the NTHREADS= option is ignored by problem generation because it is performed on the client. In this case, the maximum number of threads that are used for problem generation is based on the SAS CPUCOUNT= and THREADS options.

The NTHREADS= option and the SAS system options set the maximum number of threads. The number of threads that PROC OPTMODEL actually uses depends on the characteristics of the problem that is being solved and the requirements of the distributed computing environment. In particular, threading is not used when the problem is simple enough that threading offers no advantage.

Macro Variable _OROPTMODEL_

The OPTMODEL procedure creates a macro variable named _OROPTMODEL_. You can inspect the execution of the most recently invoked solver from the value of the macro variable. The macro variable is defined at the start of the procedure and updated after each SOLVE statement is executed. The OPTMODEL procedure also updates the macro variable when an error is detected.

The _OROPTMODEL_ value is a string that consists of several “KEYWORD=*value*” items in sequence, separated by blanks; for example:

```
STATUS=OK ALGORITHM=DS SOLUTION_STATUS=OPTIMAL OBJECTIVE=119302.04331
PRIMAL_INFEASIBILITY=3.552714E-13 DUAL_INFEASIBILITY=2.273737E-13
BOUND_INFEASIBILITY=0 ITERATIONS=82 PRESOLVE_TIME=0.02 SOLUTION_TIME=0.05
```

The information contained in _OROPTMODEL_ varies according to which solver was last called. For lists of keywords and possible values, see the individual solver chapters.

If a value has not been computed, then the corresponding element is not included in the value of the macro variable. When PROC OPTMODEL starts, for example, the macro variable value is set to “STATUS=OK” because no SOLVE statement has been executed. If the STATUS= indicates an error, then the other values from the solver might not be available, depending on when the error occurred.

Solver Status Parameters

In addition to creating the macro variable _OROPTMODEL_, the OPTMODEL procedure creates several predeclared parameters to provide simple access to solver status values. These parameters are declared as follows:

```
string _STATUS_;
string _SOLUTION_STATUS_;
set<string> _OROPTMODEL_STR_KEYS_;
set<string> _OROPTMODEL_NUM_KEYS_;
string _OROPTMODEL_STR_{_OROPTMODEL_STR_KEYS_};
number _OROPTMODEL_NUM_{_OROPTMODEL_NUM_KEYS_};
```

The value of _STATUS_ is equal to the STATUS= component of the _OROPTMODEL_ macro variable. The value of _STATUS_ is initially "OK". The value is updated during the SOLVE statement and after statement execution errors.

The value of _SOLUTION_STATUS_ is equal to the SOLUTION_STATUS= component of the _OROPTMODEL_ macro variable. The value is initially an empty string. The value is updated during the SOLVE statement.

You can use the remaining status parameters to access all the components of the _OROPTMODEL_ macro variable. The following statements demonstrate these parameters:

```
proc optmodel printlevel=0;
   var x init 1 >= 0.001;
   min z=sin(x)/x;
   solve;
   for {k in /STATUS SOLUTION_STATUS ALGORITHM/}
      put _OROPTMODEL_STR_[k]=;
   for {k in /OBJECTIVE ITERATIONS/}
      put _OROPTMODEL_NUM_[k]=;
```

These statements produce the output in Figure 9.86.

Figure 9.86 Solver Status Parameters

```
_OROPTMODEL_STR_[STATUS]=OK
_OROPTMODEL_STR_[SOLUTION_STATUS]=OPTIMAL
_OROPTMODEL_STR_[ALGORITHM]=IPDIR
_OROPTMODEL_NUM_[OBJECTIVE]=-0.217233628
_OROPTMODEL_NUM_[ITERATIONS]=6
```

The _OROPTMODEL_STR_ array contains the same character component values that are found in the _OROPTMODEL_ macro variable. Specify the component name as the array index. For example, the indices "STATUS" and "SOLUTION_STATUS" select array elements that hold the STATUS= and SOLUTION_STATUS= component values, respectively. The set _OROPTMODEL_STR_KEYS_ contains the component indices that you can use with _OROPTMODEL_STR_. The OPTMODEL procedure updates the _OROPTMODEL_STR_ and _OROPTMODEL_STR_KEYS_ parameters during the execution of the SOLVE statement and after any execution errors occur.

The _OROPTMODEL_NUM_ array contains the numeric component values that are displayed in the _OROPTMODEL_ macro variable. For example, the index "OBJECTIVE" selects the array element that holds the objective value when a solution is available. The set _OROPTMODEL_NUM_KEYS_ contains the

component indices that you can use with _OROPTMODEL_NUM_. The OPTMODEL procedure updates the _OROPTMODEL_NUM_ and _OROPTMODEL_NUM_KEYS_ parameters during the execution of the SOLVE statement and after any execution errors occur.

Macro and Statement Evaluation Order

PROC OPTMODEL reads a complete statement, such as a DO statement, before executing any code in it. But macro language statements are processed as the code is read. So you must be careful when using the _OROPTMODEL_ macro variable in code that involves SOLVE statements nested in loops or DO statements. The following statements demonstrate one example of this behavior:

```
proc optmodel;
   var x, y;
   min z=x**2 + (x*y-1)**2;
   for {n in 1..3} do;
      fix x=n;
      solve;
      %put Line 1 &_OROPTMODEL_;
      put 'Line 2 ' (symget("_OROPTMODEL_"));
   end;
quit;
```

In the preceding statements the %PUT statement is executed once, before any SOLVE statements are executed. It displays PROC OPTMODEL's initial setting of the macro variable. But the PUT statement is executed after each SOLVE statement and indicates the expected solution status.

Rewriting PROC NLP Models for PROC OPTMODEL

This section describes techniques for converting PROC NLP models to PROC OPTMODEL models. Example 9.8 also demonstrates how to rewrite a PROC NLP model for use with PROC OPTMODEL.

To illustrate the basics, consider the following first version of the PROC NLP model for the example "Simple Pooling Problem" in Chapter 6, "The NLP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*):

```
proc nlp all;
   parms amountx amounty amounta amountb amountc
         pooltox pooltoy ctox ctoy pools = 1;
   bounds 0 <= amountx amounty amounta amountb amountc,
               amountx <= 100,
               amounty <= 200,
          0 <= pooltox pooltoy ctox ctoy,
          1 <= pools <= 3;
   lincon amounta + amountb = pooltox + pooltoy,
          pooltox + ctox = amountx,
          pooltoy + ctoy = amounty,
          ctox + ctoy    = amountc;
   nlincon nlc1-nlc2 >= 0.,
           nlc3 = 0.;
   max f;
   costa = 6; costb = 16; costc = 10;
```

```
   costx = 9; costy = 15;
   f = costx * amountx + costy * amounty
       - costa * amounta - costb * amountb - costc * amountc;
   nlc1 = 2.5 * amountx - pools * pooltox - 2. * ctox;
   nlc2 = 1.5 * amounty - pools * pooltoy - 2. * ctoy;
   nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
run;
```

These statements define a model that has bounds, linear constraints, nonlinear constraints, and a simple objective function. The following statements are a straightforward conversion of the PROC NLP statements to PROC OPTMODEL form:

```
proc optmodel;
   var amountx init 1 >= 0 <= 100,
       amounty init 1 >= 0 <= 200;
   var amounta init 1 >= 0,
       amountb init 1 >= 0,
       amountc init 1 >= 0;
   var pooltox init 1 >= 0,
       pooltoy init 1 >= 0;
   var ctox init 1 >= 0,
       ctoy init 1 >= 0;
   var pools init 1 >=1 <= 3;
   con amounta + amountb = pooltox + pooltoy,
       pooltox + ctox = amountx,
       pooltoy + ctoy = amounty,
       ctox + ctoy    = amountc;
   number costa, costb, costc, costx, costy;
   costa = 6; costb = 16; costc = 10;
   costx = 9; costy = 15;
   max f = costx * amountx + costy * amounty
          - costa * amounta - costb * amountb - costc * amountc;
   con nlc1: 2.5 * amountx - pools * pooltox - 2. * ctox >= 0,
       nlc2: 1.5 * amounty - pools * pooltoy - 2. * ctoy >= 0,
       nlc3: 3 * amounta + amountb - pools * (amounta + amountb)
             = 0;
   solve;
   print amountx amounty amounta amountb amountc
         pooltox pooltoy ctox ctoy pools;
```

The PROC OPTMODEL variable declarations are split into individual declarations because PROC OPTMODEL does not permit name lists in its declarations. In the OPTMODEL procedure, you specify variable bounds as part of the variable declaration instead of in a separate BOUNDS statement. The PROC NLP statements are as follows:

```
parms amountx amounty amounta amountb amountc
      pooltox pooltoy ctox ctoy pools = 1;
bounds 0 <= amountx amounty amounta amountb amountc,
            amountx <= 100,
            amounty <= 200,
       0 <= pooltox pooltoy ctox ctoy,
       1 <= pools <= 3;
```

The following PROC OPTMODEL statements are equivalent to the preceding PROC NLP statements:

```
var amountx init 1 >= 0 <= 100,
    amounty init 1 >= 0 <= 200;
var amounta init 1 >= 0,
    amountb init 1 >= 0,
    amountc init 1 >= 0;
var pooltox init 1 >= 0,
    pooltoy init 1 >= 0;
var ctox init 1 >= 0,
    ctoy init 1 >= 0;
var pools init 1 >= 1 <= 3;
```

The linear constraints are declared in the PROC NLP model by using the following statement:

```
lincon amounta + amountb = pooltox + pooltoy,
       pooltox + ctox = amountx,
       pooltoy + ctoy = amounty,
       ctox + ctoy    = amountc;
```

The following linear constraint declarations in the PROC OPTMODEL model are quite similar to the PROC NLP LINCON declarations:

```
con amounta + amountb = pooltox + pooltoy,
    pooltox + ctox = amountx,
    pooltoy + ctoy = amounty,
    ctox + ctoy    = amountc;
```

But PROC OPTMODEL provides much more flexibility in defining linear constraints. For example, a coefficient can be a named parameter or any other expression that evaluates to a constant.

The cost parameters are declared explicitly in the PROC OPTMODEL model. Unlike the DATA step or the NLP procedure, PROC OPTMODEL requires names to be declared before they are used. There are multiple ways to set the values of these parameters. The preceding example uses assignments. You could make the values part of the declaration by using the INIT *expression* clause or the = *expression* clause. You could also read the values from a data set by using the READ DATA statement.

In the original PROC NLP statements, the assignment to a parameter such as costa occurs every time the objective function is evaluated. However, the assignment occurs just once in the PROC OPTMODEL statements, when the assignment statement is processed. This works because the values are constant. But the PROC OPTMODEL statements permit the parameters to be reassigned later so that you can interactively modify the model.

The following statements define the objective f in the PROC NLP model:

```
max f;
. . .
f = costx * amountx + costy * amounty
    - costa * amounta - costb * amountb - costc * amountc;
```

The PROC OPTMODEL version of the objective is defined by using the same expression text, as follows:

```
max f = costx * amountx + costy * amounty
       - costa * amounta - costb * amountb - costc * amountc;
```

But the MAX statement and the assignment to the name f in the PROC NLP statements are combined in PROC OPTMODEL. There are advantages and disadvantages to this approach. The PROC OPTMODEL

formulation is much closer to the mathematical formulation of the model. However, if multiple intermediate variables are used to structure the objective, then multiple IMPVAR declarations are required.

In the PROC NLP model, the nonlinear constraints use the following syntax:

```
nlincon nlc1-nlc2 >= 0.,
        nlc3 = 0.;
. . .
nlc1 = 2.5 * amountx - pools * pooltox - 2. * ctox;
nlc2 = 1.5 * amounty - pools * pooltoy - 2. * ctoy;
nlc3 = 3 * amounta + amountb - pools * (amounta + amountb);
```

In the PROC OPTMODEL model, the equivalent statements are as follows:

```
con nlc1: 2.5 * amountx - pools * pooltox - 2. * ctox >= 0,
    nlc2: 1.5 * amounty - pools * pooltoy - 2. * ctoy >= 0,
    nlc3: 3 * amounta + amountb - pools * (amounta + amountb)
           = 0;
```

The nonlinear constraints in PROC OPTMODEL use the same syntax as linear constraints. In fact, if the variable pools were declared as a parameter, then all the preceding constraints would be linear. The nonlinear constraint in PROC OPTMODEL combines the NLINCON statement of PROC NLP with the assignment in the PROC NLP statements. Objective names can be used in nonlinear constraint expressions to structure the formula as they are in objective expressions,

The PROC OPTMODEL model does not use a RUN statement to invoke the solver. Instead the solver is invoked interactively by the SOLVE statement in PROC OPTMODEL. By default, the OPTMODEL procedure prints much less information about the optimization process. Generally this information consists of messages from the solver (such as the termination reason) and a short status display. The PROC OPTMODEL statements add a PRINT statement in order to display the variable estimates from the solver.

Examples: OPTMODEL Procedure

Example 9.1: Matrix Square Root

This example demonstrates the use of PROC OPTMODEL array parameters and variables. The following statements create a randomized positive definite symmetric matrix and define an optimization model to find the matrix square root of the generated matrix:

```
proc optmodel;
   number n = 5;  /* size of matrix */
   /* random original array */
   number A{1..n, 1..n} = 10 - 20*rand('UNIFORM');
   /* compute upper triangle of the
    * symmetric matrix A*transpose(A) */
   /* should be positive def unless A is singular */
   number P{i in 1..n, j in i..n};
   for {i in 1..n, j in i..n}
       P[i,j] = sum{k in 1..n} A[i,k]*A[j,k];
```

```
/* coefficients of square root array
 * (upper triangle of symmetric matrix) */
var q{i in 1..n, i..n};
/* The default initial value q[i,j]=0 is
 * a local minimum of the objective,
 * so you must move it away from that point. */
q[1,1] = 1;
/* minimize difference of square of q from P */
min r = sum{i in 1..n, j in i..n}
        (   sum{k in 1..i} q[k,i]*q[k,j]
          + sum{k in i+1..j} q[i,k]*q[k,j]
          + sum{k in j+1..n} q[i,k]*q[j,k]
          - P[i,j] )**2;
solve;
print q;
```

These statements define a random array **A** of size $n \times n$. The product **P** is defined as the matrix product AA^T. The product is symmetric, so the declaration of the parameter P gives it upper triangular indexing. The matrix represented by P should be positive definite unless **A** is singular. But singularity is unlikely because of the random generation of **A**. If **P** is positive definite, then it has a well-defined square root, **Q**, such that $P = QQ^T$.

The objective r simply minimizes the sum of squares of the coefficients as

$$r = \sum_{1 \le i \le j \le n} R_{i,j}^2$$

where $R = QQ^T - P$. (This technique for computing matrix square roots is intended only for the demonstration of PROC OPTMODEL capabilities. Better methods exist.)

Output 9.1.1 shows part of the output from running these statements. The values that are actually displayed depend on the random numbers generated.

Output 9.1.1 Matrix Square Root Results

	q				
	1	**2**	**3**	**4**	**5**
1	-0.17114	-6.98664	8.54173	1.82270	-8.45177
2		5.19330	0.72916	-6.57673	6.84512
3			-1.78597	-7.43060	0.87878
4				3.69124	0.14268
5					4.51210

Example 9.2: Reading From and Creating a Data Set

This example demonstrates how to use the READ DATA statement to read parameters from a SAS data set. The objective is the Bard function, which is the following least squares problem with $I = \{1, 2, \ldots, 15\}$:

$$f(x) = \frac{1}{2} \sum_{k \in I} \left[y_k - \left(x_1 + \frac{k}{v_k x_2 + w_k x_3} \right) \right]^2$$

$$x = (x_1, x_2, x_3), \quad y = (y_1, y_2, \ldots, y_{15})$$

where $v_k = 16 - k$, $w_k = \min(k, v_k)$ $(k \in I)$, and

$$y = (0.14, 0.18, 0.22, 0.25, 0.29, 0.32, 0.35, 0.39, 0.37, 0.58, 0.73, 0.96, 1.34, 2.10, 4.39)$$

The minimum function value $f(x^*) = 4.107\text{E–}3$ is at the point $(0.08, 1.13, 2.34)$. The starting point $x^0 = (1, 1, 1)$ is used. This problem is identical to the example "Using the DATA= Option" in Chapter 6, "The NLP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). The following statements use the READ DATA statement to input parameter values and the CREATE DATA statement to save the solution in a SAS data set:

```
data bard;
   input y @@;
   datalines;
.14  .18  .22  .25  .29  .32  .35  .39
.37  .58  .73  .96 1.34 2.10 4.39
;
proc optmodel;
   set I = 1..15;
   number y{I};
   read data bard into [_n_] y;
   number v{k in I} = 16 - k;
   number w{k in I} = min(k, v[k]);
   var x{1..3} init 1;
   min f = 0.5*
      sum{k in I}
         (y[k] - (x[1] + k /
                  (v[k]*x[2] + w[k]*x[3])))**2;
   solve;
   print x;
   create data xdata from [i] xd=x;
```

In these statements the values for parameter y are read from the BARD data set. The set I indexes the terms of the objective in addition to the y array.

The preceding statements define two utility parameters that contain coefficients used in the objective function. These coefficients could have been defined in the expression for the objective, f, but it was convenient to give them names and simplify the objective expression.

The result is shown in Output 9.2.1.

Output 9.2.1 Bard Function Solution

[1]	x
1	0.082411
2	1.133036
3	2.343696

The final CREATE DATA statement saves the solution values determined by the solver into the data set XDATA. The data set contains an observation for each x index. Each observation contains two variables. The output variable i contains the index, while xd contains the value for the indexed entry in the array x. The resulting data can be seen by using the PRINT procedure as follows:

```
proc print data=xdata;
run;
```

The output from PROC PRINT is shown in Output 9.2.2.

Output 9.2.2 Output Data Set Contents

Obs	i	xd
1	1	0.08241
2	2	1.13304
3	3	2.34370

Example 9.3: Model Construction

This example uses PROC OPTMODEL features to simplify the construction of a mathematically formulated model. The model is based on the example "An Assignment Problem" in Chapter 4, "The LP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). A single invocation of PROC OPTMODEL replaces several steps in the PROC LP statements.

The model assigns production of various grades of cloth to a set of machines in order to maximize profit while meeting customer demand. Each machine has different capacities to produce the various grades of cloth. (See the PROC LP example "An Assignment Problem" for more details.) The mathematical formulation, where x_{ijk} represents the amount of cloth of grade j to produce on machine k for customer i, follows:

$$
\begin{array}{lll}
\max & \sum_{ijk} r_{ijk} x_{ijk} & \\
\text{subject to} & \sum_{k} x_{ijk} = d_{ij} & \text{for all } i \text{ and } j \\
 & \sum_{ij} c_{jk} x_{ijk} \leq a_k & \text{for all } k \\
 & x_{ijk} \geq 0 & \text{for all } i, j, \text{ and } k
\end{array}
$$

The OBJECT, DEMAND, and RESOURCE data sets are the same as in the PROC LP example. A new data set, GRADE, is added to help separate the data from the model.

```
title 'An Assignment Problem';

data grade(drop=i);
   do i = 1 to 6;
      grade = 'grade'||put(i,1.);
      output;
   end;
run;

data object;
   input machine customer
         grade1 grade2 grade3 grade4 grade5 grade6;
   datalines;
1 1 102 140 105 105 125 148
1 2 115 133 118 118 143 166
1 3  70 108  83  83  88  86
1 4  79 117  87  87 107 105
1 5  77 115  90  90 105 148
2 1 123 150 125 124 154   .
2 2 130 157 132 131 166   .
2 3 103 130 115 114 129   .
2 4 101 128 108 107 137   .
2 5 118 145 130 129 154   .
3 1  83   .   .  97 122 147
3 2 119   .   . 133 163 180
3 3  67   .   .  91 101 101
3 4  85   .   . 104 129 129
3 5  90   .   . 114 134 179
4 1 108 121  79   . 112 132
4 2 121 132  92   . 130 150
4 3  78  91  59   .  77  72
4 4 100 113  76   . 109 104
4 5  96 109  77   . 105 145
;

data demand;
   input customer
         grade1 grade2 grade3 grade4 grade5 grade6;
   datalines;
1 100 100 150  150  175  250
2 300 125 300  275  310  325
3 400   0 400  500  340    0
4 250   0 750  750    0    0
5   0 600 300    0  210  360
;

data resource;
   input machine
         grade1 grade2 grade3 grade4 grade5 grade6 avail;
   datalines;
1 .250 .275 .300  .350  .310  .295  744
2 .300 .300 .305  .315  .320  .     244
3 .350 .    .     .320  .315  .300  790
```

```
4 .280 .275 .260  .     .250  .295  672
;
```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called SOLUTION:

```
proc optmodel;
   /* declare index sets */
   set CUSTOMERS;
   set <str> GRADES;
   set MACHINES;

   /* declare parameters */
   num return {CUSTOMERS, GRADES, MACHINES} init 0;
   num demand {CUSTOMERS, GRADES};
   num cost {GRADES, MACHINES} init 0;
   num avail {MACHINES};

   /* read the set of grades */
   read data grade into GRADES=[grade];

   /* read the set of customers and their demands */
   read data demand
      into CUSTOMERS=[customer]
      {j in GRADES} <demand[customer,j]=col(j)>;

   /* read the set of machines, costs, and availability */
   read data resource nomiss
      into MACHINES=[machine]
      {j in GRADES} <cost[j,machine]=col(j)>
      avail;

   /* read objective data */
   read data object nomiss
      into [machine customer]
      {j in GRADES} <return[customer,j,machine]=col(j)>;

   /* declare the model */
   var AmountProduced {CUSTOMERS, GRADES, MACHINES} >= 0;
   max TotalReturn = sum {i in CUSTOMERS, j in GRADES, k in MACHINES}
      return[i,j,k] * AmountProduced[i,j,k];
   con req_demand {i in CUSTOMERS, j in GRADES}:
      sum {k in MACHINES} AmountProduced[i,j,k] = demand[i,j];
   con req_avail {k in MACHINES}:
      sum {i in CUSTOMERS, j in GRADES}
         cost[j,k] * AmountProduced[i,j,k] <= avail[k];

   /* call the solver and save the results */
   solve;
   create data solution
      from [customer grade machine] = {i in CUSTOMERS, j in GRADES,
         k in MACHINES: AmountProduced[i,j,k].sol >= 1e-6}
      amount=AmountProduced;
quit;
```

The statements use both numeric (NUM) and character (STR) index sets, which are populated from the corresponding data set variables in the READ DATA statements. The OPTMODEL parameters can be either single-dimensional (AVAIL) or multiple-dimensional (COST, DEMAND, RETURN). The RETURN and COST parameters are given initial values of 0, and the NOMISS option in the READ DATA statement tells PROC OPTMODEL to read only the nonmissing values from the input data sets. The model declaration is nearly identical to the mathematical formulation. The logical condition **`AmountProduced[i,j,k].sol >= 1e-6`** in the CREATE DATA statement ensures that only the nonzero parts of the solution appear in the SOLUTION data set. In the PROC LP example, the creation of this data set required postprocessing of the PROC LP output data set.

The solver produces the following problem summary and solution summary:

Output 9.3.1 LP Solver Result

An Assignment Problem

Problem Summary	
Objective Sense	Maximization
Objective Function	TotalReturn
Objective Type	Linear
Number of Variables	120
Bounded Above	0
Bounded Below	120
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	34
Linear LE (<=)	4
Linear EQ (=)	30
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	220

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	TotalReturn
Solution Status	Optimal
Objective Value	871426.03763
Primal Infeasibility	2.165464E-15
Dual Infeasibility	2.711995E-16
Bound Infeasibility	2.046363E-12
Iterations	46
Presolve Time	0.01
Solution Time	0.02

The SOLUTION data set can be processed by PROC PRINT as follows to create a compact representation of the solution:

```
proc sort data=solution;
   by grade;
run;
proc print data=solution;
   id machine customer;
   by grade;
run;
```

These statements produce the table shown in Output 9.3.2.

Output 9.3.2 An Assignment Problem

An Assignment Problem

grade=grade1

machine	customer	amount
4	1	100
4	2	300
4	3	400
4	4	250

grade=grade2

machine	customer	amount
1	1	100.000
1	5	92.270
4	2	125.000
4	5	507.730

grade=grade3

machine	customer	amount
1	1	150.000
1	2	300.000
1	3	256.721
1	4	750.000
2	3	143.279
2	5	300.000

grade=grade4

machine	customer	amount
1	1	150.000
1	3	210.312
3	2	275.000
3	3	289.688
3	4	750.000

Output 9.3.2 *continued*

grade=grade5

machine	customer	amount
1	1	175
2	3	340
3	2	310
3	5	210

grade=grade6

machine	customer	amount
1	1	250
3	2	325
3	5	360

Example 9.4: Set Manipulation

This example demonstrates PROC OPTMODEL set manipulation operators. These operators are used to compute the set of primes up to a given limit. This example does not solve an optimization problem, but similar set manipulation could be used to set up an optimization model. Here are the statements:

```
proc optmodel;
   number maxprime;  /* largest number to consider */
   set composites =
       union {i in 3..sqrt(maxprime) by 2} i*i..maxprime by 2*i;
   set primes = {2} union (3..maxprime by 2 diff composites);
   maxprime = 500;
   put primes;
```

The set composites contains the odd composite numbers up to the value of the parameter maxprime. The even numbers are excluded here to reduce execution time and memory requirements. The UNION aggregation operation is used in the definition to combine the sets of odd multiples of i for $i = 3, 5, \ldots$. Any composite number less than the value of the parameter maxprime has a divisor $\leq \sqrt{\text{maxprime}}$, so the range of i can be limited. The set of multiples of i can also be started at $i \times i$ since smaller multiples are found in the set of multiples for a smaller index.

You can then define the set primes. The odd primes are determined by using the DIFF operator to remove the composites from the set of odd numbers no greater than the parameter maxprime. The UNION operator adds the single even prime, 2, to the resulting set of primes.

The PUT statement produces the result in Output 9.4.1.

Output 9.4.1 Primes less than or equal to 500

```
{2,3,5,7,11,13,17,19,23,29,31,37,41,43,47,53,59,61,67,71,73,79,83,89,97,101,103,
107,109,113,127,131,137,139,149,151,157,163,167,173,179,181,191,193,197,199,211,
223,227,229,233,239,241,251,257,263,269,271,277,281,283,293,307,311,313,317,331,
337,347,349,353,359,367,373,379,383,389,397,401,409,419,421,431,433,439,443,449,
457,461,463,467,479,487,491,499}
```

Note that you were able to delay the definition of the value of the parameter maxprime until just before the PUT statement. Since the defining expressions of the SET declarations are handled symbolically, the value of maxprime is not necessary until you need the value of the set primes. Because the sets composites and primes are defined symbolically, their values reflect any changes to the parameter maxprime. You can see this update by appending the following statements to the preceding statements:

```
maxprime = 50;
put primes;
```

The additional statements produce the results in Output 9.4.2. The value of the set primes has been recomputed to reflect the change to the parameter maxprime.

Output 9.4.2 Primes less than or equal to 50

```
{2,3,5,7,11,13,17,19,23,29,31,37,41,43,47}
```

Example 9.5: Multiple Subproblems

Many important optimization problems cannot be solved directly using a standard solver, either because the problem has constraints that cannot be modeled directly or because the resulting model would be too large to be practical. For these types of problems, you can use PROC OPTMODEL to synthesize solution methods by using a combination of the existing solvers and the modeling language programming constructions. This example demonstrates the use of multiple subproblems to solve the cutting stock problem.

The cutting stock problem determines how to efficiently cut raw stock into finished widths based on the demands for the final product. Consider the example from page 195 of Chvátal (1983), where raw stock has a width of 100 inches and the demands are shown in Table 9.18.

Table 9.18 Cutting Stock Demand

Finished Width	Demand
45 inches	97
35 inches	610
31 inches	395
14 inches	211

A portion of the demand can be satisfied using a cutting pattern. For example, with the demands in Table 9.18 a possible pattern cuts one final of width 35 inches, one final of width 31 inches, and two finals of width 14 inches. This gives:

$$100 = 0 * 45 + 1 * 35 + 1 * 31 + 2 * 14 + \text{waste}.$$

The cutting stock problem can be formulated as follows, where x_j represents the number of times pattern j appears, a_{ij} represents the number of times demand item i appears in pattern j, d_i is the demand for item i, w_i is the width of item i, N represents the set of patterns, M represents the set of items, and W is the width of the raw stock:

$$\begin{array}{lll} \text{minimize} & \sum_{j \in N} x_j & \\ \text{subject to} & \sum_{j \in N} a_{ij} x_j \geq d_i & \text{for all } i \in M \\ & x_j \text{ integer}, \geq 0 & \text{for all } j \in N \end{array}$$

Also for each feasible pattern j you must have:

$$\sum_{i \in M} w_i a_{ij} \leq W$$

The difficulty with this formulation is that the number of patterns can be very large, with too many columns x_j to solve efficiently. But you can use column generation, as described on page 198 of Chvátal (1983), to generate a smaller set of useful patterns, starting from an initial feasible set.

The dual variables, π_i, of the demand constraints are used to price out the columns. From linear programming (LP) duality theory, a column that improves the primal solution must have a negative reduced cost. For this problem the reduced cost for column x_j is

$$1 - \sum_{i \in M} \pi_i a_{ij}$$

Using this observation produces a knapsack subproblem:

$$\begin{array}{lll} \text{minimize} & 1 - \sum_{i \in M} \pi_i a_i & \\ \text{subject to} & \sum_{i \in M} w_i a_i \leq W & \\ & a_i \text{ integer}, \geq 0 & \text{for all } j \in N \end{array}$$

where the objective is equivalent to:

$$\text{maximize} \quad \sum_{i \in M} \pi_i a_i$$

The pattern is useful if the associated reduced cost is negative:

$$1 - \sum_{i \in M} \pi_i a_i^* < 0$$

So you can use the following steps to generate the patterns and solve the cutting stock problem:

1. Initialize a set of trivial (one item) patterns.
2. Solve the problem using the LP solver.
3. Minimize the reduced cost using a knapsack solver.
4. Include the new pattern if the reduced cost is negative.
5. Repeat steps 2 through 4 until there are no more negative reduced cost patterns.

These steps are implemented in the following statements. Since adding columns preserves primal feasibility, the statements use the primal simplex solver to take advantage of a warm start. The statements also solve the LP relaxation of the problem, but you want the integer solution. So the statements finish by using the MILP solver with the integer restriction applied. The result is not guaranteed to be optimal, but lower and upper bounds can be provided for the optimal objective.

```
/* cutting-stock problem */
/* uses delayed column generation from
   Chvatal's Linear Programming (1983), page 198 */

%macro csp(capacity);
proc optmodel printlevel=0;
   /* declare parameters and sets */
   num capacity = &capacity;
   set ITEMS;
   num demand {ITEMS};
   num width  {ITEMS};
   num num_patterns init card(ITEMS);
   set PATTERNS = 1..num_patterns;
   num a {ITEMS, PATTERNS};
   num c {ITEMS} init 0;
   num epsilon = 1E-6;

   /* read input data */
   read data indata into ITEMS=[_N_] demand width;

   /* generate trivial initial columns */
   for {i in ITEMS, j in PATTERNS}
      a[i,j] = (if (i = j) then floor(capacity/width[i]) else 0);

   /* define master problem */
   var x {PATTERNS} >= 0 integer;
   minimize NumberOfRaws = sum {j in PATTERNS} x[j];
   con demand_con {i in ITEMS}:
      sum {j in PATTERNS} a[i,j] * x[j] >= demand[i];
   problem Master include x NumberOfRaws demand_con;

   /* define column generation subproblem */
   var y {ITEMS} >= 0 integer;
   maximize KnapsackObjective = sum {i in ITEMS} c[i] * y[i];
   con knapsack_con:
      sum {i in ITEMS} width[i] * y[i] <= capacity;
   problem Knapsack include y KnapsackObjective knapsack_con;

   /* main loop */
   do while (1);
      print _page_ a;

      /* master problem */
      /* minimize sum_j x[j]
         subj. to sum_j a[i,j] * x[j] >= demand[i]
                  x[j] >= 0 and integer */
      use problem Master;
      put "solve master problem";
      solve with lp relaxint /
         presolver=none algorithm=ps basis=warmstart logfreq=1;
      print x;
      print demand_con.dual;
      for {i in ITEMS} c[i] = demand_con[i].dual;
```

```
      /* knapsack problem */
      /* maximize sum_i c[i] * y[i]
         subj. to sum_i width[i] * y[i] <= capacity
                  y[i] >= 0 and integer */
      use problem Knapsack;
      put "solve column generation subproblem";
      solve with milp / logfreq=0;
      for {i in ITEMS} y[i] = round(y[i]);
      print y;
      print KnapsackObjective;

      if KnapsackObjective <= 1 + epsilon then leave;

      /* include new pattern */
      num_patterns = num_patterns + 1;
      for {i in ITEMS} a[i,num_patterns] = y[i];
   end;

   /* solve IP, using rounded-up LP solution as warm start */
   use problem Master;
   for {j in PATTERNS} x[j] = ceil(x[j].sol);
   put "solve (restricted) master problem as IP";
   solve with milp / primalin;

   /* cleanup solution and save to output data set */
   for {j in PATTERNS} x[j] = round(x[j].sol);
   create data solution from [pattern]={j in PATTERNS: x[j] > 0}
      raws=x {i in ITEMS} <col('i'||i)=a[i,j]>;
quit;
%mend csp;

/* Chvatal, p.199 */
data indata;
   input demand width;
   datalines;
78 25.5
40 22.5
30 20
30 15
;
%csp(91)
/* LP solution is integer */

/* Chvatal, p.195 */
data indata;
   input demand width;
   datalines;
 97 45
610 36
395 31
211 14
;
%csp(100)
```

```
/* LP solution is fractional */
```

The contents of the output data set for the second problem instance are shown in Output 9.5.1.

Output 9.5.1 Cutting Stock Solution

Obs	pattern	raws	i1	i2	i3	i4
1	1	49	2	0	0	0
2	5	206	0	2	0	2
3	6	198	0	1	2	0

Example 9.6: Traveling Salesman Problem

This example demonstrates the use of the SUBMIT statement to execute a block of SAS statements from within a PROC OPTMODEL session. In this case, the SUBMIT block calls the SGPLOT procedure to display intermediate results during the solution of an instance of the traveling salesman problem (TSP). The problem is described in Example 14.4. For an example of how to use PROC OPTNETWORK to solve the TSP, see "Traveling Salesman Problem Applied to a Directed Graph" (Chapter 2, *SAS Optimization: The OPTNETWORK Procedure*).

The following DATA step converts a TSPLIB instance of type EUC_2D into a SAS data set that contains the coordinates of the vertices:

```
/* convert the TSPLIB instance into a data set */
data tspData(drop=H);
   infile "&tsplib";
   input H $1. @;
   if H not in ('N','T','C','D','E');
   input @1 var1-var3;
run;
```

The following macro generates plots of the solution and objective value:

```
%macro plotTSP;
   /* create Annotate data set to draw subtours */
   data anno;
      retain drawspace 'datavalue' linethickness 1 function 'line';
      set solData;
   run;

   title1 h=2 "TSP: Iter = &i, Objective = &&obj&i";
   title2;

   proc sgplot data=tspData sganno=anno;
      scatter x=var2 y=var3 / datalabel=var1;
      xaxis display=none;
      yaxis display=none;
   run;
%mend plotTSP;
```

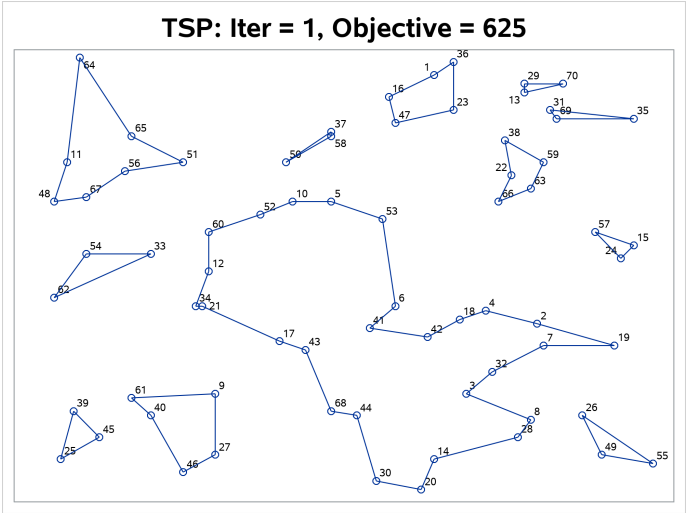
The following PROC OPTMODEL statements solve the TSP by using the subtour formulation and iteratively adding subtour constraints. The SUBMIT statement calls the **%plotTSP** macro to plot the solution and objective value at each stage.

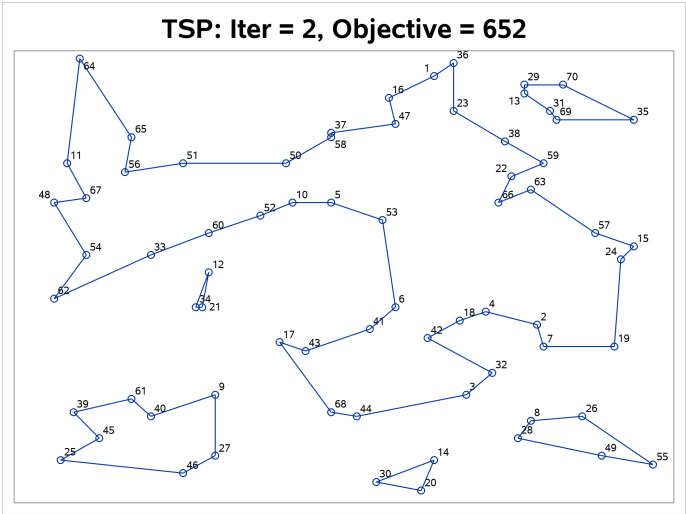
```
/* iterative solution using the subtour formulation */
proc optmodel;
   set VERTICES;
   set EDGES = {i in VERTICES, j in VERTICES: i > j};
   num xc {VERTICES};
   num yc {VERTICES};

   num numsubtour init 0;
   set SUBTOUR {1..numsubtour};

   /* read in the instance and customer coordinates (xc, yc) */
   read data tspData into VERTICES=[var1] xc=var2 yc=var3;

   /* the cost is the euclidean distance rounded to the nearest integer */
   num c {<i,j> in EDGES}
      init floor( sqrt( ((xc[i]-xc[j])**2 + (yc[i]-yc[j])**2)) + 0.5);

   var x {EDGES} binary;

   /* minimize the total cost */
   min obj =
       sum {<i,j> in EDGES} c[i,j] * x[i,j];

   /* each vertex has exactly one in-edge and one out-edge */
   con two_match {i in VERTICES}:
      sum {j in VERTICES: i > j} x[i,j]
      + sum {j in VERTICES: i < j} x[j,i] = 2;

   /* no subtours (these constraints are generated dynamically) */
   con subtour_elim {s in 1..numsubtour}:
      sum {<i,j> in EDGES: (i in SUBTOUR[s] and j not in SUBTOUR[s])
         or (i not in SUBTOUR[s] and j in SUBTOUR[s])} x[i,j] >= 2;

   /* this starts the algorithm to find violated subtours */
   set <num,num> EDGES1;
   set VERTICES1 = union{<i,j> in EDGES1} {i, j};
   num component {VERTICES1};
   num numcomp  init 2;
   num iter     init 1;
   call symput('i',trim(left(put(round(iter),best.))));
   num numiters init 1;

   /* initial solve with just matching constraints */
   solve;
   call symput(compress('obj'||put(iter,best.)),
               trim(left(put(round(obj),best.))));

   /* create a data set for use by PROC SGPLOT */
   create data solData from
      [i j]={<i,j> in EDGES: x[i,j].sol > 0.5}
```

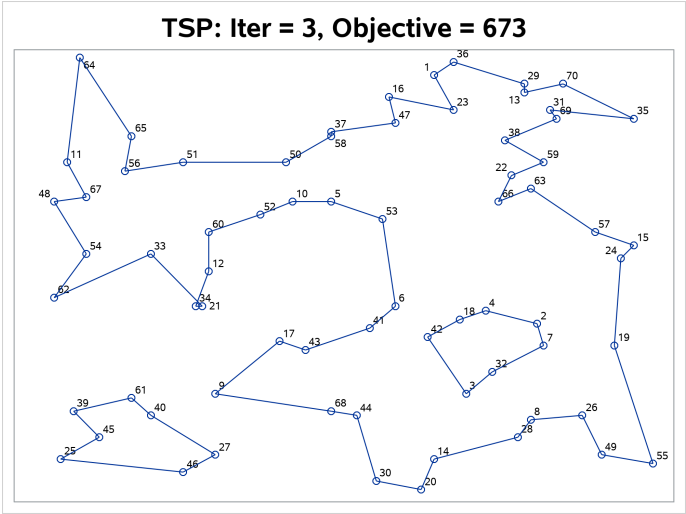
```
      x1=xc[i] y1=yc[i] x2=xc[j] y2=yc[j];
   submit;
      %plotTSP;
   endsubmit;
   /* while the solution is disconnected, continue */
   do while (numcomp > 1);
      iter = iter + 1;
      call symput('i',trim(left(put(round(iter),best.))));

      /* find connected components of support graph   */
      EDGES1 = {<i,j> in EDGES: round(x[i,j].sol) = 1};
      solve with network /
         links   = (include=EDGES1)
         nodes   = (include=VERTICES1)
         concomp
         out     = (concomp=component);

      numcomp = _oroptmodel_num_["NUM_COMPONENTS"];
      if numcomp = 1 then leave;

      numiters = iter;
      numsubtour = numsubtour + numcomp;
      for {comp in 1..numcomp} do;
         SUBTOUR[numsubtour-numcomp+comp]
           = {i in VERTICES: component[i] = comp};
      end;

      solve;
      call symput(compress('obj'||put(iter,best.)),
                 trim(left(put(round(obj),best.))));

      /* create a data set for use by PROC SGPLOT */
      create data solData from
         [i j]={<i,j> in EDGES: x[i,j].sol > 0.5}
         x1=xc[i] y1=yc[i] x2=xc[j] y2=yc[j];

      call symput('numiters',put(numiters,best.));
      submit;
         %plotTSP;
      endsubmit;
   end;
quit;
```

The plot in Output 9.6.1 shows the solution and objective value at each stage. Each stage restricts some subset of subtours. When you reach the final stage, you have a valid tour.

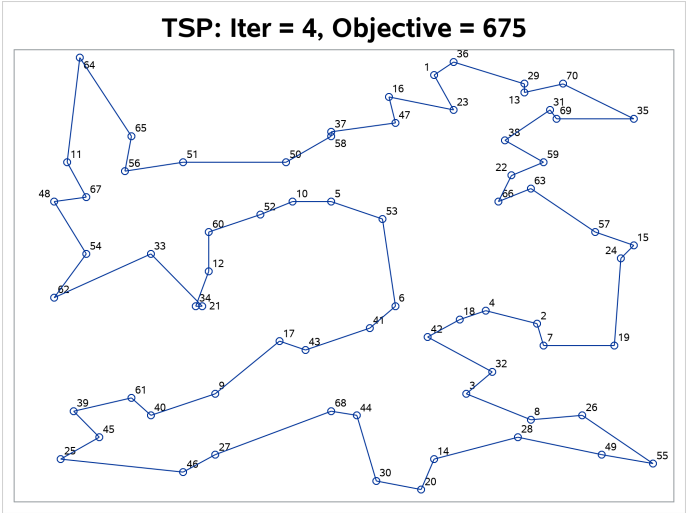
Output 9.6.1 Iterative Solution of Traveling Salesman Problem







Output 9.6.1 *continued*



Example 9.7: Sparse Modeling

This example demonstrates how to rewrite certain models for more efficient processing. Sometimes optimization models that run out of memory during problem generation can be rewritten to take advantage of sparsity to use memory more efficiently. This often occurs when a large array is modeled in a dense format but most of its entries are zeros. Usually, the array provides problem coefficients or it contains optimization variables.

The model for this example solves the facility location problem that is described in Example 14.3. This example is concerned with the resources that are required for PROC OPTMODEL problem generation and solver initialization. So the size of the problem has been increased, but the model has also been modified to make it easier to solve. In order to handle the larger problem size, the model eliminates a large number of the potential assignments of customers to facilities based on distance, making the problem sparse.

The following code generates a random instance of the facility location problem:

```
%let NumCustomers  = 1500;
%let NumSites      = 250;
%let SiteCapacity  = 50;
%let MaxDemand     = 10;
%let xmax          = 200;
%let ymax          = 100;
%let seed          = 938;

/* generate random customer locations */
data cdata(drop=i);
   length name $8;
   call streaminit(&seed);
   do i = 1 to &NumCustomers;
      name = compress('C'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      demand = 1;
```

```
      output;
   end;
run;

/* generate random site locations and fixed charge */
data sdata(drop=i);
   length name $8;
   call streaminit(&seed);
   do i = 1 to &NumSites;
      name = compress('SITE'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      fixed_charge = 300 * (abs(&xmax/2-x)/&xmax + abs(&ymax/2-y)/&ymax);
      output;
   end;
run;
```

The following code uses a dense version of the facility location model. This model is equivalent to the model from Example 14.3 except for the added constraint distance_at_most_30. This constraint eliminates from consideration the assignment of customers to facilities over long distances by forcing the corresponding Assign variables to 0.

```
proc optmodel printlevel=2;
   profile on percent=0.1;
   set <str> CUSTOMERS;
   set <str> SITES init {};

   /* x and y coordinates of CUSTOMERS and SITES */
   num x {CUSTOMERS union SITES};
   num y {CUSTOMERS union SITES};
   num demand {CUSTOMERS};
   num fixed_charge {SITES};

   /* distance from customer i to site j */
   num dist {i in CUSTOMERS, j in SITES}
       = sqrt((x[i] - x[j])^2 + (y[i] - y[j])^2);

   read data cdata into CUSTOMERS=[name] x y demand;
   read data sdata into SITES=[name] x y fixed_charge;

   var Assign {CUSTOMERS, SITES} binary;
   var Build {SITES} binary;

   min CostNoFixedCharge
       = sum {i in CUSTOMERS, j in SITES} dist[i,j] * Assign[i,j];
   min CostFixedCharge
       = CostNoFixedCharge + sum {j in SITES} fixed_charge[j] * Build[j];

   /* each customer assigned to exactly one site */
   con assign_def {i in CUSTOMERS}:
      sum {j in SITES} Assign[i,j] = 1;

   /* if customer i assigned to site j, then facility must be built at j */
   con link {i in CUSTOMERS, j in SITES}:
```

```
      Assign[i,j] <= Build[j];

   /* each site can handle at most &SiteCapacity demand */
   con capacity {j in SITES}:
      sum {i in CUSTOMERS} demand[i] * Assign[i,j] <=
         &SiteCapacity * Build[j];

   /* do not assign customer to site more than 30 units away */
   con distance_at_most_30 {i in CUSTOMERS, j in SITES: dist[i,j] > 30}:
      Assign[i,j] = 0;

   /* solve the MILP */
   solve with milp/timetype=real;

quit;
```

If you inspect the log after running the preceding code, then you will see that the MILP presolver has pruned down the problem size considerably. If you also run the code with the SAS option FULLSTIMER enabled on a 64-bit system, then you will notice that about 1.1GB of memory is required for the PROC OPTMODEL step when you are running on a single CPU.

The solution and timing results for the dense model are shown in Output 9.7.1. The PROFILE ON statement requests further timing details, including evaluation time for declarations used by problem generation.

Output 9.7.1 Dense Model Results

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	CostFixedCharge
Solution Status	Optimal within Relative Gap
Objective Value	18001.140353
Relative Gap	0.0000868876
Absolute Gap	1.5639396138
Primal Infeasibility	8.881784E-15
Bound Infeasibility	8.881784E-15
Integer Infeasibility	1.487699E-14
Best Bound	17999.576414
Nodes	1
Solutions Found	5
Iterations	24177
Presolve Time	4.33
Solution Time	37.63

Output 9.7.1 *continued*

Procedure Task Timing		
Task	Time (sec.)	% Time
Problem Generation	4.46	10.10%
Solver Initialization	1.21	2.75%
Code Generation	0.07	0.15%
Presolve	4.33	9.80%
Root Node Processing	33.27	75.28%
Branch And Cut	0.00	0.00%
Synchronization	0.02	0.04%
Idle	0.00	0.00%
Other Tasks	0.01	0.03%
Solver Postprocessing	0.82	1.86%

Profile Information						
Item	Line	Col.	Execution Count	Net Time (sec.)	Wait Time (sec.)	% Total Time
SOLVE	3827	4	1	40.62	1.08	85.6%
Constraint distance_at_most_30	3823	8		2.79	0.00	5.9%
Constraint link	3814	8		1.86	0.00	3.9%
Min CostNoFixedCharge	3804	8		0.58	0.00	1.2%
Number dist	3795	8		0.57	0.00	1.2%
Var Assign	3801	8		0.38	0.00	0.8%
Constraint capacity	3818	8		0.34	0.00	0.7%
Constraint assign_def	3810	8		0.31	0.00	0.7%
Other profiled items				0.01	0.00	0.0%

Note: Total profiled time is 47.46 seconds.

The best approach for reducing the memory requirements is to eliminate the Assign variables that are always going to be 0. This is accomplished in the following sparse version of the code. Instead of indexing Assign over the crossproduct of CUSTOMERS and SITES, now the code defines a new set of pairs that satisfy the distance requirement, CUSTOMERS_SITES. This set replaces the constraint distance_at_most_30 in the dense model. The objective and constraints have been modified to use the new indexing scheme, with implicit set slicing (as described in the section "More on Index Sets" on page 464) for constraints assign_def and capacity.

```
proc optmodel printlevel=2;
   profile on percent=0.1;
   set <str> CUSTOMERS;
   set <str> SITES init {};

   /* x and y coordinates of CUSTOMERS and SITES */
   num x {CUSTOMERS union SITES};
   num y {CUSTOMERS union SITES};
   num demand {CUSTOMERS};
   num fixed_charge {SITES};

   /* distance from customer i to site j */
   num dist {i in CUSTOMERS, j in SITES}
```

```
        = sqrt((x[i] - x[j])^2 + (y[i] - y[j])^2);

    read data cdata into CUSTOMERS=[name] x y demand;
    read data sdata into SITES=[name] x y fixed_charge;

    set CUSTOMERS_SITES = {i in CUSTOMERS, j in SITES: dist[i,j] <= 30};
    var Assign {CUSTOMERS_SITES} binary;
    var Build {SITES} binary;

    min CostNoFixedCharge
        = sum {<i,j> in CUSTOMERS_SITES} dist[i,j] * Assign[i,j];
    min CostFixedCharge
        = CostNoFixedCharge + sum {j in SITES} fixed_charge[j] * Build[j];

    /* each customer assigned to exactly one site */
    con assign_def {i in CUSTOMERS}:
       sum {<(i),j> in CUSTOMERS_SITES} Assign[i,j] = 1;

    /* if customer i assigned to site j, then facility must be built at j */
    con link {<i,j> in CUSTOMERS_SITES}:
       Assign[i,j] <= Build[j];

    /* each site can handle at most &SiteCapacity demand */
    con capacity {j in SITES}:
       sum {<i,(j)> in CUSTOMERS_SITES} demand[i] * Assign[i,j] <=
          &SiteCapacity * Build[j];

    /* solve the MILP */
    solve with milp/timetype=real;

quit;
```

The log from running the preceding code shows that the MILP presolver does not find anything to improve with this version of the model. On a 64-bit system, the FULLSTIMER option shows that memory requirements have been reduced to about 320MB when you are running on a single CPU, less than half the requirements of the previous model.

The solution and timing results for the sparse model are shown in Output 9.7.2. Note that the dense model (Output 9.7.1) and the sparse model (Output 9.7.2) are equivalent after presolver processing and generate the same result using similar amounts of solver time. On the other hand, problem generation time is significantly reduced as are other times including presolve time. Both models used the solver option TIMETYPE=REAL so that all times are reported in seconds of real time. You can see from the “Profile Information” table that the overhead associated with problem declarations has been significantly reduced.

Output 9.7.2 Sparse Model Results

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	CostFixedCharge
Solution Status	Optimal within Relative Gap
Objective Value	18001.140353
Relative Gap	0.0000868876
Absolute Gap	1.5639396138
Primal Infeasibility	8.881784E-15
Bound Infeasibility	8.881784E-15
Integer Infeasibility	1.487699E-14
Best Bound	17999.576414
Nodes	1
Solutions Found	7
Iterations	24177
Presolve Time	2.38
Solution Time	36.47

Procedure Task Timing		
Task	**Time (sec.)**	**% Time**
Problem Generation	1.35	3.57%
Solver Initialization	0.11	0.28%
Code Generation	0.00	0.01%
Presolve	2.38	6.26%
Root Node Processing	33.96	89.47%
Branch And Cut	0.00	0.00%
Synchronization	0.02	0.05%
Idle	0.00	0.00%
Other Tasks	0.11	0.28%
Solver Postprocessing	0.03	0.08%

Profile Information						
Item	**Line**	**Col.**	**Execution Count**	**Net Time (sec.)**	**Wait Time (sec.)**	**% Total Time**
SOLVE	3876	4	1	36.65	0.08	95.9%
Set CUSTOMERS_SITES	3853	8		0.57	0.00	1.5%
Number dist	3847	8		0.55	0.00	1.4%
Constraint link	3867	8		0.20	0.00	0.5%
Constraint capacity	3871	8		0.08	0.00	0.2%
Constraint assign_def	3863	8		0.08	0.00	0.2%
Min CostNoFixedCharge	3857	8		0.05	0.00	0.1%
Var Assign	3854	8		0.04	0.00	0.1%
Other profiled items				0.01	0.00	0.0%

Note: Total profiled time is 38.23 seconds.

Example 9.8: Chemical Equilibrium

This example illustrates how to convert PROC NLP code that handles arrays into PROC OPTMODEL form. The following PROC NLP model finds an equilibrium state for a mixture of chemicals. The same model is used in "Example 7.8: Chemical Equilibrium" in Chapter 6, "The NLP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*).

```
proc nlp tech=tr pall;
   array c[10] -6.089 -17.164 -34.054  -5.914 -24.721
              -14.986 -24.100 -10.708 -26.662 -22.179;
   array x[10] x1-x10;
   min y;
   parms x1-x10 = .1;
   bounds 1.e-6 <= x1-x10;
   lincon 2. = x1 + 2. * x2 + 2. * x3 + x6 + x10,
          1. = x4 + 2. * x5 + x6 + x7,
          1. = x3 + x7  + x8 + 2. * x9 + x10;
   s = x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10;
   y = 0.;
   do j = 1 to 10;
      y = y + x[j] * (c[j] + log(x[j] / s));
   end;
run;
```

The following statements show a corresponding PROC OPTMODEL model:

```
proc optmodel;
   set CMP = 1..10;
   number c{CMP} = [-6.089 -17.164 -34.054  -5.914 -24.721
                    -14.986 -24.100 -10.708 -26.662 -22.179];
   var x{CMP} init 0.1 >= 1.e-6;
   con 2. = x[1] + 2. * x[2] + 2. * x[3] + x[6] + x[10],
       1. = x[4] + 2. * x[5] + x[6] + x[7],
       1. = x[3] + x[7]  + x[8] + 2. * x[9] + x[10];

   /* replace the variable s in the PROC NLP model */
   impvar s = sum{i in CMP} x[i];

   min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));
   solve;
   print x y;
```

The PROC OPTMODEL model uses the set CMP to represent the set of compounds, which are numbered 1 to 10 in the example. The array c was initialized by using the equivalent PROC OPTMODEL syntax. The individual array locations could also have been initialized by assignment or by READ DATA statements.

The VAR declaration for variable x combines the VAR and BOUNDS statements of the PROC NLP model. The index set of the array is based on the set of compounds CMP to simplify changes to the model.

The linear constraints are similar in form to the PROC NLP model. However, the PROC OPTMODEL version uses the array form of the variable names because it treats arrays as distinct variables, not as aliases of lists of scalar variables.

The implicit variable s replaces the intermediate variable of the same name in the PROC NLP model. This

is an example of translating an intermediate variable from the other models to PROC OPTMODEL. An alternative way is to use an additional constraint for every intermediate variable. Instead of declaring objective s as in the preceding statements, you can use the following statements:

```
. . .
var s;
con s = sum{i in CMP} x[i];
. . .
```

Note that this alternative formulation passes an extra variable and constraint to the solver. This formulation can sometimes be solved more efficiently, depending on the characteristics of the model.

The PROC OPTMODEL version uses a SUM operator over the set CMP, which enhances the flexibility of the model to accommodate possible changes in the set of compounds.

In the PROC NLP model, the objective function y is determined by an explicit loop. The DO loop in PROC NLP is replaced by a SUM aggregation operation in PROC OPTMODEL. The accumulation in the PROC NLP model is now performed by PROC OPTMODEL by using the SUM operator.

This PROC OPTMODEL model can be generalized further. Note that the array initialization and constraints assume a fixed set of compounds. You can rewrite the model to handle an arbitrary number of compounds and chemical elements. The new model loads the linear constraint coefficients from a data set along with the objective coefficients for the parameter c, as follows:

```
data comp;
   input c a_1 a_2 a_3;
   datalines;
-6.089   1 0 0
-17.164  2 0 0
-34.054  2 0 1
-5.914   0 1 0
-24.721  0 2 0
-14.986  1 1 0
-24.100  0 1 1
-10.708  0 0 1
-26.662  0 0 2
-22.179  1 0 1
;

data atom;
   input b @@;
   datalines;
2. 1. 1.
;

proc optmodel;
   set CMP;
   set ELT;
   number c{CMP};
   number a{ELT,CMP};
   number b{ELT};
   read data atom into ELT=[_n_] b;
   read data comp into CMP=[_n_]
        c {i in ELT} < a[i,_n_]=col("a_"||i) >;
```

```
var x{CMP} init 0.1 >= 1.e-6;
con bal{i in ELT}: b[i] = sum{j in CMP} a[i,j]*x[j];
impvar s = sum{i in CMP} x[i];
min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));
print a b;
solve;
print x;
```

This version adds coefficients for the linear constraints to the comp data set. The data set variable a_*n* represents the number of atoms in the compound for element *n*. The READ DATA statement for comp uses the iterated column syntax to read each of the data set variables a_*n* into the appropriate location in the array a. In this example the expanded data set variable names are a_1, a_2, and a_3.

The preceding version also adds a new set, ELT, of chemical elements and a numeric parameter, b, that represents the left-hand side of the linear constraints. The data values for the parameters ELT and b are read from the data set atom. The model can handle varying sets of chemical elements because of this extra data set and the new parameters.

The linear constraints have been converted to a single, indexed family of constraints. One constraint is applied for each chemical element in the set ELT. The constraint expression uses a simple form that applies generally to linear constraints. The following PRINT statement in the model shows the values that are read from the data sets to define the linear constraints:

```
print a b;
```

The PRINT statements in the model produce the results shown in Output 9.8.1.

Output 9.8.1 PROC OPTMODEL Output

	a									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	2	2	0	0	1	0	0	0	1
2	0	0	0	1	2	1	1	0	0	0
3	0	0	1	0	0	0	1	1	2	1

[1]	b
1	2
2	1
3	1

[1]	x
1	0.04066819
2	0.14773050
3	0.78315310
4	0.00141431
5	0.48524653
6	0.00069326
7	0.02739938
8	0.01794736
9	0.03731440
10	0.09687136

In the preceding model, the chemical elements and compounds are designated by numbers. So in the PRINT output, for example, the row that is labeled "3" represents the amount of the compound H_2O. PROC OPTMODEL is capable of using more symbolic strings to designate array indices. The following version of the model uses strings to index arrays:

```
data comp;
   input name $ c a_h a_n a_o;
   datalines;
H     -6.089   1 0 0
H2    -17.164  2 0 0
H2O   -34.054  2 0 1
N     -5.914   0 1 0
N2    -24.721  0 2 0
NH    -14.986  1 1 0
NO    -24.100  0 1 1
O     -10.708  0 0 1
O2    -26.662  0 0 2
OH    -22.179  1 0 1
;
data atom;
   input name $ b;
   datalines;
H  2.
N  1.
O  1.
;
proc optmodel;
   set<string> CMP;
   set<string> ELT;
   number c{CMP};
   number a{ELT,CMP};
   number b{ELT};
   read data atom into ELT=[name] b;
   read data comp into CMP=[name]
        c {i in ELT} < a[i,name]=col("a_"||i) >;
   var x{CMP} init 0.1 >= 1.e-6;
   con bal{i in ELT}: b[i] = sum{j in CMP} a[i,j]*x[j];
   impvar s = sum{i in CMP} x[i];
   min y = sum{j in CMP} x[j] * (c[j] + log(x[j] / s));
   solve;
   print x;
```

In this model, the sets CMP and ELT are now sets of strings. The data sets provide the names of the compounds and elements. The names of the data set variables for atom counts in the data set comp now include the chemical element symbol as part of their spelling. For example, the atom count for the element hydrogen (H) is named a_h. Note that these changes do not require any modification to the specifications of the linear constraints or of the objective.

The PRINT statement in the preceding statements produces the results shown in Output 9.8.2. The indices of variable x are now strings that represent the actual compounds.

Output 9.8.2 PROC OPTMODEL Output with Strings

[1]	x
H	0.04066819
H2	0.14773050
H2O	0.78315310
N	0.00141431
N2	0.48524653
NH	0.00069326
NO	0.02739938
O	0.01794736
O2	0.03731440
OH	0.09687136

Example 9.9: Geometric Median

This example demonstrates the use of conic transformation to automatically convert a nonlinear problem formulation to conic form for use with the conic solver. See also "Example 11.2: Geometric Median" on page 564, which uses manual transformations with the same model.

Given a set of m fixed sample points $p_1, p_2, \ldots, p_m$, with each $p_i \in \mathbb{R}^n$, the geometric median is the point that minimizes the sum of distances to the sample points. Equivalently, the geometric median is the solution of the optimization problem

$$\text{minimize} \sum_{i=1}^{m} \|x - p_i\|_2$$

The objective is the sum of Euclidean norms and can be automatically transformed. The following code solves the model:

```
proc optmodel;
   /* let (x, y) be the geometric median */
   var x, y;

   /* sample points */
   num samples{1..3, 1..2} = [0 0, 1 4, 3 2];

   /* minimize the sum of distances */
   minimize f = sum{i in 1..3}sqrt((x-samples[i,1])^2+(y-samples[i,2])^2);
   expand / conic;

   solve with conic;

   /* print the optimal solution */
   print x y;
quit;
```

The EXPAND output and optimal solution are displayed in Output 9.9.1. The first three added variables and constraints correspond to the d variables and distance constraints, respectively, in the manually transformed

version. The EXPAND statement with the CONIC option also displays the added variables and constraints that are passed to the solver in place of linear expressions that are used as predicate operands.

Output 9.9.1 Geometric Median

```
Var x
Var y
Var _ADDED_VAR_[1] >= 0
Var _ADDED_VAR_[2] >= 0
Var _ADDED_VAR_[3] >= 0
Var _ADDED_VAR_[4]
Var _ADDED_VAR_[5]
Var _ADDED_VAR_[6]
Var _ADDED_VAR_[7]
Minimize f=_ADDED_VAR_[1] + _ADDED_VAR_[2] + _ADDED_VAR_[3]
Constraint _ADDED_CON_[1]: SOC(_ADDED_VAR_[1], x y)
Constraint _ADDED_CON_[2]: SOC(_ADDED_VAR_[2], _ADDED_VAR_[4] _ADDED_VAR_[5])
Constraint _ADDED_CON_[3]: SOC(_ADDED_VAR_[3], _ADDED_VAR_[6] _ADDED_VAR_[7])
Constraint _ADDED_CON_[4]: - _ADDED_VAR_[4] + x = 1
Constraint _ADDED_CON_[5]: - _ADDED_VAR_[5] + y = 4
Constraint _ADDED_CON_[6]: - _ADDED_VAR_[6] + x = 3
Constraint _ADDED_CON_[7]: - _ADDED_VAR_[7] + y = 2
```

x	y
1.7238	2.1853

References

Abramowitz, M., and Stegun, I. A., eds. (1972). *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables.* 10th printing. New York: Dover.

Bazaraa, M. S., Sherali, H. D., and Shetty, C. M. (1993). *Nonlinear Programming: Theory and Algorithms*. New York: John Wiley & Sons.

Chvátal, V. (1983). *Linear Programming*. New York: W. H. Freeman.

Dennis, J. E., and Schnabel, R. B. (1983). *Numerical Methods for Unconstrained Optimization and Nonlinear Equations*. Englewood Cliffs, NJ: Prentice-Hall.

Erickson, J., and Fourer, R. (2019). *Detection and Transformation of Second-Order Cone Programming Problems in a General-Purpose Algebraic Modeling Language*. Technical report, Department of Industrial Engineering and Management Sciences, Northwestern University. https://optimization-online.org/?p=15791.

Fletcher, R. (1987). *Practical Methods of Optimization*. 2nd ed. Chichester, UK: John Wiley & Sons.

Nocedal, J., and Wright, S. J. (1999). *Numerical Optimization*. New York: Springer-Verlag.

Chapter 10
The Black-Box Optimization Solver

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Overview: Black-Box Solver

The black-box optimization solver, which you can access through PROC OPTMODEL, provides a framework for specifying optimization problems and solving them by using derivative-free methods. It does this by optimizing general nonlinear functions over both continuous and integer variables. You do not need to express these functions in analytic closed form, and they can be non-smooth, discontinuous, and computationally expensive to evaluate. Problem types can be single-objective or multiobjective. The black-box solver runs in either single-machine mode or distributed mode.

The general problem formulation is given by

$$
\begin{array}{lrcccl}
\min\limits_{x} & & & f(x) & & \\
 & x_\ell & \leq & x & \leq & x_u \\
\text{subject to} & b_\ell & \leq & Ax & \leq & b_u \\
 & c_\ell & \leq & c(x) & \leq & c_u \\
 & x_i & \in & \mathbb{Z},\ i \in \mathcal{I} & &
\end{array}
$$

where $x \in \mathbb{R}^n$ is the vector of the decision variables; $f(x) : \mathbb{R}^n \to \mathbb{R}$ is the objective function; A is an $m \times n$ linear coefficient matrix; $c(x) : \mathbb{R}^n \to \mathbb{R}^p$ is the vector of general nonlinear constraint functions—that is, $c = (c_1, \ldots, c_p)$; x_ℓ and x_u are the vectors of the lower and upper bounds, respectively, on the decision variables; b_ℓ and b_u are the vectors of the lower and upper bounds, respectively, on the linear constraints; and c_ℓ and c_u are the vectors of the lower and upper bounds, respectively, on the nonlinear constraint functions. Equality constraints can be represented by equating the lower and upper bounds of the desired variable or constraint.

Because of the limited assumptions that are made about the objective function $f(x)$ and constraint functions $c(x)$, the black-box solver uses a parallel hybrid derivative-free approach similar to approaches that are used in Taddy et al. (2009), Plantenga (2009), Gray, Fowler, and Griffin (2010), and Griffin and Kolda (2010a). Derivative-free methods are effective whether or not derivatives are available, provided that the dimension of x is not too large (Gray and Fowler 2011). As a rule of thumb, derivative-free algorithms are rarely applied to black-box optimization problems that have more than 100 variables. The term *black-box* emphasizes that the function is used only as a mapping operator and makes no implicit assumption or requirement about the structure of the functions themselves. In contrast, derivative-based algorithms commonly require the nonlinear objectives and constraints to be continuous and smooth and to have an exploitable analytic representation.

The black-box solver optimizes general nonlinear problems by simultaneously applying multiple instances of global and local search algorithms in parallel. This hybrid approach streamlines the process of needing to first apply a global algorithm in order to determine a good starting point to initialize a local algorithm. For example, if the problem is convex, a local algorithm should be sufficient, and using a global algorithm would create unnecessary overhead. If the problem instead has many local minima, failing to run a global search algorithm first could result in an inferior solution. Rather than attempting to guess which paradigm is best, the black-box solver simultaneously performs global and local searches while continuously sharing computational resources and function evaluations. Given a suitable number of threads and processors, the resulting run time and solution quality should be similar to those from having automatically selected the best global and local search combination. Moreover, because information is shared, the robustness of this hybrid approach can exceed that of hybrid combinations that simply use the output of one algorithm to hot-start another algorithm.

The black-box solver uses different strategies to handle different types of constraints. It handles linear constraints by using both linear programming and strategies similar to those in Griffin, Kolda, and Lewis (2008), where tangent directions to nearby constraints are constructed and used as search directions. It handles nonlinear constraints by using smooth merit functions (Griffin and Kolda 2010b) and handles integer and categorical variables by using strategies and concepts similar to those in Griffin et al. (2011). Its approach can be viewed as a genetic algorithm that includes an additional "growth" step, in which selected points from the population are allotted a small fraction of the total evaluation budget to improve their fitness score (that is, the objective function value) by using local optimization over the continuous variables.

Because the black-box solver is a parallel/distributed solver, it also does the following:

- enables you to run the solver in a session on a CAS server; this can be a single machine or a distributed computing environment, depending on the number of computing nodes that the CAS session is running on
- enables you to run in single-machine mode on the server where SAS is installed
- exploits all the available cores and concurrent threads, regardless of execution mode

Getting Started: Black-Box Solver

Introductory Examples

The following introductory examples illustrate how to get started using the black-box solver.

A Bound-Constrained Problem

Consider the simple example of minimizing the Branin function,

$$f(x) = \left(x_2 - \frac{5.1}{4\pi^2}x_1^2 + \frac{5}{\pi}x_1 - 6\right)^2 + 10\left(1 - \frac{1}{8\pi}\right)\cos(x_1) + 10$$

subject to $-5 \le x_1 \le 10$ and $0 \le x_2 \le 15$ (Jones, Perttunen, and Stuckman 1993). The minimum function value is $f(x^*) = 0.397887$ at $x^* = (-\pi, 12.275), (\pi, 2.275), (9.42478, 2.475)$. You can use the following statements to solve this bound-constrained problem:

```
proc optmodel;
   var x {1..2};
   x[1].lb = -5;
   x[1].ub = 10;
   x[2].lb = 0;
   x[2].ub = 15;
   num pi = constant('PI');
   min f = (x[2]-(5.1/(4*pi^2))*x[1]^2+5*x[1]/pi-6)^2
           + 10*(1-1/(8*pi))*cos(x[1]) + 10;
   solve with blackbox;
```

```
    print x;
quit;
```

The VAR declaration in the PROC OPTMODEL statement declares an array of two decision variables, x[1] and x[2]. Also, lower and upper bounds are set for the variables. The MIN declaration defines the BRANIN function as the objective function to be minimized.

Figure 10.1 shows the ODS tables that are produced by default.

Figure 10.1 Bound-Constrained Problem: Output

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	0.3978873578
Infeasibility	0
Random Seed Used	1
Evaluations	1541
Cached Evaluations	48
Iterations	28
Presolve Time	0.00
Solution Time	0.15

[1]	x
1	3.1416
2	2.2750

Adding a Linear Constraint

You can use a CONSTRAINT declaration to specify general equality or inequality constraints. For example, suppose that in addition to the bound constraints on the decision variables, you need to guarantee that the sum $x_1 + x_2$ is less than or equal to 0.6. To enforce this, you can add a CON declaration to the PROC OPTMODEL statements, as follows:

```
title3 'Linear Constraint on the Decision Variables';
/* Linear Constraint on the Decision Variables */
proc optmodel;
   var x {1..2};
   x[1].lb = -5;
   x[1].ub = 10;
   x[2].lb = 0;
   x[2].ub = 15;
   num pi = constant('PI');
   min f = (x[2]-(5.1/(4*pi^2))*x[1]^2+5*x[1]/pi-6)^2
           + 10*(1-1/(8*pi))*cos(x[1]) + 10;
   con a1: x[1] + x[2] <= 0.6;
   solve with blackbox;
quit;
```

Here the symbol a1 denotes the name of the given linear constraint.

Nonlinear Constraints on the Decision Variables

You can specify general nonlinear equality or inequality constraints by using the same CON declaration as in the preceding code to add the linear constraint a1. Consider the previous problem with the following additional constraint:

$$x_1^2 - 2x_2 \geq 14$$

You can specify this constraint by adding a new CON declaration, as in the following statements:

```
title3 'Nonlinear Constraints on the Decision Variables';
/* Nonlinear Constraints on the Decision Variables */
proc optmodel;
   var x {1..2};
   x[1].lb = -5;
   x[1].ub = 10;
   x[2].lb = 0;
   x[2].ub = 15;
   num pi = constant('PI');
   min f = (x[2]-(5.1/(4*pi^2))*x[1]^2+5*x[1]/pi-6)^2
           + 10*(1-1/(8*pi))*cos(x[1]) + 10;
   con a1: x[1] + x[2] <= 0.6;
   con c1: x[1]^2 - 2*x[2] >= 14;
   solve with blackbox;
quit;
```

Here the symbol c1 has been added to denote the name of the given nonlinear constraint.

A Simple Maximum Likelihood Example

The following is a very simple example of a maximum likelihood estimation problem that uses the log-likelihood function:

$$l(\mu, \sigma) = -\log(\sigma) - \frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2$$

The maximum likelihood estimates of the parameters μ and σ form the solution to

$$\max_{\mu,\sigma} \sum_i l_i(\mu, \sigma)$$

where $\sigma > 0$ and

$$l_i(\mu, \sigma) = -\log(\sigma) - \frac{1}{2}\left(\frac{x_i-\mu}{\sigma}\right)^2$$

In addition to specifying objective and constraint functions directly with PROC OPTMODEL syntax as shown in the first example, you can also specify these functions by using the FCMP procedure. In PROC FCMP, you specify the objective and constraint functions by using SAS statements that are similar to syntax in the SAS DATA step; these functions are then compiled into function libraries for subsequent use. The SAS CMPLIB= system option specifies where to look for previously compiled functions and subroutines. All procedures (including PROC FCMP) that support the use of FCMP functions and subroutines use this system option. After you specify your objective and constraint functions in a library, PROC OPTMODEL requires the names and context of the functions within this library that are relevant to the current optimization problem. You can provide this information to PROC OPTMODEL by using the same function names that you used in the PROC FCMP statements.

The following sets of statements use PROC FCMP functions and demonstrate two ways to formulate this example problem. In the first example, the FCMP function is "stand-alone" because all the necessary data are defined within the function itself. Notice how the values of $(1, 3, 4, 5, 7)$ are assigned directly to X within the FCMP function.

```
title3 'Maximum Likelihood Example';
/* Maximum Likelihood Example */
proc fcmp outlib=work.myfuncs.mypkg;
   function loglkh1(mu, sigma);
      array x[5] / nosym (1 3 4 5 7);
      s=0;
      do j=1 to 5;
         s = s - log(sigma) - 0.5*((x[j]-mu)/sigma)**2;
      end;
      return (s);
   endsub;
run;

options cmplib = work.myfuncs;
proc optmodel;
   var mu, sigma >= 0;
   max f = loglkh1(mu, sigma);
   solve with blackbox;
quit;
```

The second example shows how you can use an external data set to store the necessary observations and run PROC OPTMODEL to feed each observation to an FCMP function that processes a single line of data. In this case, the objective definition in PROC OPTMODEL is the sum of the individual observation results. This mode is particularly useful when the data set is large and therefore cumbersome to enter directly into a function definition. The following statements demonstrate how to store the necessary observations in an external data set for use with PROC FCMP:

```
data logdata;
   input x @@;
   datalines;
1 3 4 5 7
;

proc fcmp outlib=work.myfuncs.mypkg;
   function loglkh2(mu, sigma, x);
      return (-log(sigma) -0.5*((x-mu)/sigma)**2);
   endsub;
run;

options cmplib = work.myfuncs;
proc optmodel;
   var mu, sigma >= 0;
   set OBS;
   num x {OBS};
   read data logdata into OBS=[_N_] x;
   max f = sum {j in OBS} loglkh2(mu, sigma, x[j]);
   solve with blackbox;
quit;
```

In this case, for each line of data in the data set LogData, the FCMP function LOGLKH2 is called.

Another variation of this same problem involves bypassing the use of PROC FCMP altogether and defining your objective function directly in PROC OPTMODEL as a function of the LogData data read into X:

```
proc optmodel;
   var mu, sigma >= 0;
   set OBS;
   num x {OBS};
   read data logdata into OBS=[_N_] x;
   max f = sum {j in OBS} (-log(sigma) - 0.5*((x[j]-mu)/sigma)**2);
   solve with blackbox;
quit;
```

Syntax: Black-Box Solver

The following statement is available in the OPTMODEL procedure:

SOLVE WITH BLACKBOX < / *options* > **;**

Functional Summary

Table 10.1 outlines the *options* available in the SOLVE WITH BLACKBOX statement.

Table 10.1 Options for the Black-Box Solver

Description	Option
Input Data Option	
Specifies the input cache set	CACHEIN=
Specifies the initial genetic algorithm population	FIRSTGEN=
Specifies whether to use the initial trial points	PRIMALIN
Output Data Options	
Specifies the output cache set	CACHEOUT=
Specifies the members of the genetic algorithm population on exit	LASTGEN=
Stopping Condition Options	
Specifies the absolute function convergence criterion	ABSFCONV=
Specifies the number of iterations without improvement for convergence	NABSFCONV=
Specifies the maximum number of function evaluations	MAXFUNC=
Specifies the maximum number of genetic algorithm iterations	MAXGEN=
Specifies the upper limit on real time	MAXTIME=
Optimization Control Options	
Specifies the feasibility tolerance	FEASTOL=
Specifies the number of global searches	NGLOBAL=
Specifies the number of local searches	NLOCAL=
Specifies the genetic algorithm population size	POPSIZE=
Technical Options	
Specifies the cache tolerance	CACHETOL=
Specifies the maximum cache size	CACHEMAX=
Specifies the maximum size of the Pareto-optimal set	PARETOMAX=
Specifies how frequently to print the solution progress	LOGFREQ=
Specifies how much detail of solution progress to print in the log	LOGLEVEL=
Initializes the seed for sampling routines	SEED=
Specifies the number of threads for the black-box solver to use per node	NTHREADS=

Black-Box Solver Options

This section describes the options that the black-box solver recognizes in PROC OPTMODEL. You can specify these options after a forward slash (/) in the SOLVE statement, provided that you explicitly specify the black-box solver by using a WITH clause. For example, the following line could appear in PROC OPTMODEL statements:

```
solve with blackbox / maxtime=600 nthreads=4 primalin;
```

Input Data Options

You can specify the following *options* that are related to input data sets:

CACHEIN=*set*
names a previously computed sample set. Using a previously computed sample set enables the black-box solver to warm-start. It is crucial that the nonlinear objective and function values be identical to those that were used when the cache data set was generated.

FIRSTGEN=*set*
specifies an initial sample set that defines a subset of the genetic algorithm's initial population. If the population size p is smaller than the size of this set, only the first p points of this set are used.

PRIMALIN
requests that an initial sample set be evaluated by the black-box solver. Adding this option to the SOLVE statement requests that the black-box solver use the current variable values as a starting point. This option might be useful over a sequence of runs when you want to ensure that the black-box solver generates points that are at least as good as your current best solution. You can also specify other starting points by setting the _NSOL_ parameter to the number of points that you want to specify and setting the variable .sol[n] values (`for n in 1.._NSOL_`).

Output Data Options

You can specify the following *options* that are related to output data sets:

CACHEOUT=*set*
specifies the set to which all completed function evaluations are output. This set can be specified in the CACHEIN= option in subsequent calls to the black-box solver.

LASTGEN=*set*
specifies the set to which the members of the current genetic algorithm population are returned on exit. If more than one genetic algorithm is used, the set combines the members from each population into a single set. This set can be specified in the FIRSTGEN= option in subsequent calls to the black-box solver.

Stopping Condition Options

You can specify the following *options* to determine when to stop optimization:

ABSFCONV=*r*

specifies an absolute function convergence criterion. The black-box solver stops when the changes in the objective function and constraint violation values in successive iterations meet the criterion

$$|f(x^{(k-1)}) - f(x^{(k)})| + |\theta(x^{(k-1)}) - \theta(x^{(k)})| \leq r$$

where $\theta(x)$ denotes the maximum constraint violation at point x. By default, r=1E–6.

MAXFUNC=*i*

specifies the maximum number of function calls in the optimization process. The actual number of function evaluations can exceed this number in order to ensure deterministic results.

MAXGEN=*i*

specifies the maximum number of genetic algorithm iterations. By default, MAXGEN=500.

MAXTIME=*r*

specifies an upper limit (in seconds) on the real time that the optimization process uses. The actual run time of the black-box solver might be longer, because the actual run time includes the time needed to finish current function evaluations and the time needed to output the (temporary) results. The value of *r* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

NABSFCONV=*i*

specifies the number of successive iterations for which the criterion that you specify in the ABSFCONV= option must be satisfied before the optimization process is terminated. By default, NABSFCONV=10. To cause an early exit, you must specify a value for *i* that is less than the value of the MAXGEN= option.

Optimization Control Options

You can specify the following *options* to tailor the black-box solver to your specific optimization problem:

FEASTOL=*r*

specifies a feasibility tolerance for the provided constraints. Specify $r \geq$1E–9. By default, r=1E–3.

NGLOBAL=*i*

specifies the number of genetic algorithms to create; each algorithm works on a separate population of the size that you specify in the POPSIZE= option. Specify *i* as an integer greater than 0. By default, NGLOBAL=1.

NLOCAL=*i*

specifies the number of local solvers to create. Specify *i* as an integer greater than 0. The default is twice the number of variables in the problem.

POPSIZE=*i*

specifies the population size for the genetic algorithm to use. The default is $40 \times \text{ceil}(\log(n) + 1)$, where n denotes the number of variables.

Technical Options

You can specify the following technical *options*:

CACHEMAX=*i*

specifies the maximum number of points that can be cached. By default, the black-box solver automatically calculates the maximum number of points.

CACHETOL=*r*

specifies the cache tolerance to be used for caching and referencing previously evaluated points. For more information about this tolerance, see the section "Function Value Caching" on page 516. The value of *r* can be any number in the interval [0, 1]. By default, *r*=1E–9.

LOGFREQ=*i*

requests that the solution progress be printed to the iteration log after every *i* iterations if the value of the LOGLEVEL= option is equal to 1. LOGFREQ=0 disables the printing of the solution progress. The solution progress of the final iteration is always printed if $i \geq 1$ and the value of the LOGLEVEL= option is nonzero. By default, LOGFREQ=1.

LOGLEVEL=0 | 1

controls how much information is printed to the log. If LOGLEVEL=0, nothing is printed. If LOGLEVEL=1, a short summary of the problem description and final solution status is printed. If LOGLEVEL=0, this option overrides the LOGFREQ= option. By default, LOGLEVEL=1.

NTHREADS=*i*

specifies the maximum number of threads for the black-box solver to use for multithreaded processing. When running in a distributed computing environment, the black-box solver uses up to *i* threads per worker node. The default is the value of the NTHREADS= option in PROC OPTMODEL.

PARETOMAX=*i*

specifies the maximum number of points in the Pareto-optimal set, which is produced for multiobjective optimization. By default, PARETOMAX=5000.

SEED=*i*

specifies a nonnegative integer as a seed value for the pseudorandom number generator. Pseudorandom numbers are used within the genetic algorithm. By default, SEED=1.

Details: Black-Box Solver

The black-box solver uses a hybrid of genetic algorithms (Goldberg 1989; Holland 1975), which optimize integer and continuous variables, and the generating set search (Kolda, Lewis, and Torczon 2003), which performs a local search on the continuous variables to improve the robustness of both algorithms. Both genetic algorithms (GAs) and the generating set search (GSS) have proven to be effective algorithms for many classes of derivative-free optimization problems. When only continuous variables are present, a GA usually requires more function evaluations than a GSS to converge to a minimum. This is partly due to the GA's need to simultaneously perform a global search of the solution space. In a hybrid setting, the requirement for the GA to find accurate local minima can be relaxed, and internal parameters can be tuned to find promising starting points for the GSS.

The Black-Box Algorithm

The black-box solver is based on a genetic algorithm (GA). GAs are a family of local search algorithms that seek optimal solutions to problems by applying the principles of natural selection and evolution. You can apply genetic algorithms to almost any optimization problem. They are especially useful for problems where calculus-based techniques do not work, such as when the objective function has many local optima, when the objective function is not differentiable or continuous, or when solution elements are constrained to be integers or sequences. In most cases, genetic algorithms require more computation than specialized techniques that take advantage of specific problem structures or characteristics. However, for optimization problems for which no such techniques are available, genetic algorithms provide a robust general method of solution.

In general, genetic algorithms use some variation of the following process to search for an optimal solution:

initialization: An initial population of solutions is randomly generated, and the objective function is evaluated for each member of this initial iteration.

selection: Individual members of the current iteration are chosen stochastically either to parent the next iteration or to be passed on to it such that the fittest members are more likely to be selected. A solution's fitness is based on its objective value; a better objective value reflects greater fitness.

crossover: Some of the selected solutions are passed to a crossover operator. The crossover operator combines two or more parents to produce new offspring solutions for the next iteration. The crossover operator tends to produce new offspring that retain the common characteristics of the parent solutions while combining the other traits in new ways. In this way, new areas of the search space are explored while the operator attempts to retain optimal solution characteristics.

mutation: Some of the next-iteration solutions are passed to a mutation operator, which introduces random variations in the solutions. The purpose of the mutation operator is to ensure that the solution space is adequately searched in order to prevent premature convergence to a local optimum.

repeat: The current iteration of solutions is replaced by the new iteration. If the stopping criterion is not satisfied, the process returns to the selection phase.

The crossover and mutation operators are commonly called *genetic operators*. Selection and crossover distinguish genetic algorithms from a purely random search and direct the algorithm toward finding an optimum.

There are many ways to implement the general strategy just outlined, and it is also possible to combine the genetic algorithm approach with other heuristic solution improvement techniques. In the traditional genetic algorithm, the solution space is composed of bit strings, which are mapped to an objective function, and the genetic operators are modeled after biological processes. Although there is a theoretical foundation for the convergence of genetic algorithms that are formulated in this way, in practice most problems do not fit naturally into this paradigm. Modern research has shown that optimizations can be set up by using the natural solution domain (for example, a real vector or integer sequence) and by applying crossover and mutation operators that are analogous to the traditional genetic operators but are more appropriate to the natural formulation of the problem.

Although genetic algorithms have been demonstrated to work well for a variety of problems, there is no guarantee of convergence to a global optimum. Also, the convergence of genetic algorithms can be sensitive to the choice of genetic operators, mutation probability, and selection criteria, so some initial experimentation and fine-tuning of these parameters are often required.

The black-box solver seeks to automate this process by using hybrid optimization in which several genetic algorithms can run in parallel and each algorithm is initialized with different default option settings. The black-box solver also adds a step to the GA; this step permits generating set search (GSS) algorithms to be used on a selected subset of the current population. GSS algorithms are designed for problems that have continuous variables and have the advantage that, in practice, they often require significantly fewer evaluations than GAs in order to converge. Furthermore, GSS can provide a measure of local optimality that is very useful in performing multimodal optimization.

The following additional "growth steps" are used whenever continuous variables are present:

local search selection: A small subset of points are selected based on their fitness score and distance to (1) other points and (2) pre-existing locally optimal points.

local search optimization: Local search optimization begins concurrently for each selected point. The only change that is made to the original optimization problem is that the variables' lower and upper bounds are modified to temporarily fix integer variables at their current setting.

The black-box solver performs these additional growth steps at each iteration; they permit selected members of the population (based on diversity and fitness) to benefit from local optimization over the continuous variables. If only integer variables are present, these additional steps are not used.

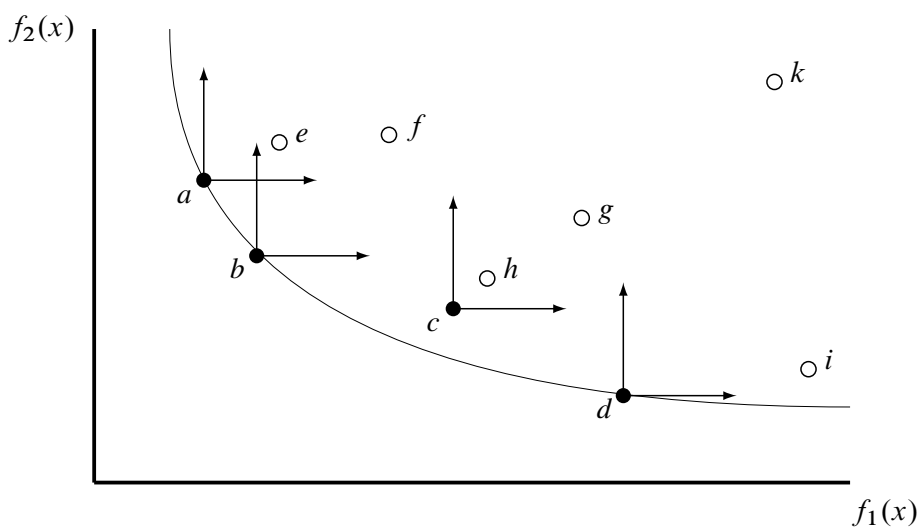
Multiobjective Optimization

Many practical optimization problems involve more than one objective criterion, so the decision maker needs to examine trade-offs between conflicting objectives. For example, for a particular financial model you might want to maximize profit while minimizing risk, or for a structural model you might want to minimize weight while maximizing strength. The desired result for such problems is usually not a single solution but rather a range of solutions that you can use to identify an acceptable compromise. Ideally each point represents a necessary compromise in the sense that no single objective can be improved without causing at least one remaining objective to deteriorate. The goal of the black-box solver in the multiobjective case is thus to provide to the decision maker a set of points that represent the continuum of best-case scenarios. Multiobjective optimization is performed in the black-box solver whenever more than one objective function exists. For an example, see "Example 10.7: Multiobjective Optimization" on page 536.

Mathematically, you can define multiobjective optimization in terms of *dominance* and *Pareto optimality*. For a k-objective minimizing optimization problem, a point x is *dominated* by a point y if $f_i(x) \geq f_i(y)$ for all $i = 1, \ldots, k$ and $f_j(x) > f_j(y)$ for some $j = 1, \ldots, k$.

A Pareto-optimal set contains only nondominated solutions. In Figure 10.2, a Pareto-optimal frontier is plotted with respect to minimization objectives $f_1(x)$ and $f_2(x)$ along with a corresponding population of 10 points that are plotted in the objective space. In this example, point a dominates $\{e, f, k\}$, b dominates $\{e, f, g, k\}$, c dominates $\{g, h, k\}$, and d dominates $\{k, i\}$. Although no other point in the population dominates point c, it has not yet converged to the true Pareto-optimal frontier. Thus there are points in a neighborhood of c that have smaller values of f_1 and f_2.

Figure 10.2 Pareto-Optimal Set



In the constrained case, a point x is dominated by a point y if $\theta(x) > \epsilon$ and $\theta(y) < \theta(x)$, where $\theta(x)$ denotes the maximum constraint violation at point x and the feasibility tolerance is ϵ; thus feasibility takes precedence over objective function values.

Genetic algorithms enable you to attack multiobjective problems directly in order to evolve a set of Pareto-optimal solutions in one run of the optimization process instead of solving multiple separate problems. In addition, the black-box solver conducts local searches in neighborhoods around nondominated points to improve objective function values and reduce crowding. Because the number of nondominated points that are encountered might be greater than the total population size, the black-box solver stores nondominated points in an archived set $\mathcal{N}$; you can specify the PARETOMAX= option in the SOLVE WITH BLACKBOX statement to control the size of this set.

Although it is difficult to verify directly that a point lies on the true Pareto-optimal frontier without using derivatives, you can measure convergence indirectly by monitoring movement of the population with respect to $\mathcal{N}$, the current set of nondominated points. A number of metrics for measuring convergence in multiobjective evolutionary algorithms have been suggested, such as the generational distance by Van Veldhuizen (1999), the inverted generational distance by Coello Coello and Cruz Cortes (2005), and the averaged Hausdorff distance by Schütze et al. (2012). The black-box solver uses a variation of the averaged Hausdorff distance that is extended for general constraints.

Distance between sets is computed in terms of the distance between a point and a set, which in turn is defined in terms of the distance between two points. The distance measure that the black-box solver uses for two points x and y is calculated as

$$d(x, y) = |\theta(x) - \theta(y)| + \sum_{i=1}^{k} |f_i(x) - f_i(y)|$$

where $\theta(x)$ denotes the maximum constraint violation at point x. Then the distance between a point x and a set $\mathcal{A}$ is defined as

$$d(x, \mathcal{A}) = \min_{y \in \mathcal{A}} d(x, y)$$

Let $\mathcal{F}_j$ denote the set of all nondominated points within the current population at the start of generation j. Let $\mathcal{N}_j$ denote the set of all nondominated points at the start of generation j. At the beginning of each generation, $\mathcal{F}_j \subseteq \mathcal{N}_j$ is always satisfied. Then progress that the solver makes during iteration j+1 is defined as

$$\text{Progress}(j + 1) = \frac{1}{|\mathcal{F}_j|} \sum_{x \in \mathcal{F}_j} d(x, \mathcal{N}_{j+1})$$

Because $d(x, \mathcal{N}_{j+1}) = 0$ whenever $x \in \mathcal{F}_j \cap \mathcal{F}_{j+1}$, the preceding sum is over the set of points in the population that move from a status of nondominated to dominated. In this case, the progress that the solver makes is measured as the distance to the nearest dominating point.

Specifying and Returning Trial Points

You can use the CACHEIN= and FIRSTGEN= options to initialize the black-box solver with user-specified points. You can use the CACHEOUT= and LASTGEN= options to have trial points returned to you.

Both input and output point sets are represented using PROC OPTMODEL triples. Each triple has the form (*Num*, *Str*, *Val*), where *Num* specifies the point's unique solution tag, *Str* specifies the variable (function) ID name, and *Val* specifies the variable (function) value.

The following PROC OPTMODEL code demonstrates how to use the CACHEIN= input set to warm-start the black-box solver. In this simple example, the black-box solver is called once with a maximum of two generations of the genetic algorithm. The evaluations that are computed during this solve are saved in a set that is specified in the CACHEOUT= option. Then, this set is passed as input to the CACHEIN= option, which uses those values to warm-start the second call to the black-box solver.

```
proc optmodel;
   var x {1..2};
   x[1].lb = -5;
   x[1].ub = 10;
   x[2].lb = 0;
   x[2].ub = 15;
   num pi = constant('PI');
   min f = (x[2]-(5.1/(4*pi^2))*x[1]^2+5*x[1]/pi-6)^2
           + 10*(1-1/(8*pi))*cos(x[1]) + 10;
   set <num,str,num> cache;
   solve with blackbox / maxgen=2 cacheout=cache;
   put cache;
   solve with blackbox / cachein=cache;
   print x;
quit;
```

The PUT statement between the calls to the black-box solver prints the contents of the *cache* set to the screen. You can examine the screen to see which points have been selected by the genetic algorithm thus far through the first two generations, before you proceed with the next call to the black-box solver.

Function Value Caching

To improve performance, the black-box solver implements a caching system. This system helps reduce the overall workload of the solver by eliminating duplicate function evaluations. As the individual optimizers submit new trial points for evaluation, the points are saved in the cache along with their function evaluation values. Then, before beginning the potentially expensive function evaluations for a new trial point, the black-box solver determines whether a similar point already exists within the cache. If a similar point is found in the cache, its function values are immediately returned for the newly submitted point. By returning function values from the cache instead of duplicating the effort of computing new function values, the solver can achieve significant performance improvements in the overall procedure.

The cache is implemented as a splay tree, similar to that used in Gray and Kolda (2006) and Hough, Kolda, and Patrick (2000). The splay tree rebalances itself as new points are added to the cache. This rebalancing ensures that recently added or accessed points are maintained at the root of the tree and are therefore available for quick retrieval. This splay tree data structure lends itself nicely to the needs of a caching system.

When determining whether a newly submitted trial point has a similar point already in the cache, the black-box solver compares the new trial point to all previous trial points by using the value of the CACHETOL= option in the SOLVE WITH BLACKBOX statement. This value specifies a tolerance to use in comparing two points and determining whether the two points are similar enough.

Two points x and y are considered *cache equivalent* if

$$|x_i - y_i| \leq s_i \epsilon, \text{ for } i = 1, \ldots, n$$

where s denotes the corresponding scaling vector. Thus, if a point x has been evaluated (or is being evaluated) and a point y is submitted for evaluation and satisfies the preceding criteria, then y is "cache evaluated" instead of being evaluated directly. In this case, y is associated with $f(x)$ and $c(x)$. Although the splay tree is very efficient, the cache lookup time for quick evaluation might eventually dominate the evaluation process time. You can use the CACHEMAX= option in the SOLVE WITH BLACKBOX statement to limit the size of the cache.

Even when nonlinear objective functions are not defined, the cache system helps avoid redundant computations when the linear constraints are explicitly handled.

Iteration Log

The iteration log provides detailed information about the progress of the black-box solver. The log appears by default or if you specify LOGLEVEL=1 in the SOLVE WITH BLACKBOX statement. The iteration log provides this information in the following columns:

Iteration	Displays the number of completed genetic algorithm iterations.
Best Objective	Displays the best objective that is found at each iteration with respect to the current value of the FEASTOL= option. **NOTE:** This column is included only for single-objective optimization.
Nondom	Displays the number of nondominated solutions in the current Pareto-optimal set. **NOTE:** This column is included only for multiobjective optimization.
Progress	Displays a numerical indication of the progress that the solver is making from one iteration to the next. For a description of how this value is computed, see the section "Multiobjective Optimization" on page 514. **NOTE:** This column is included only for multiobjective optimization.
Infeasibility	Displays the aggregate constraint violation of the current best point.
Evals	Displays the cumulative number of function evaluations.
Time	Displays the time needed to achieve the current best solution.

Solver Termination Messages

After the black-box solver terminates, one of the following messages is displayed:

Interrupted by user.
The solver's execution was interrupted by the user.

Function convergence criteria reached.
The best objective value and feasibility have not sufficiently improved in the specified number of iterations. This condition is a typical exit state if the solver reaches the global optimum early in the process.

Maximum function evaluations reached.
The black-box solver has attempted to exceed the maximum number of function evaluations.

Generations complete.
The maximum number of GA generations (iterations) has been reached. In this situation, no new points are generated, and the solver exits.

Maximum time reached.
The black-box solver has exceeded the maximum allotted time.

Problem might be unbounded.
The objective value appears to take on arbitrarily large values at points that satisfy the feasibility tolerance.

Infeasible.
The problem is infeasible.

Failed.
The solver exited for a reason other than the preceding reasons.

Macro Variable _OROPTMODEL_

The OPTMODEL procedure defines a macro variable named _OROPTMODEL_. This variable contains a character string that indicates the status of the procedure upon termination. The contents of the macro variable depend on which solver was invoked. For the black-box solver, the various terms of _OROPTMODEL_ are interpreted as follows.

STATUS
indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	Syntax was used incorrectly.
DATA_ERROR	The input data are inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the solver.
IO_ERROR	A problem in reading or writing of data has occurred.

SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, has occurred.
ERROR	The status cannot be classified into any of the preceding categories.

SOLUTION_STATUS

indicates the status of the solution at termination. It can take one of the following values:

ABORTED	The user signaled that the solver should terminate.
ABSFCONV	The solver terminated on the absolute function convergence criterion.
INFEASIBLE	Problem is globally infeasible. This value is returned only if all constraints are linear.
MAXFUNC	The solver terminated on the maximum number of function evaluations.
MAXGEN	The maximum number of genetic algorithm iterations was completed.
MAXTIME	The maximum time limit was reached.
UNBOUNDED	The problem might be unbounded.
FAILED	The status cannot be classified into any of the preceding categories.

OBJECTIVE

indicates the objective value that the solver obtains at termination. **NOTE:** This value is missing for multiobjective optimization.

NONDOMINATED

indicates the number of nondominated solutions in the Pareto-optimal set. **NOTE:** This value is included only for multiobjective optimization.

PROGRESS

indicates the progress that the solver made during the last iteration. For a description of how this value is computed, see the section "Multiobjective Optimization" on page 514. **NOTE:** This value is included only for multiobjective optimization.

INFEASIBILITY

indicates the level of infeasibility of the constraints at the solution.

EVALUATIONS

indicates the total number of evaluations that were not cached.

ITERATIONS

indicates the number of iterations that were required in order to solve the problem.

PRESOLVE_TIME

indicates the real time (in seconds) that is used to set up the optimization problem and distribute data.

SOLUTION_TIME

indicates the real time (in seconds) that is used by the solver to perform iterations for solving the problem.

Examples: Black-Box Solver

Example 10.1: Linear Constraints and a Quadratic Objective

This example uses data from Floudas and Pardalos (1992) and illustrates how to use the SOLVE WITH BLACKBOX statement in the OPTMODEL procedure. The problem has nine linear constraints and a quadratic objective function. Suppose you want to minimize

$$f(x) = 5\sum_{i=1}^{4} x_i - 5\sum_{i=1}^{4} x_i^2 - \sum_{i=5}^{13} x_i$$

subject to

$$\begin{aligned}
&2x_1 + 2x_2 + x_{10} + x_{11} \le 10\\
&2x_1 + 2x_3 + x_{10} + x_{12} \le 10\\
&2x_1 + 2x_3 + x_{11} + x_{12} \le 10\\
&-8x_1 + x_{10} \le 0\\
&-8x_2 + x_{11} \le 0\\
&-8x_3 + x_{12} \le 0\\
&-2x_4 - x_5 + x_{10} \le 0\\
&-2x_6 - x_7 + x_{11} \le 0\\
&-2x_8 - x_9 + x_{12} \le 0
\end{aligned}$$

and

$$\begin{aligned}
&0 \le x_i \le 1, && i = 1, 2, \ldots, 9\\
&0 \le x_i \le 100, && i = 10, 11, 12\\
&0 \le x_{13} \le 1
\end{aligned}$$

The following statements use the black-box solver within PROC OPTMODEL:

```
proc optmodel;
   var x {i in 1..13} >= 0 <= (if i in 10..12 then 100 else 1);
   min f = 5 * sum {i in 1..4} x[i]
           - 5 * sum {i in 1..4} x[i]^2
           - sum {i in 5..13} x[i];
   con a1: 2*x[1] + 2*x[2] + x[10] + x[11] <= 10;
   con a2: 2*x[1] + 2*x[3] + x[10] + x[12] <= 10;
   con a3: 2*x[1] + 2*x[3] + x[11] + x[12] <= 10;
   con a4: -8*x[1] + x[10] <= 0;
   con a5: -8*x[2] + x[11] <= 0;
   con a6: -8*x[3] + x[12] <= 0;
   con a7: -2*x[4] - x[5] + x[10] <= 0;
   con a8: -2*x[6] - x[7] + x[11] <= 0;
   con a9: -2*x[8] - x[9] + x[12] <= 0;
   solve with blackbox / nthreads=2;
   print x;
quit;
```

Output 10.1.1 shows the output from running these statements.

Output 10.1.1 Linear Constraints and a Quadratic Objective

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	13
Bounded Above	0
Bounded Below	0
Bounded Below and Above	13
Free	0
Fixed	0
Number of Constraints	9
Linear LE (<=)	9
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	27

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	-15.00106903
Infeasibility	0.0009956259
Random Seed Used	1
Evaluations	3496
Cached Evaluations	547
Iterations	30
Presolve Time	0.00
Solution Time	0.34

Output 10.1.1 *continued*

[1]	x
1	1.000
2	1.000
3	1.000
4	1.000
5	1.000
6	1.000
7	1.000
8	1.000
9	1.000
10	3.000
11	3.001
12	3.000
13	1.000

Example 10.2: Linear Constraints and a Nonlinear Objective

The problem in this example is to minimize the six-hump camelback function (Michalewicz 1996, Appendix B). Minimize

$$f(x) = \left(4 - 2.1x_1^2 + \frac{x_1^4}{3}\right) x_1^2 + x_1 x_2 + \left(-4 + 4x_2^2\right) x_2^2$$

subject to

$$\begin{aligned} 2x_1 + x_2 &\leq 2 \\ x_1 - x_2 &\geq -2 \\ x_1 + 2x_2 &\geq -2 \end{aligned}$$

Providing derivative-free algorithms with good estimates for lower and upper bounds often greatly improves performance because it prevents the algorithm from unnecessarily sampling in regions that you do not want to explore. For this problem, the following statements add the explicit variable bounds $-2 \leq x_1 \leq 2$ and $-2 \leq x_2 \leq 2$:

```
proc optmodel;
   var x {1..2} >= -2 <= 2;
   con a1: 2*x[1] +   x[2] <=  2;
   con a2:   x[1] -   x[2] >= -2;
   con a3:   x[1] + 2*x[2] >= -2;
   min f = (4 - 2.1*x[1]^2 + x[1]^4/3)*x[1]^2 + x[1]*x[2]
           + (-4 + 4*x[2]^2)*x[2]^2;
   solve with blackbox / nthreads=2;
   print x;
quit;
```

Output 10.2.1 shows the output from running these steps.

Output 10.2.1 Linear Constraints and a Nonlinear Objective

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	2
Linear Range	0
Constraint Coefficients	6

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	-1.031628453
Infeasibility	0
Random Seed Used	1
Evaluations	1414
Cached Evaluations	32
Iterations	25
Presolve Time	0.00
Solution Time	0.12

[1]	x
1	0.089843
2	-0.712655

Example 10.3: Using Nonlinear Constraints

The following optimization problem is discussed in Haverly (1978) and Liebman et al. (1986). This example illustrates a problem that has both linear and nonlinear constraints and a linear objective. Maximize

$$f(x) = 9x_1 + 15x_2 - 6x_3 - 16x_4 - 10x_5$$

subject to

$$\begin{aligned}
&x_3 + x_4 = x_6 + x_7 \\
&x_6 + x_8 = x_1 \\
&x_7 + x_9 = x_2 \\
&x_8 + x_9 = x_5 \\
&2.5x_1 - x_{10}x_6 - 2x_8 \geq 0 \\
&1.5x_2 - x_{10}x_7 - 2x_9 \geq 0 \\
&3x_3 + x_4 - x_{10}(x_3 + x_4) = 0
\end{aligned}$$

and

$$\begin{aligned}
&0 \leq x_1 \leq 100 \\
&0 \leq x_2 \leq 200 \\
&1 \leq x_{10} \leq 3 \\
&0 \leq x_i, \text{ for } i = 3, \ldots, 9
\end{aligned}$$

In the following steps, the problem definition is described in PROC OPTMODEL. This example also demonstrates the distributed computing capabilities of the black-box solver. By simply passing a reference to a running CAS session via the SESSREF= option, you can direct the black-box solver to run in the distributed CAS environment.

```
proc optmodel sessref=mysess;
   var x{1..10} >= 0;
   x[1].ub = 100;
   x[2].ub = 200;
   x[10].lb = 1;
   x[10].ub = 3;
   max f = 9*x[1] + 15*x[2] - 6*x[3] - 16*x[4] - 10*x[5];
   con x[3] + x[4] = x[6] + x[7],
   x[6] + x[8] = x[1],
   x[7] + x[9] = x[2],
   x[8] + x[9] = x[5],
   2.5*x[1] - x[10]*x[6] - 2*x[8] >= 0,
   1.5*x[2] - x[10]*x[7] - 2*x[9] >= 0,
   3*x[3] + x[4] - x[10]*(x[3] + x[4]) = 0;
   solve with blackbox / logfreq=10 nthreads=8 popsize=400;
   print x;
quit;
```

Output 10.3.1 shows the ODS tables that are produced by running these steps.

Output 10.3.1 Using Nonlinear Constraints: ODS Tables

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	f
Objective Type	Linear
Number of Variables	10
Bounded Above	0
Bounded Below	7
Bounded Below and Above	3
Free	0
Fixed	0
Number of Constraints	7
Linear LE (<=)	0
Linear EQ (=)	4
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	1
Nonlinear GE (>=)	2
Nonlinear Range	0
Constraint Coefficients	13

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	400.05057437
Infeasibility	0.0009748175
Random Seed Used	1
Evaluations	20404
Cached Evaluations	1024
Iterations	74
Presolve Time	0.00
Solution Time	3.71

Output 10.3.1 *continued*

[1]	x
1	0.000
2	200.000
3	0.000
4	99.996
5	100.001
6	0.000
7	99.997
8	0.000
9	100.002
10	1.000

Output 10.3.2 shows the iteration log from running these steps.

Output 10.3.2 Using Nonlinear Constraints: Log

```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 10 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (0 LE, 4 EQ, 0 GE, 0 range).
NOTE: The problem has 13 linear constraint coefficients.
NOTE: The problem has 3 nonlinear constraints (0 LE, 1 EQ, 2 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: The SOLVE statement is executing in the distributed computing environment
      with 8 worker nodes.
NOTE: The Black-Box solver is using up to 64 total threads across 8 machines.
NOTE: The Black-Box solver is using the EAGLS optimizer algorithm.
NOTE: The problem has 10 variables (0 integer, 10 continuous).
NOTE: The problem has 7 constraints (4 linear, 3 nonlinear).
NOTE: The problem has 3 user-defined functions.
NOTE: The deterministic parallel mode is enabled.
                         Best
        Iteration        Objective    Infeasibility    Evals     Time
                1                0                0      410        0
               11      399.42803994  2.842170943E-14     3177        0
               21      400.00140276       0.00023380     5959        1
               31      400.01856702       0.00086262     8621        1
               41      400.03490778       0.00091128    11313        1
               51      400.04426966       0.00099865    14124        2
               61      400.04890802       0.00096176    16824        2
               71      400.05057437       0.00097482    19622        2
               74      400.05057437       0.00097482    20404        3
NOTE: Function convergence criteria reached.

STATUS=OK SOLUTION_STATUS=ABSFCONV OBJECTIVE=400.05057437
INFEASIBILITY=0.0009748175 EVALUATIONS=20404 ITERATIONS=74 PRESOLVE_TIME=0.00
SOLUTION_TIME=2.70
```

Example 10.4: Using External Data Sets

This example illustrates the use of external data that are required in order to evaluate the objective function. The Bard function (Moré, Garbow, and Hillstrom 1981) is a least squares problem that has $n = 3$ parameters and $m = 15$ functions f_k,

$$f(x) = \frac{1}{2}\sum_{k=1}^{15} f_k^2(x), \quad x = (x_1, x_2, x_3)$$

where

$$f_k(x) = y_k - \left(x_1 + \frac{k}{v_k x_2 + w_k x_3}\right)$$

with $v_k = 16 - k$, $w_k = \min(u_k, v_k)$, and

$$y = (0.14, 0.18, 0.22, 0.25, 0.29, 0.32, 0.35, 0.39, 0.37, 0.58, 0.73, 0.96, 1.34, 2.10, 4.39)$$

The minimum function value $f(x^*) = 4.107\text{E–}3$ occurs at the point (0.08, 1.13, 2.34). In this example, the additional variable bounds $-1{,}000 \le x_i \le 1{,}000$ for $i = 1, 2, 3$ are added.

The following example code shows two approaches to specifying the objective function. The first approach assumes that the necessary data are stored within the FCMP function that defines the objective. In this case, you can specify the objective function without using an external data set, as follows:

```
proc fcmp outlib=work.myfuncs.mypkg;
   function bard(x1, x2, x3);
      array y[15] /nosym (0.14 0.18 0.22 0.25 0.29
                          0.32 0.35 0.39 0.37 0.58
                          0.73 0.96 1.34 2.10 4.39);
      fx = 0;
      do k=1 to 15;
         vk = 16 - k;
         wk = min(k,vk);
         fxk = y[k] - (x1 + k/(vk*x2 + wk*x3));
         fx = fx + fxk**2;
      end;
      return (0.5*fx);
   endsub;
run;

options cmplib = work.myfuncs;
proc optmodel;
   var x {1..3} >= -1000 <= 1000;
   min f = bard(of x[*]);
   solve with blackbox / nthreads=2;
   print x;
quit;
```

Output 10.4.1 shows the output from running these steps.

Output 10.4.1 Using External Data Sets

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	3
Bounded Above	0
Bounded Below	0
Bounded Below and Above	3
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	0.0041074408
Infeasibility	0
Random Seed Used	1
Evaluations	4589
Cached Evaluations	55
Iterations	53
Presolve Time	0.00
Solution Time	0.16

[1]	x
1	0.082419
2	1.133250
3	2.343536

The preceding approach can be prohibitive if the data set is large. As a second approach to specifying the objective function, you can define data in a SAS data set, read the data set into PROC OPTMODEL, and then use the values from that data set as part of the objective computation. This approach is shown in the following statements:

```
data barddata;
   k = _n_;
   input y @@;
   datalines;
0.14 0.18 0.22 0.25 0.29
0.32 0.35 0.39 0.37 0.58
```

```
0.73 0.96 1.34 2.10 4.39
;

proc fcmp outlib=work.myfuncs.mypkg;
   function bard(x1, x2, x3, k, y);
      vk = 16 - k;
      wk = min(k,vk);
      fxk = y - (x1 + k/(vk*x2 + wk*x3));
      return (0.5*fxk**2);
   endsub;
run;

options cmplib = work.myfuncs;
proc optmodel;
   set KSET;
   num y {KSET};
   read data barddata into KSET=[k] y;
   var x {1..3} >= -1000 <= 1000;
   min f = sum {k in KSET} bard(of x[*], k, y[k]);
   solve with blackbox / nthreads=2;
   print x;
quit;
```

Output 10.4.2 shows the output from running these statements.

Output 10.4.2 Using External Data Sets (II)

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	3
Bounded Above	0
Bounded Below	0
Bounded Below and Above	3
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Output 10.4.2 *continued*

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	0.0041074408
Infeasibility	0
Random Seed Used	1
Evaluations	4589
Cached Evaluations	55
Iterations	53
Presolve Time	0.00
Solution Time	0.22

Example 10.5: Johnson's Systems of Distributions

This example further illustrates the use of external data that are required in order to evaluate the objective function. For this example, a data set that contains $n = 20{,}000$ randomly generated observations is used to estimate the parameters for the Johnson S_U family of distributions (Bowman and Shenton 1983). The objective is the log likelihood for the family, which involves four variables, $x = (x_1, x_2, x_3, x_4)$,

$$f(x) = n \log x_4 - n \log x_2 - \frac{1}{2} \sum_{k=1}^{n} \left((x_3 + x_4 \log z_k)^2 + \log(1 + y_k^2) \right)$$

where

$$z_k = y_k + \sqrt{1 + y_k^2} \text{ with } y_k = \frac{d_k - x_1}{x_2}$$

Here, d_k denotes the value of d in the kth observation of the data set that is generated by the following DATA step:

```
data sudata;
   n = 20000;
   theta = -1;
   sigma = 1;
   delta = 3;
   gamma = 5;
   rngSeed=12345;
   call streaminit(rngSeed);
   do i = 1 to n;
      z = rand('NORMAL');
      a = exp( (z - gamma)/delta );
      d = sigma * ( (a**2 - 1)/(2*a) ) + theta;
      output;
   end;
   keep d;
```

```
 run;
```

This generates a data set called suData that contains $n = 20{,}000$ observations. You can modify n to increase or decrease the computational work per function evaluation, as follows:

```
proc optmodel;
   set OBS;
   num d {OBS};
   read data sudata into OBS=[_N_] d;
   num n = card(OBS);
   var x {1..4};
   x[2].lb = 1e-12;
   x[4].lb = 1e-12;
   impvar y {k in OBS} = (d[k] - x[1]) / x[2];
   impvar z {k in OBS} = y[k] + sqrt(1 + y[k]^2);
   max f = n * (log(x[4]) - log(x[2]))
           - 0.5 * sum {k in OBS} ((x[3] + x[4]*log(z[k]))^2 + log(1 + y[k]^2));
   solve with blackbox / maxgen=1000 nthreads=8;
   print x;
quit;
```

Output 10.5.1 shows the output from running these steps.

Output 10.5.1 Estimation for Johnson S_U Family of Distributions

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	4
Bounded Above	0
Bounded Below	2
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Output 10.5.1 *continued*

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	-8222.095503
Infeasibility	0
Random Seed Used	1
Evaluations	23096
Cached Evaluations	90
Iterations	263
Presolve Time	0.00
Solution Time	7.88

Example 10.6: Discontinuous Function with a Lookup Table

This example illustrates the ability of the black-box solver to optimize a discontinuous function. The example generates arrays of discrete values that approximate a given smooth nonlinear function. The function that is optimized is simply using those data as a lookup table to find the appropriate discretized value. The underlying smooth function is defined as follows:

$$f(x) = x\sin(x) + x^2\cos(x)$$

This first PROC OPTMODEL call shows how to optimize this function by using the discretized lookup approach:

```
%let N = 100;
%let L = 0;
%let U = 10;

proc optmodel;
   set OBS = 1..&N;
   num xdata {i in OBS} = &L + (i/&N)*(&U-&L);
   num ydata {i in OBS} = xdata[i]*sin(xdata[i]) + xdata[i]^2*cos(xdata[i]);
   var x >= &L <= &U;
   min f = sum {i in 1..&N-1} ydata[i] * (xdata[i] <= x < xdata[i+1]);
   solve with blackbox;
   print x;
quit;
```

The previous statements first create the lookup arrays (*xdata* and *ydata*) for x values at 100 (N) uniformly spaced points between 0 (L) and 10 (U). The objective function f is simply returning the discretized function value when the given x value is between two neighboring x values in the array. When the solver finds the appropriate location in the arrays, the smaller of the two nearest points is returned as the function value.

Output 10.6.1 shows the ODS tables that are produced.

Output 10.6.1 Discontinuous Function: ODS Tables

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	1
Bounded Above	0
Bounded Below	0
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	-93.18498962
Infeasibility	0
Random Seed Used	1
Evaluations	284
Cached Evaluations	51
Iterations	11
Presolve Time	0.00
Solution Time	0.05

x
9.7436

The following statements optimize the smooth version of the same function to demonstrate that virtually the same result is achieved in both cases:

```
proc optmodel;
   var x >= &L <= &U;
   min f = x*sin(x) + x^2*cos(x);
   solve with blackbox;
   print x;
quit;
```

Output 10.6.2 shows the ODS tables that are produced.

Output 10.6.2 Smooth Function: ODS Tables

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	1
Bounded Above	0
Bounded Below	0
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Solution Summary	
Solver	Black-Box
Objective Function	f
Solution Status	Function Convergence
Objective Value	-93.22152602
Infeasibility	0
Random Seed Used	1
Evaluations	616
Cached Evaluations	95
Iterations	24
Presolve Time	0.00
Solution Time	0.05

x
9.7269

Example 10.7: Multiobjective Optimization

The following optimization problem is discussed in Huband et al. (2006) and Custódio et al. (2011). This example illustrates how to optimize a problem that contains multiple nonlinear objectives. This problem minimizes

$$f_1(x) = (x_1 - 1)^2 + (x_1 - x_2)^2 \text{ and } f_2(x) = (x_1 - x_2)^2 + (x_2 - 3)^2$$

subject to $0 \leq x_1, x_2 \leq 5$. The variable information and the objective functions are defined using the standard PROC OPTMODEL syntax. This example shows how you can specify the objective names as part of the SOLVE WITH BLACKBOX statement. By default, all currently defined objectives are used, so specifying the objective names is optional unless you want to exclude some previously defined objectives from your problem.

The following PROC OPTMODEL code shows how to define the two objective functions in the multiobjective optimization problem. This code also demonstrates how to use the OBJ keyword in the SOLVE WITH BLACKBOX statement.

```
proc optmodel;
   var x {1..2} >= 0 <= 5;
   min f1 = (x[1]-1)^2 + (x[1]-x[2])^2;
   min f2 = (x[1]-x[2])^2 + (x[2]-3)^2;
   solve with blackbox obj (f1 f2) / logfreq=50;
   num f1sol {1.._NSOL_};
   num f2sol {1.._NSOL_};
   for {s in 1.._NSOL_} do;
      for {i in 1..2} x[i] = x[i].sol[s];
      f1sol[s] = f1;
      f2sol[s] = f2;
   end;
   create data pareto from [s]=(1.._NSOL_) {i in 1..2} <col('x'||i)=x[i].sol[s]>
      f1=f1sol[s] f2=f2sol[s];
quit;

%put &_OROPTMODEL_;
proc sgplot data=pareto;
   scatter x=f1 y=f2;
run;
```

Output 10.7.1 shows the ODS tables that are produced.

Output 10.7.1 Multiobjective: ODS Tables

The OPTMODEL Procedure

Problem Summary	
Number of Objectives	2
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2
Free	0
Fixed	0
Number of Constraints	0
Constraint Coefficients	0

Solution Summary	
Solver	Black-Box
Objective Function	(MULTIPLE)
Solution Status	Function Convergence
Nondominated Solutions	4932
Progress	7.0494933E-7
Infeasibility	0
Random Seed Used	1
Evaluations	22734
Cached Evaluations	139
Iterations	428
Presolve Time	0.00
Solution Time	6.53

Output 10.7.2 shows the iteration log.

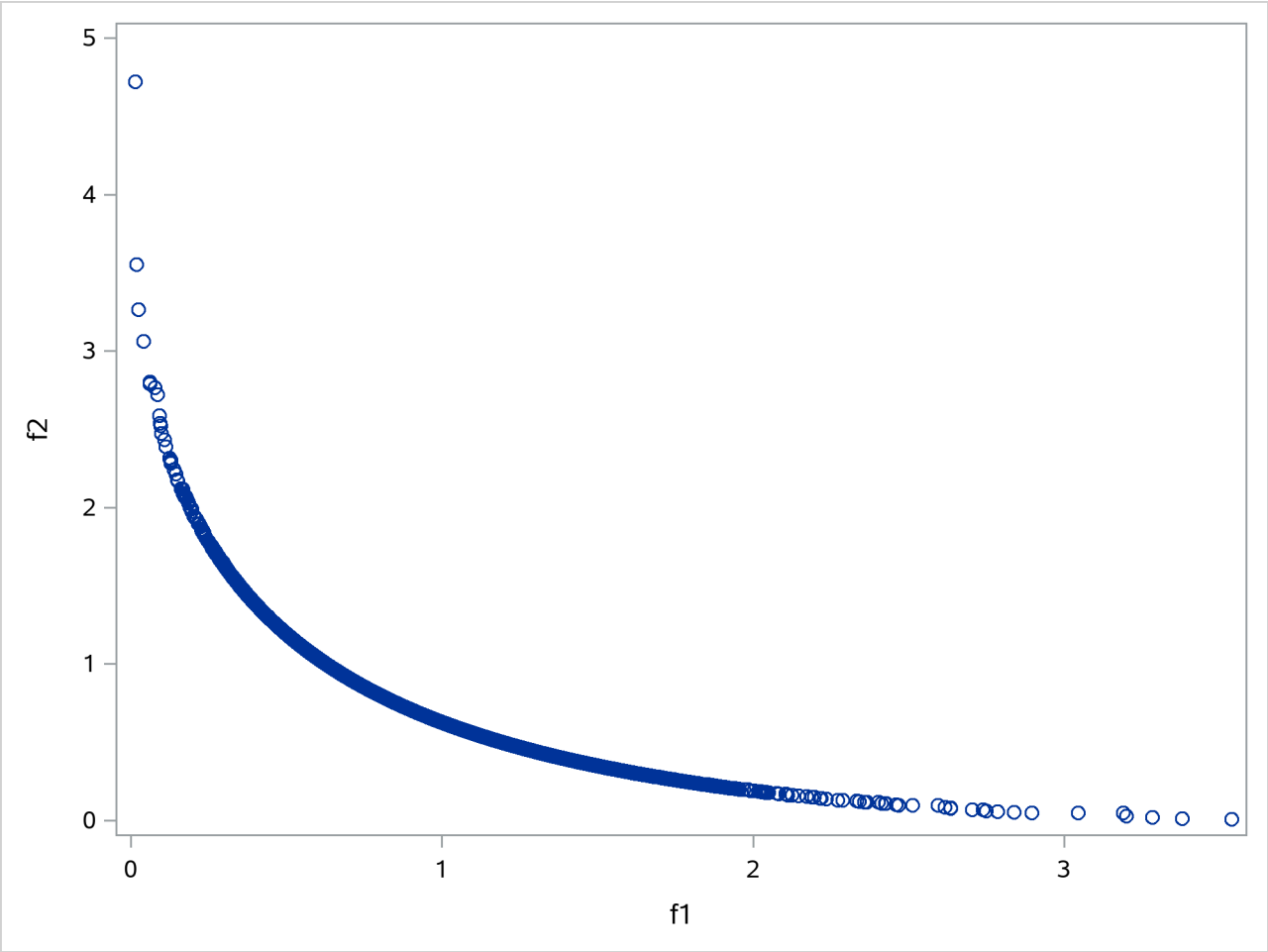
Output 10.7.2 Multiobjective: Log

```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 2 variables (0 free, 0 fixed).
NOTE: The problem has 0 linear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: The Black-Box solver is using up to 16 threads.
NOTE: The Black-Box solver is using the EAGLS optimizer algorithm.
NOTE: The problem has 2 variables (0 integer, 2 continuous).
NOTE: The problem has 0 constraints (0 linear, 0 nonlinear).
NOTE: The problem has 2 user-defined functions.
NOTE: The deterministic parallel mode is enabled.
        Iteration    Nondom        Progress    Infeasibility    Evals     Time
                1         4               .                0       84        0
               51       877       0.0000811                0     2876        0
              101      1654       0.0000123                0     5576        1
              151      2290  0.000003230545                0     8181        1
              201      2874       0.0000182                0    10796        2
              251      3422  0.000003148003                0    13447        3
              301      3847  0.000001559509                0    16046        4
              351      4282  0.000001159917                0    18733        5
              401      4712  0.000002423149                0    21315        6
              428      4932  0.000000704949                0    22734        6
NOTE: Function convergence criteria reached.
NOTE: The data set WORK.PARETO has 4932 observations and 5 variables.

STATUS=OK SOLUTION_STATUS=ABSFCONV OBJECTIVE=. NONDOMINATED=4932
PROGRESS=7.0494933E-7 INFEASIBILITY=0 EVALUATIONS=22734 ITERATIONS=428

PRESOLVE_TIME=0.00 SOLUTION_TIME=6.53
```

When you are solving a multiobjective problem that contains two objectives, it can be helpful to use PROC SGPLOT to create a plot of the Pareto-optimal set that the black-box solver finds.

Output 10.7.3 shows a plot of the Pareto-optimal set that the black-box solver finds.

Output 10.7.3 Multiobjective: Plot of Pareto-Optimal Set



References

Bowman, K. O., and Shenton, L. R. (1983). "Johnson's System of Distributions." In *Encyclopedia of Statistical Sciences*, vol. 4, edited by S. Kotz, N. L. Johnson, and C. B. Read. New York: John Wiley & Sons.

Coello Coello, C. A., and Cruz Cortes, N. (2005). "Solving Multiobjective Optimization Problems Using an Artificial Immune System." *Genetic Programming and Evolvable Machines* 6:163–190.

Custódio, A. L., Madeira, J. F. A., Vaz, A. I. F., and Vicente, L. N. (2011). "Direct Multisearch for Multiobjective Optimization." *SIAM Journal on Optimization* 21:1109–1140.

Floudas, C. A., and Pardalos, P. M. (1992). *Recent Advances in Global Optimization*. Princeton, NJ: Princeton University Press.

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. Reading, MA: Addison-Wesley.

Gray, G. A., and Fowler, K. R. (2011). "The Effectiveness of Derivative-Free Hybrid Methods for Black-Box Optimization." *International Journal of Mathematical Modeling and Numerical Optimization* 2:112–133.

Gray, G. A., Fowler, K. R., and Griffin, J. D. (2010). "Hybrid Optimization Schemes for Simulation-Based Problems." *Procedia Computer Science* 1:1349–1357.

Gray, G. A., and Kolda, T. G. (2006). "Algorithm 856: APPSPACK 4.0—Asynchronous Parallel Pattern Search for Derivative-Free Optimization." *ACM Transactions on Mathematical Software* 32:485–507.

Griffin, J. D., Fowler, K. R., Gray, G. A., and Hemker, T. (2011). "Derivative-Free Optimization via Evolutionary Algorithms Guiding Local Search (EAGLS) for MINLP." *Pacific Journal of Optimization* 7:425–443.

Griffin, J. D., and Kolda, T. G. (2010a). "Asynchronous Parallel Hybrid Optimization Combining DIRECT and GSS." *Optimization Methods and Software* 25:797–817.

Griffin, J. D., and Kolda, T. G. (2010b). "Nonlinearly Constrained Optimization Using Heuristic Penalty Methods and Asynchronous Parallel Generating Set Search." *Applied Mathematics Research Express* 2010:36–62.

Griffin, J. D., Kolda, T. G., and Lewis, R. M. (2008). "Asynchronous Parallel Generating Set Search for Linearly Constrained Optimization." *SIAM Journal on Scientific Computing* 30:1892–1924.

Haverly, C. A. (1978). "Studies of the Behavior of Recursion for the Pooling Problem." *SIGMAP Bulletin, Association for Computing Machinery* 25:19–28.

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Ann Arbor: University of Michigan Press.

Hough, P. D., Kolda, T. G., and Patrick, H. A. (2000). *Usage Manual for APPSPACK 2.0*. Technical Report SAND2000-8843, Sandia National Laboratories, Albuquerque, NM, and Livermore, CA.

Huband, S., Hingston, P., Barone, L., and While, L. (2006). "A Review of Multiobjective Test Problems and a Scalable Test Problem Toolkit." *IEEE Transactions on Evolutionary Computation* 10:477–506.

Jones, D. R., Perttunen, C. D., and Stuckman, B. E. (1993). "Lipschitzian Optimization without the Lipschitz Constant." *Journal of Optimization Theory and Applications* 79:157–181.

Kolda, T. G., Lewis, R. M., and Torczon, V. (2003). "Optimization by Direct Search: New Perspectives on Some Classical and Modern Methods." *SIAM Review* 45:385–482.

Liebman, J., Lasdon, L., Schrage, L., and Waren, A. (1986). *Modeling and Optimization with GINO*. Redwood City, CA: Scientific Press.

Michalewicz, Z. (1996). *Genetic Algorithms + Data Structures = Evolution Programs*. New York: Springer-Verlag.

Moré, J. J., Garbow, B. S., and Hillstrom, K. E. (1981). "Testing Unconstrained Optimization Software." *ACM Transactions on Mathematical Software* 7:17–41.

Plantenga, T. (2009). *HOPSPACK 2.0 User Manual (v 2.0.2)*. Technical report, Sandia National Laboratories.

Schütze, O., Esquivel, X., Lara, A., and Coello Coello, C. A. (2012). "Using the Averaged Hausdorff Distance as a Performance Measure in Evolutionary Multiobjective Optimization." *IEEE Transactions on Evolutionary Computation* 16:504–522. http://dx.doi.org/10.1109/TEVC.2011.2161872.

Taddy, M. A., Lee, H. K. H., Gray, G. A., and Griffin, J. D. (2009). "Bayesian Guided Pattern Search for Robust Local Optimization." *Technometrics* 51:389–401.

Van Veldhuizen, D. A. (1999). "Multiobjective Evolutionary Algorithms: Classifications, Analyses, and New Innovations." Ph.D. diss., Air Force Institute of Technology.

Chapter 11
The Conic Optimization Solver

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Overview: Conic Optimization Solver

The OPTMODEL procedure provides a framework for specifying and solving conic optimization problems. A conic optimization problem has the following formulation:

$$\begin{array}{rl} \min & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x} = \mathbf{b} \\ & \mathbf{x} \in \mathcal{K} \end{array}$$

where $\mathcal{K}$ is the Cartesian product of several cones. For most real-life applications, only three types of cones need to be considered:

- nonnegative orthant
- second-order cone
- positive semidefinite cone

The cone constraints can be any combination of these three basic types of cones. The resulting feasible region is a convex set, making it possible to solve efficiently for a globally optimal solution up to a very large size.

In conic optimization, data are provided in linear programming format. Cone structure is defined on a set of variables, independent of values of data. This separation between data and structure enables conic problems to be represented in a concise way. By limiting structure on three types of cones as building blocks, conic optimization does not need complicated functions to describe objective and constraints. This is a big advantage over general nonlinear optimization.

The crucial advantage of conic optimization is that it has a well-defined closed-form dual problem, and hence it has well-developed duality theory and convergence theory, as well as practically efficient algorithms.

Details about cones that can be solved by the conic optimization solver are provided in the following sections.

Nonnegative Orthant

A nonnegative orthant, $\{\mathbf{x} \in \mathbb{R}^n \mid x_1 \geq 0, \ldots, x_n \geq 0\}$, is sometimes called a linear cone. If only nonnegative orthants are presented, a conic optimization problem is reduced to a linear programming (LP) problem. The theory and algorithms for LP can be easily extended to quadratic programming (QP). Because LP and QP problems are so important, the OPTMODEL procedure has dedicated chapters for them. For more information, see Chapter 13, "The Linear Programming Solver," and Chapter 17, "The Quadratic Programming Solver."

Second-Order Cone

A second-order cone (SOC) is defined as

$$\left\{ \mathbf{x} \in \mathbb{R}^n \mid x_1^2 \geq x_2^2 + x_3^2 + \cdots + x_n^2,\ x_1 \geq 0 \right\}$$

The second-order cone is also known as the quadratic cone, ice cream cone, or Lorentz cone.

A rotated second-order cone (RSOC) is defined as

$$\left\{ \mathbf{x} \in \mathbb{R}^n \mid 2x_1x_2 \geq x_3^2 + x_4^2 + \cdots + x_n^2,\ x_1, x_2 \geq 0 \right\}$$

As the name indicates, there is a simple relationship between second-order and rotated second-order cones. Define an orthogonal transformation

$$T = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & I_{n-2} \end{bmatrix}$$

This transformation corresponds to a rotation of $\frac{\pi}{4}$ radians in the (x_1, x_2) plane. If $\mathbf{x}$ is in a second-order cone, then $T\mathbf{x}$ is in a rotated second-order cone, and vice versa.

If cone structure is a combination of nonnegative orthants, second-order cones, and rotated second-order cones, then this conic problem is called a second-order cone programming (SOCP) problem.

Quadratically Constrained Quadratic Programming

In a quadratically constrained quadratic programming (QCQP) problem, both the objective function and any constraint can be quadratic functions. The problem has the following formulation:

$$\begin{array}{rl} \min & \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}_0\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}_i\mathbf{x} + \mathbf{a}_i^{\mathrm{T}}\mathbf{x} \leq b_i, \quad i = 1, \ldots, m \end{array}$$

If all $\mathbf{Q}_i$ are positive semidefinite, a QCQP problem is a convex optimization problem. The conic solver automatically transforms each quadratic function into a rotated second-order cone and some additional linear constraints. Even though QCQP problems have no explicit cone structure, the conic solver can solve them as a special type of SOCP problem. For more information, see the section "Quadratically Constrained Quadratic Programming (QCQP)" on page 556.

Conic Transformation

Other than standard forms, many nonlinear function families can be formulated in conic forms, usually through the introduction of additional variables and constraints. The resulting reformulated problems can be solved by the conic solver. The OPTMODEL procedure provides convenient ways to detect these nonlinear function families and perform transformation automatically. For more information, see Chapter 9, "The OPTMODEL Procedure."

Getting Started: Conic Optimization Solver

The example in this section illustrates how you can use the OPTMODEL procedure to solve conic optimization problems. Suppose you want to solve the following second-order cone problem:

$$
\begin{aligned}
\min \quad & 5x_1 + x_4 + x_5 + x_6 \\
\text{subject to} \quad & -3x_3 + x_4 + x_5 \geq 0 \\
& x_3 - 0.1x_5 - 0.25x_6 \geq 0 \\
& x_4 + x_5 + x_6 \geq 2 \\
& x_2 = 0.5 \\
& 2x_1x_2 \geq x_3^2 + x_4^2 \\
& x_1, x_2, x_4 \geq 0 \\
& 0.2 \leq x_3 \leq 1 \\
& 0 \leq x_5, x_6 \leq 1
\end{aligned}
$$

The fifth constraint is a rotated second-order cone that is defined on the variables x_1, x_2, x_3, and x_4. This cone constraint together with the fourth constraint transforms the following general nonlinear constraint into a second-order cone programming formulation:

$$x_1 \geq x_3^2 + x_4^2$$

You can use the following statements to call the OPTMODEL procedure to solve this SOCP problem:

```
/* getting started example for conic solver */
proc optmodel;
   /* declare variables */
   var x {1..6} >= 0;

   /* objective function */
   min Z = 5*x[1] + x[4] + x[5] + x[6];

   /* linear constraints */
   con c1: -3*x[3] + x[4] + x[5] >= 0;
   con c2: x[3] - 0.1*x[5] - 0.25*x[6] >= 0;
   con c3: x[4] + x[5] + x[6] >= 2;
   con c4: x[2] = 0.5;
```

```
    /* rotated second-order cone constraint */
    con cone: rsoc(x[1], x[2], x[3] x[4]);

    /* bounds on variables */
    x[3].lb = 0.2;
    x[3].ub = 1;
    for{i in 5..6} x[i].ub = 1;

    /* specify conic solver */
    solve with conic;

    /* print optimal primal solution and dual cone solution */
    print x x.dcone;
  quit;
```

The output and optimal solution are displayed in Figure 11.1. The dual cone values are returned in each *variable.dcone* suffix.

Figure 11.1 Summaries and Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	Z
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	3
Bounded Below and Above	3
Free	0
Fixed	0
Number of Constraints	5
Linear LE (<=)	0
Linear EQ (=)	1
Linear GE (>=)	3
Linear Range	0
Rotated Second-Order Cone	1

Figure 11.1 *continued*

Solution Summary	
Solver	Conic
Algorithm	Interior Point
Objective Function	Z
Solution Status	Optimal
Objective Value	2.576470543
Primal Infeasibility	2.7662483E-8
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	4.6776548E-8
Complementarity	6.4866402E-8
Iterations	8
Presolve Time	0.00
Solution Time	0.00

[1]	x	x.DCONE
1	0.115294	5.00000
2	0.500000	1.15348
3	0.329415	-3.29488
4	0.082341	-0.82372
5	1.000000	.
6	0.917659	.

The iteration log that displays problem statistics, the progress of the solution, and the optimal objective value is shown in Figure 11.2.

Figure 11.2 Log

```
NOTE: Problem generation will use 4 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (0 LE, 1 EQ, 3 GE, 0 range).
NOTE: The problem has 10 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 1 predicate constraints.
NOTE: The conic presolver value AUTOMATIC is applied.
NOTE: The conic presolver removed 0 variables and 1 constraints.
NOTE: The conic presolver removed 1 constraint coefficients.
NOTE: The presolved problem has 6 variables, 4 constraints, and 11 constraint
      coefficients.
NOTE: The presolved problem has 1 second-order cone constraints.
NOTE: The conic solver is called.
NOTE: The Interior Point algorithm is used.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Interior Point algorithm is using up to 4 threads.
                                      Primal       Bound        Dual
      Iter  Complement Duality Gap      Infeas      Infeas      Infeas   Time
         0  1.2000E+01  6.3355E+00  1.1554E+00  9.5998E-01  9.9645E-01      0
         1  6.2502E+00  2.3692E+00  4.3206E-01  3.5899E-01  3.7262E-01      0
         2  1.9365E+00  6.9667E-01  1.7791E-01  1.4782E-01  1.5344E-01      0
         3  2.1123E-01  8.1739E-02  3.4021E-02  2.8266E-02  2.9340E-02      0
         4  5.8675E-02  2.5400E-02  1.1679E-02  9.7038E-03  1.0072E-02      0
         5  4.5766E-03  2.0031E-03  9.3971E-04  7.8077E-04  8.1043E-04      0
         6  2.0916E-04  9.2153E-05  4.3295E-05  3.5972E-05  3.7339E-05      0
         7  1.6809E-05  7.4083E-06  3.4809E-06  2.8921E-06  3.0020E-06      0
         8  2.2432E-07  9.8865E-08  4.6453E-08  3.8596E-08  4.0062E-08      0
NOTE: Optimal.
NOTE: Objective = 2.576470543.
NOTE: The Interior Point solve time is 0.00 seconds.
```

Syntax: Conic Optimization Solver

The following statement is available in the OPTMODEL procedure:

SOLVE WITH CONIC < / *options* > **;**

Functional Summary

Table 11.1 summarizes the list of options available in the SOLVE WITH CONIC statement, classified by function.

Table 11.1 Options for the Conic Solver

Description	Option
Presolver Option	
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the feasibility tolerance	FEASTOL=
Specifies the frequency of printing solution progress	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the optimality tolerance	OPTTOL=
Specifies units of CPU time or real time	TIMETYPE=
Parallel Option	
Specifies the maximum number of threads	NTHREADS=

Conic Solver Options

The conic solver recognizes a number of options. You can specify these options after a forward slash (/) in the SOLVE statement, provided that you explicitly specify the conic solver by using a WITH clause.

The conic solver does not provide an intermediate solution if the solver terminates before reaching optimality.

Presolver Option

PRESOLVER=AUTOMATIC | **NONE** | **BASIC** | **MODERATE** | **AGGRESSIVE**

specifies the level of presolve processing. You can specify the following values:

AUTOMATIC applies the presolver by using the default settings. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER= AGGRESSIVE, but in a reasonable time.

NONE disables the presolver. Only the necessary problem transformation steps are performed.

BASIC performs a basic presolve, such as removing empty rows, columns, and fixed variables. Only some very fast operations are performed.

MODERATE performs a basic presolve and applies other inexpensive presolve techniques. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

AGGRESSIVE performs a moderate presolve and applies other aggressive (but computationally expensive) presolve techniques. All the presolver techniques are called with no limits. This reduces the problem the most, but it can take a very long time.

By default, PRESOLVER=AUTOMATIC.

Control Options

FEASTOL=ϵ

specifies the maximum allowed relative violation on constraints, including primal constraints, bound constraints, and dual constraints. Cone constraints are considered as part of the primal constraints. Because the conic solver applies primal-dual algorithms, primal feasibility and dual feasibility are controlled by the same option. The allowed range for ϵ is [1E–9, 1E–4]. By default, FEASTOL=1E–6. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

LOGFREQ=*k*

prints the solution progress to the iteration log after every k iterations. The print frequency, k, is an integer between 0 and the largest four-byte signed integer, which is $2^{31} - 1$. The value $k = 0$ disables the printing of the solution progress. By default, LOGFREQ=1.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that the conic solver displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXITER=*k*

specifies the maximum number of iterations. The value k can be any integer between 1 and the largest four-byte signed integer, which is $2^{31} - 1$. If you omit this option, the procedure does not stop on the basis of the number of iterations performed.

MAXTIME=*t*

specifies an upper limit of *t* units of time for the optimization process, including problem generation time and solution time. The value of the TIMETYPE= option determines the type of units that are used. If you omit the MAXTIME= option, the solver does not stop on the basis of the amount of time elapsed. The value of *t* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

OPTTOL=ϵ

specifies the maximum allowed relative violation on duality gap and complementarity, $\epsilon \in$ [1E–9, 1E–4]. By default, OPTTOL=1E–6. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

TIMETYPE=CPU | REAL

specifies the units of time that are used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMODEL_ macro variable. You can specify the following values:

CPU specifies units of CPU time.

REAL specifies units of real time.

By default, TIMETYPE=REAL.

Parallel Option

NTHREADS=*k*

specifies the maximum number of threads for the conic solver to use for multithreaded processing. The value of *k* can be any integer between 1 and 256, inclusive. The default is the value of the NTHREADS= option in PROC OPTMODEL.

Specifying *k* as a number greater than the actual number of available cores might result in reduced performance. Specifying a high *k* value does not guarantee a shorter solution time; the actual change in solution time depends on the computing hardware and the scalability of the underlying algorithms in the conic solver. In some circumstances, the conic solver might use fewer than *k* threads because the solver has determined that a smaller number of threads is preferable.

Predicates

A predicate asserts a fact about its subject. The OPTMODEL procedure accepts a set of predefined functions as constraints. Each of these functions can be specified by a predicate identifier in a constraint declaration. For more information about predicates, see the section "Predicates" on page 578 in Chapter 12, "The Constraint Programming Solver."

You can specify the following predicates for the conic solver:

SOC specifies a second-order cone.

RSOC specifies a rotated second-order cone.

Common Syntax Components

The following syntax components are used in multiple predicates. They depend on the definition of an *identifier-expression*. For more information, see the section "Identifier Expressions" on page 383 in Chapter 9, "The OPTMODEL Procedure."

variable-item
: is a single element of variable data. It can resolve to a variable, a linear expression, or a constant numeric value.

variable-list
: is a space-separated list of *variable-items*. The values from the items are juxtaposed in a single list. If an item is a linear expression, it should be enclosed in parentheses.

SOC Predicate

SOC(*variable-item***,** *variable-list***)**
SOCONE(*variable-item***,** *variable-list***)**

Even though a second-order cone can be defined as a general constraint in its quadratic function format, it is more convenient to consider a second-order cone as a list of variables. Then use an SOC predicate in constraint declaration. For example, a second-order cone

$$x_1^2 \geq x_2^2 + x_3^2 + x_5^2, \quad x_1 \geq 0$$

can be defined as any one of the following predicates:

```
con soc1: soc(x[1], x[2] x[3] x[5]);
con soc2: soc(x[1], x[2] x[5] x[3]);
con soc3: soc(x[1], {i in 2..3} x[i] x[5]);
```

Any item in an SOC predicate can be a linear function. The SOC predicate

```
con soc4: soc(2*x[1]+3*x[2], (5*x[2]-1) 2);
```

defines a second-order cone:

$$\begin{aligned} & y_1^2 \geq y_2^2 + y_3^2, \quad y_1 \geq 0 \\ & y_1 = 2x_1 + 3x_2 \\ & y_2 = 5x_2 - 1 \\ & y_3 = 2 \end{aligned}$$

RSOC Predicate

RSOC(*variable-item1***,** *variable-item2***,** *variable-list***)**
RSOCONE(*variable-item1***,** *variable-item2***,** *variable-list***)**

This predicate defines a rotated second-order cone. For example, the rotated second-order cone

$$2x_1x_5 \geq x_2^2 + x_3^2, \quad x_1, x_5 \geq 0$$

can be defined as any one of the following predicates:

```
con rsoc1: rsoc(x[1], x[5], x[2] x[3]);
con rsoc2: rsoc(x[5], x[1], x[2] x[3]);
con rsoc3: rsoc(x[1], x[5], {i in 2..3} x[i]);
```

Any item in an RSOC predicate can be a linear function. The RSOC predicate

```
con rsoc4: rsoc(x[1], 1.0, (2*x[2]-1) (3*x[2]+5));
```

defines a rotated second-order cone:

$$
\begin{aligned}
2x_1 y_1 \geq y_2^2 + y_3^2, \quad & x_1, y_1 \geq 0 \\
y_1 &= 1.0 \\
y_2 &= 2x_2 - 1 \\
y_3 &= 3x_2 + 5
\end{aligned}
$$

Details: Conic Optimization Solver

Interior Point Algorithm: Overview

The conic optimization solver implements primal-dual interior point methods (also referred to as IPM or barrier methods) algorithm. A conic optimization problem has the following standard formulation (the primal):

$$
\begin{aligned}
\min \quad & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\
\text{subject to} \quad & \mathbf{A}\mathbf{x} = \mathbf{b} \\
& \mathbf{x} \in \mathcal{K}
\end{aligned}
$$

The corresponding dual formulation is as follows:

$$
\begin{aligned}
\max \quad & \mathbf{b}^{\mathrm{T}}\mathbf{y} \\
\text{subject to} \quad & \mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{s} = \mathbf{c} \\
& \mathbf{s} \in \mathcal{K}
\end{aligned}
$$

where $\mathcal{K}$ is any of the three types of cones: nonnegative orthant, second-order cone, or positive semidefinite cone. These cones are self-dual, which means that for any of these three types of cones, its dual cone is of the same type and has the same dimension.

The constraints in the primal problem and dual problem, combined with complementarity conditions, define the first-order optimality conditions, also known as KKT (Karush-Kuhn-Tucker) conditions. These can be stated as follows:

$$
\begin{aligned}
\mathbf{A}\mathbf{x} &= \mathbf{b} && \text{(primal feasibility)} \\
\mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{s} &= \mathbf{c} && \text{(dual feasibility)} \\
\mathbf{x} \circ \mathbf{s} &= \mathbf{0} && \text{(complementarity)} \\
\mathbf{x}, \mathbf{s} &\in \mathcal{K}
\end{aligned}
$$

The binary operator "$\circ$" denotes multiplication of two points in the same cone. The actual meaning of this operator differs, depending on the type of cone, which significantly affects the construction of interior point algorithms. More detailed information about this operator is provided in the following sections.

One type of IPM algorithm applies Newton's method to solve the Karush-Kuhn-Tucker (KKT) system. This type of algorithm has good performance in solving large-scale problems if optimal solutions exist. However, it has difficulty detecting infeasibility or unboundedness.

To alleviate this shortcoming, another type of IPM algorithm solves the following homogeneous self-dual (HSD) model:

$$\begin{aligned}
\mathbf{A}\mathbf{x} &= \mathbf{b}\tau \\
\mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{s} &= \mathbf{c}\tau \\
-\mathbf{c}^{\mathrm{T}}\mathbf{x} + \mathbf{b}^{\mathrm{T}}\mathbf{y} &= \kappa \\
\mathbf{x} \circ \mathbf{s} &= \mathbf{0} \\
\tau \cdot \kappa &= 0 \\
\mathbf{x},\, \mathbf{s} &\in \mathcal{K} \\
\tau,\, \kappa &\geq 0
\end{aligned}$$

The HSD model increases both primal space and dual space by one dimension. Its solution can be easily transformed to an optimal solution of the original problem, or to prove infeasibility or unboundedness. However, the computational cost is slightly higher. One more linear system of equations needs to be solved in each iteration.

The conic solver implements Mehrotra's predictor-corrector scheme on either the KKT system or the HSD model. In both cases, the conic solver needs to solve a series of linear systems in the format

$$\begin{bmatrix} -\mathbf{H} & \mathbf{A}^{\mathrm{T}} \\ \mathbf{A} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{y} \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \end{bmatrix}$$

or alternatively in the format

$$\mathbf{A}\mathbf{D}\mathbf{A}^{\mathrm{T}}\Delta\mathbf{y} = \mathbf{r}$$

where the matrix $\mathbf{H}$ or $\mathbf{D}$ depends on cone type and algorithm construction.

The interior point algorithm works simultaneously in the primal and dual spaces. It attains optimality when both primal and dual feasibility are achieved and when complementarity conditions hold. Therefore, it is of interest to observe the following four measures, where $\|\mathbf{v}\|_2$ is the Euclidean norm of the vector $\mathbf{v}$:

- relative primal infeasibility measure:

$$\alpha = \frac{\|\mathbf{A}\mathbf{x} - \mathbf{b}\|_2}{\|\mathbf{b}\|_2 + 1}$$

- relative dual infeasibility measure:

$$\beta = \frac{\|\mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{s} - \mathbf{c}\|_2}{\|\mathbf{c}\|_2 + 1}$$

- relative duality gap:

$$\delta = \frac{|\mathbf{c}^{\mathrm{T}}\mathbf{x} - \mathbf{b}^{\mathrm{T}}\mathbf{y}|}{|\mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

- relative complementarity:

$$\gamma = \frac{\mathbf{x}^{\mathrm{T}}\mathbf{s} + \tau\kappa}{|\mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

These measures are displayed in the iteration log.

Nonnegative Orthant

If only nonnegative orthants exist, a conic optimization problem reduces to an LP problem. The cone structure becomes a Cartesian product of individual variable bounds $x_i \geq 0$. The point multiplication in the KKT system is regular real number multiplication. The matrix $\mathbf{H}$ is diagonal.

Second-Order Cone

Given two vectors in an $(n + 1)$-dimensional second-order cone, their multiplication is defined as

$$\mathbf{x} \circ \mathbf{s} = \begin{bmatrix} \mathbf{x}^{\mathrm{T}}\mathbf{s} \\ x_0 s_1 + s_0 x_1 \\ \vdots \\ x_0 s_n + s_0 x_n \end{bmatrix}$$

If you extend LP theory directly to SOCP, then the matrix $\mathbf{H}$ is a complicated formulation and is not symmetric. To achieve polynomial-time complexity proof and satisfying practical performance, the conic solver applies Nesterov-Todd scaling to second-order cones. Given a point $\mathbf{x}$ in a second-order cone and $\mathbf{s}$ in its dual cone, after Nesterov-Todd scaling, $\mathbf{x}$ and $\mathbf{s}$ are the same point, and the matrix $\mathbf{H}$ is positive semidefinite.

Quadratically Constrained Quadratic Programming (QCQP)

The conic solver solves only convex optimization problems. If the problem is to minimize the objective function, then the quadratic matrix $\mathbf{Q}_0$ must be positive semidefinite. If the objective function is not convex, the conic solver returns a NONCONVEX status and exits. Similarly, if the problem is to maximize the objective function, then the quadratic matrix $\mathbf{Q}_0$ must be negative semidefinite. Otherwise, the conic solver returns a NONCONCAVE status and exits.

When a QCQP problem has quadratic functions in its constraints, each quadratic constraint must define a convex feasible set. Assume that one quadratic constraint is in its standard format:

$$\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}_i\mathbf{x} + \mathbf{a}_i^{\mathrm{T}}\mathbf{x} \leq b_i$$

Then the quadratic matrix $\mathbf{Q}_i$ being positive semidefinite guarantees that the feasible set is convex. If $\mathbf{Q}_i$ is neither positive nor negative semidefinite, then the feasible set of this quadratic constraint is not convex, and the conic solver returns a NONCONVEX_CON status and exits. However, if the quadratic matrix $\mathbf{Q}_i$ is negative semidefinite, the feasible set can still be convex under certain conditions, such as $\mathbf{a}_i = \mathbf{0}$ and $b_i \geq 0$.

When a QCQP problem is a convex optimization problem, it can be written in standard format, where all $\mathbf{Q}_i$, $i = 0, \ldots, m$, are symmetric and positive semidefinite. Hence, there must exist another matrix $\mathbf{F}_i$ for each i, such that

$$\mathbf{Q}_i = \mathbf{F}_i^T\mathbf{F}_i$$

After this matrix factorization, the quadratic constraint becomes

$$\frac{1}{2}\|\mathbf{F}_i\mathbf{x}\|^2 + \mathbf{a}_i^{\mathrm{T}}\mathbf{x} \le b_i$$

With proper variable substitution, this constraint is equivalent to

$$\begin{aligned}&\mathbf{F}_i\mathbf{x} = \mathbf{s}_i\\&t_i + \mathbf{a}_i^{\mathrm{T}}\mathbf{x} = b_i\\&\mathrm{rsoc}\,(t_i, 1, \{\mathbf{s}_i\})\end{aligned}$$

Similarly, the quadratic objective function can be replaced by the linear objective function

$$\min \quad t_0 + \mathbf{c}^{\mathrm{T}}\mathbf{x}$$

with the following additional constraints:

$$\begin{aligned}&\mathbf{F}_0\mathbf{x} = \mathbf{s}_0\\&\mathrm{rsoc}\,(t_0, 1, \{\mathbf{s}_0\})\end{aligned}$$

The conic solver automatically performs matrix factorization in an efficient and numerically stable way and then proceeds to solve the resulting SOCP problem.

Iteration Log

The following information is displayed in the iteration log:

Iter	indicates the iteration number.
Complement	indicates the relative complementarity.
Duality Gap	indicates the relative duality gap.
Primal Infeas	indicates the relative primal infeasibility measure.
Bound Infeas	indicates the relative bound infeasibility measure.
Dual Infeas	indicates the relative dual infeasibility measure.
Time	indicates the time elapsed (in seconds).

If the sequence of solutions converges to an optimal solution of the problem, you should see all columns in the iteration log converge to zero or very close to zero. Nonconvergence can result when insufficient iterations are performed to reach optimality. In this case, you might need to increase the value that you specify in the MAXITER= or MAXTIME= option. If the complementarity or the duality gap does not converge, the problem might be infeasible or unbounded. If the infeasibility columns do not converge, the problem might be infeasible.

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTMODEL procedure causes the ODS table ProblemStatistics to be generated when the conic solver is called. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 11.3 demonstrates the contents of the ODS table ProblemStatistics.

Figure 11.3 ODS Table ProblemStatistics

The OPTMODEL Procedure

Problem Statistics	
Number of Constraint Matrix Nonzeros	10
Maximum Constraint Matrix Coefficient	3
Minimum Constraint Matrix Coefficient	0.1
Average Constraint Matrix Coefficient	1.035
Number of Objective Nonzeros	4
Maximum Objective Coefficient	5
Minimum Objective Coefficient	1
Average Objective Coefficient	2
Number of RHS Nonzeros	2
Maximum RHS	2
Minimum RHS	0.5
Average RHS	1.25
Maximum Number of Nonzeros per Column	3
Minimum Number of Nonzeros per Column	0
Average Number of Nonzeros per Column	1.67
Maximum Number of Nonzeros per Row	3
Minimum Number of Nonzeros per Row	1
Average Number of Nonzeros per Row	2.50

Macro Variable _OROPTMODEL_

The OPTMODEL procedure always creates and initializes a SAS macro called _OROPTMODEL_. The macro variable contains a character string. After each PROC OPTMODEL run, you can examine this macro by specifying `%put &_OROPTMODEL_;` and check the execution of the most recently invoked solver from the value of the macro variable. The various terms of the variable after the conic solver is called are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data were inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
SEMANTIC_ERROR	An evaluation error occurred, such as an invalid operand type.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates which algorithm produced the solution data in the macro variable. This term appears only when STATUS=OK. It always takes the following value for the conic solver:

IP	The interior point algorithm produced the solution data.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The solution is optimal, but some infeasibilities (primal, dual, or bound) exceed tolerances because of scaling or preprocessing.
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
NONCONVEX	The quadratic matrix in the objective function is nonconvex (minimization).
NONCONCAVE	The quadratic matrix in the objective function is nonconcave (maximization).
NONCONVEX_CON	At least one quadratic constraint defines a nonconvex feasible set.
BAD_PROBLEM_TYPE	The problem type is unsupported by the solver.

ITERATION_LIMIT_REACHED	The solver reached its maximum allowable number of iterations.
TIME_LIMIT_REACHED	The solver reached its execution time limit.
FUNCTION_CALL_LIMIT_REACHED	The solver reached its limit on function evaluations.
INTERRUPTED	The solver was interrupted externally.
FAILED	The solver failed to converge, possibly because of numerical issues.

OBJECTIVE
indicates the objective value that the solver obtained at termination.

PRIMAL_INFEASIBILITY
indicates the relative violation of the primal constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

DUAL_INFEASIBILITY
indicates the relative violation of the dual constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

BOUND_INFEASIBILITY
indicates the relative violation of the lower or upper bounds (or both) at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

DUALITY_GAP
indicates the relative duality gap at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

COMPLEMENTARITY
indicates the relative complementarity at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 554.

ITERATIONS
indicates the number of iterations that are required in order to solve the problem.

PRESOLVE_TIME
indicates the time (in seconds) taken for preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time that is reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

When SOLUTION_STATUS has a value of OPTIMAL or CONDITIONAL_OPTIMAL, all terms of the _OROPTMODEL_ macro variable are present; for other values of SOLUTION_STATUS, some terms do not appear.

Examples: Conic Optimization Solver

Example 11.1: Portfolio Optimization

This example is shown as a quadratic programming problem in "Example 17.2: Portfolio Optimization" on page 1025 in Chapter 17, "The Quadratic Programming Solver." It is included here to show how to transform a QP problem into an SOCP problem.

Consider a portfolio optimization example. The two competing goals of investment are (1) long-term growth of capital and (2) low risk. A good portfolio grows steadily without wild fluctuations in value. The Markowitz model is an optimization model for balancing the return and risk of a portfolio. The decision variables are the amounts that are invested in each asset. The objective is to minimize the variance of the portfolio's total return, subject to the constraints that (1) the expected growth of the portfolio reaches at least some target level and (2) you do not invest more capital than you have.

Let $x_1, \ldots, x_n$ be the amount that is invested in each asset, $\mathcal{B}$ be the amount of capital that you have, $\mathbf{R}$ be the random vector of asset returns over some period, and $\mathbf{r}$ be the expected value of $\mathbf{R}$. Let G be the minimum growth that you hope to obtain and $\mathcal{C}$ be the covariance matrix of $\mathbf{R}$. The objective function is $\mathrm{Var}\left(\sum_{i=1}^{n} x_i R_i\right)$, which can be equivalently denoted as $\mathbf{x}^{\mathrm{T}}\mathcal{C}\mathbf{x}$.

Assume, for example, $n = 4$. Let $\mathcal{B} = 10{,}000$, $G = 1{,}000$, $\mathbf{r} = [0.05, -0.2, 0.15, 0.30]$, and

$$\mathcal{C} = \begin{bmatrix} 0.08 & -0.05 & -0.05 & -0.05 \\ -0.05 & 0.16 & -0.02 & -0.02 \\ -0.05 & -0.02 & 0.35 & 0.06 \\ -0.05 & -0.02 & 0.06 & 0.35 \end{bmatrix}$$

The QP formulation can be written as

$$\begin{aligned} \min \quad & 0.08x_1^2 - 0.1x_1x_2 - 0.1x_1x_3 - 0.1x_1x_4 + 0.16x_2^2 \\ & -0.04x_2x_3 - 0.04x_2x_4 + 0.35x_3^2 + 0.12x_3x_4 + 0.35x_4^2 \end{aligned}$$

$$\begin{array}{lrcl} \text{subject to} & & & \\ \text{(budget)} & x_1 + x_2 + x_3 + x_4 & \leq & 10000 \\ \text{(growth)} & 0.05x_1 - 0.2x_2 + 0.15x_3 + 0.30x_4 & \geq & 1000 \\ & x_1,\ x_2,\ x_3,\ x_4 & \geq & 0 \end{array}$$

Because the covariance matrix $\mathcal{C}$ is positive semidefinite, there exists a matrix $\mathcal{F}$ such that

$$\mathcal{C} = \mathcal{F}^{\mathrm{T}}\mathcal{F}$$

There are some practical ways to decompose a positive semidefinite matrix. For example, if you apply Cholesky decomposition, then

$$\mathcal{F} = \begin{bmatrix} 0.2828427 & -0.1767767 & -0.1767767 & -0.17677670 \\ 0 & 0.3588175 & -0.1428303 & -0.14283027 \\ 0 & 0 & 0.5462138 & 0.01528617 \\ 0 & 0 & 0 & 0.54599986 \end{bmatrix}$$

Then the objective becomes to minimize

$$\mathbf{x}^{\mathrm{T}}\mathcal{C}\mathbf{x} = \|\mathcal{F}\mathbf{x}\|^2$$

By introducing one auxiliary variable, you can write the portfolio optimization problem in the following SOCP formulation:

$$\begin{array}{rrcl}
\min & x_5 & & \\
\text{subject to} & & & \\
\text{(budget)} & x_1 + x_2 + x_3 + x_4 & \leq & 10000 \\
\text{(growth)} & 0.05x_1 - 0.2x_2 + 0.15x_3 + 0.30x_4 & \geq & 1000 \\
\text{(soc)} & \|\mathcal{F}\mathbf{x}\|^2 & \leq & x_5^2 \\
 & x_1,\, x_2,\, x_3,\, x_4,\, x_5 & \geq & 0
\end{array}$$

Use the following SAS statements to solve the problem:

```
/* example 1: portfolio optimization */
proc optmodel;
   /* let x1, x2, x3, x4 be the amount invested in each asset      */
   /* x5 is the auxiliary variable introduced for SOCP formulation */
   var x{1..5} >= 0;

   num r{1..4}=[0.05 -.20 0.15 0.30];

   /* objective function is the auxiliary variable */
   minimize f = x[5];

   /* subject to the following constraints */
   con BUDGET: sum{i in 1..4}x[i] <= 10000;
   con GROWTH: sum{i in 1..4}r[i]*x[i] >= 1000;

   /* second-order cone constraint to
      minimize the variance of the portfolio's total return */
   con cone: soc(x[5],
      (0.2828427*x[1] - 0.1767767*x[2] - 0.1767767*x[3] - 0.17677670*x[4])
                      (0.3588175*x[2] - 0.1428303*x[3] - 0.14283027*x[4])
                                        (0.5462138*x[3] + 0.01528617*x[4])
                                                          (0.54599986*x[4])
   );

   solve with conic;

   /* print the optimal solution */
   print x;
quit;
```

The output and optimal solution are displayed in Output 11.1.1.

Output 11.1.1 Portfolio Optimization

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	5
Bounded Above	0
Bounded Below	5
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Second-Order Cone	1

Solution Summary	
Solver	Conic
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	1494.0927851
Primal Infeasibility	6.2712091E-9
Dual Infeasibility	2.923827E-9
Bound Infeasibility	0
Duality Gap	3.5817563E-7
Complementarity	2.7568982E-7
Iterations	9
Presolve Time	0.00
Solution Time	0.00

[1]	x
1	3452.6
2	0.0
3	1068.8
4	2223.5
5	1494.1

Compared with the QP formulation, the optimal solution that you obtain from solving the SOCP formulation is exactly the same, whereas the optimal objective function value is the square root.

Example 11.2: Geometric Median

This example demonstrates how to solve a second-order cone programming (SOCP) problem. Given a set of m fixed sample points $p_1, p_2, \ldots, p_m$, with each $p_i \in \mathbb{R}^n$, the geometric median is the point that minimizes the sum of distances to the sample points. Equivalently, the geometric median is the solution of the optimization problem

$$\min \sum_{i=1}^{m} \|x - p_i\|$$

This problem has many variants that are studied in many disciplines. In its wide applications it has several names, including the Fermat-Torricelli problem, the Weber problem, the Steiner problem, and the spatial median problem.

The geometric median is a special case of the sum of norms problem. After an auxiliary variable is introduced, each norm in the objective function can be expressed as a second-order cone constraint. Then the unconstrained problem is transformed to

$$\begin{array}{rl} \min & \sum_{i=1}^{m} d_i \\ \text{subject to} & \|x - p_i\|^2 \le d_i^2 \\ & d_i \ge 0 \end{array}$$

Consider the following geometric median problem. A set of three sample points are given in two-dimensional space: $(0, 0)$, $(1, 4)$, and $(3, 2)$. The geometric median of these sample points is the solution to

$$\min \sqrt{x^2 + y^2} + \sqrt{(x-1)^2 + (y-4)^2} + \sqrt{(x-3)^2 + (y-2)^2}$$

The SOCP formulation becomes

$$\begin{array}{rl} \min & d_1 + d_2 + d_3 \\ \text{subject to} & x^2 + y^2 \le d_1^2 \\ & (x-1)^2 + (y-4)^2 \le d_2^2 \\ & (x-3)^2 + (y-2)^2 \le d_3^2 \\ & d_1,\ d_2,\ d_3 \ge 0 \end{array}$$

Use the following SAS statements to solve the problem:

```
/* example 2: geometric median */
proc optmodel;
   /* let (x, y) be the geometric median */
   var x, y;

   /* let d[i] be the distance from geometric median to each sample point */
   var d{1..3} >= 0;

   /* minimize the sum of distances */
   minimize f = sum{i in 1..3}d[i];

   /* sample points */
```

```
    num samples{1..3, 1..2} = [0 0, 1 4, 3 2];

    /* calculate each distance */
    con distance{i in 1..3}: soc(d[i], (x-samples[i,1]) (y-samples[i,2]));
    expand;

    solve with conic;

    /* print the optimal solution */
    print x y;
  quit;
```

The output and optimal solution are displayed in Output 11.2.1.

Output 11.2.1 Geometric Median

The OPTMODEL Procedure

```
Var x
Var y
Var d[1] >= 0
Var d[2] >= 0
Var d[3] >= 0
Minimize f=d[1] + d[2] + d[3]
Constraint distance[1]: SOC(d[1], (x) (y))
Constraint distance[2]: SOC(d[2], (x - 1) (y - 4))
Constraint distance[3]: SOC(d[3], (x - 3) (y - 2))
```

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	5
Bounded Above	0
Bounded Below	3
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	3
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Second-Order Cone	3

Output 11.2.1 *continued*

Solution Summary	
Solver	Conic
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	6.0266492285
Primal Infeasibility	1.6345398E-7
Dual Infeasibility	1.213185E-11
Bound Infeasibility	0
Duality Gap	1.6798442E-8
Complementarity	1.8025407E-7
Iterations	6
Presolve Time	0.00
Solution Time	0.00

x	y
1.7238	2.1853

Example 11.3: Euclidean Distance between Sets

This example demonstrates how to solve a quadratically constrained quadratic programming (QCQP) problem. Let $\mathcal{A}$ and $\mathcal{B}$ be two closed convex sets in $\mathbb{R}^n$. The Euclidean distance between them is defined as the smallest distance between one point in $\mathcal{A}$ and another point in $\mathcal{B}$. You can find the Euclidean distance between these two sets by solving the following optimization problem:

$$\begin{array}{rl} \min & \|a-b\|^2 \\ \text{subject to} & a \in \mathcal{A},\ b \in \mathcal{B} \end{array}$$

Consider the following Euclidean distance problem. Set $\mathcal{A}$ is an ellipse in two-dimensional space. A point in set $\mathcal{A}$ is denoted as (x_1, y_1). Set $\mathcal{B}$ is a polyhedron that is defined by two linear inequalities. A point in set $\mathcal{B}$ is denoted as (x_2, y_2). The QCQP problem is as follows:

$$\begin{array}{rl} \min & (x_1-x_2)^2+(y_1-y_2)^2 \\ \text{subject to} & 3(x_1-2)^2+(y_1-3)^2+2(x_1-2)(y_1-3) \le 5 \\ & x_2+y_2 \le 1 \\ & 2x_2+y_2 \le 0 \end{array}$$

Use the following SAS statements to solve the problem:

```
/* example 3: Euclidean distance between sets */
proc optmodel;
   /* let (x, y) be a point in two-dimensional space */
   var x{1..2}, y{1..2};
```

```
    /* minimize the distance between two points in different sets */
    minimize f = (x[1] - x[2])^2 + (y[1] - y[2])^2;

    /* set A is an ellipse */
    con ellipse: 3*(x[1] - 2)^2 + (y[1] - 3)^2 + 2*(x[1] - 2)*(y[1] - 3) <= 5;

    /* set B is a polyhedron defined by two linear inequalities */
    con line1: x[2] + y[2] <= 1;
    con line2: 2*x[2] + y[2] <= 0;

    solve with conic;

    /* print the optimal solution */
    print x y;
  quit;
```

The output and optimal solution are displayed in Output 11.3.1.

Output 11.3.1 Euclidean Distance between Sets

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	4
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	4
Fixed	0
Number of Constraints	3
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	1
Nonlinear EQ (=)	0
Nonlinear GE (>=)	0
Nonlinear Range	0

Output 11.3.1 *continued*

Solution Summary	
Solver	Conic
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	3.631884584
Primal Infeasibility	1.1715218E-7
Dual Infeasibility	3.4277832E-7
Bound Infeasibility	0
Duality Gap	2.9966075E-8
Complementarity	4.8755354E-7
Iterations	8
Presolve Time	0.00
Solution Time	0.00

[1]	x	y
1	1.08658	2.0882
2	-0.61798	1.2360

References

Alizadeh, F., and Goldfarb, D. (2003). "Second-Order Cone Programming." *Mathematical Programming* 95:3–51.

Andersen, E. D., Gondzio, J., Mészáros, C., and Xu, X. (1996). "Implementation of Interior-Point Methods for Large Scale Linear Programs." In *Interior Point Methods of Mathematical Programming*, edited by T. Terlaky, 189–252. Dordrecht, Netherlands: Kluwer Academic.

Andersen, E. D., Roos, C., and Terlaky, T. (2003). "On Implementing a Primal-Dual Interior-Point Method for Conic Quadratic Optimization." *Mathematical Programming* 95:249–277.

Lobo, M. S., Vandenberghe, L., Boyd, S., and Lebret, H. (1998). "Applications of Second-Order Cone Programming." *Linear Algebra and Its Applications* 284:193–228.

Mehrotra, S. (1992). "On the Implementation of a Primal-Dual Interior Point Method." *SIAM Journal on Optimization* 2:575–601.

Nesterov, Y., and Nemirovskii, A. (1994). *Interior-Point Polynomial Algorithms in Convex Programming*. Philadelphia: SIAM.

Chapter 12
The Constraint Programming Solver

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Overview: CLP Solver

You can use the constraint logic programming (CLP) solver in the OPTMODEL procedure to address finite-domain constraint satisfaction problems (CSPs) that have linear, logical, and global constraints. In addition to providing an expressive syntax for representing CSPs, the CLP solver features powerful built-in consistency routines and constraint propagation algorithms, a choice of nondeterministic search strategies, and controls for guiding the search mechanism. These features enable you to solve a diverse array of combinatorial problems.

Many important problems in areas such as artificial intelligence (AI) and operations research (OR) can be formulated as constraint satisfaction problems. A CSP is defined by a finite set of variables that take values from finite domains and by a finite set of constraints that restrict the values that the variables can simultaneously take.

A solution to a CSP is an assignment of values to the variables in order to satisfy all the constraints. The problem amounts to finding one or more solutions, or possibly determining that a solution does not exist.

A constraint satisfaction problem (CSP) can be defined as a triplet $\langle X, D, C \rangle$:

- $X = \{x_1, \ldots, x_n\}$ is a finite set of *variables*.
- $D = \{D_1, \ldots, D_n\}$ is a finite set of *domains*, where D_i is a finite set of possible values that the variable x_i can take. D_i is known as the *domain* of variable x_i.
- $C = \{c_1, \ldots, c_m\}$ is a finite set of *constraints* that restrict the values that the variables can simultaneously take.

The domains do not need to represent consecutive integers. For example, the domain of a variable could be the set of all even numbers in the interval [0, 100]. In PROC OPTMODEL, variables are always numeric. Therefore, if your problem contains nonnumeric domains (such as colors), you must map the values in the domain to integers. For more information, see "Example 12.5: Car Painting Problem" on page 609.

You can use the CLP solver to find one or more (and in some instances, all) solutions to a CSP that has linear, logical, and global constraints. The numeric components of all variable domains are required to be integers.

Getting Started: CLP Solver

The following examples illustrate the use of the CLP solver in formulating and solving two well-known logical puzzles in constraint programming.

Send More Money

The Send More Money problem consists of finding unique digits for the letters D, E, M, N, O, R, S, and Y such that S and M are different from zero (no leading zeros) and the following equation is satisfied:

$$\begin{array}{r} \text{S E N D} \\ +\text{M O R E} \\ \hline \text{M O N E Y} \end{array}$$

You can use the CLP solver to formulate this problem as a CSP by using an integer variable to represent each letter in the expression. The comments before each statement in the following code introduce variables, domains, and constraints:

```
/*  Send More Money  */

proc optmodel;
   /* Declare all variables as integer. */
   var S integer, E integer, N integer, D integer, M integer, O integer,
       R integer, Y integer;
   /* Set all domains to between 0 and 9. Domains are unbounded by default.
      Always declare domains to be as tight as possible. */
   for {j in 1.._NVAR_} do;
      _VAR_[j].lb = 0;
      _VAR_[j].ub = 9;
   end;
   /* Describe the arithmetic constraint.*/
   con Arithmetic:           1000*S + 100*E + 10*N + D
                 +           1000*M + 100*O + 10*R + E
                 = 10000*M + 1000*O + 100*N + 10*E + Y;
   /* Forbid leading letters from taking the value zero.
      Constraint names are optional. */
   con S ne 0;
   con M ne 0;
   /* Require all variables to take distinct values. */
   con alldiff(S E N D M O R Y);

   solve;
   print S E N D M O R Y;
```

```
quit;
```

The domain of each variable is the set of digits 0 through 9. The VAR statement identifies the variables in the problem. The Arithmetic constraint defines the linear constraint SEND + MORE = MONEY and the restrictions that S and M cannot take the value 0. (Alternatively, you can simply specify the domain for S and M as $\geq 1 \leq 9$ in the VAR statement.) Finally, the ALLDIFF predicate enforces the condition that the assignment of digits should be unique.

The PRINT statement produces the solution output as shown in Figure 12.1.

Figure 12.1 Solution to SEND + MORE = MONEY

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	(0)
Objective Type	Constant
Number of Variables	8
Bounded Above	0
Bounded Below	0
Bounded Below and Above	8
Free	0
Fixed	0
Binary	0
Integer	8
Number of Constraints	4
Linear LE (<=)	0
Linear EQ (=)	1
Linear GE (>=)	0
Linear LT (<)	0
Linear NE (~=)	2
Linear GT (>)	0
Linear Range	0
Alldiff	1
Cumulative	0
Element	0
GCC	0
Lexico (<=)	0
Lexico (<)	0
Pack	0
Reify	0
Constraint Coefficients	10

Figure 12.1 *continued*

Solution Summary	
Solver	CLP
Variable Selection	MINR
Objective Function	(0)
Solution Status	Solution Limit Reached
Objective Value	0
Solutions Found	1
Presolve Time	0.00
Solution Time	0.01

S	E	N	D	M	O	R	Y
9	5	6	7	1	0	8	2

The CLP solver determines the following unique solution to this problem:

$$\begin{array}{r} 9\,5\,6\,7 \\ +\,1\,0\,8\,5 \\ \hline 1\,0\,6\,5\,2 \end{array}$$

Eight Queens

The Eight Queens problem is a special instance of the N-Queens problem, where the objective is to position N queens on an $N \times N$ chessboard such that no two queens can attack each other. The CLP solver provides an expressive constraint for variable arrays that can be used for solving this problem very efficiently.

You can model this problem by using a variable array $\boldsymbol{a}$ of dimension N, where a_i is the row number of the queen in column i. Because no two queens can be in the same row, it follows that all the a_i's must be pairwise distinct.

In order to ensure that no two queens can be on the same diagonal, the following two expressions should be true for all i and j:

$$a_j - a_i <> j - i$$

$$a_j - a_i <> i - j$$

These expressions can be reformulated as follows:

$$a_i - i <> a_j - j$$

$$a_i + i <> a_j + j$$

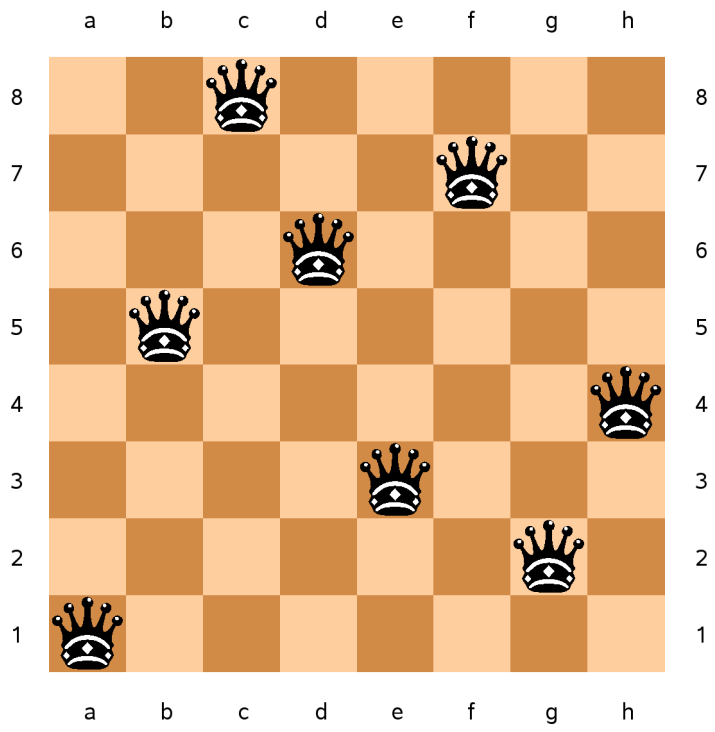
Hence, the $(a_i + i)$'s are pairwise distinct, and the $(a_i - i)$'s are pairwise distinct. One possible formulation is as follows:

```
proc optmodel;
   num n init 8;
   var A {1..n}        >= 1     <= n     integer;
   /* Define artificial offset variables. */
   var B {1..n, -1..1} >= 1 - n <= n + n integer;
   con Bdef {i in 1..n, k in -1..1}:
      B[i,k] = A[i] + k * i;

   con OffsetsMustBeAlldifferent {k in -1..1}:
      alldiff({i in 1..n} B[i,k]);
   solve with CLP / varselect=fifo;
   /* Replicate typical PROC CLP output from an OPTMODEL array */
   create data out from {i in 1..n}<col('A'||i)=A[i]>;
quit;
```

The VARSELECT= option specifies the variable selection strategy to be first-in, first-out—the order in which the CLP solver encounters the variables.

The corresponding solution to the Eight Queens problem is displayed in Figure 12.2.

Figure 12.2 A Solution to the Eight Queens Problem



Syntax: CLP Solver

SOLVE WITH CLP /
< **FINDALLSOLNS** >
< **LOGLEVEL=0 | 1** >
< **MAXSOLNS=***number* >
< **MAXTIME=***number* >
< **NOPREPROCESS** >
< **OBJTOL=***number* >
< **PREPROCESS** >
< **SHOWPROGRESS** >
< **TIMETYPE=***number* | *string* >
< **VARASSIGN=***string* >
< **VARSELECT=***string* >
;

The section "Functional Summary" on page 575 provides a quick reference for each option. Each option is then described in more detail in its own section, in alphabetical order.

Functional Summary

Table 12.1 summarizes the options available in the SOLVE WITH CLP statement.

Table 12.1 Functional Summary of SOLVE WITH CLP Options

Description	Option
General Options	
Finds all possible solutions	FINDALLSOLNS
Controls the amount of information in the log	LOGLEVEL=
Specifies the number of solution attempts	MAXSOLNS=
Specifies the maximum time to spend calculating results	MAXTIME=
Suppresses preprocessing	NOPREPROCESS
Specifies the tolerance of the objective value	OBJTOL=
Permits preprocessing	PREPROCESS
Indicates progress in the log	SHOWPROGRESS
Specifies whether time units are CPU time or real time	TIMETYPE=
Specifies the variable assignment strategy	VARASSIGN=
Specifies the variable selection strategy	VARSELECT=

SOLVE WITH CLP Statement

SOLVE WITH CLP / < *options* > **;**

The SOLVE WITH CLP statement invokes the CLP solver. You can specify the following *options* to define various processing and diagnostic controls and to tune the algorithm to run.

General Options

You can specify the following general options.

FINDALLSOLNS
ALLSOLNS
FINDALL
attempts to find all possible solutions to the CSP.

LOGLEVEL=0 | 1
controls the amount of information that the CLP solver prints in the log. If you specify LOGLEVEL=0, only warnings and errors are printed. If you specify LOGLEVEL=1, the solver prints messages when it starts, when it finds a new solution (if you specify the SHOWPROGRESS option), and when it determines the final solution status. By default, LOGLEVEL=1.

MAXSOLNS=*number*
specifies the number of solution attempts to be generated for the CSP. By default, MAXSOLNS=1.

MAXTIME=*number*
specifies the maximum time to spend calculating results. The type of time (either CPU time or real time) is determined by the value of the TIMETYPE= option. The value of *number* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

NOPREPROCESS
suppresses any preprocessing that would usually be performed for the problem.

OBJTOL=*number*
specifies the tolerance of the objective value. By default, OBJTOL=1E–6.

PREPROCESS
permits any preprocessing that would usually be performed for the problem.

SHOWPROGRESS
prints a message to the log whenever a solution is found.

TIMETYPE=*number* | *string*
specifies whether to use CPU time or real time for the MAXTIME= option. Table 12.2 describes the valid values of the TIMETYPE= option.

Table 12.2 Values for TIMETYPE= Option

number	*string*	**Description**
0	CPU	Specifies units of CPU time
1	REAL	Specifies units of real time

By default, TIMETYPE=REAL.

VARASSIGN=*string*

specifies the variable assignment strategy. You can specify two value selection strategies:

- MAX, which selects the maximum value from the domain of the selected variable
- MIN, which selects the minimum value from the domain of the selected variable

By default, VARASSIGN=MIN.

VARSELECT=*string*

specifies the variable selection strategy. The strategy could be static, dynamic, or conflict-directed. Typically, static strategies exploit information about the initial state of the search, whereas dynamic strategies exploit information about the current state of the search process. Conflict-directed strategies exploit information from previous states of the search process as well as the current state (Boussemart et al. 2004). Table 12.3 describes the valid values of the VARSELECT= option.

Table 12.3 Values for VARSELECT= Option

string	**Description**
Static Strategies	
FIFO	Uses the first-in, first-out ordering of the variables as encountered by the procedure after adjusting for the values in the .priority suffix
MAXCS	Selects the variable that has the maximum number of constraints
Dynamic Strategies	
DOMDDEG	Selects the variable that has the smallest ratio of domain size to dynamic degree
DOMDEG	Selects the variable that has the smallest ratio of domain size to degree
MAXC	Selects the variable that has the largest number of active constraints
MINR	Selects the variable that has the smallest range (that is, the minimum value of the upper bound minus the lower bound)
MINRMAXC	Selects the variable that has the smallest range, breaking ties by selecting one that has the largest number of active constraints
Conflict-Directed Strategies	
DOMWDEG	Selects the variable that has the smallest ratio of domain size to weighted degree
WDEG	Selects the variable that has the largest weighted degree

The dynamic strategies embody the "fail-first principle" (FFP) of Haralick and Elliott (1980), which suggests, "To succeed, try first where you are most likely to fail." By default, VARSELECT=MINR.

You can change the order in which the CLP solver selects variables after you have declared them by setting the .priority suffix for your variables. Variables with higher priority are selected first.

PROC OPTMODEL usually honors the variable declaration order when it invokes the CLP solver. However, when variables are indexed over dynamically computed sets, the variable order might be undefined. The value of .priority always overrides declaration order. To ensure that the CLP solver considers variables in the exact order that you want, set the .priority suffix for all variables. You can also experiment with the priorities by changing the suffixes without having to reorder the variable declarations in your code.

For more information, see the section "Integer Variable Suffixes" on page 424 in Chapter 9, "The OPTMODEL Procedure."

Predicates

A predicate asserts a fact about its subject. You use a predicate as the first identifier in a constraint declaration to define what must hold true in any feasible solution. The following is an example of a constraint that uses the ELEMENT predicate:

```
var X integer, Y integer;
con ElementConstraintExample: element(X, 1 2 3 4, Y);
```

The following predicates are available in PROC OPTMODEL:

ALLDIFF(*variable-list*)
CUMULATIVE(*options*)
ELEMENT(*scalar-variable*,*data-list*,*scalar-variable*)
GCC(*variable-list*,*set-of-numeric-triplets*)
LEXICO(*variable-list order-type variable-list*)
PACK(*variable-list*,*data-list*,*variable-list*)
REIFY(*scalar-variable*, *linear-constraint*)

Common Syntax Components

The following syntax components are used in multiple predicates. They depend on the definition of an *identifier-expression*. For more information, see the section "Identifier Expressions" on page 383 in Chapter 9, "The OPTMODEL Procedure." For information about other syntactic components, see the section that describes the corresponding predicate.

data-item
is a single element of constant data for a predicate argument. It is resolved to a list of zero or more constant values. Each *data-item* must conform to one of the following syntax forms:

- a number
- an *identifier-expression*, but excluding suffixes
- the name of a numeric array

- (*expression*), which must evaluate to a number

An array name resolves to a list of the element values in the array. The other forms resolve to a single list value.

Each of the preceding syntax forms can also be prefixed by an index set in braces ({}). This form produces a list that contains a value for each member in the index set. An array name that is prefixed by an indexing set is expanded using the member indices to select the array elements.

data-list

is a space-separated list of *data-items*. The values from the *data-items* are juxtaposed into a single list.

For example, the first three constraints in the following statements refer to valid *data-lists*, whereas the last four do not. Each incorrect constraint is preceded by a comment that explains why the constraint is incorrect.

```
var X integer, Y integer, Z integer;
num n;
con CorrectDataList1:   element(X, 1 2 3 4, Y);
con CorrectDataList2:   element(X, 1 2 3 4 n, Y);
con CorrectDataList3:   element(X, {i in 1..4} i n, Y);
/* The parentheses imply a scalar expression */
con IncorrectDataList1: element(X, ({i in 1..4} i) n, Y);
/* [1 2 3 4] is an array initializer, not an array name */
con IncorrectDataList2: element(X, [1 2 3 4], Y);
/* Z is a variable */
con IncorrectDataList3: element(X, 1 2 3 4 Z, Y);
/* Impossible to distinguish Z.sol from [ Z . sol ] */
con IncorrectDataList4: element(X, 1 2 3 4 Z.sol, Y);
```

scalar-variable

is an *identifier-expression* that refers to a single variable (that is, not to an array of variables).

variable-item

is a single element of variable data for a predicate argument. It is resolved to a list of zero or more variable values. This item is like a *data-item*, except that it can resolve to a variable, variable array, linear expression, or constant numeric value.

Each *variable-item* must conform to one of the following syntax forms:

- a number
- an *identifier-expression* (but excluding suffixes) that specifies a variable, implicit variable, objective, or numeric parameter
- the name of a variable, implicit variable, objective, or numeric array
- (*expression*), which must evaluate to a linear equation or numeric constant

An array name resolves to a list of the element values in the array. The other forms resolve to a single list value.

Each of the preceding syntax forms can also be prefixed by an index set in braces ({}). This form produces a list that contains a value for each member in the index set. An array name that is prefixed by an indexing set is expanded using the member indices to select the array elements.

When the value of a *variable-item* refers to a linear equation or numeric constant, it is handled like a solver variable equal to the value.

variable-list
is a space-separated list of *variable-items*. The values from the items are juxtaposed into a single list.

As an example, the first four constraints in the following statements refer to valid *variable-lists*, whereas the last two do not. Each incorrect constraint is preceded by a comment that explains why the constraint is incorrect.

```
var X{1..3} integer, A integer, B integer;
impvar IX{i in 1..3} = X[i] + i;
num n init 2;
con CorrectVariableList1: alldiff({j in 1..3} X[j]);
con CorrectVariableList2: alldiff(A B);
con CorrectVariableList3: alldiff({j in 1..3} X[j] A B);
con CorrectVariableList4: alldiff(1 n (n+1) IX);
/* Indexing is not distributive in variable lists */
var Y{1..3} integer;
con IncorrectVariableList1: alldiff({j in 1..3} (X[j] Y[j]));
/* Expressions and suffixed ids must appear in parentheses */
con IncorrectVariableList2: alldiff(A.dual);
```

ALLDIFF Predicate

ALLDIFF(*variable-list***)**
ALLDIFFERENT(*variable-list***)**

The ALLDIFF predicate defines an all-different constraint, which defines a unique global constraint on a set of variables that requires all of them to be different from each other. A global constraint is equivalent to a conjunction of elementary constraints.

The syntax of the all-different constraint consists of one part, a *variable-list*, which is defined in the section "Common Syntax Components" on page 578. For example, the statements

```
var X{1..3} integer, A integer, B integer;
con AD1: alldiff({j in 1..3} X[j]);
con AD2: alldiff(A B);
```

are equivalent to

$$\begin{array}{rcl} X[1] & \neq & X[2] \text{ AND} \\ X[2] & \neq & X[3] \text{ AND} \\ X[1] & \neq & X[3] \text{ AND} \\ A & \neq & B \end{array}$$

To apply the all-different constraint to all the variables, use the problem symbol _VAR_ as follows:

```
con alldiff(_VAR_);
```

For a description of problem symbols, see the section "Problem Symbols" on page 456 in Chapter 9, "The OPTMODEL Procedure."

CUMULATIVE Predicate

CUMULATIVE(*options*)

The CUMULATIVE predicate specifies a cumulative (scheduling) constraint. A cumulative constraint conveys that a collection of tasks (activities) is to be executed on a resource that has limited capacity. Each task is defined by its start time, duration (processing time), end time (finish time), and demand (resource usage). A task i is said to overlap a time point t if and only if its start time is less than or equal to t and its end time is strictly greater than t. The cumulative constraint enforces that at each point in time, the accumulated demand (resource usage) of the tasks that overlap the time point does not exceed the specified capacity of the resource.

A cumulative constraint also enforces the following equation for all tasks i:

$$\text{start_time}[i] + \text{duration}[i] = \text{end_time}[i]$$

Each CUMULATIVE predicate specifies starting and ending times (one of which can be implied by specifying a duration), and optionally specifies demand and capacity. The CUMULATIVE predicate is specified using a sequence of options separated by commas. Each option uses a *variable-list* or *variable-item*, which are defined in the section "Common Syntax Components" on page 578. You can specify variables, linear expressions, and constant values in the same list. You can specify the following options in any order:

START=*variable-list*
: specifies the time at which the resource starts being used for each task.

END=*variable-list*
: specifies the time at which the resource finishes being used for each task.

DURATION=*variable-list*
DUR=*variable-list*
: specifies the length of time the resource is used for each task. The values must be nonnegative.

DEMAND=*variable-list*
HEIGHT=*variable-list*
: specifies the resource usage for each task. The values must be nonnegative. If you omit this option, the demand of each task is 1.

LIMIT=*variable-item*
CAPACITY=*variable-item*
: specifies the capacity limit for the resource. Only a single value can be specified. Array names and indexing sets are not allowed in the *variable-item*. The value must be nonnegative. If you omit this option, the capacity limit is 1.

The CUMULATIVE predicate is subject to the following additional restrictions:

- You must specify at least two of the START=, DURATION=, and END= options.
- The *variable-list* of at least one of the START=, DURATION= , and END= options must contain a nonconstant value.
- The *variable-lists* specified in the START=, DURATION=, END=, and DEMAND= options must have the same number of values after the lists are expanded.

For example, the following statements use the CUMULATIVE predicate to schedule tasks that use two resources with varying requirements for each resource:

```
proc optmodel;
   set TASKS=1..5;
   var start{TASKS} integer >= 0;
   var end{TASKS} integer >= 0;
   num dur{TASKS} = [1 1 2 3 1];
   var z integer >= 0 <= 100;
   con done{i in TASKS}: end[i] <= z;
   min obj = z;
   con c1: cumulative(start=start, end=end, dur=dur,
                      demand=4 3 3 2 1, limit=5);
   con c2: cumulative(start=start, end=end, dur=dur,
                      demand=1 1 2 2 2, limit=3);
   solve;
   print start end;
quit;
```

ELEMENT Predicate

ELEMENT(*scalar-variable***,***data-list***,***scalar-variable***)**

The ELEMENT predicate specifies an array element lookup constraint, which enables you to define dependencies (which are not necessarily functional) between variables.

The predicate ELEMENT(I, L, V) sets the variable V to be equal to the Ith element in the list L, where $L = (v_1, \ldots, v_n)$ is a list of values (not necessarily distinct) that the variable V can take. The variable I is the index variable, and its domain is considered to be $[1, n]$. Each time the domain of I is modified, the domain of V is updated, and vice versa.

For example, the following statements use the ELEMENT predicate to determine whether there are squares greater than 1 that are also elements of the Fibonacci sequence:

```
/* Are there any squares > 1 in the Fibonacci sequence? */
proc optmodel;
   num n = 20;
   /* 1 appears twice in the Fibonacci sequence */
   num fib{i in 1..n} = if i < 3 then 1 else fib[i-1] + fib[i-2];

   var IFib integer, ISq integer,
       XFib integer, XSq integer;

   con IsFibAndIsSquare: XFib = XSq;
   /* You can use a numeric array to refer to a list */
   con IdxOfFib: element( IFib, fib, XFib );
   /* You can also build a list from a set iterator */
   con IdxOfSq:  element( ISq,  {i in 2..n} (i * i),  XSq );
   solve;
   print XFib XSq;
quit;
```

An element constraint enforces the propagation rules

$$V = v \Leftrightarrow I \in \{i_1, \ldots, i_m\}$$

where v is a value in the list L and $i_1, \ldots, i_m$ are all the indices in L whose value is v.

An element constraint is equivalent to a conjunction of reify and linear constraints. For example, both of the following examples implement the quadratic function, $Y = X^2$:

- Using the ELEMENT predicate:

```
proc optmodel;
   var X >= 1 <= 5 integer, Y >= 1 <= 25 integer;
   num a {i in 1..5} = i^2;
   con Mycon: element(X, a, Y);
   solve;
quit;
```

- Using linear constraints and the REIFY predicate:

```
proc optmodel;
   var X >= 1 <= 5 integer, Y >= 1 <= 25 integer, R {1..5} binary;
   con MyconX {i in 1..5}:
      reify(R[i], X = i);
   con MyconY {i in 1..5}:
      reify(R[i], Y = i^2);
   con SumToOne:
      sum {i in 1..5} R[i] = 1;
   solve;
quit;
```

You can also use element constraints to define positional mappings between two variables. For example, suppose the function $Y = X^2$ is defined on only odd numbers in the interval $[-5, 5]$. You can relate X and Y by using two element constraints and an artificial index variable:

```
var I integer, X integer, Y integer;
/* You can also build a list by providing explicit literals. */
con XsubI: element (I, -5 -3 -1 1 3  5, X);
con YsubI: element (I, 25  9  1 1 9 25, Y);
```

GCC Predicate

GCC(*variable-list***,***set-of-numeric-triplets***)**

The GCC predicate specifies a global cardinality constraint (GCC), which sets the minimum and maximum number of times each value can be assigned to a group of variables.

The syntax of the GCC constraint consists of two parts:

variable-list
: See the section "Common Syntax Components" on page 578.

set-of-numeric-triplets

The triplets $< v, l_v, u_v >$ provide, for each value v, the minimum l_v and maximum u_v number of times that v can be assigned to the variables in the *variable-list*. The PROC OPTMODEL option INTFUZZ= determines which values are rounded to integers.

Consider the following statements:

```
var X {1..6} >= 1 <= 4 integer;
con Mycon: gcc(X, /<1,1,2>, <2,1,3>, <3,1,3>, <4,2,3>/);
```

These statements specify a constraint that expresses the following requirements about the values of variables $\{X[1], \ldots, X[6]\}$:

- The value 1 must appear at least once but no more than twice.
- The value 2 must appear at least once but no more than three times.
- The value 3 must appear at least once but no more than three times.
- The value 4 must appear at least twice but no more than three times.

The assignment $X[1] = 1, X[2] = 1, X[3] = 2, X[4] = 3, X[5] = 4$, and $X[6] = 4$ satisfies the constraint.

In general, a GCC constraint consists of a set of variables $\{x_1, \ldots, x_n\}$ and, for each value v in $D = \bigcup_{i=1}^{n} \mathrm{Dom}(x_i)$, a pair of numbers l_v and u_v. A GCC is satisfied if and only if the number of times that a value v in D is assigned to the variables $x_1, \ldots, x_n$ is at least l_v and at most u_v.

Values in the domain of *variable-list* that do not appear in any triplet are unconstrained. They can be assigned to as many of the variables in *variable-list* as needed to produce a feasible solution.

The following statements specify that each of the values in the set $\{1, \ldots, 9\}$ can be assigned to at most one of the variables $X[1], \ldots, X[9]$:

```
var X {1..9} >= 1 <= 9 integer;
con Mycon: gcc(X, setof{i in 1..9} <i,0,1>);
```

Note that the preceding global cardinality constraint is equivalent to the all-different constraint that is expressed as follows:

```
var X {1..9} >= 1 <= 9 integer;
con Mycon: alldiff(X);
```

The global cardinality constraint also provides a convenient way to define disjoint domains for a set of variables. For example, the following syntax limits assignment of the variables $X[1], \ldots, X[9]$ to even numbers between 0 and 10:

```
var X {1..9} >= 0 <= 10 integer;
con Mycon: gcc(X, setof{i in 1..9 by 2} <i,0,0>);
```

LEXICO Predicate

LEXICO(*variable-list order-type variable-list***)**

The LEXICO predicate defines a lexicographic ordering constraint, which compares two arrays of the same size from left to right. For example, a standings table in a sports competition is usually ordered lexicographically, with certain attributes (such as wins or points) to the left of others (such as goal difference).

The *order-type* can be either $\leq$, to indicate lexicographically less than or equal to ($\leq_{\text{lex}}$), or $<$, to indicate lexicographically less than ($<_{\text{lex}}$). Given two n-tuples $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$, the n-tuple x is lexicographically less than or equal to y ($x \leq_{\text{lex}} y$) if and only if

$$\big(x_i = y_i \ \forall i = 1, \ldots, n\big) \vee \big(\exists j \text{ with } 1 \leq j \leq n \text{ s.t. } x_i = y_i \ \forall i = 1, \ldots, j-1 \text{ and } x_j < y_j\big)$$

The n-tuple x is lexicographically less than y ($x <_{\text{lex}} y$) if and only if $x \leq_{\text{lex}} y$ and $x \neq y$. Equivalently, $x <_{\text{lex}} y$ if and only if

$$\exists j \text{ with } 1 \leq j \leq n \text{ s.t. } x_i = y_i \ \forall i = 1, \ldots, j-1 \text{ and } x_j < y_j$$

Informally, you can think of the lexicographic constraint $\leq_{\text{lex}}$ as sorting the n-tuples in alphabetical order. Mathematically, $\leq_{\text{lex}}$ is a partial order on a subset of n-tuples, and $<_{\text{lex}}$ is a strict partial order on a subset of n-tuples (Brualdi 2010).

For example, you can express the lexicographic constraint $(X[1], \ldots, X[6]) \leq_{\text{lex}} (Y[1], \ldots, Y[6])$ by using a LEXICO predicate as follows:

```
con Mycon: lexico({j in 1..6} X[j] <= {j in 1..6} Y[j]);
```

The assignment $X[1]=1$, $X[2]=2$, $X[3]=2$, $X[4]=1$, $X[5]=2$, $X[6]=5$, $Y[1]=1$, $Y[2]=2$, $Y[3]=2$, $Y[4]=1$, $Y[5]=4$, and $Y[6]=3$ satisfies this constraint because $X[i] = Y[i]$ for $i = 1, \ldots, 4$ and $X[5] < Y[5]$. The fact that $X[6] > Y[6]$ is irrelevant in this ordering.

Lexicographic ordering constraints can be useful for breaking a certain type of symmetry that arises in CSPs and involves matrices of decision variables. Frisch et al. (2002) introduce an optimal algorithm to establish generalized arc consistency (GAC) for the $\leq_{\text{lex}}$ constraint between two vectors of variables.

PACK Predicate

PACK(*variable-list*,*data-list*,*variable-list***)**

The PACK predicate specifies a pack constraint, which is used to assign items to bins, subject to the sizes of the items and the capacities of the bins.

For example, suppose you have three bins, whose capacities are 3, 4, and 5, and you have five items of sizes 4, 3, 2, 2, and 1, to be assigned to these three bins. The following statements formulate the problem and find a solution:

```
proc optmodel;
   var SpaceUsed {bin in 1..3} integer >= 0 <= bin + 2;
   var WhichBin {1..5} >= 1 <= 3 integer;
   num itemSize {1..5} = [4 3 2 2 1];
   con pack( WhichBin, itemSize, SpaceUsed );
   solve with clp / findall;
quit;
```

Each row of Table 12.4 represents a solution to the problem. The number in each item column is the number of the bin to which the corresponding item is assigned.

Table 12.4 Bin Packing Solutions

WhichBin Variable				
WhichBin[1]	**WhichBin[2]**	**WhichBin[3]**	**WhichBin[4]**	**WhichBin[5]**
2	3	3	1	1
2	3	1	3	1
2	1	3	3	3
3	1	2	2	3

When you assign a set of k items to m bins, the item variable $b_i, i \in \{1, \ldots, k\}$ (WhichBin in the preceding example), contains the bin number for the ith item. The constant s_i (itemSize in the preceding example) holds the size or weight of the ith item. The domain of the load variable l_j (SpaceUsed in the preceding example) constrains the capacity of bin j. The value of l_j in the solution is the amount of space used in bin j.

NOTE: It can be more efficient to assign higher priority to item variables than to load variables, and within the item variables, to assign higher priority to larger items.

REIFY Predicate

REIFY(*scalar-variable***,** *linear-constraint***)**

The REIFY predicate specifies a reify constraint, which associates a binary variable with a constraint. The value of the binary variable is 1 or 0, depending on whether the constraint is satisfied or not, respectively. The constraint is said to be reified, and the binary variable is referred to as the *control variable*. Currently, only linear constraints can be reified.

The REIFY predicate provides a convenient mechanism for expressing logical constraints, such as disjunctive and implicative constraints. For example, the disjunctive constraint

$$(3X + 4Y < 20) \vee (5X - 2Y > 50)$$

can be expressed by the following statements:

```
var X integer, Y integer,
    P binary,  Q binary;
con reify(P, 3 * X + 4 * Y < 20);
con reify(Q, 5 * X - 2 * Y > 50);
con AtLeastOneHolds: P + Q >= 1;
```

The binary variable P reifies the linear constraint

$$3X + 4Y < 20$$

The binary variable Q reifies the linear constraint

$$5X - 2Y > 50$$

The following linear constraint enforces the desired disjunction:

$$P + Q \geq 1$$

The following implicative constraint

$$(3X + 4Y < 20) \Rightarrow (5X - 2Y > 50)$$

can be enforced by the linear constraint

$$P \leq Q$$

You can also use the REIFY constraint to express a constraint that involves the absolute value of a variable. For example, the constraint

$$|X| = 5$$

can be expressed by the following statements:

```
var X integer, P binary, Q binary;
con Xis5:      reify(P, X = 5);
con XisMinus5: reify(Q, X = -5);
con OneMustHold: P + Q = 1;
```

Details: CLP Solver

Types of CSPs

The CLP solver is a finite-domain constraint programming solver for CSPs. A *standard CSP* is characterized by integer variables, linear constraints, global constraints, and reify constraints. The solver expects only linear, ALLDIFF, CUMULATIVE, ELEMENT, GCC, LEXICO, PACK, and REIFY predicates.

Both PROC OPTMODEL and PROC CLP support standard CSPs. The CLP procedure also supports *scheduling CSP*s, which are characterized by activities, temporal constraints, and resource requirement constraints. For more information about the CLP procedure see *SAS/OR User's Guide: Constraint Programming*.

Techniques for Solving CSPs

Several techniques for solving CSPs are available. Kumar (1992) and Tsang (1993) present a good overview of these techniques. It should be noted that the satisfiability problem (SAT) (Garey and Johnson 1979) can be regarded as a CSP. Consequently, most problems in this class are nondeterministic polynomial-time complete (NP-complete) problems, and a backtracking search mechanism is an important technique for solving them (Floyd 1967).

One of the most popular tree search mechanisms is chronological backtracking. However, a chronological backtracking approach is not very efficient because conflicts are detected late; that is, the approach is oriented toward *recovering* from failures rather than *avoiding* them to begin with. The search space is reduced only after a failure is detected, and the performance of this technique is drastically reduced as the problem size increases. Another drawback of using chronological backtracking, for the same reason, is encountering repeated failures, sometimes called "thrashing." The presence of late detection and "thrashing" has led researchers to develop consistency techniques that can achieve superior pruning of the search tree. This strategy uses constraints actively, rather than passively.

Constraint Propagation

A more efficient technique than backtracking is constraint propagation, which uses consistency techniques to effectively prune the domains of variables. Consistency techniques are based on the idea of a priori pruning, which uses the constraint to reduce the domains of the variables. Consistency techniques are also known as relaxation algorithms (Tsang 1993), and the process is also called problem reduction, domain filtering, or pruning.

One of the earliest applications of consistency techniques was in the AI field to solve the scene labeling problem, which required recognizing objects in three-dimensional space by interpreting two-dimensional line drawings of the object. The Waltz filtering algorithm (Waltz 1975) analyzes line drawings by systematically labeling the edges and junctions while maintaining consistency between the labels.

Constraint propagation is characterized by the extent of propagation (also called the level of consistency) and whether domain propagation or interval propagation is the domain pruning scheme that is followed. In practice, interval propagation is preferred because of its lower computational costs. This mechanism is discussed in detail in Van Hentenryck (1989). However, constraint propagation is not a complete solution technique and needs to be complemented by a search technique in order to ensure success (Kumar 1992).

Finite-Domain Constraint Programming

Finite-domain constraint programming is an effective and complete solution technique that embeds incomplete constraint propagation techniques into a nondeterministic backtracking search mechanism that is implemented as follows: Whenever a node is visited, constraints are propagated to attain a desired level of consistency. If the domain of each variable reduces to a singleton set, the node represents a solution to the CSP. If the domain of a variable becomes empty, the node is pruned. Otherwise a variable is selected, its domain is distributed, and a new set of CSPs is generated, each of which is a child node of the current node. Several factors play a role in determining the outcome of this mechanism, such as the extent of propagation (or level of consistency enforced), the variable selection strategy, and the variable assignment or domain distribution strategy.

For example, the lack of any propagation reduces this technique to a simple generate-and-test approach, whereas performing consistency checking using variables that are already selected reduces this approach to chronological backtracking, one of the systematic search techniques. These are also known as look-back schemas, because they share the disadvantage of late conflict detection. Look-ahead schemas, on the other hand, work to prevent future conflicts. Some popular examples of look-ahead schemas, in increasing degree of consistency level, are forward checking (FC), partial look ahead (PLA), and full look ahead (LA) (Kumar 1992). Forward checking enforces consistency between the current variable and future variables; PLA and LA extend this even further to pairs of not yet instantiated variables.

Two important consequences of this technique are that inconsistencies are discovered early and that the current set of alternatives that are coherent with the existing partial solution is dynamically maintained. These consequences are powerful enough to prune large parts of the search tree, thereby reducing the "combinatorial explosion" of the search process. However, although constraint propagation at each node results in fewer nodes in the search tree, the processing at each node is more expensive. The ideal scenario is to strike a balance between the extent of propagation and the subsequent computation cost.

Variable selection is another strategy that can affect the solution process. The order in which variables are chosen for instantiation can have a substantial impact on the complexity of the backtrack search. Several heuristics have been developed and analyzed for selecting variable ordering. One of the most common ones is a dynamic heuristic based on the *fail-first principle* (Haralick and Elliott 1980), which selects the variable

whose domain has minimal size. Subsequent analysis of this heuristic by several researchers has validated this strategy as providing substantial improvement for a significant class of problems. Another popular strategy is to instantiate the most constrained variable first. Both these strategies are based on the principle of selecting the variable most likely to fail and detecting such failures as early as possible.

The domain distribution strategy for a selected variable is yet another area that can influence the performance of a backtracking search. However, good value-ordering heuristics are expected to be very problem-specific (Kumar 1992).

Consistency Techniques

The CLP solver features a full look-ahead algorithm for standard CSPs that follows a strategy of maintaining a version of generalized arc consistency that is based on the AC-3 consistency routine (Mackworth 1977). This strategy maintains consistency between the selected variables and the unassigned variables and also maintains consistency between unassigned variables.

Selection Strategy

A search algorithm for CSPs searches systematically through the possible assignments of values to variables. The order in which a variable is selected can be based on a *static* ordering, which is determined before the search begins, or on a *dynamic* ordering, in which the choice of the next variable depends on the current state of the search. The VARSELECT= option in the SOLVE statement defines the variable selection strategy for a standard CSP. The default strategy is the dynamic MINR strategy, which selects the variable that has the smallest range.

Assignment Strategy

After a variable is selected, the assignment strategy dictates the value that is assigned to it. For variables, the assignment strategy is specified in the VARASSIGN= option in the SOLVE statement. The default assignment strategy selects the minimum value from the domain of the selected variable.

Differences between PROC OPTMODEL and PROC CLP

You can invoke the CLP solver from PROC OPTMODEL by using any of the predicates that are defined in the standard mode of PROC CLP. The *standard mode* gives you access to all-different, element, GCC, linear, pack, and reify constraints.

To replicate the FOREACH statement that PROC CLP supports, you can use PROC OPTMODEL's expressions and iteration machinery. For an example, see the Eight Queens example in "Getting Started: CLP Solver" on page 571. For more information about the FOREACH predicate, see the section "FOREACH Statement" on page 37 in Chapter 4, "The CLP Procedure."

PROC OPTMODEL has different syntax and semantics for variable declarations:

- Because all CLP variables are discrete, you must declare every variable that a CLP model uses as integer or binary.
- The default variable bounds in PROC OPTMODEL are $-\infty$ to ∞. The default lower bound in PROC CLP is 0. Thus, to replicate the behavior of PROC CLP, you must explicitly add a lower bound of 0 to the variable declaration.

Macro Variable _OROPTMODEL_

The OPTMODEL procedure always creates and initializes a SAS macro variable called _OROPTMODEL_, which contains a character string. The variable contains information about the execution of the most recently invoked solver.

Each keyword and value pair in _OROPTMODEL_ also appears in two other places: the PROC OPTMODEL automatic arrays _OROPTMODEL_NUM_ and _OROPTMODEL_STR_; and the ODS tables ProblemSummary and SolutionSummary, which appear after a SOLVE statement, unless you set the PRINTLEVEL= option to NONE. You can use these variables to obtain details about the solution.

After the solver is called, the various keywords in the variable are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	The use of syntax is incorrect.
DATA_ERROR	The input data are inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem in reading or writing of data has occurred.
SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, has occurred.
ERROR	The status cannot be classified into any of the preceding categories.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

ABORT_NOSOL	The solver was stopped by the user and did not find a solution.
ABORT_SOL	The solver was stopped by the user but still found a solution.
ALL_SOLUTIONS	All solutions were found.
BAD_PROBLEM_TYPE	The problem type is not supported by the solver.
CONDITIONAL_OPTIMAL	The optimality of the solution cannot be proven.
ERROR	The algorithm encountered an error.
FAIL_NOSOL	The solver stopped because of errors and did not find a solution.
FAIL_SOL	The solver stopped because of errors but still found a solution.
INFEASIBLE	The problem is infeasible.
INTERRUPTED	The solver was interrupted by the system or the user before completing its work.
OK	The algorithm terminated normally.

OPTIMAL	The solution is optimal.
OUTMEM_NOSOL	The solver ran out of memory and either did not find a solution or failed to output the solution because of insufficient memory.
OUTMEM_SOL	The solver ran out of memory but still found a solution.
SOLUTION_LIM	The solver reached the maximum number of solutions specified in the MAXSOLNS= option.
TIME_LIM_NOSOL	The solver reached the execution time limit specified in the MAXTIME= option and did not find a solution.
TIME_LIM_SOL	The solver reached the execution time limit specified in the MAXTIME= option and found a solution.
UNBOUNDED	The problem is unbounded.

ALGORITHM

indicates the algorithm that produces the solution data in the macro variable. This term appears only when STATUS=OK. It can take only one value in the CLP solver: CLP, which indicates that the constraint satisfaction algorithm produced the solution data.

OBJECTIVE

indicates the objective value that the solver obtained at termination. If a problem does not have an explicit objective, the value of this keyword in the _OROPTMODEL_ macro variable is missing (.).

PRESOLVE_TIME

indicates the time (in seconds) that the algorithm used for preprocessing. You can use the TIMETYPE= option to select real time or CPU time.

SOLUTION_TIME

indicates the time (in seconds) that the algorithm used to perform iterations to solve the problem. You can use the TIMETYPE= option to select real time or CPU time.

SOLUTIONS_FOUND

indicates the number of solutions found, which might be 0 if the problem is infeasible. This keyword is always present in the solution status when you call the CLP solver. The value might not be the total number of solutions possible (for example, if the solver reached its time limit).

Examples: CLP Solver

Example 12.1: Logic-Based Puzzles

Many logic-based puzzles can be formulated as CSPs. Several such puzzles are shown in this example.

Sudoku

Sudoku is a logic-based, combinatorial number-placement puzzle that uses a partially filled 9 × 9 grid. The objective is to fill the grid with the digits 1 to 9 so that each column, each row, and each of the nine 3 × 3 blocks contains only one of each digit. Figure 12.1.1 shows an example of a sudoku grid.

Output 12.1.1 Example of an Unsolved Sudoku Grid

		5			7			1
	7			9			3	
			6					
		3			1			5
	9			8			2	
1			2			4		
		2			6			9
				4			8	
8			1			5		

This example illustrates the use of the all-different constraint to solve the preceding sudoku problem. The data set Indata contains the partially filled values for the grid.

```
data Indata;
   input C1-C9;
   datalines;
. . 5 . . 7 . . 1
. 7 . . 9 . . 3 .
. . . 6 . . . . .
. . 3 . . 1 . . 5
. 9 . . 8 . . 2 .
1 . . 2 . . 4 . .
. . 2 . . 6 . . 9
. . . . 4 . . 8 .
8 . . 1 . . 5 . .
;
```

Let the variable X_{ij} $(i = 1, \ldots, 9, j = 1, \ldots, 9)$ represent the value of cell (i, j) in the grid. The domain of each of these variables is $[1, 9]$. When cell (i, j) is not missing in the data set, X_{ij} is fixed to that value.

Three sets of all-different constraints specify the required rules for each row, each column, and each of the 3×3 blocks. The RowCon constraint forces all values in row i to be different, the ColumnCon constraint forces all values in column j to be different, and the BlockCon constraint forces all values in each block to be different.

The following statements express the preceding constraints in PROC OPTMODEL and solve the sudoku puzzle:

```
proc optmodel;
   /* Declare variables */
   set ROWS = 1..9;
   set COLS = ROWS; /* Use an alias for convenience and clarity */
   var X {ROWS, COLS} >= 1 <= 9 integer;

   /* Nine row constraints */
   con RowCon {i in ROWS}:
      alldiff({j in COLS} X[i,j]);

   /* Nine column constraints */
   con ColCon {j in COLS}:
      alldiff({i in ROWS} X[i,j]);

   /* Nine 3x3 block constraints */
   con BlockCon {s in 0..2, t in 0..2}:
      alldiff({i in 3*s+1..3*s+3, j in 3*t+1..3*t+3} X[i,j]);

   /* Fix variables to cell values */
   /* X[i,j] = c[i,j] if c[i,j] is not missing */
   num c {ROWS, COLS};
   read data indata into [_N_] {j in COLS} <c[_N_,j]=col('C'||j)>;
   for {i in ROWS, j in COLS: c[i,j] ne .}
      fix X[i,j] = c[i,j];

   solve;
quit;
```

Output 12.1.2 shows the solution.

Output 12.1.2 Solution of the Sudoku Grid

9	8	5	3	2	7	6	4	1
6	7	1	5	9	4	2	3	8
3	2	4	6	1	8	9	5	7
2	4	3	7	6	1	8	9	5
5	9	7	4	8	3	1	2	6
1	6	8	2	5	9	4	7	3
4	5	2	8	3	6	7	1	9
7	1	6	9	4	5	3	8	2
8	3	9	1	7	2	5	6	4

Pi Day Sudoku

The basic structure of the classical sudoku problem can easily be extended to formulate more complex puzzles. One such example is the Pi Day sudoku puzzle.

Pi Day is a celebration of the number π that occurs every March 14. In honor of Pi Day, Brainfreeze Puzzles (Riley and Taalman 2008) celebrates this day with a special 12×12 grid sudoku puzzle. The 2008 Pi Day sudoku puzzle is shown in Figure 12.1.3.

Output 12.1.3 Pi Day Sudoku 2008

3			1	5	4			1		9	5
	1			3					1	3	6
		4			3		8			2	
5			1			9	2	5			1
	9			5			5				
5	8	1			9			3		6	
	5		8			2			5	5	3
				5			6			1	
2			5	1	5			5			9
	6			4		1			3		
1	5	1					5			5	
5	5		4			3	1	6			8

The rules for this puzzle are a little different from the rules for standard sudoku:

1. Rather than using regular 3×3 blocks, this puzzle uses jigsaw regions such that highlighted regions in the middle resemble the Greek letter π. Each jigsaw region consists of 12 contiguous cells.

2. The first 12 digits of π are used instead of the digits 1–9. Each row, column, and jigsaw region contains the first 12 digits of π (314159265358) in some order. In other words, there are no 7s; one each of 2, 4, 6, 8, and 9; two each of 1 and 3; and three 5s.

To generalize the original sudoku model:

1. Replace the expression that calculates the starting and ending cells of a region by an array that maps each cell to one region.

2. Replace the all-different constraints with GCC constraints. GCC constraints describe how often each value can be assigned to a set of variables. Conceptually, an all-different constraint is a specialized GCC constraint in which both the lower bound and the upper bound of every value is 1.

The data set Raw contains the partially filled values for the grid. It contains missing values where the cell does not yet contain a number.

```
data Raw;
   input C1-C12;
   datalines;
3  .  .  1  5  4  .  .  1  .  9  5
.  1  .  .  3  .  .  .  .  1  3  6
.  .  4  .  .  3  .  8  .  .  2  .
5  .  .  1  .  .  9  2  5  .  .  1
.  9  .  .  5  .  .  5  .  .  .  .
5  8  1  .  .  9  .  .  3  .  6  .
.  5  .  8  .  .  2  .  .  5  5  3
.  .  .  .  5  .  .  6  .  .  1  .
2  .  .  5  1  5  .  .  5  .  .  9
.  6  .  .  4  .  1  .  .  3  .  .
1  5  1  .  .  .  .  5  .  .  5  .
5  5  .  4  .  .  3  1  6  .  .  8
;
```

The following statements define the GCC constraints in order to find all solutions of the Pi Day sudoku 2008 puzzle:

```
proc optmodel;
   set ROWS = 1..12;
   /* These declarations are inexpensive and improve clarity: */
   set COLS = ROWS, REGIONS = ROWS, CELLS = ROWS cross COLS;

   /* specify a 12x12 array of region identifiers.
      The spacing is just to make the regions easier to visualize. */
   num region{CELLS} = [
       1  1  1    2  2  2  2  2  2    3  3  3
       1  1  1    2  2  2  2  2  2    3  3  3
       1  1   4  4  4  4    5  5  5  5   3  3
       1  1   4  4  4  4    5  5  5  5   3  3
       1  1   4  4  4  4    5  5  5  5   3  3
```

```
         6  6  6   7  7   8  8   9  9  10 10 10
         6  6  6   7  7   8  8   9  9  10 10 10
         6  6  6   7  7   8  8   9  9  10 10 10
         6  6  6   7  7   8  8   9  9  10 10 10
        11 11 11   7  7   8  8   9  9  12 12 12
        11 11 11   7  7   8  8   9  9  12 12 12
        11 11 11 11 11 11     12 12 12 12 12 12 ];

   /* Each area must contain two 1's, two 3's, three 5's, no 7's,
      and one for each of other values from 1 to 9. */
                     /* 1 2 3 4 5 6 7 8 9 */
   num nTimes{1..9} = [2 1 2 1 3 1 0 1 1];
   /* For convenience, create a triplet set version of nTimes.
      In this model, GCC's lower and upper bounds are the same. */
   set N_TIMES = setof{ni in 1..9} <ni,nTimes[ni],nTimes[ni]>;

   /* The number assigned to the ith row and jth column. */
   var X {CELLS} >= 1 <= 9 integer;

   /* X[i,j] = c[i,j] if c[i,j] is not missing */
   num c {CELLS};
   read data raw into [_N_] {j in COLS} <c[_N_,j]=col('C'||j)>;
   for {<i,j> in CELLS: c[i,j] ne .}
      fix X[i,j] = c[i,j];

   con RowCon {i in ROWS}:
      gcc({j in COLS} X[i,j], N_TIMES);

   con ColCon {j in COLS}:
      gcc({i in ROWS} X[i,j], N_TIMES);

   con RegionCon {ri in REGIONS}:
      gcc({<i,j> in CELLS: region[i,j] = ri} X[i,j], N_TIMES);

   solve;
   /* Replicate typical PROC CLP output from PROC OPTMODEL arrays */
   create data pdsout from
      {<i,j> in ROWS cross COLS}<col('X_'||i||'_'||j)=X[i,j]>;
quit;
```

The only solution of the 2008 Pi Day sudoku puzzle is shown in Output 12.1.4.

Output 12.1.4 Solution to Pi Day Sudoku 2008

Pi Day Sudoku 2008

Obs	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
1	3	2	5	1	5	4	6	3	1	8	9	5
2	4	1	5	2	3	8	5	9	5	1	3	6
3	6	1	4	5	9	3	5	8	3	1	2	5
4	5	3	3	1	8	5	9	2	5	6	4	1
5	8	9	2	6	5	1	1	5	4	3	3	5
6	5	8	1	5	2	9	4	3	3	5	6	1
7	1	5	3	8	1	6	2	4	9	5	5	3
8	9	4	5	3	5	1	5	6	8	2	1	3
9	2	3	6	5	1	5	3	1	5	4	8	9
10	3	6	8	9	4	5	1	5	1	3	5	2
11	1	5	1	3	6	3	8	5	2	9	5	4
12	5	5	9	4	3	2	3	1	6	5	1	8

The corresponding completed grid is shown in Figure 12.1.5.

Output 12.1.5 Solution to Pi Day Sudoku 2008

3	2	5	1	5	4	6	3	1	8	9	5
4	1	5	2	3	8	5	9	5	1	3	6
6	1	4	5	9	3	5	8	3	1	2	5
5	3	3	1	8	5	9	2	5	6	4	1
8	9	2	6	5	1	1	5	4	3	3	5
5	8	1	5	2	9	4	3	3	5	6	1
1	5	3	8	1	6	2	4	9	5	5	3
9	4	5	3	5	1	5	6	8	2	1	3
2	3	6	5	1	5	3	1	5	4	8	9
3	6	8	9	4	5	1	5	1	3	5	2
1	5	1	3	6	3	8	5	2	9	5	4
5	5	9	4	3	2	3	1	6	5	1	8

Magic Square

A magic square is an arrangement of the distinct positive integers from 1 to n^2 in an $n \times n$ matrix such that the sum of the numbers of any row, any column, or any main diagonal is the same number, known as the magic constant. The magic constant of a normal magic square depends only on n and has the value $n(n^2 + 1)/2$.

This example illustrates the use of the MINRMAXC selection strategy, which is controlled by the VARSELECT= option.

```
%macro magic(n);
   proc optmodel;
      num n = &n;
      /* magic constant */
      num sum = n*(n^2+1)/2;
      set ROWS = 1..n;
      set COLS = 1..n;

      /* X[i,j] = entry (i,j) */
      var X {ROWS, COLS} >= 1 <= n^2 integer;

      /* row sums */
      con RowCon {i in ROWS}:
         sum {j in COLS} X[i,j] = sum;

      /* column sums */
      con ColCon {j in COLS}:
         sum {i in ROWS} X[i,j] = sum;

      /* diagonal: upper left to lower right */
      con DiagCon:
         sum {i in ROWS} X[i,i] = sum;

      /* diagonal: upper right to lower left */
      con AntidiagCon:
         sum {i in ROWS} X[n+1-i,i] = sum;

      /* symmetry-breaking */
      con BreakRowSymmetry:
         X[1,1] + 1 <= X[n,1];
      con BreakDiagSymmetry:
         X[1,1] + 1 <= X[n,n];
      con BreakAntidiagSymmetry:
         X[1,n] + 1 <= X[n,1];

      con alldiff(X);

      solve with CLP / varselect=minrmaxc maxtime=3;
   quit;
%mend magic;

%magic(7)
```

The solution is displayed in Output 12.1.6.

Output 12.1.6 Solution of the Magic Square

1	39	24	40	31	38	2
43	4	34	41	42	5	6
18	20	23	29	30	22	33
36	37	25	3	7	35	32
14	19	44	13	47	12	26
17	45	9	21	8	48	27
46	11	16	28	10	15	49

Example 12.2: Alphabet Blocks Problem

This example illustrates the use of the global cardinality constraint (GCC). The alphabet blocks problem consists of finding an arrangement of letters on four alphabet blocks. Each alphabet block has a single letter on each of its six sides. Collectively, the four blocks contain every letter of the alphabet except Q and Z. By arranging the blocks in various ways, the following words should be spelled out: BAKE, ONYX, ECHO, OVAL, GIRD, SMUG, JUMP, TORN, LUCK, VINY, LUSH, and WRAP.

You can formulate this problem as a CSP by representing each of the 24 letters as an integer variable. The domain of each variable is the set $\{1, 2, 3, 4\}$, which represents block1 through block4. The assignment A = 1 indicates that the letter A is on a side of block1. Because each block has six sides, each value v in $\{1, 2, 3, 4\}$ must be assigned to exactly six variables so that each side of a block has a letter on it. This restriction can be formulated as a global cardinality constraint over all 24 variables, with common lower and upper bounds set equal to 6.

Moreover, in order to spell all the words listed previously, the four letters in each of the 12 words must be on different blocks. Another GCC statement that specifies 12 global cardinality constraints enforces these conditions. You can also formulate these restrictions by using 12 all-different constraints. Finally, four FIX statements break the symmetries that blocks are interchangeable. These constraints preset the blocks that contain the letters B, A, K, and E as block1, block2, block3, and block4, respectively.

The complete representation of the problem is as follows:

```
proc optmodel;
   /* Each letter except Q and Z is represented with a variable. */
   /* The domain of each variable is the set of 4 blocks,        */
   /*   or {1, 2, 3, 4} for short.                               */
   set LETTERS = / A B C D E F G H I J K L M N O P R S T U V W X Y /;
   var Block {LETTERS} integer >= 1 <= 4;
   set BLOCKS = 1..4;
```

```
   /* There are exactly 6 letters on each alphabet block */
   con SixLettersPerBlock:
      gcc(Block, setof {b in BLOCKS} <b,6,6>);

   /* The letters in each word must be on different blocks. */
   set WORDS = / BAKE ONYX ECHO OVAL GIRD SMUG JUMP TORN LUCK VINY LUSH WRAP /;
   con CanSpell {w in WORDS}:
      gcc({k in 1..length(w)} Block[char(w,k)], setof {b in BLOCKS} <b,0,1>);

   /* Note 2: These restrictions can also be enforced by ALLDIFF constraints:
   con CanSpellv2 {w in WORDS}:
      alldiff({k in 1..length(w)} Block[char(w,k)]);
   */

   /* Breaking the symmetry that blocks can be interchanged by setting
      the block that contains the letter B as block1, the block that
      contains the letter A as block2, etc. */
   for {k in 1..length('BAKE')} fix Block[char('BAKE',k)] = k;

   solve;
   print Block;
quit;
```

The solution to this problem is shown in Output 12.2.1.

Output 12.2.1 Solution to Alphabet Blocks Problem

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	(0)
Objective Type	Constant
Number of Variables	24
Bounded Above	0
Bounded Below	0
Bounded Below and Above	20
Free	0
Fixed	4
Binary	1
Integer	23
Number of Constraints	13
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Alldiff	0
Cumulative	0
Element	0
GCC	13
Lexico (<=)	0
Lexico (<)	0
Pack	0
Reify	0
Constraint Coefficients	0

Solution Summary	
Solver	CLP
Variable Selection	MINR
Objective Function	(0)
Solution Status	Solution Limit Reached
Objective Value	0
Solutions Found	1
Presolve Time	0.00
Solution Time	0.00

Output 12.2.1 *continued*

[1]	Block
A	2
B	1
C	2
D	2
E	4
F	1
G	4
H	3
I	1
J	2
K	3
L	4
M	3
N	2
O	1
P	4
R	3
S	2
T	4
U	1
V	3
W	1
X	3
Y	4

Example 12.3: Work-Shift Scheduling Problem

This example illustrates the use of the GCC constraint to find a feasible solution to a work-shift scheduling problem and then the use of the element constraint to incorporate cost information in order to find a minimum-cost schedule.

Six workers (Alan, Bob, Juanita, Mike, Ravi, and Aisha) are to be assigned to three working shifts. The first shift needs at least one and at most four people; the second shift needs at least two and at most three people; and the third shift needs exactly two people. Alan cannot work on the first shift; Bob can work only on the third shift. The others can work on any shift. The objective is to find a feasible assignment for this problem.

You can model the minimum and maximum shift requirements by using a GCC constraint and formulate the problem as a standard CSP. The variables W[1],. . . ,W[6] identify the shift to which each of the six workers is assigned: Alan, Bob, Juanita, Mike, Ravi, and Aisha.

```
proc optmodel;
   /*  Six workers (Alan, Bob, Juanita, Mike, Ravi and Aisha)
       are to be assigned to 3 working shifts.            */
   set WORKERS = 1..6;
   var W {WORKERS} integer >= 1 <= 3;
```

```
   /* The first shift needs at least 1 and at most 4 people;
      the second shift needs at least 2 and at most 3 people;
      and the third shift needs exactly 2 people. */
   con ShiftNeeds:
      gcc(W, /<1,1,4>,<2,2,3>,<3,2,2>/);

   /* Alan doesn't work on the first shift. */
   con Alan:
      W[1] ne 1;

   /* Bob works only on the third shift. */
   fix W[2] = 3;

   solve;
   print W;
quit;
```

The resulting assignment is shown in Output 12.3.1.

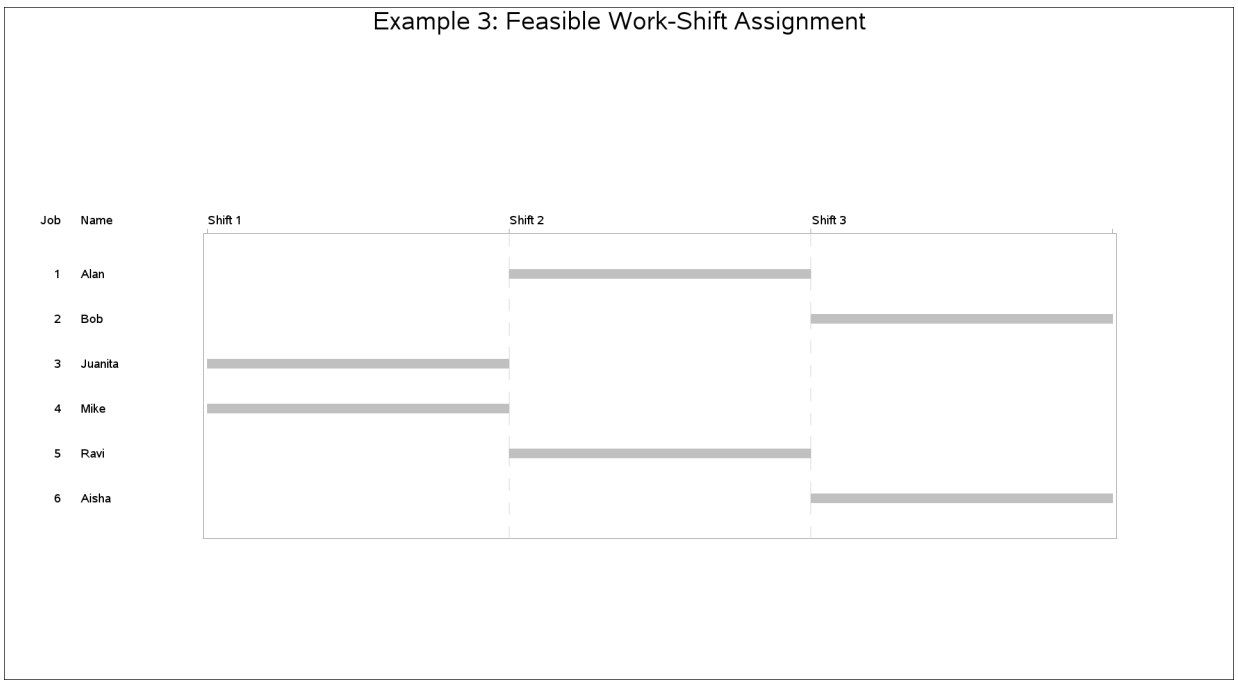
Output 12.3.1 Solution to Work-Shift Scheduling Problem

Solution to Work-Shift Scheduling Problem

Obs	W1	W2	W3	W4	W5	W6
1	2	3	1	1	2	3

A Gantt chart of the corresponding schedule is displayed in Output 12.3.2.

Output 12.3.2 Work-Shift Schedule



Now suppose that every work-shift assignment has a cost associated with it and that the objective of interest is to determine the schedule that has the lowest cost.

The costs of assigning the workers to the different shifts are shown in Table 12.5. A dash ("-") in position (i, j) indicates that worker i cannot work on shift j.

Table 12.5 Costs of Assigning Workers to Shifts

	Shift 1	Shift 2	Shift 3
Alan	-	12	10
Bob	-	-	6
Juanita	16	8	12
Mike	10	6	8
Ravi	6	6	8
Aisha	12	4	4

Based on the cost structure in Table 12.5, the previously derived schedule has a cost of $54. The objective now is to determine the optimal schedule—one that results in the minimum cost.

Let the variable C_i represent the cost of assigning worker i to a shift. This variable is shift-dependent and is given a high value (for example, 100) if the worker cannot be assigned to a shift. The costs can also be interpreted as preferences if desired. You can use an element constraint to associate the cost C_i with the shift assignment for each worker. For example, C_1, the cost of assigning Alan to a shift, can be determined by the constraint ELEMENT$(W_1, (100, 12, 10), C_1)$.

By adding a linear constraint, $\sum_{i=1}^{n} C_i \leq \mathrm{obj}$, you can limit the solutions to feasible schedules that cost no more than obj. Although an upper bound of $100 is used in this example, it would suffice to use an upper bound of $54, the cost of the feasible schedule that was determined earlier.

```
proc optmodel;
   /* Six workers (Alan, Bob, Juanita, Mike, Ravi and Aisha)
      are to be assigned to 3 working shifts.  */
   set WORKERS = 1..6;
   set SHIFTS  = 1..3;
   var W {WORKERS} integer >= 1 <= 3;
   var C {WORKERS} integer >= 1 <= 100;

   /* The first shift needs at least 1 and at most 4 people;
      the second shift needs at least 2 and at most 3 people;
      and the third shift needs exactly 2 people. */
   con GccCon:
      gcc(W, /<1,1,4>,<2,2,3>,<3,2,2>/);

   /* Alan doesn't work on the first shift. */
   con Alan:
      W[1] ne 1;

   /* Bob works only on the third shift. */
   fix W[2] = 3;

   /* Specify the costs of assigning the workers to the shifts.
      Use 100 (a large number) to indicate an assignment
```

```
      that is not possible.*/
   num a {WORKERS, SHIFTS} = [
      100,  12, 10,
      100, 100,  6,
       16,   8, 12
       10,   6,  8
        6,   6,  8
       12,   4,  4
   ];
   con ElementCon {j in WORKERS}:
      element(W[j], {k in SHIFTS} a[j,k], C[j]);

   /* Minimize total cost. */
   min TotalCost = sum {j in WORKERS} C[j];
   con TotalCost_bounds:
      1 <= TotalCost <= 100;

   solve;
   print W;
   create data clpout from
      {j in WORKERS} <col('W'||j)=W[j]> {j in WORKERS} <col('C'||j)=C[j]>;
quit;
```

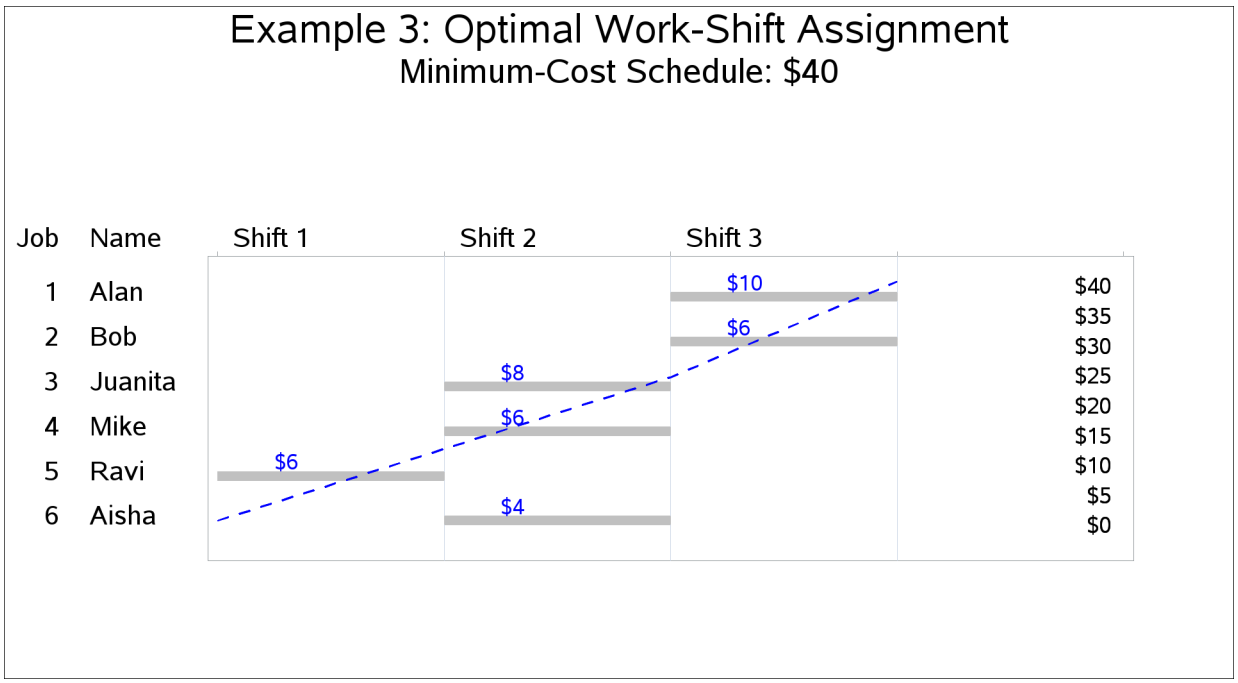
The cost of the optimal schedule, which corresponds to the solution shown in the following output, is $40.

Solution to Optimal Work-Shift Scheduling Problem

Obs	W1	W2	W3	W4	W5	W6	C1	C2	C3	C4	C5	C6
1	3	3	2	2	1	2	10	6	8	6	6	4

The minimum-cost schedule is displayed in the Gantt chart in Output 12.3.3.

Output 12.3.3 Work-Shift Schedule with Minimum Cost



Example 12.4: A Nonlinear Optimization Problem

This example illustrates how you can use the element constraint to represent almost any function between two variables in addition to representing nonstandard domains. Consider the following nonlinear optimization problem:

$$\text{maximize } f(x) = x_1^3 + 5x_2 - 2^{x_3}$$

$$\text{subject to } \begin{cases} x_1 - .5x_2 + x_3^2 \leq 50 \\ \text{mod}(x_1, 4) + .25x_2 \geq 1.5 \end{cases}$$

where x_1 is any integer in [–5, 5], x_2 is any *odd* integer in [–5, 9], and x_3 is any integer in [1, 10].

You can solve this problem by introducing four artificial variables, y_1–y_4, to represent each of the nonlinear terms. Let $y_1 = x_1^3$, $y_2 = 2^{x_3}$, $y_3 = x_3^2$, and $y_4 = \text{mod}(x_1, 4)$. You can represent the domains of x_1 and x_2 (which are not consecutive integers that start from 1) by using element constraints and index variables. For example, any of the following three element constraints specifies that the domain of x_2 is the set of odd integers in $[-5, 9]$:

```
con element(z2,-5 -3 -1 1 3 5 7 9,x2);
con element(z2, {ri in -5..9 by 2} ri, x2);
num range{ri in -5..9 by 2} = ri;
con element(z2,range,x2);
```

Any functional dependencies on x_1 or x_2 can now be defined using z_1 or z_2, respectively, as the index variable in an element constraint. Because the domain of x_3 is $[1, 10]$, you can directly use x_3 as the index variable in an element constraint to define dependencies on x_3.

For example, the following constraint specifies the function $y_1 = x_1^3$, $x_1 \in [-5, 5]$:

```
con element(z1,-125 -64 -27 -8 -1 0 1 8 27 64 125,y1);
/* or, con element(z1, {ri in -5..5} (ri**3), y1}; */
num range{ri in -5..5} = ri**3;
con element(z1,range,y1);
```

To solve the problem, define the objective function as demonstrated in the following statements:

```
proc optmodel;
   set DOM{1..3} = [ (-5 .. 5) (-5 .. 9 by 2) (1 .. 10) ];
   var X{i in 1..3} integer >= min{j in DOM[i]} j <= max{j in DOM[i]} j;

   /* map the domain of X[1] and X[2] to 1 .. list size */
   var Z {1..2} integer;
   /* map nonlinear expressions */
   var Y {1..4} integer;

   /* Use an element constraint to represent noncontiguous domains */
   /* domains with negative numbers, and nonlinear functions. */
   /* Z[2] does not appear anywhere else. Its only purpose is
      to restrict X[2] to take a value from DOM[2]. */
   con MapDomainTo1ToCard{i in 1..2}:
      element(Z[i], {k in DOM[i]} k, X[i]);

   /* Functional Dependencies on X[1] */
   /* Y[1] = X[1]^3 -- Use Z[1] for X[1] for proper indexing */
   con Y1:
      element(Z[1], {k in DOM[1]} (k^3), Y[1]);

   /* Y[4] = mod(X[1], 4) */
   con Y4:
      element(Z[1], {k in DOM[1]} (mod(k,4)), Y[4]);


   /* Functional Dependencies on X[3] */
   /* Y[2] = 2^X[3] */
   con Y2:
      element(X[3], {k in DOM[3]} (2^k), Y[2]);

   /* Y[3] = X[3]^2 */
   con Y3:
      element(X[3], {k in DOM[3]} (k^2), Y[3]);

   /* X[1] - 0.5 * X[2] + X[3]^2 <= 50 */
   con Con1:
      X[1] - 0.5 * X[2] + Y[3] <= 50;

   /* mod(X[1],4) + 0.25 * X[2] >= 1.5 */
   con Con2:
      Y[4] + 0.25 * X[2] >= 1.5;

   /* Objective function: X[1]^3 + 5 * X[2] - 2^X[3] */
   max Objective = Y[1] + 5 * X[2] - Y[2];
```

```
    solve;
    print X Y Z;
quit;
```

Output 12.4.1 shows the solution that corresponds to the optimal objective value of 168.

Output 12.4.1 Nonlinear Optimization Problem Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	Objective
Objective Type	Linear
Number of Variables	9
Bounded Above	0
Bounded Below	0
Bounded Below and Above	3
Free	6
Fixed	0
Binary	0
Integer	9
Number of Constraints	8
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Alldiff	0
Cumulative	0
Element	6
GCC	0
Lexico (<=)	0
Lexico (<)	0
Pack	0
Reify	0
Constraint Coefficients	5

Solution Summary	
Solver	CLP
Variable Selection	MINR
Objective Function	Objective
Solution Status	Optimal
Objective Value	168
Solutions Found	1
Presolve Time	0.00
Solution Time	0.00

Output 12.4.1 *continued*

[1]	X	Y	Z
1	5	125	11
2	9	2	8
3	1	1	
4		1	

Example 12.5: Car Painting Problem

The car painting process is an important part of the automobile manufacturing industry. Purging (the act of changing colors during assembly) is expensive because of the added cost of wasted paint and solvents from each color change and the extra time that the purging process requires. The objective of the car painting problem is to sequence the cars in the assembly line in order to minimize the number of paint color changes (Sokol 2002; Trick 2004).

Suppose an assembly line contains 10 cars, which are ordered 1, 2, . . . , 10. A car must be painted within three positions of its assembly order. For example, car 5 can be painted in positions 2 through 8. Cars 1, 5, and 9 are red; 2, 6, and 10 are blue; 3 and 7 green; and 4 and 8 are yellow. The initial sequence 1, 2, . . . , 10 corresponds to the color pattern RBGYRBGYRB and has nine purgings. The objective is to find a solution that minimizes the number of purgings.

This problem can be formulated as a CSP as follows:

- The input is the color of each car currently on the assembly line.
- The output variables are the slot in which each car will be painted and whether purging will be required after that painting operation.
- Set the bounds of the slot variables to their feasible range, at most three slots before or after the car's current position.
- To determine whether purging is needed, use another variable to store the color of the car painted in each slot.
- Use an element constraint to determine the color used in each slot from the car assigned to that slot.
- Use a reify constraint to determine whether two consecutive slots are assigned different colors, and thus whether purging is required.
- Finally, use a linear constraint to limit the total number of purgings.

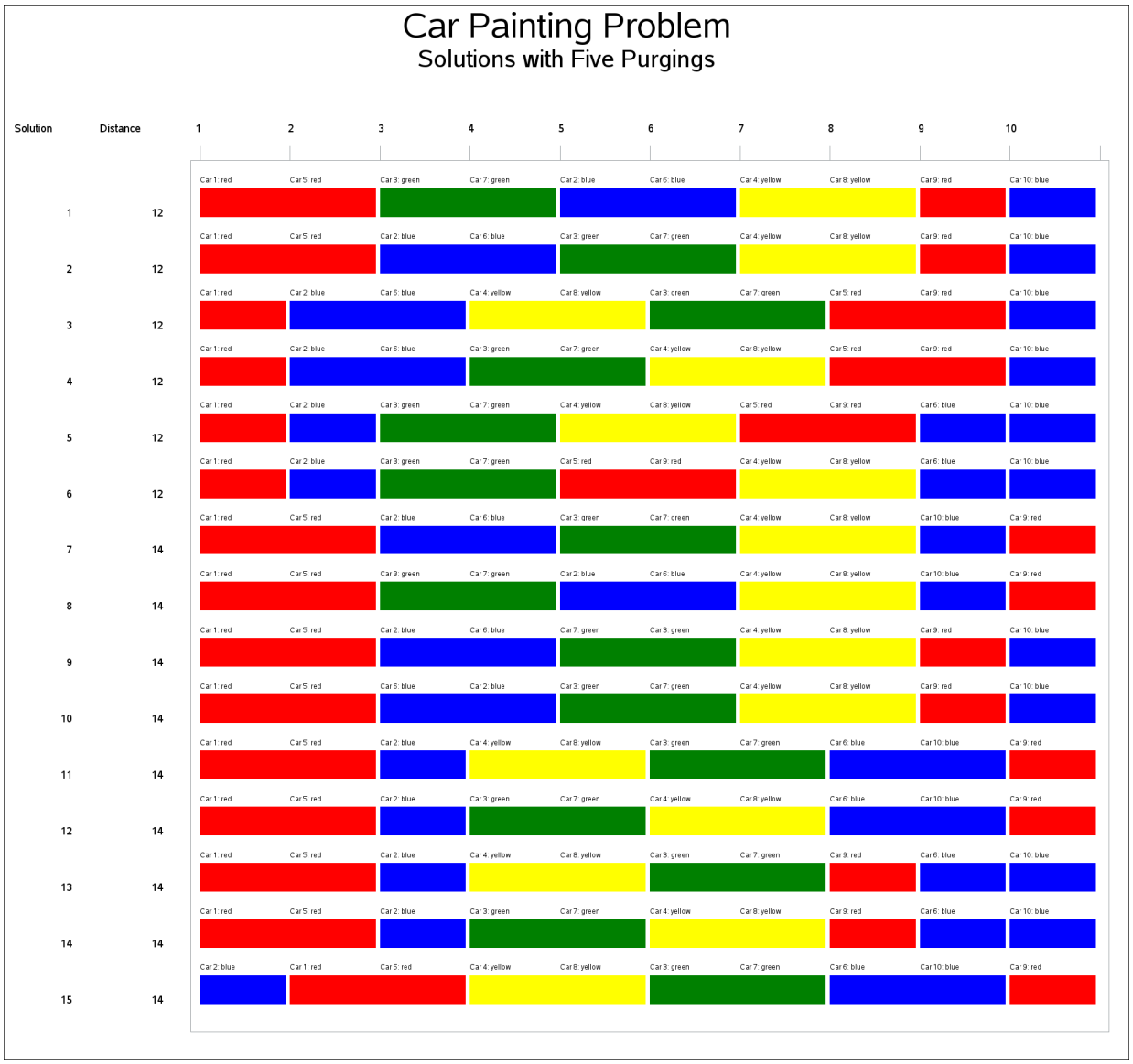
The following %CAR_PAINTING macro determines all feasible solutions for the number of purgings that is specified as a parameter to the macro:

```
%macro car_painting(purgings);
   proc optmodel;
      num nCars = 10;
      /* a car is identified by its original slots */
      set SLOTS = 1..nCars;
```

```
      /* maximum reshuffling of any car on the line*/
      num maxMove init 3;
      /* which car is in slot i. */
      var S {si in SLOTS} integer >= max(1, si - maxMove)
                                  <= min(nCars, si + maxMove) ;

      /* which color the car in slot i is. */
      /* Red=1; Blue=2; Green=3; Yellow=4 */
      num nColors=4;
      num colorOf{SLOTS} = [ 1 2 3 4 1 2 3 4 1 2 ];
      var C {SLOTS} integer >= 1 <= nColors;

      con ElementCon {i in SLOTS}:
         element(S[i], colorOf, C[i]);

      /* A car can be painted only once. */
      con PaintOnlyOnce:
         alldiff(S);

      /* Whether there is a purge after slot i.
        You can ignore any purging that would happen at the end of the shift. */
      var P {SLOTS diff {nCars}} binary;

      con ReifyCon {i in SLOTS diff {nCars}}:
         reify(P[i], C[i] ne C[i+1]);

      /* Calculate the number of purgings. */
      con PurgingsCon:
         sum {i in SLOTS diff {nCars}} P[i] <= &purgings;

      solve with CLP / findall;
      /* Replicate typical PROC CLP output from PROC OPTMODEL arrays */
      create data car_ds(drop=k) from [k]=(1.._NSOL_)
         {i in SLOTS} <col('S'||i)=S[i].sol[k]>
         {i in SLOTS} <col('C'||i)=C[i].sol[k]>;
   quit;
%mend;
%car_painting(5);
```

The problem is infeasible for four purgings. The CLP solver finds 87 possible solutions for the five-purgings problem. The solutions are sorted by the total distance that all cars are moved in the sequencing, which ranges from 12 to 22 slots. The first 15 solutions are displayed in the Gantt chart in Output 12.5.1. Each row represents a solution, and each color transition represents a paint purging.

Output 12.5.1 Car Painting Schedule with Five Purgings



Example 12.6: Scene Allocation Problem

The scene allocation problem consists of deciding when to shoot each scene of a movie in order to minimize the total production cost (Van Hentenryck 2002). Each scene involves a number of actors, and at most five scenes a day can be shot. All actors who appear in a scene must be present in the studio on the day the scene is shot. Each actor earns a daily rate for each day spent in the studio, regardless of the number of scenes in which he or she appears on that day. The goal is to shoot the movie for the lowest possible production cost.

The actors' names, their daily fees, and the scenes in which they appear are contained in the Scene data set, which is shown in Output 12.6.1. The data set variables S_Var1, . . . , S_Var9 indicate the scenes in which the actor appears. For example, the first observation indicates that Patt's daily fee is 26,481 and that Patt appears in scenes 2, 5, 7, 10, 11, 13, 15, and 17.

Output 12.6.1 Scene Data Set

Obs	Number	Actor	DailyFee	S_Var1	S_Var2	S_Var3	S_Var4	S_Var5	S_Var6	S_Var7	S_Var8	S_Var9
1	1	Patt	26481	2	5	7	10	11	13	15	17	.
2	2	Casta	25043	4	7	9	10	13	16	19	.	.
3	3	Scolaro	30310	3	6	9	10	14	16	17	18	.
4	4	Murphy	4085	2	8	12	13	15	.	.	.	.
5	5	Brown	7562	2	3	12	17	.	.	.	.	.
6	6	Hacket	9381	1	2	12	13	18	.	.	.	.
7	7	Anderson	8770	5	6	14	.	.	.	.	.	.
8	8	McDougal	5788	3	5	6	9	10	12	15	16	18
9	9	Mercer	7423	3	4	5	8	9	16	.	.	.
10	10	Spring	3303	5	6	.	.	.	.	.	.	.
11	11	Thompson	9593	6	9	12	15	18	.	.	.	.

There are 19 scenes. At most 5 scenes can be filmed in one day, so at least four days are needed to schedule all the scenes ($\lceil \frac{19}{5} \rceil = 4$). Let S_{jk} be a binary variable that equals 1 if scene j is shot on day k. Let A_{ik} be another binary variable that equals 1 if actor i is present on day k. The input daily_fee$_i$ is the daily cost of the ith actor.

The objective function that represents the total production cost is

$$\min \sum_{i=1}^{11} \sum_{k=1}^{4} \text{daily_fee}_i \times A_{ik}$$

This example illustrates the use of symmetry-breaking constraints. In this model, the "1" in day 1 does not refer to sequence but simply to the label of the day. Thus, you can call day 1 the day on which scene 1 is shot, whichever day that is. Similarly, either scene 2 is shot on the same day as scene 1 (day 1) or it is shot on another day, which you can call day 2. Scene 3 is shot either on one of those two days or on another day. Adding constraints that eliminate symmetry can significantly improve the performance of a CLP model. In this model, the symmetry-breaking constraints prevent the solver from considering three other assignments that do not differ in any meaningful way.

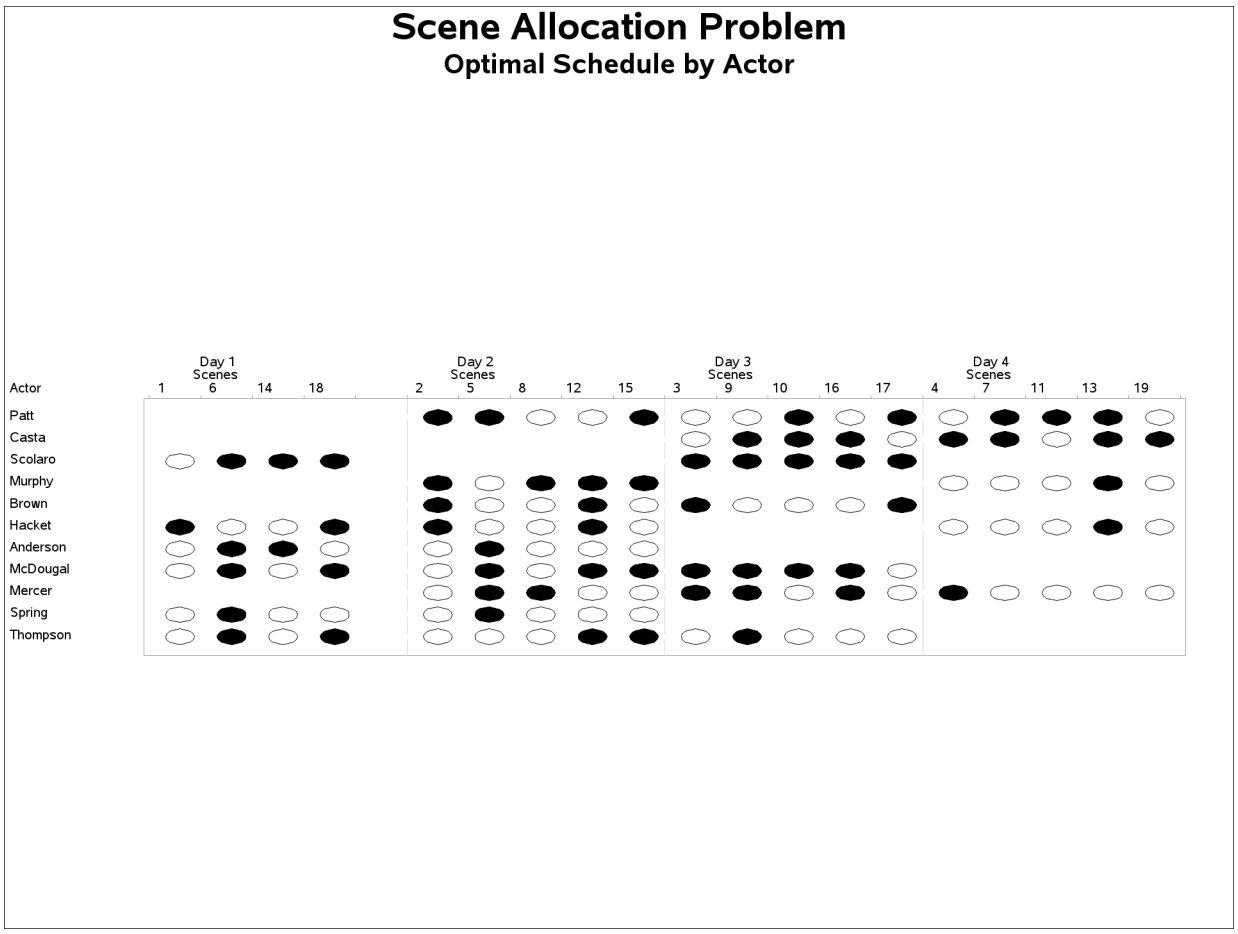
The following PROC OPTMODEL statements implement these ideas:

```
proc optmodel;
   set ACTORS;
   str actor_name {ACTORS};
   num daily_fee {ACTORS};
   num most_scenes = 9; /* most scenes by any actor */
   num scene_list {ACTORS, 1..most_scenes};
   read data scene into ACTORS=[_N_]
      actor_name=Actor daily_fee=DailyFee
      {j in 1..most_scenes} <scene_list[_N_,j]=col('S_Var'||j)>;
   print actor_name daily_fee scene_list;

   set SCENES_actor {i in ACTORS} =
      (setof {j in 1..most_scenes} scene_list[i,j]) diff {.};
   set SCENES = 1..19;
   set DAYS = 1..4;

   /* Indicates if actor i is present on day k. */
   var A {ACTORS, DAYS} binary;

   /* Indicates if scene j is shot on day k. */
   var S {SCENES, DAYS} binary;

   /* Every scene is shot exactly once.*/
   con SceneCon {j in SCENES}:
      gcc({k in DAYS} S[j,k], {<1,1,1>});

   /* At least 4 and at most 5 scenes are shot per day. */
   con NumScenesPerDayCon {k in DAYS}:
      gcc({j in SCENES} S[j,k], {<1,4,5>});

   /* Actors for a scene must be present on day of shooting. */
   con LinkCon {i in ACTORS, j in SCENES_actor[i], k in DAYS}:
      S[j,k] <= A[i,k];

   /* Symmetry-breaking constraints. Without loss of any generality, you
      can assume Scene1 to be shot on day 1, Scene2 to be shot on day 1
      or day 2, and Scene3 to be shot on either day 1, day 2, or day 3.  */
   fix S[1,1] = 1;
   for {k in 2..4} fix S[1,k] = 0;
   for {k in 3..4} fix S[2,k] = 0;
   fix S[3,4] = 0;

   /* If Scene2 is shot on day 1, (as opposed to day 2) */
   /* then Scene3 can be shot on day 1 or day 2 (but not day 3). */
   con Symmetry:
      S[2,1] + S[3,3] <= 1;

   /* Minimize total cost. */
   min TotalCost = sum {i in ACTORS, k in DAYS} daily_fee[i] * A[i,k];

   /* Set lower and upper bounds for the objective value   */
   /* Lower bound: every actor appears on one day.         */
   /* Upper bound: every actor appears on all four days.   */
```

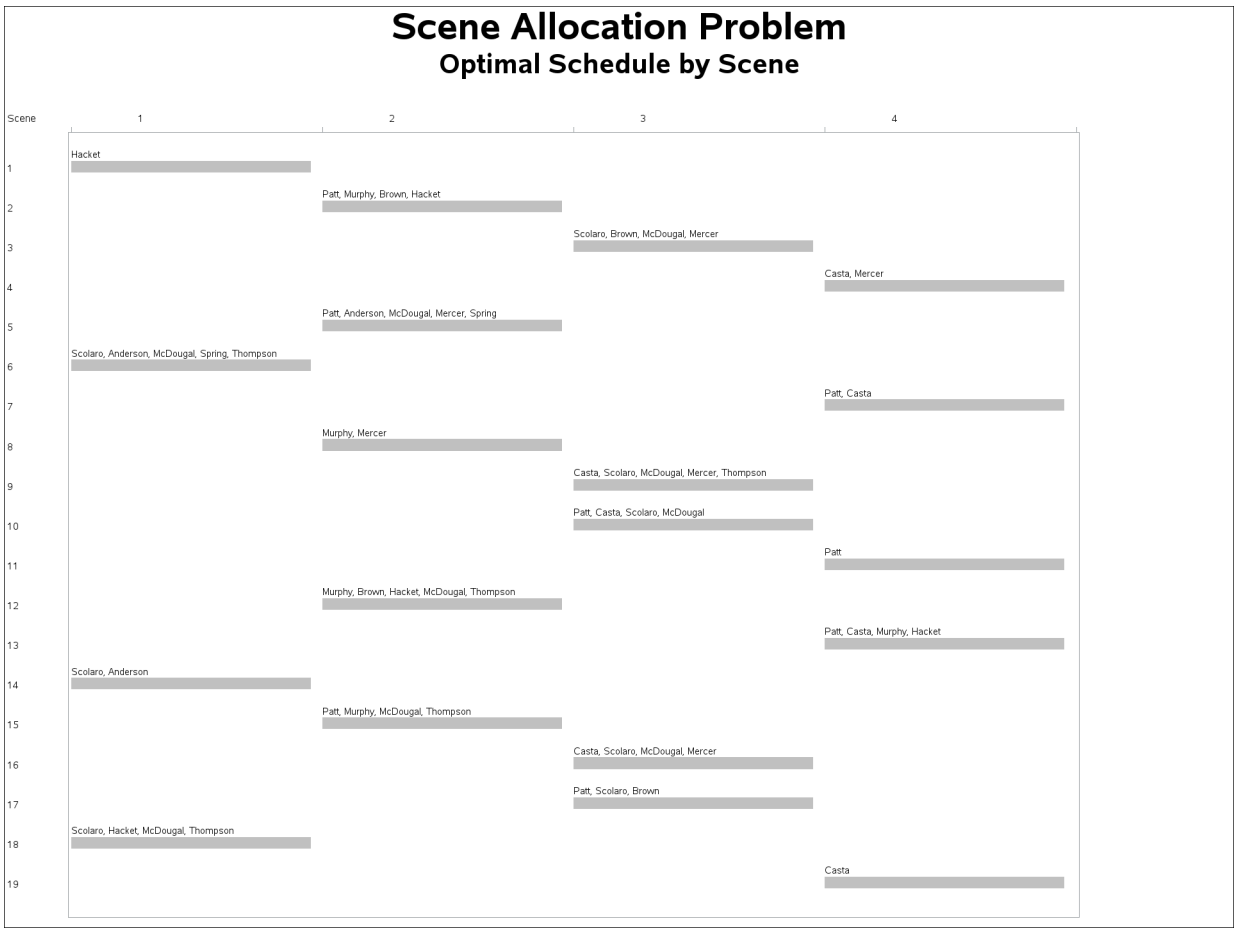
```
    num obj_lb = sum {i in ACTORS} daily_fee[i];
    num obj_ub = sum {i in ACTORS, k in DAYS} daily_fee[i];
    put obj_lb= obj_ub=;
    con TotalCost_bounds:
       obj_lb <= TotalCost <= obj_ub;

    solve with CLP / varselect=maxc;
  quit;
```

The optimal production cost is 334,144, as reported in the _OROPTMODEL_ macro variable. The corresponding actor schedules and scene schedules are displayed in Output 12.6.2 and Output 12.6.3, respectively.

Output 12.6.2 Scene Allocation Problem: Actor Schedules



Output 12.6.3 Scene Allocation Problem: Scene Schedules



Example 12.7: Car Sequencing Problem

This problem is an instance of a category of problems known as the car sequencing problem. A considerable amount of literature discusses this problem (Dincbas, Simonis, and Van Hentenryck 1988; Gravel, Gagne, and Price 2005; Solnon et al. 2008).

A number of cars are to be produced on an assembly line. Each car is customized to include a specific set of options, such as air conditioning, a sunroof, a navigation system, and so on. The assembly line moves through several workstations for installation of these options. The cars cannot be positioned randomly, because each workstation has limited capacity and needs time to set itself up to install the options as the car moves in front of the station. These capacity constraints are formalized using constraints of the form m out of N, which indicates that the workstation can install the option on m out of every sequence of N cars. The car sequencing problem is to determine a sequencing of the cars on the assembly line that satisfies the demand constraints for each set of car options and the capacity constraints for each workstation.

This example comes from Dincbas, Simonis, and Van Hentenryck (1988). Ten cars need to be customized with five possible options. A class of car is defined by a specific set of options; there are six classes of cars.

The data are presented in Table 12.6.

Table 12.6 Option Installation Data

Option		Capacity	Car Class					
Name	**Type**	**m/N**	**1**	**2**	**3**	**4**	**5**	**6**
Option 1	1	1/2	1	0	0	0	1	1
Option 2	2	2/3	0	0	1	1	0	1
Option 3	3	1/3	1	0	0	0	1	0
Option 4	4	2/5	1	1	0	1	0	0
Option 5	5	1/5	0	0	1	0	0	0
Number of Cars			**1**	**1**	**2**	**2**	**2**	**2**

For example, car class 4 requires installation of option 2 and option 4, and two cars of this class are required. The workstation for option 2 can process only two out of every sequence of three cars. The workstation for option 4 has even less capacity—two out of every five cars.

The data for this problem are used to create a SAS data set, which drives the generation of variables and constraints in PROC OPTMODEL.

The decision variables for this problem are shown in Table 12.7.

Table 12.7 Decision Variables

Variable Definition	Description
S{SLOTS} >=1 <= 6	S_i is the class of cars assigned to slot i.
var O {SLOTS, OPTIONS} binary	$O_{ij} = 1$ if the class assigned to slot i needs option j.

The following SAS statements express the workstation capacity constraints by using a set of linear constraints for each workstation. A single GCC constraint expresses the demand constraints for each car class. An element constraint for each option variable expresses the relationships between slot variables and option variables.

This model also includes a set of redundant constraints, in the sense that the preceding logical constraints correctly represent the set of feasible solutions. However, the redundant constraints provide the solver with further information specific to this problem, significantly improving the efficiency of domain propagation. Redundant constraints are a core fixture of CLP models. They can determine whether a model will linger and be unsolvable for real data or will produce instant results.

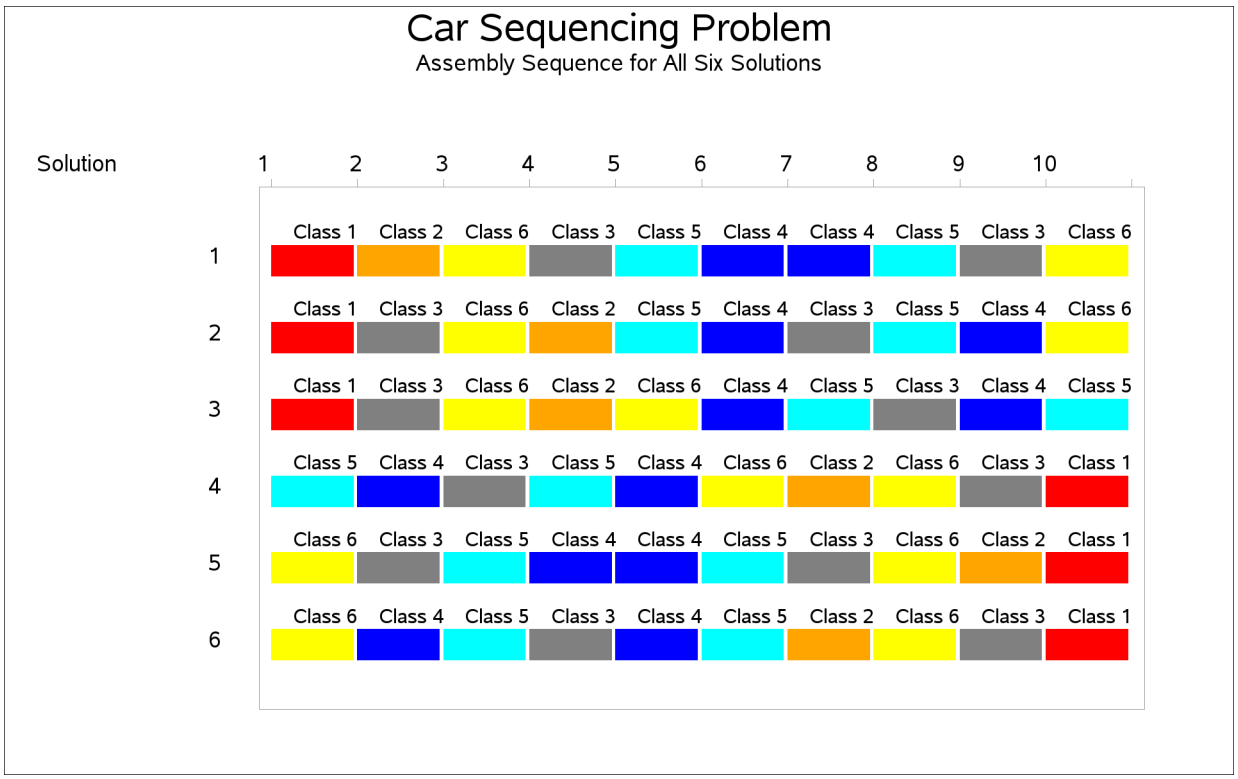
The idea behind the redundant constraint in this model is the following realization: if the workstation for option j has capacity r out of s, then at most r cars in the sequence $(n - s + 1), \ldots, n$ can have option j, where n is the total number of cars. Consequently, at least $n_j - r$ cars in the sequence $1, \ldots, n - s$ must have option j, where n_j is the number of cars that have option j. Generalizing this further, at least $n_j - k \times r$ cars in the sequence $1, \ldots, (n - k \times s)$ must have option j, $k = 1, \ldots, \lfloor n/s \rfloor$.

```
data class_data;
   input class cars_cls;
   datalines;
1 1
2 1
3 2
4 2
5 2
6 2
;

data option_data;
   input option max blSz class1-class6;
   datalines;
1 1 2 1 0 0 0 1 1
2 2 3 0 0 1 1 0 1
3 1 3 1 0 0 0 1 0
4 2 5 1 1 0 1 0 0
5 1 5 0 0 1 0 0 0
;

%macro car_sequencing(outdata);
   proc optmodel;
      set CLASSES;
      num nClasses = card(CLASSES);
      num cars_cls {CLASSES};
      read data class_data into CLASSES=[class] cars_cls;

      set OPTIONS;
      num max {OPTIONS};
      num blSz {OPTIONS};
      num list {OPTIONS, CLASSES};
      num cars_opt {i in OPTIONS} = sum {k in CLASSES} cars_cls[k] * list[i,k];
      read data option_data into OPTIONS=[option] max blSz
         {k in CLASSES} <list[option,k]=col('class'||k)>;

      num nCars = sum {k in CLASSES} cars_cls[k];
      set SLOTS = 1..nCars;

      /* Declare Variables */
      /* Slot variables: S[i] - class of car assigned to Slot i */
      var S {SLOTS} integer >= 1 <= nClasses;

      /* Option variables: O[i,j]
      - indicates if class assigned to Slot i needs Option j */
      var O {SLOTS, OPTIONS} binary;

      /* Capacity Constraints: for each option j */
      /* Install in at most max[j] out of every sequence of blSz[j] cars */
      con CapacityCon {j in OPTIONS, i in 0..(nCars-blSz[j])}:
         sum {k in 1..blSz[j]} O[i+k,j] <= max[j];

      /* Demand Constraints: for each class k */
```

```
      /* Exactly cars_cls[k] cars */
      con MeetDemandCon:
         gcc(S, setof{k in CLASSES} <k,cars_cls[k],cars_cls[k]>);

      /* Element Constraints: For each slot i and each option j */
      /* relate the slot variable to the option variables.      */
      /* O[i,j] = list[j,S[i]]                                  */
      con OptionsAtSlotCon {i in SLOTS, j in OPTIONS}:
         element(S[i], {k in CLASSES} list[j,k], O[i,j]);

      /* Redundant Constraints to improve efficiency - for every  */
      /*    option j.                                             */
      /* At most max[j] out of every sequence of blSz[j] cars     */
      /*    requires option j.                                    */
      /* All the other slots contain at least cars_opt[j] - max[j]*/
      /*    cars with option j                                    */
      con BoundRemainingCon {j in OPTIONS, i in 1..(nCars/blSz[j])}:
         sum {k in 1..(nCars-i*blSz[j])} O[k,j] >= cars_opt[j] - i * max[j];

      solve with CLP / varselect=minrmaxc findall;

      /* Replicate typical PROC CLP output from PROC OPTMODEL arrays */
      create data &outdata.(drop=sol) from [sol]=(1.._NSOL_)
         {i in SLOTS} <col('S_'||i)=S[i].sol[sol]>
         {i in SLOTS, j in OPTIONS} <col('O_'||i||'_'||j)=O[i,j].sol[sol]>;
   quit;
%mend;
%car_sequencing(sequence_out);
```

This problem has six solutions, as shown in Output 12.7.1.

Output 12.7.1 Car Sequencing



Example 12.8: Balanced Incomplete Block Design

Balanced incomplete block design (BIBD) generation is a standard combinatorial problem from design theory. The concept was originally developed in the design of statistical experiments; applications have expanded to other fields, such as coding theory, network reliability, and cryptography. A BIBD is an arrangement of v distinct objects into b blocks such that the following conditions are met:

- Each block contains exactly k distinct objects.
- Each object occurs in exactly r different blocks.
- Every two distinct objects occur together in exactly λ blocks.

A BIBD is therefore specified by its parameters (v, b, r, k, λ). It can be proved that when a BIBD exists, its parameters must satisfy the following conditions:

- $rv = bk$
- $\lambda(v-1) = r(k-1)$
- $b \geq v$

The preceding conditions are not sufficient to guarantee the existence of a BIBD (Prestwich 2001). For example, the parameters $(15, 21, 7, 5, 2)$ satisfy the preceding conditions, but a BIBD that has these parameters does not exist. Computational methods of BIBD generation usually suffer from combinatorial explosion, in part because of the large number of symmetries: for any solution, any two objects or blocks can be exchanged to obtain another solution.

This example demonstrates how to express a BIBD problem as a CSP and how to use lexicographic ordering constraints to break symmetries. Note that this example is for illustration only. SAS provides an autocall macro, MKTBIBD, for solving BIBD problems. The most direct CSP model for BIBD, as described in Meseguer and Torras (2001), represents a BIBD as a $v \times b$ matrix $\boldsymbol{X}$. Each matrix entry is a Boolean decision variable $X_{i,c}$ that satisfies $X_{i,c} = 1$ if and only if block c contains object i. The condition that each object occurs in exactly r blocks (or, equivalently, that there are r 1s per row) can be expressed as v linear constraints:

$$\sum_{c=1}^{b} X_{i,c} = r \quad \text{for } i = 1, \ldots, v$$

Alternatively, you can use global cardinality constraints to ensure that there are exactly $b - r$ 0s and r 1s in $X_{i,1}, \ldots, X_{i,b}$ for each object i:

$$\text{gcc}(X_{i,1}, \ldots, X_{i,b}) = ((0, 0, b - r)(1, 0, r)) \quad \text{for } i = 1, \ldots, v$$

Similarly, you can use the following constraints to specify the condition that each block contain exactly k objects (there are k 1s per column):

$$\text{gcc}(X_{1,c}, \ldots, X_{v,c}) = ((0, 0, v - k)(1, 0, k)) \quad \text{for } c = 1, \ldots, b$$

To enforce the final condition that every two distinct objects occur together in exactly λ blocks (equivalently, that the scalar product of every pair of rows equal λ), you can introduce the auxiliary variables $P_{i,j,c}$ for every $i < j$, which indicate whether objects i and j both occur in block c. The following reify constraint ensures that $P_{i,j,c} = 1$ if and only if block c contains both objects i and j:

$$\text{reify } P_{i,j,c} : (X_{i,c} + X_{j,c} = 2)$$

The following constraints ensure that the final condition holds:

$$\text{gcc}(P_{i,j,1}, \ldots, P_{i,j,b}) = ((0, 0, b - \lambda)(1, 0, \lambda)) \quad \text{for } i = 1, \ldots, v - 1 \text{ and } j = i + 1, \ldots, v$$

The objects and the blocks are interchangeable, so the matrix $\boldsymbol{X}$ has total row symmetry and total column symmetry. Because of the constraints on the rows, no pair of rows can be equal unless $r = \lambda$. To break the row symmetry, you can impose strict lexicographic ordering on the rows of X as follows:

$$(X_{i,1}, \ldots, X_{i,b}) <_{\text{lex}} (X_{i-1,1}, \ldots, X_{i-1,b}) \quad \text{for } i = 2, \ldots, v$$

To break the column symmetry, you can impose lexicographic ordering on the columns of X as follows:

$$(X_{1,c}, \ldots, X_{v,c}) \leq_{\text{lex}} (X_{1,c-1}, \ldots, X_{v,c-1}) \quad \text{for } c = 2, \ldots, b$$

The following SAS macro incorporates all the preceding constraints. For the specified parameters (v, b, r, k, λ), the macro either finds BIBDs or proves that a BIBD does not exist.

```
%macro bibd(v, b, r, k, lambda, out=bibdout);
   /* Arrange v objects into b blocks such that:
         (i) each object occurs in exactly r blocks,
         (ii) each block contains exactly k objects,
         (iii) every pair of objects occur together in exactly lambda blocks.

      Equivalently, create a binary matrix with v rows and b columns,
      with r 1s per row, k 1s per column,
      and scalar product lambda between any pair of distinct rows.
   */

   /* Check necessary conditions */
   %if (%eval(&r * &v) ne %eval(&b * &k)) or
      (%eval(&lambda * (&v - 1)) ne %eval(&r * (&k - 1))) or
      (&v > &b) %then %do;
      %put BIBD necessary conditions are not met.;
      %goto EXIT;
   %end;

   proc optmodel;
      num v = &v;
      num b = &b;
      num r = &r;
      num k = &k;
      num lambda = &lambda;
      set OBJECTS = 1..v;
      set BLOCKS = 1..b;

      /* Decision variable X[i,c] = 1 iff object i occurs in block c. */
      var X {OBJECTS, BLOCKS} binary;

      /* Mandatory constraints: */
      /* (i) Each object occurs in exactly r blocks. */
      con Exactly_r_blocks {i in OBJECTS}:
         gcc({c in BLOCKS} X[i,c], {<0,0,b-r>,<1,0,r>});

      /* (ii) Each block contains exactly k objects. */
      con Exactly_k_objects {c in BLOCKS}:
         gcc({i in OBJECTS} X[i,c], {<0,0,v-k>,<1,0,k>});

      /* (iii) Every pair of objects occurs in exactly lambda blocks. */
      set PAIRS = {i in OBJECTS, j in OBJECTS: i < j};
      /* auxiliary variable P[i,j,c] = 1 iff both i and j occur in c */
      var P {PAIRS, BLOCKS} binary;
      con Pairs_reify {<i,j> in PAIRS, c in BLOCKS}:
         reify(P[i,j,c], X[i,c] + X[j,c] = 2);
      con Pairs_gcc {<i,j> in PAIRS}:
         gcc({c in BLOCKS} P[i,j,c], {<0,0,b-lambda>,<1,0,lambda>});

      /* symmetry-breaking constraints: */
      /* Break row symmetry via lexicographic ordering constraints. */
      con Symmetry_i {i in OBJECTS diff {1}}:
         lexico({c in BLOCKS} X[i,c] < {c in BLOCKS} X[i-1,c]);
```

```
      /* Break column symmetry via lexicographic ordering constraints. */
      con Symmetry_c {c in BLOCKS diff {1}}:
         lexico({i in OBJECTS} X[i,c] <= {i in OBJECTS} X[i,c-1]);

      solve with CLP / varselect=FIFO;
      create data &out from
         {i in OBJECTS, c in BLOCKS} <col('X'||i||'_'||c)=X[i,c]>;
   quit;
   %put &_oroptmodel_;
%EXIT:
%mend bibd;
```

The following statement invokes the macro to find a BIBD design for the parameters (15, 15, 7, 7, 3):

```
%bibd(15,15,7,7,3);
```

The output is displayed in Output 12.8.1.

Output 12.8.1 Balanced Incomplete Block Design for (15,15,7,7,3)

Balanced Incomplete Block Design Problem
(15, 15, 7, 7, 3)

Obs	Block1	Block2	Block3	Block4	Block5	Block6	Block7	Block8	Block9	Block10	Block11
1	1	1	1	1	1	1	1	0	0	0	0
2	1	1	1	0	0	0	0	1	1	1	1
3	1	1	0	1	0	0	0	1	0	0	0
4	1	0	1	0	1	0	0	0	1	0	0
5	1	0	0	1	0	1	0	0	0	1	1
6	1	0	0	0	1	0	1	0	0	1	1
7	1	0	0	0	0	1	1	1	1	0	0
8	0	1	1	0	0	0	1	0	0	1	0
9	0	1	0	1	0	0	1	0	1	0	1
10	0	1	0	0	1	1	0	1	0	1	0
11	0	1	0	0	1	1	0	0	1	0	1
12	0	0	1	1	1	0	0	1	0	0	1
13	0	0	1	1	0	1	0	0	1	1	0
14	0	0	1	0	0	1	1	1	0	0	1
15	0	0	0	1	1	0	1	1	1	1	0

Obs	Block12	Block13	Block14	Block15
1	0	0	0	0
2	0	0	0	0
3	1	1	1	0
4	1	1	0	1
5	1	0	0	1
6	0	1	1	0
7	0	0	1	1
8	1	0	1	1
9	0	1	0	1
10	0	1	0	1
11	1	0	1	0
12	0	0	1	1
13	0	1	1	0
14	1	1	0	0
15	1	0	0	0

Example 12.9: Progressive Party Problem

This example demonstrates the use of the pack constraint to solve an instance of the progressive party problem (Smith et al. 1996). In the original progressive party problem, a number of yacht crews and their boats congregate at a yachting rally. In order for each crew to socialize with as many other crews as possible, some of the boats are selected to serve as "host boats" for six rounds of parties. The crews of the host boats stay with their boats for all six rounds. The crews of the remaining boats, called "guest crews," are assigned to visit a different host boat in each round.

Given the number of boats at the rally, the capacity of each boat, and the size of each crew, the objective of the original problem is to assign all the guest crews to host boats for each of the six rounds, using the minimum number of host boats. The partitioning of crews into guests and hosts is fixed throughout all rounds. No two crews should meet more than once. The assignments are constrained by the spare capacities (total capacity minus crew size) of the host boats and the crew sizes of the guest boats. Some boats cannot be hosts (zero spare capacity), and other boats must be hosts.

In this instance of the problem, the designation of the minimum requirement of 13 hosts is assumed (boats 1 through 12 and 14). The formulation solves up to eight rounds, but only two rounds are scheduled for this example. The total capacities and crew sizes of the boats are shown in Figure 12.3.

Figure 12.3 Progressive Party Problem Input

Progressive Party Problem Input

boatnum	capacity	crewsize
1	6	2
2	8	2
3	12	2
4	12	2
5	12	4
6	12	4
7	12	4
8	10	1
9	10	2
10	10	2
11	10	2
12	10	3
13	8	4
14	8	2
15	8	3
16	12	6
17	8	2
18	8	2
19	8	4
20	8	2
21	8	4

boatnum	capacity	crewsize
22	8	5
23	7	4
24	7	4
25	7	2
26	7	2
27	7	4
28	7	5
29	6	2
30	6	4
31	6	2
32	6	2
33	6	2
34	6	2
35	6	2
36	6	2
37	6	4
38	6	5
39	9	7
40	0	2
41	0	3
42	0	4

The following statements and DATA steps process the data and designate host boats:

```
data hostability;
   set capacities;
   spareCapacity = capacity - crewsize;
run;

data hosts guests;
   set hostability;
   if (boatnum <= 12 or boatnum eq 14) then do;
      output hosts;
   end;
   else do;
      output guests;
   end;
run;

/* sort so guest boats with larger crews appear first */
proc sort data=guests;
   by descending crewsize;
run;

data capacities;
   format boatnum capacity 2.;
   set hosts guests;
   seqno = _n_;
run;
```

To model the progressive party problem for the CLP solver, first define the following sets of variables:

- Item variables x_{it} contain the host boat number for the assignment of guest boat i in round t.
- Load variables L_{ht} contain the load of host boat h in round t.
- Variable m_{ijt} are binary variables that take a value of 1 if and only if guest boats i and j are assigned to the same host boat in round t.

Next, describe the set of constraints that are used in the model:

- All-different constraints ensure that a guest boat is not assigned to the same host boat in different rounds.
- Reify constraints regulate the values that are assigned to the aforementioned indicator variables m_{ijt}.
- The reified indicator variables appear in linear constraints to enforce the requirement to meet no more than once.
- One pack constraint per round maintains the capacity limits of the host boats.
- Finally, a symmetry-breaking linear constraint orders the host boat assignments for the highest-numbered guest boat across rounds.

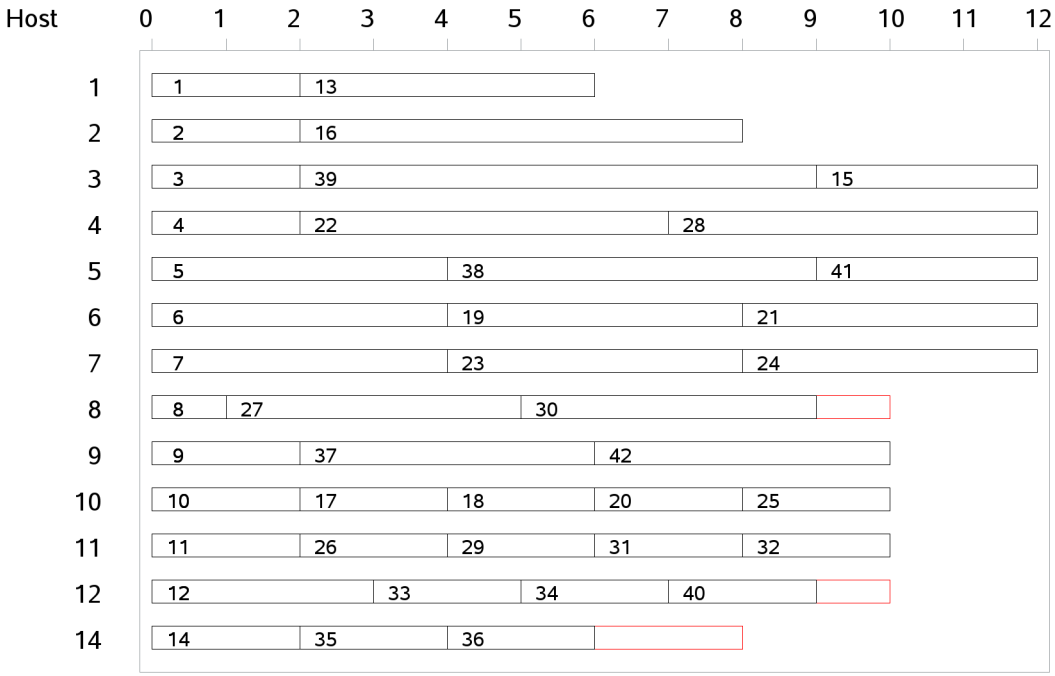
The following statements call PROC OPTMODEL to define the variables, specify the constraints, and solve the problem:

```
%let rounds=2;
%let numhosts=13;
proc optmodel;
   num numrounds = &rounds;
   set ROUNDS = 1..numrounds;
   num numhosts = &numhosts;
   set HOSTS = 1..numhosts;
   set BOATS;
   num numboats = card(BOATS);
   num capacity {BOATS};
   num crewsize {BOATS};
   num spareCapacity{hi in HOSTS} = capacity[hi] - crewsize[hi];
   /* Use the descending crew order for guests (seqno)
      rather than the actual boat id (boatnum)
      to help the performance of the PACK predicate. */
   read data capacities into BOATS=[seqno] capacity crewsize;

   /* Assume that the first numhosts boats are hosts,
      and process each round in turn.
      X is the host assigned to non-host i for round t. */
   var X {numhosts+1..numboats, ROUNDS} integer >= 1 <= numhosts;
   /* The load of the host boat. */
   var L {hi in HOSTS, ROUNDS} integer >= 0 <= spareCapacity[hi];

   /* Assign different hosts each round. */
   con AlldiffCon {i in numhosts+1..numboats}:
      alldiff({t in ROUNDS} X[i,t]);

   /* Two crews cannot meet more than once. */
   var M {i in numhosts+1..numboats-1, j in i+1..numboats, t in ROUNDS} binary;
   con ReifyCon {i in numhosts+1..numboats-1, j in i+1..numboats, t in ROUNDS}:
      reify(M[i,j,t], X[i,t] = X[j,t]);
   con Assign {i in numhosts+1..numboats-1, j in i+1..numboats}:
      sum {t in ROUNDS} M[i,j,t] <= 1;

   /* Honor capacities. */
   con PackCon {t in ROUNDS}:
      pack(
         {i in numhosts+1..numboats} X[i,t],
         {i in numhosts+1..numboats} crewsize[i],
         {h in HOSTS} L[h,t]
      );

   /* Break symmetries. */
   con SymmetryCon {t in 1..numrounds-1}:
      X[numboats,t] < X[numboats,t+1];

   solve with CLP / varselect=FIFO;
quit;
```

The two charts in Output 12.9.1 show the boat assignments for the first two rounds. The horizontal axis shows the load for each host boat. Slack capacity is highlighted in red.

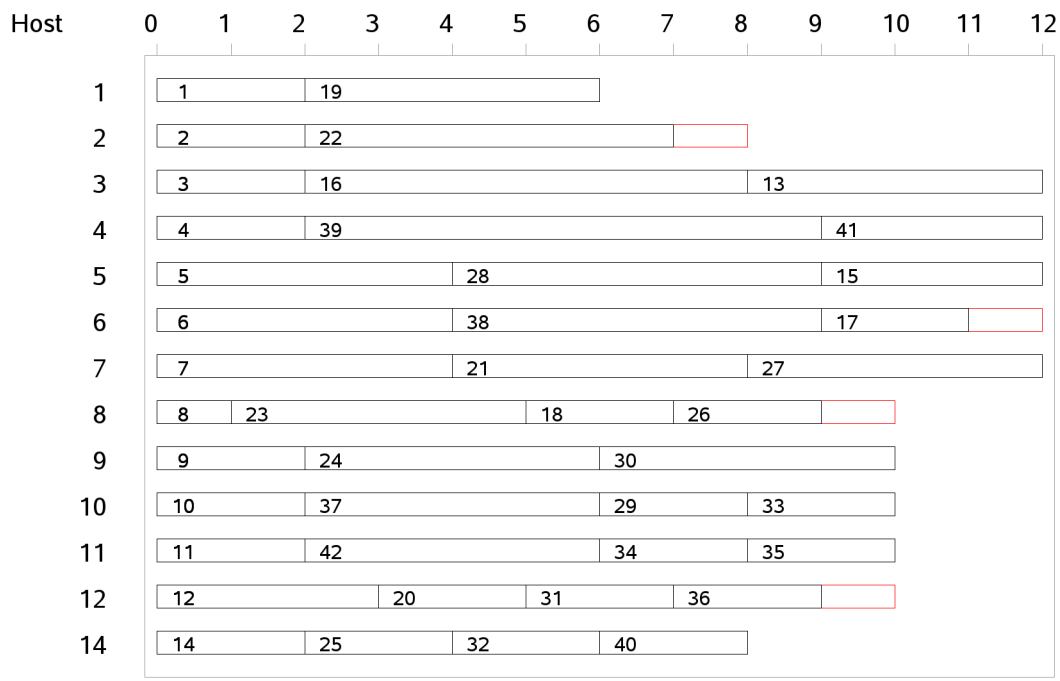
Output 12.9.1 Gantt Chart: Boat Schedule by Round

Schedule for Round 1



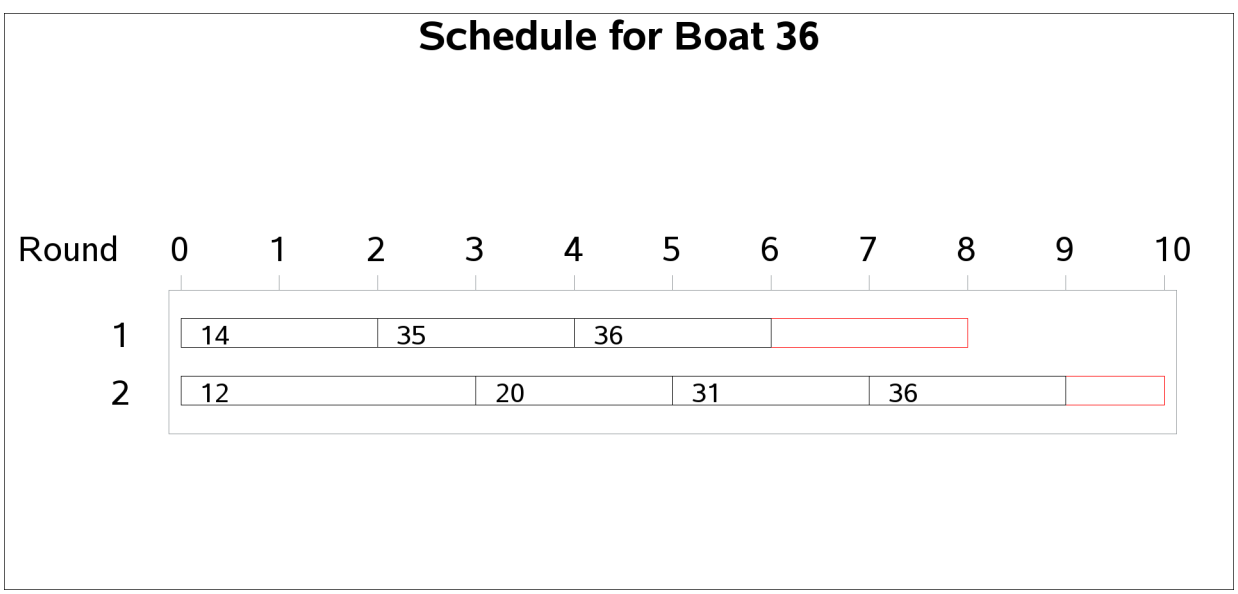
Output 12.9.1 *continued*

Schedule for Round 2

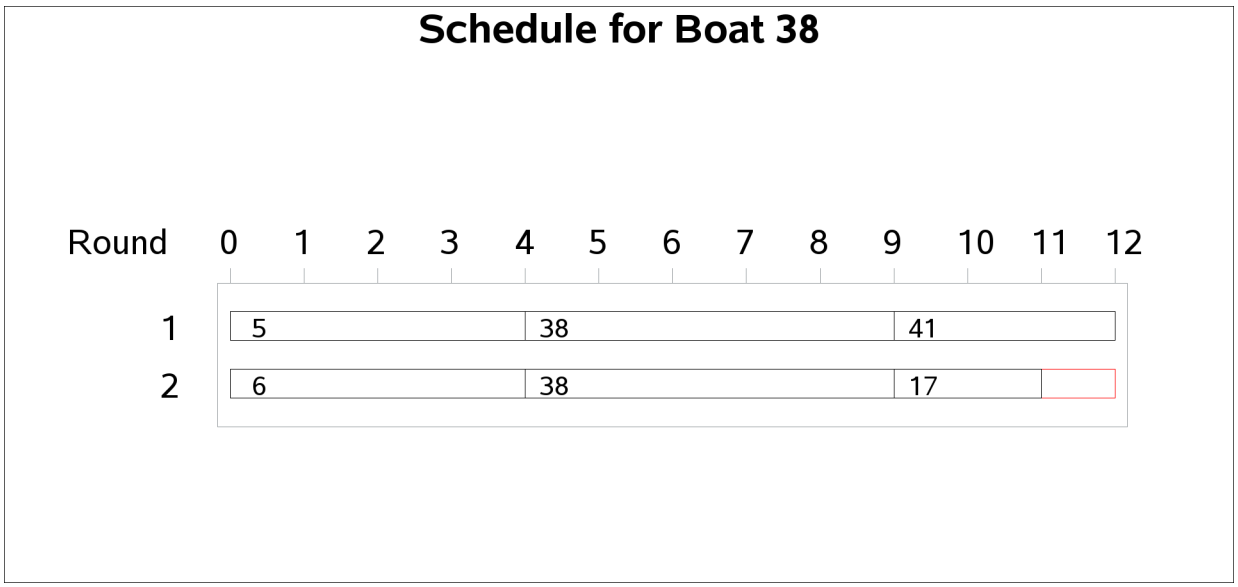


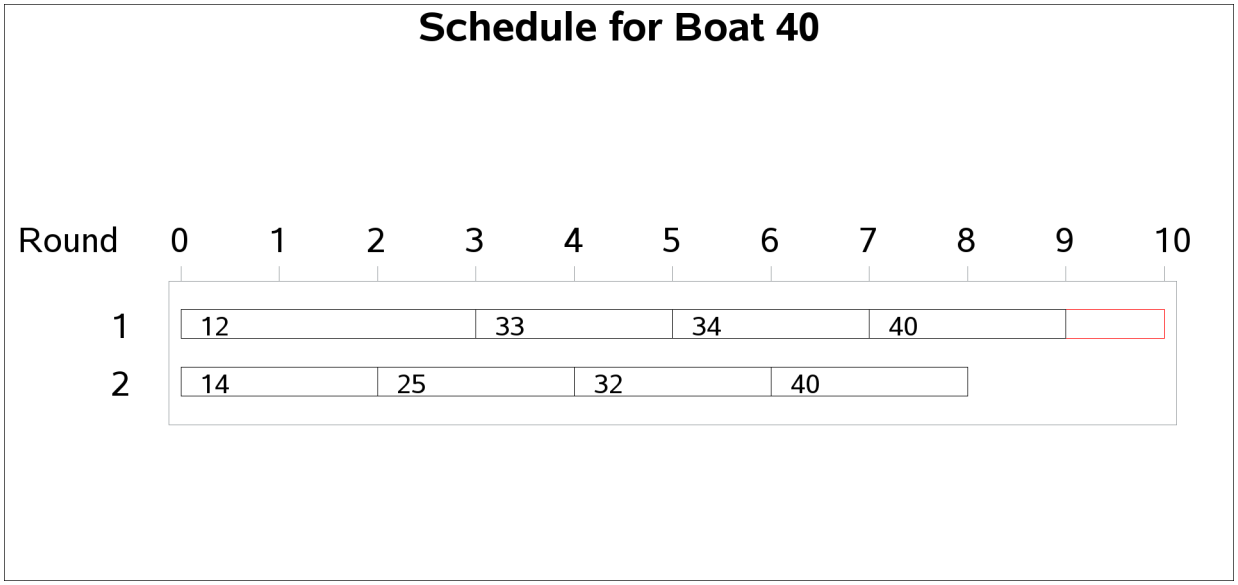
The charts in Output 12.9.2 break down the assignments by boat number for selected boats.

Output 12.9.2 Gantt Chart: Host Boat Schedule by Round

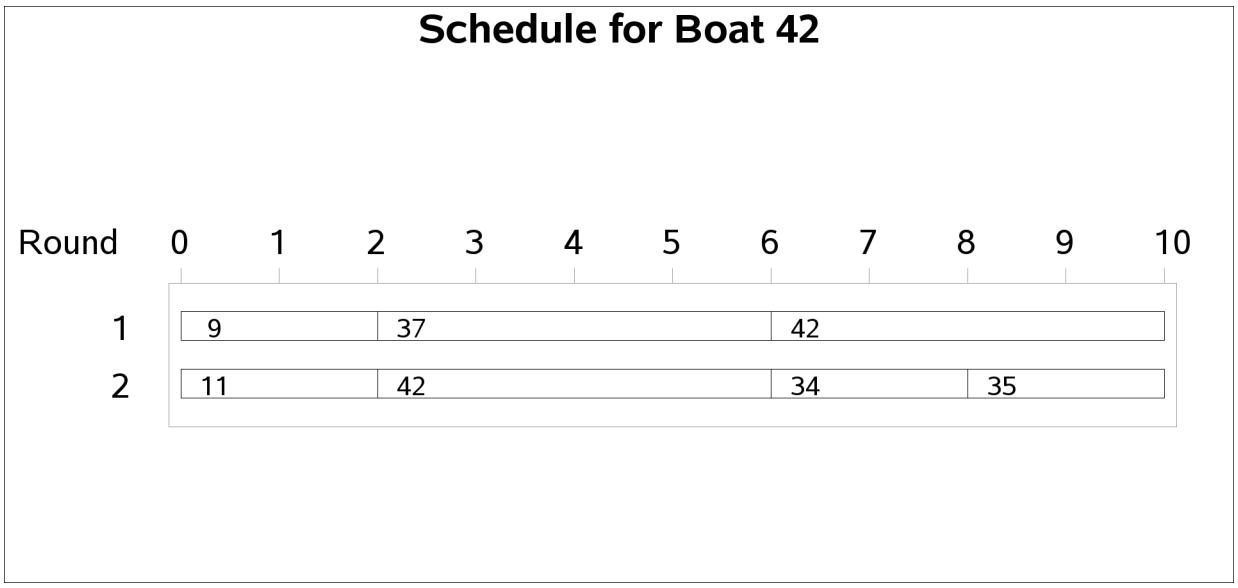


Output 12.9.2 *continued*





Output 12.9.2 *continued*



References

Boussemart, F., Hemery, F., Lecoutre, C., and Sais, L. (2004). "Boosting Systematic Search by Weighting Constraints." In *ECAI 2004: Proceedings of the Sixteenth European Conference on Artificial Intelligence*, 146–150. Amsterdam: IOS Press.

Brualdi, R. A. (2010). *Introductory Combinatorics*. 5th ed. Englewood Cliffs, NJ: Prentice-Hall.

Dincbas, M., Simonis, H., and Van Hentenryck, P. (1988). "Solving the Car-Sequencing Problem in Constraint Logic Programming." In *Proceedings of the European Conference on Artificial Intelligence, ECAI-88*, edited by Y. Kodratoff, 290–295. London: Pitman.

Floyd, R. W. (1967). "Nondeterministic Algorithms." *Journal of the ACM* 14:636–644.

Frisch, A. M., Hnich, B., Kiziltan, Z., Miguel, I., Pearson, J., and Walsh, T. (2002). "Global Constraints for Lexicographic Orderings." In *Proceedings of the Eighth International Conference on Principles and Practice of Constraint Programming (CP 2002)*, edited by P. Van Hentenryck, 93–108. Berlin: Springer-Verlag.

Garey, M. R., and Johnson, D. S. (1979). *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York: W. H. Freeman.

Gravel, M., Gagne, C., and Price, W. L. (2005). "Review and Comparison of Three Methods for the Solution of the Car Sequencing Problem." *Journal of the Operational Research Society* 56:1287–1295.

Haralick, R. M., and Elliott, G. L. (1980). "Increasing Tree Search Efficiency for Constraint Satisfaction Problems." *Artificial Intelligence* 14:263–313.

Kumar, V. (1992). "Algorithms for Constraint-Satisfaction Problems: A Survey." *AI Magazine* 13:32–44.

Mackworth, A. K. (1977). "Consistency in Networks of Relations." *Artificial Intelligence* 8:99–118.

Meseguer, P., and Torras, C. (2001). "Exploiting Symmetries within Constraint Satisfaction Search." *Artificial Intelligence* 129:133–163.

Prestwich, S. D. (2001). "Balanced Incomplete Block Design as Satisfiability." In *Twelfth Irish Conference on Artificial Intelligence and Cognitive Science*, 189–198. Maynooth: National University of Ireland.

Riley, P., and Taalman, L. (2008). "Brainfreeze Puzzles." http://www.geekhaus.com/brainfreeze/piday2008.html.

Smith, B. M., Brailsford, S. C., Hubbard, P. M., and Williams, H. P. (1996). "The Progressive Party Problem: Integer Linear Programming and Constraint Programming Compared." *Constraints* 1:119–138.

Sokol, J. (2002). "Modeling Automobile Paint Blocking: A Time Window Traveling Salesman Problem." Ph.D. diss., Massachusetts Institute of Technology.

Solnon, C., Cung, V. D., Nguyen, A., and Artigues, C. (2008). "The Car Sequencing Problem: Overview of State-of-the-Art Methods and Industrial Case-Study of the ROADEF 2005 Challenge Problem." *European Journal of Operational Research* 191:912–927.

Trick, M. A. (2004). "Constraint Programming: A Tutorial." https://mat.tepper.cmu.edu/trick/cp.ppt.

Tsang, E. (1993). *Foundations of Constraint Satisfaction*. London: Academic Press.

Van Hentenryck, P. (1989). *Constraint Satisfaction in Logic Programming*. Cambridge, MA: MIT Press.

Van Hentenryck, P. (2002). "Constraint and Integer Programming in OPL." *INFORMS Journal on Computing* 14:345–372.

Waltz, D. L. (1975). "Understanding Line Drawings of Scenes with Shadows." In *The Psychology of Computer Vision*, edited by P. H. Winston, 19–91. New York: McGraw-Hill.

Chapter 13
The Linear Programming Solver

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Overview: LP Solver

The OPTMODEL procedure provides a framework for specifying and solving linear programs (LPs). A linear program has the following formulation:

$$\begin{array}{rl} \min & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{array}$$

where

$\mathbf{x}$	$\in$	$\mathbb{R}^n$	is the vector of decision variables
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the matrix of constraints
$\mathbf{c}$	$\in$	$\mathbb{R}^n$	is the vector of objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^m$	is the vector of constraints' right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^n$	is the vector of lower bounds on variables
$\mathbf{u}$	$\in$	$\mathbb{R}^n$	is the vector of upper bounds on variables

The following LP algorithms are available in the OPTMODEL procedure:

- primal simplex algorithm
- dual simplex algorithm
- network simplex algorithm
- interior point algorithm

The primal and dual simplex algorithms implement the two-phase simplex method. In phase I, the algorithm tries to find a feasible solution. If no feasible solution is found, the LP is infeasible; otherwise, the algorithm enters phase II to solve the original LP. The network simplex algorithm extracts a network substructure, solves this using network simplex, and then constructs an advanced basis to feed to either primal or dual simplex. The interior point algorithm implements a primal-dual predictor-corrector interior point algorithm. If any of the decision variables are constrained to be integer-valued, then the relaxed version of the problem is solved.

Getting Started: LP Solver

The following example illustrates how you can use the OPTMODEL procedure to solve linear programs. Suppose you want to solve the following problem:

$$
\begin{array}{rrcrcrcl}
\max & x_1 & + & x_2 & + & x_3 & & \\
\text{subject to} & 3x_1 & + & 2x_2 & - & x_3 & \leq & 1 \\
 & -2x_1 & - & 3x_2 & + & 2x_3 & \leq & 1 \\
 & & & x_1, & & x_2, \; x_3 & \geq & 0
\end{array}
$$

You can use the following statements to call the OPTMODEL procedure for solving linear programs:

```
proc optmodel;
   var x{i in 1..3} >= 0;
   max f =    x[1] +   x[2] +   x[3];
   con c1:  3*x[1] + 2*x[2] -   x[3] <= 1;
   con c2: -2*x[1] - 3*x[2] + 2*x[3] <= 1;
   solve with lp / algorithm = ps presolver = none logfreq = 1;
   print x;
quit;
```

The optimal solution and the optimal objective value are displayed in Figure 13.1.

Figure 13.1 Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	f
Objective Type	Linear
Number of Variables	3
Bounded Above	0
Bounded Below	3
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	2
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	6

Figure 13.1 *continued*

Solution Summary	
Solver	LP
Algorithm	Primal Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	8
Primal Infeasibility	0
Dual Infeasibility	8.881784E-16
Bound Infeasibility	0
Iterations	4
Presolve Time	0.01
Solution Time	0.02

[1]	x
1	0
2	3
3	5

The iteration log displaying problem statistics, progress of the solution, and the optimal objective value is shown in Figure 13.2.

Figure 13.2 Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 2 linear constraints (2 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 6 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                          Objective                Entering      Leaving
      Phase Iteration       Value          Time     Variable      Variable
       P 2          1    0.000000E+00         0       x[1]             c1 (S)
       P 2          2    3.333333E-01         0       x[3]             c2 (S)
       P 2          3    2.000000E+00         0       x[2]           x[1]
       P 2          4    8.000000E+00         0
NOTE: Optimal.
NOTE: Objective = 8.
NOTE: The Primal Simplex solve time is 0.00 seconds.
```

Syntax: LP Solver

The following statement is available in the OPTMODEL procedure:

SOLVE WITH LP < / *options* > **;**

Functional Summary

Table 13.1 summarizes the list of options available for the SOLVE WITH LP statement, classified by function.

Table 13.1 Options for the LP Solver

Description	Option
Solver Options	
Specifies the type of algorithm	ALGORITHM=
Specifies the type of algorithm called after network simplex	ALGORITHM2=
Enables or disables IIS detection	IIS=
Presolve Options	
Controls the dualization of the problem	DUALIZE=
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the feasibility tolerance	FEASTOL=
Specifies the frequency of printing solution progress	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the optimality tolerance	OPTTOL=
Specifies units of CPU time or real time	TIMETYPE=
Simplex Algorithm Options	
Specifies the type of initial basis	BASIS=
Specifies the type of pricing strategy	PRICETYPE=
Specifies the queue size for pricing	QUEUESIZE=
Enables or disables scaling of the problem	SCALE=
Specifies the initial seed for the random number generator	SEED=
Interior Point Algorithm Options	
Enables or disables interior crossover	CROSSOVER=
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Sensitivity Analysis Option	
Enables the sensitivity analysis algorithm and specifies general control options	SENSITIVITY=()

Table 13.1 *continued*

Description	Option
Decomposition Algorithm Options	
Enables the decomposition algorithm and specifies general control options	DECOMP=()
Specifies options for the master problem	DECOMPMASTER=()
Specifies options for the subproblem	DECOMPSUBPROB=()
Parallel Options	
Enables the LP solver to run deterministically	DETERMINISTIC=
Specifies number of threads for the parallel LP solver to use	NTHREADS=

LP Solver Options

This section describes the options recognized by the LP solver. These options can be specified after a forward slash (/) in the SOLVE statement, provided that the LP solver is explicitly specified using a WITH clause.

If the LP solver terminates before reaching an optimal solution, an intermediate solution is available. You can access this solution by using the .sol variable suffix in the OPTMODEL procedure. See the section "Suffixes" on page 420 for details.

Solver Options

ALGORITHM=*option*

SOLVER=*option*

SOL=*option*

specifies an LP algorithm. You can specify the following *options*:

PRIMAL (PS) uses the primal simplex algorithm.

DUAL (DS) uses the dual simplex algorithm.

NETWORK (NS) uses the network simplex algorithm.

INTERIORPOINT (IP) uses the interior point algorithm.

CONCURRENT (CON) uses several different algorithms in parallel.

SIFTING (SIFT) uses the sifting algorithm.

SIMPLEX (SPX) uses one of the simplex-based algorithms: PS, DS, NS, and SIFT. The algorithm is determined automatically on the basis of the problem structure.

The valid abbreviated value for each option is indicated in parentheses. By default, ALGORITHM=SIMPLEX.

ALGORITHM2=*option*
SOLVER2=*option*

specifies an LP algorithm if ALGORITHM=NS. You can specify the following values:

PRIMAL (PS) uses the primal simplex algorithm (after network simplex).

DUAL (DS) uses the dual simplex algorithm (after network simplex).

The valid abbreviated value for each option is indicated in parentheses. By default, the LP solver decides which algorithm is best to use after calling the network simplex algorithm on the extracted network.

IIS=FALSE | TRUE

specifies whether the LP solver attempts to identify a set of constraints and variables that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection.

If an IIS is found, information about infeasible constraints or variable bounds can be found in the .status values of the constraints and variables. For more information about the .status suffix, see the section "Suffixes" on page 420. For more information about IIS, see the section "Irreducible Infeasible Set" on page 655. By default, IIS=FALSE.

Presolve Options

DUALIZE=AUTOMATIC | OFF | ON

controls the dualization of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to dualize the problem or not.

OFF disables dualization. The optimization problem is solved in the form that you specify.

ON specifies that the presolver formulate the dual of the linear optimization problem.

Dualization is usually helpful for problems that have many more constraints than variables. You can use this option with all simplex algorithms in the SOLVE WITH LP statement, but it is most effective with the primal and dual simplex algorithms.

By default, DUALIZE=AUTOMATIC.

FOLD=AUTOMATIC | OFF | ON

controls the folding of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to fold the problem or not.

OFF disables folding. The optimization problem is not further reduced by folding.

ON specifies that the presolver try to fold the linear optimization problem.

Folding is helpful for problems that have a symmetric structure. When you use this option with a simplex algorithm in the SOLVE WITH LP statement, a crossover step must be used to find a basic solution.

By default, FOLD=AUTOMATIC.

PRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

PRESOL=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the level of presolve processing. You can specify the following values:

AUTOMATIC applies the presolver by using the default settings. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

NONE disables the presolver. Only the necessary problem transformation steps are performed.

BASIC performs a basic presolve, such as removing empty rows, columns, and fixed variables. Only some very fast operations are performed.

MODERATE performs a basic presolve and applies other inexpensive presolve techniques. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

AGGRESSIVE performs a moderate presolve and applies other aggressive (but computationally expensive) presolve techniques. All the presolver techniques are called with no limits. This reduces the problem the most, but can take a very long time.

By default, PRESOLVER=AUTOMATIC. For more information, see the section "Presolve" on page 645.

Control Options

FEASTOL=ϵ

specifies the feasibility tolerance $\epsilon \in [1E{-}9, 1E{-}4]$ for determining the feasibility of variable and constraint values. The default value is 1E–6. Both simplex and interior point algorithms use the relative error for the computation of feasibility tolerance.

LOGFREQ=k

PRINTFREQ=k

specifies that the printing of the solution progress to the iteration log is to occur after every k iterations. The print frequency, k, is an integer between zero and the largest four-byte signed integer, which is $2^{31} - 1$.

The value $k = 0$ disables the printing of the progress of the solution.

If the LOGFREQ= option is not specified, then the LP solver displays the iteration log with a dynamic frequency according to the problem size if the primal or dual simplex algorithm is used, with frequency 10,000 if the network simplex algorithm is used, or with frequency 1 if the interior point algorithm is used.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that the LP solver displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXITER=*k*

specifies the maximum number of iterations. The value k can be any integer between one and the largest four-byte signed integer, which is $2^{31} - 1$. If you do not specify this option, the procedure does not stop based on the number of iterations performed. For network simplex, this iteration limit corresponds to the algorithm called after network simplex (either primal or dual simplex).

MAXTIME=*t*

specifies an upper limit of t units of time for the optimization process, including problem generation time and solution time. The value of the TIMETYPE= option determines the type of units used. If you do not specify this option, the solver does not stop based on the amount of time elapsed. The value of t can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

OPTTOL=ϵ

specifies the optimality tolerance $\epsilon \in$[1E–9, 1E–4] for declaring optimality. The default value is 1E–6. Both simplex and interior point algorithms use the relative error for the computation of optimality tolerance.

TIMETYPE=CPU | REAL

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMODEL_ macro variable. You can specify the following values:

CPU specifies units of CPU time.

REAL specifies units of real time.

By default, TIMETYPE=REAL.

Simplex Algorithm Options

BASIS=CRASH | SLACK | WARMSTART

specifies the option for generating an initial basis. You can specify the following values:

CRASH generates an initial basis by using crash techniques (Maros 2003). The procedure creates a triangular basic matrix consisting of both decision variables and slack variables.

SLACK generates an initial basis by using all slack variables.

WARMSTART starts the primal and dual simplex algorithms with the available basis.

The default option is determined automatically based on the problem structure. For network simplex, this option has no effect.

PRICETYPE=DEVEX | FULL | HYBRID | PARTIAL | STEEPESTEDGE

specifies the pricing strategy for the primal and dual simplex algorithms. You can specify the following values:

DEVEX uses the Devex pricing strategy.

FULL uses Dantzig's rule on all decision variables.

HYBRID uses a hybrid of the Devex and steepest-edge pricing strategies. This strategy is available only for the primal simplex algorithm.

PARTIAL uses Dantzig's rule on a queue of decision variables. Optionally, you can specify QUEUESIZE=*k*. This strategy is available only for the primal simplex algorithm.

STEEPESTEDGE uses the steepest-edge pricing strategy.

The default option is determined automatically according to the problem structure. For the network simplex algorithm, this option applies only to the algorithm that is specified in the ALGORITHM2= option. For more information, see the section "Pricing Strategies for the Primal and Dual Simplex Algorithms" on page 645.

QUEUESIZE=*k*

specifies the queue size $k \in [1, n]$, where n is the number of decision variables. This queue is used for finding an entering variable in the simplex iteration. The default value is chosen adaptively based on the number of decision variables. This option is used only when PRICETYPE=PARTIAL.

SCALE=AUTOMATIC | NONE

specifies a scaling option. You can specify the following values:

AUTOMATIC automatically applies scaling procedure if necessary.

NONE disables scaling.

By default, SCALE=AUTOMATIC.

SEED=*number*

specifies the initial seed for the random number generator. Because the seed affects the perturbation in the simplex algorithms, the result might be a different optimal solution and a different solver path, but the effect is usually negligible. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. By default, SEED=100.

Interior Point Algorithm Options

CROSSOVER=FALSE | TRUE

specifies whether to convert the interior point solution to a basic simplex solution. If the interior point algorithm terminates with a solution, the crossover algorithm uses the interior point solution to create an initial basic solution. After performing primal fixing and dual fixing, the crossover algorithm calls a simplex algorithm to locate an optimal basic solution.

You can specify the following values:

FALSE	does not convert the interior point solution to a basic simplex solution.
TRUE	converts the interior point solution to a basic simplex solution.

By default, CROSSOVER=TRUE.

DUALITYGAP=*δ*

specifies the desired relative duality gap $\delta \in$[1E–9, 1E–4], which is the relative difference between the primal and dual objective function values and is the primary solution quality parameter. For more information, see the section "The Interior Point Algorithm" on page 647. The default value is 1E–6.

Parallel Options

The LP solver has several components that take advantage of shared-memory parallel architectures. You can use the following options to control parallel processing:

DETERMINISTIC=TRUE | FALSE

specifies whether to run the LP solver in deterministic or nondeterministic parallel mode. You can specify the following values:

TRUE	runs the LP solver in deterministic parallel mode.
FALSE	runs the LP solver in nondeterministic parallel mode.

By default, DETERMINISTIC=TRUE.

NTHREADS=*number*

specifies the maximum number of threads for the LP solver to use for multithreaded processing. The value of *number* can be any integer between 1 and 256, inclusive. The default is the value of the NTHREADS= option in PROC OPTMODEL.

Sensitivity Analysis Option

The following option enables sensitivity analysis in the LP solver:

SENSITIVITY=(*options*)
enables sensitivity analysis and specifies overall control options for the algorithm. You can specify the following *options*:

CHANGE=(ALL LB OBJ RANGE RHS UB)
specifies which parts of the problem data to run the sensitivity analysis algorithm on. You can specify the following values:

ALL	runs sensitivity analysis on all the supported pieces of the input data.
LB	runs sensitivity analysis on the variable lower bounds.
OBJ	runs sensitivity analysis on the objective coefficients.
RANGE	runs sensitivity analysis on the range row bounds.
RHS	runs sensitivity analysis on the row right-hand sides.
UB	runs sensitivity analysis on the variable upper bounds.

This is a required option with no default value.

For more information about sensitivity analysis, see the section "Sensitivity Analysis" on page 652.

Decomposition Algorithm Options

The following options are available for the decomposition algorithm in the LP solver. For information about the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm."

DECOMP=(*options*)
enables the decomposition algorithm and specifies overall control options for the algorithm. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

DECOMPMASTER=(*options*)
specifies options for the master problem. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

DECOMPSUBPROB=(*options*)
specifies option for the subproblem. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

Details: LP Solver

Presolve

Presolve in the LP solver of PROC OPTMODEL uses a variety of techniques to reduce the problem size, improve numerical stability, and detect infeasibility or unboundedness (Andersen and Andersen 1995; Gondzio 1997). During presolve, redundant constraints and variables are identified and removed. Presolve can further reduce the problem size by substituting variables. Variable substitution is a very effective technique, but it might occasionally increase the number of nonzero entries in the constraint matrix.

In most cases, using presolve is very helpful in reducing solution times. You can enable presolve at different levels or disable it by specifying the PRESOLVER= option.

Pricing Strategies for the Primal and Dual Simplex Algorithms

Several pricing strategies for the primal and dual simplex algorithms are available. Pricing strategies determine which variable enters the basis at each simplex pivot. They can be controlled by specifying the PRICETYPE= option.

The primal simplex algorithm has the following five pricing strategies:

DEVEX	implements the Devex pricing strategy developed by Harris (1973).
FULL	uses Dantzig's most violated reduced cost rule. It compares the reduced costs of all decision variables and selects the variable with the most violated reduced cost as the entering variable.
HYBRID	uses a hybrid of the Devex and steepest-edge pricing strategies.
PARTIAL	uses Dantzig's most violated reduced cost rule (Dantzig 1963). It scans a queue of decision variables and selects the variable with the most violated reduced cost as the entering variable. You can optionally specify the QUEUESIZE= option to control the length of this queue.
STEEPESTEDGE	uses the steepest-edge pricing strategy developed by Forrest and Goldfarb (1992).

The dual simplex algorithm has only three pricing strategies available: DEVEX, FULL, and STEEPEST-EDGE.

Warm Start for the Primal and Dual Simplex Algorithms

You can warm-start the primal and dual simplex algorithms by specifying the option BASIS=WARMSTART. The warm start technique uses the basis of the solved LP as a starting point, and you can solve the modified LP problem usually faster than it can be solved again from scratch. You can thus continue to solve several variations of the original problem by not quitting the OPTMODEL procedure. The primal and dual simplex algorithms start with the stored basis. If this basis cannot form a valid basis for the original problem variant, the algorithms use the basis that is generated using their *crash* techniques.

After an LP model is solved using the primal and dual simplex algorithms, the BASIS=WARMSTART option enables you to perform sensitivity analysis, such as modifying the objective function, changing the right-hand sides of the constraints, adding or deleting constraints or decision variables, and combinations of these cases. You can usually obtain a faster solution to such a modified LP model by starting with the basis in the optimal solution to the original LP model. You can do this by using the BASIS=WARMSTART option and modifying the problem parameters. Example 13.2 illustrates how to reoptimize various modifications of the original LP problem.

The network simplex algorithm ignores the BASIS=WARMSTART option.

The Network Simplex Algorithm

The network simplex algorithm in PROC OPTMODEL attempts to leverage the speed of the network simplex algorithm to more efficiently solve linear programs by using the following process:

1. It heuristically extracts the largest possible network substructure from the original problem.
2. It uses the network simplex algorithm to solve for an optimal solution to this substructure.
3. It uses this solution to construct an advanced basis to warm-start either the primal or dual simplex algorithm on the original linear programming problem.

The network simplex algorithm is a specialized version of the simplex algorithm that uses spanning-tree bases to more efficiently solve linear programming problems that have a pure network form. Such LPs can be modeled using a formulation over a directed graph, as a minimum-cost flow problem. Let $G = (N, A)$ be a directed graph, where N denotes the nodes and A denotes the arcs of the graph. The decision variable x_{ij} denotes the amount of flow sent from node i to node j. The cost per unit of flow on the arcs is designated by c_{ij}, and the amount of flow sent across each arc is bounded to be within $[l_{ij}, u_{ij}]$. The demand (or supply) at each node is designated as b_i, where $b_i > 0$ denotes a supply node and $b_i < 0$ denotes a demand node. The corresponding linear programming problem is as follows:

$$\begin{array}{rrcll} \min & \sum_{(i,j)\in A} c_{ij} x_{ij} & & & \\ \text{subject to} & \sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} & = & b_i & \forall i \in N \\ & x_{ij} & \leq & u_{ij} & \forall (i,j) \in A \\ & x_{ij} & \geq & l_{ij} & \forall (i,j) \in A \end{array}$$

The network simplex algorithm used in PROC OPTMODEL is the primal network simplex algorithm. This algorithm finds the optimal primal feasible solution and a dual solution that satisfies complementary slackness.

Sometimes the directed graph G is disconnected. In this case, the problem can be decomposed into its weakly connected components and each minimum-cost flow problem can be solved separately. After solving each component, the optimal basis for the network substructure is augmented with the non-network variables and constraints from the original problem. This advanced basis is then used as a starting point for the primal or dual simplex method. The solver automatically selects the algorithm to use after network simplex. However, you can override this selection with the ALGORITHM2= option.

The network simplex algorithm can be more efficient than the other algorithms on problems with a large network substructure. You can view the size of the network structure in the log.

The Interior Point Algorithm

The interior point algorithm in PROC OPTMODEL implements an infeasible primal-dual predictor-corrector interior point algorithm. To illustrate the algorithm and the concepts of duality and dual infeasibility, consider the following LP formulation (the primal):

$$\begin{array}{rl} \min & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{array}$$

The corresponding dual formulation is as follows:

$$\begin{array}{rlcrcl} \max & \mathbf{b}^{\mathrm{T}}\mathbf{y} & & & & \\ \text{subject to} & \mathbf{A}^{\mathrm{T}}\mathbf{y} & + & \mathbf{w} & = & \mathbf{c} \\ & & & \mathbf{y} & \geq & \mathbf{0} \\ & & & \mathbf{w} & \geq & \mathbf{0} \end{array}$$

where $\mathbf{y} \in \mathbb{R}^m$ refers to the vector of dual variables and $\mathbf{w} \in \mathbb{R}^n$ refers to the vector of dual slack variables.

The dual formulation makes an important contribution to the certificate of optimality for the primal formulation. The primal and dual constraints combined with complementarity conditions define the first-order optimality conditions, also known as KKT (Karush-Kuhn-Tucker) conditions, which can be stated as follows:

$$\begin{array}{rcll} \mathbf{A}\mathbf{x} - \mathbf{s} & = & \mathbf{b} & \text{(primal feasibility)} \\ \mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{w} & = & \mathbf{c} & \text{(dual feasibility)} \\ \mathbf{W}\mathbf{X}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{S}\mathbf{Y}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{x},\ \mathbf{y},\ \mathbf{w},\ \mathbf{s} & \geq & \mathbf{0} & \end{array}$$

where $\mathbf{e} \equiv (1, \ldots, 1)^{\mathrm{T}}$ of appropriate dimension and $\mathbf{s} \in \mathbb{R}^m$ is the vector of primal *slack* variables.

NOTE: Slack variables (the s vector) are automatically introduced by the algorithm when necessary; it is therefore recommended that you not introduce any slack variables explicitly. This enables the algorithm to handle slack variables much more efficiently.

The letters $\mathbf{X}$, $\mathbf{Y}$, $\mathbf{W}$, and $\mathbf{S}$ denote matrices with corresponding x, y, w, and s on the main diagonal and zero elsewhere, as in the following example:

$$\mathbf{X} \equiv \begin{bmatrix} x_1 & 0 & \cdots & 0 \\ 0 & x_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x_n \end{bmatrix}$$

If $(\mathbf{x}^*, \mathbf{y}^*, \mathbf{w}^*, \mathbf{s}^*)$ is a solution of the previously defined system of equations that represent the KKT conditions, then $\mathbf{x}^*$ is also an optimal solution to the original LP model.

At each iteration the interior point algorithm solves a large, sparse system of linear equations,

$$\begin{bmatrix} \mathbf{Y}^{-1}\mathbf{S} & \mathbf{A} \\ \mathbf{A}^{\mathrm{T}} & -\mathbf{X}^{-1}\mathbf{W} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{y} \\ \Delta\mathbf{x} \end{bmatrix} = \begin{bmatrix} \Xi \\ \Theta \end{bmatrix}$$

where $\Delta\mathbf{x}$ and $\Delta\mathbf{y}$ denote the vector of *search directions* in the primal and dual spaces, respectively, and Θ and Ξ constitute the vector of the right-hand sides.

The preceding system is known as the reduced KKT system. The interior point algorithm uses a preconditioned quasi-minimum residual algorithm to solve this system of equations efficiently.

An important feature of the interior point algorithm is that it takes full advantage of the sparsity in the constraint matrix, thereby enabling it to efficiently solve large-scale linear programs.

The interior point algorithm works simultaneously in the primal and dual spaces. It attains optimality when both primal and dual feasibility are achieved and when complementarity conditions hold. Therefore, it is of interest to observe the following four measures:

- Relative primal infeasibility measure α:

$$\alpha = \frac{\|\mathbf{Ax} - \mathbf{b} - \mathbf{s}\|_2}{\|\mathbf{b}\|_2 + 1}$$

- Relative dual infeasibility measure β:

$$\beta = \frac{\|\mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y} - \mathbf{w}\|_2}{\|\mathbf{c}\|_2 + 1}$$

- Relative duality gap δ:

$$\delta = \frac{|\mathbf{c}^{\mathrm{T}}\mathbf{x} - \mathbf{b}^{\mathrm{T}}\mathbf{y}|}{|\mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

- Absolute complementarity γ:

$$\gamma = \sum_{i=1}^{n} x_i w_i + \sum_{i=1}^{m} y_i s_i$$

where $\|v\|_2$ is the Euclidean norm of the vector v. These measures are displayed in the iteration log.

The Sifting Algorithm

The sifting algorithm is a simplex-based column-generation algorithm. This algorithm starts by solving a reduced problem that includes a subset of variables. At each iteration, the algorithm adds new variables and solves the problem again. The algorithm stops when the optimal solution of the current iteration is found to be optimal for the original problem.

The sifting algorithm is usually helpful for problems that have many more variables than constraints.

Iteration Log for the Primal and Dual Simplex Algorithms

The primal and dual simplex algorithms implement a two-phase simplex algorithm. Phase I finds a feasible solution, which phase II improves to an optimal solution.

When LOGFREQ=1, the following information is printed in the iteration log:

Algorithm	indicates which simplex method is running by printing the letter P (primal) or D (dual).
Phase	indicates whether the algorithm is in phase I or phase II of the simplex method.
Iteration	indicates the iteration number.
Objective Value	indicates the current amount of infeasibility in phase I and the primal objective value of the current solution in phase II.
Time	indicates the time elapsed (in seconds).
Entering Variable	indicates the entering pivot variable. A slack variable that enters the basis is indicated by the corresponding row name followed by “(S)”. If the entering nonbasic variable has distinct and finite lower and upper bounds, then a “bound swap” can take place in the primal simplex method.
Leaving Variable	indicates the leaving pivot variable. A slack variable that leaves the basis is indicated by the corresponding row name followed by “(S)”. The leaving variable is the same as the entering variable if a bound swap has taken place.

When you omit the LOGFREQ= option or specify a value greater than 1, only the algorithm, phase, iteration, objective value, and time information is printed in the iteration log.

The behavior of objective values in the iteration log depends on both the current phase and the chosen algorithm. In phase I, both simplex methods have artificial objective values that decrease to 0 when a feasible solution is found. For the dual simplex method, phase II maintains a dual feasible solution, so a minimization problem has increasing objective values in the iteration log. For the primal simplex method, phase II maintains a primal feasible solution, so a minimization problem has decreasing objective values in the iteration log.

During the solution process, some elements of the LP model might be perturbed to improve performance. In this case the objective values that are printed correspond to the perturbed problem. After reaching optimality for the perturbed problem, the LP solver solves the original problem by switching from the primal simplex method to the dual simplex method (or from the dual to the primal simplex method). Because the problem might be perturbed again, this process can result in several changes between the two algorithms.

Iteration Log for the Network Simplex Algorithm

After finding the embedded network and formulating the appropriate relaxation, the network simplex algorithm uses a primal network simplex algorithm. In the case of a connected network, with one (weakly connected) component, the log shows the progress of the simplex algorithm. The following information is displayed in the iteration log:

Iteration	indicates the iteration number.
PrimalObj	indicates the primal objective value of the current solution.
Primal Infeas	indicates the maximum primal infeasibility of the current solution.
Time	indicates the time spent on the current component by network simplex.

The frequency of the simplex iteration log is controlled by the LOGFREQ= option. The default value of the LOGFREQ= option is 10,000.

If the network relaxation is disconnected, the information in the iteration log shows progress at the component level. The following information is displayed in the iteration log:

Component	indicates the component number being processed.
Nodes	indicates the number of nodes in this component.
Arcs	indicates the number of arcs in this component.
Iterations	indicates the number of simplex iterations needed to solve this component.
Time	indicates the time spent so far in network simplex.

The frequency of the component iteration log is controlled by the LOGFREQ= option. In this case, the default value of the LOGFREQ= option is determined by the size of the network.

The LOGLEVEL= option adjusts the amount of detail shown. By default, LOGLEVEL= is set to MODERATE and reports as described previously. If set to NONE, no information is shown. If set to BASIC, the only information shown is a summary of the network relaxation and the time spent solving the relaxation. If set to AGGRESSIVE, in the case of one component, the log displays as described previously; in the case of multiple components, for each component, a separate simplex iteration log is displayed.

Iteration Log for the Interior Point Algorithm

The interior point algorithm implements an infeasible primal-dual predictor-corrector interior point algorithm. The following information is displayed in the iteration log:

Iter	indicates the iteration number.
Complement	indicates the (absolute) complementarity.
Duality Gap	indicates the (relative) duality gap.
Primal Infeas	indicates the (relative) primal infeasibility measure.
Bound Infeas	indicates the (relative) bound infeasibility measure.

Dual Infeas	indicates the (relative) dual infeasibility measure.
Time	indicates the time elapsed (in seconds).

If the sequence of solutions converges to an optimal solution of the problem, you should see all columns in the iteration log converge to zero or very close to zero. If they do not, it can be the result of insufficient iterations being performed to reach optimality. In this case, you might need to increase the value specified in the MAXITER= or MAXTIME= options. If the complementarity or the duality gap do not converge, the problem might be infeasible or unbounded. If the infeasibility columns do not converge, the problem might be infeasible.

Iteration Log for the Crossover Algorithm

The crossover algorithm takes an optimal solution from the interior point algorithm and transforms it into an optimal basic solution. The iterations of the crossover algorithm are similar to simplex iterations; this similarity is reflected in the format of the iteration logs.

When LOGFREQ=1, the following information is printed in the iteration log:

Phase	indicates whether the primal crossover (PC) or dual crossover (DC) technique is used.
Iteration	indicates the iteration number.
Objective Value	indicates the total amount by which the superbasic variables are off their bound. This value decreases to 0 as the crossover algorithm progresses.
Time	indicates the time elapsed (in seconds).
Entering Variable	indicates the entering pivot variable. A slack variable that enters the basis is indicated by the corresponding row name followed by “(S).”
Leaving Variable	indicates the leaving pivot variable. A slack variable that leaves the basis is indicated by the corresponding row name followed by “(S).”

When you omit the LOGFREQ= option or specify a value greater than 1, only the phase, iteration, objective value, and time information is printed in the iteration log.

After all the superbasic variables have been eliminated, the crossover algorithm continues with regular primal or dual simplex iterations.

Concurrent LP

The ALGORITHM=CON option starts several different linear optimization algorithms in parallel in a single-machine mode. The LP solver automatically determines which algorithms to run and how many threads to assign to each algorithm. When the first algorithm finishes, the solver returns the results from that algorithm and terminates any other algorithms that are still running. If you specify a value of TRUE for the DETERMINISTIC= option, the algorithm for which the results are returned is not necessarily the one that finished first. The LP solver deterministically selects the algorithm for which the results are returned. Regardless of which mode (deterministic or nondeterministic) is in effect, terminating algorithms that are still running might take a significant amount of time.

During concurrent optimization, the procedure displays the iteration log for the dual simplex algorithm. For more information about this iteration log, see the section "Iteration Log for the Primal and Dual Simplex Algorithms" on page 649. Upon termination, the solver displays the iteration log for the algorithm that finishes first, unless the dual simplex algorithm finishes first. If you specify LOGLEVEL=AGGRESSIVE, the LP solver displays the iteration logs for all algorithms that are run concurrently.

If you specify PRINTLEVEL=2 in the PROC OPTMODEL statement and ALGORITHM=CON in the SOLVE WITH LP statement, the LP solver produces an ODS table called ConcurrentSummary. This table contains a summary of the solution statuses of all algorithms that are run concurrently.

Sensitivity Analysis

The optimal basis, solution, and objective value of a linear optimization problem are functions of the input data. You can use sensitivity analysis to quantify this dependence. You can invoke sensitivity analysis by specifying the SENSITIVITY= option in the SOLVE WITH LP statement.

The sensitivity analysis algorithm in the LP solver supports analyzing the dependence with respect to the variable bounds, row bounds, or objective coefficients. Sensitivities to the matrix coefficients are not supported. You can use the CHANGE= option to select which parts of the data to run the algorithm on. Sensitivity analysis calculates a stability interval for each of these pieces of the problem data. Changing the data within the stability interval guarantees that the current optimal basis stays optimal.

The output of sensitivity analysis is returned in the .lbmin, .lbmax, .ubmin, .ubmax, .objmin, and .objmax suffixes. See the section "Suffixes" on page 420 to learn more about these suffixes. See Example 13.10 for an example of how to use sensitivity analysis.

Parallel Processing

The interior point, concurrent LP, and decomposition algorithms can be run in single-machine mode; in this mode, the computation is executed by multiple threads on a single computer.

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTMODEL procedure causes the ODS table "ProblemStatistics" to be generated when the LP solver is called. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 13.3 demonstrates the contents of the ODS table "ProblemStatistics."

Figure 13.3 ODS Table ProblemStatistics

The OPTMODEL Procedure

Problem Statistics	
Number of Constraint Matrix Nonzeros	6
Maximum Constraint Matrix Coefficient	3
Minimum Constraint Matrix Coefficient	1
Average Constraint Matrix Coefficient	2.1666666667
Number of Objective Nonzeros	3
Maximum Objective Coefficient	1
Minimum Objective Coefficient	1
Average Objective Coefficient	1
Number of RHS Nonzeros	2
Maximum RHS	1
Minimum RHS	1
Average RHS	1
Maximum Number of Nonzeros per Column	2
Minimum Number of Nonzeros per Column	2
Average Number of Nonzeros per Column	2
Maximum Number of Nonzeros per Row	3
Minimum Number of Nonzeros per Row	3
Average Number of Nonzeros per Row	3

Variable and Constraint Status

Upon termination of the LP solver, the .status suffix of each decision variable and constraint stores information about the status of that variable or constraint. For more information about suffixes in the OPTMODEL procedure, see the section "Suffixes" on page 420.

Variable Status

The .status suffix of a decision variable specifies the status of that decision variable. The suffix can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A superbasic variable (a nonbasic variable that has a value strictly between its bounds)

I LP model infeasible (all decision variables have .status equal to I)

For the interior point algorithm with IIS=FALSE, .status is blank.

The following values can appear only if IIS=TRUE. See the section "Irreducible Infeasible Set" on page 655 for details.

I_L the lower bound of the variable is needed for the IIS

I_U the upper bound of the variable is needed for the IIS

I_F both bounds of the variable are needed for the IIS (the variable is fixed or has conflicting bounds)

Constraint Status

The .status suffix of a constraint specifies the status of the slack variable for that constraint. The suffix can take one of the following values:

B basic variable

L nonbasic variable at its lower bound

U nonbasic variable at its upper bound

F free variable

A superbasic variable (a nonbasic variable that has a value strictly between its bounds)

I LP model infeasible (all decision variables have .status equal to I)

The following values can appear only if option IIS=TRUE. See the section "Irreducible Infeasible Set" on page 655 for details.

I_L the "GE" (≥) condition of the constraint is needed for the IIS

I_U the "LE" (≤) condition of the constraint is needed for the IIS

I_F both conditions of the constraint are needed for the IIS (the constraint is an equality or a range constraint with conflicting bounds)

Irreducible Infeasible Set

For a linear programming problem, an irreducible infeasible set (IIS) is an infeasible subset of constraints and variable bounds that will become feasible if any single constraint or variable bound is removed. It is possible to have more than one IIS in an infeasible LP. Identifying an IIS can help isolate the structural infeasibility in an LP.

The presolver in the LP solver can detect infeasibility, but it identifies only the variable bound or constraint that triggers the infeasibility.

The IIS=TRUE option directs the LP solver to search for an IIS in a specified LP. The LP solver does not apply the presolver to the problem during the IIS search. If the LP solver detects an IIS, it updates the .status suffix of the decision variables and constraints, and then it stops. The number of iterations that are reported in the macro variable and the ODS table is the total number of simplex iterations. This total includes the initial LP solve and all subsequent iterations during the constraint deletion phase.

The IIS= option can add special values to the .status suffixes of variables and constraints. (For more information, see the section "Variable and Constraint Status" on page 654.) For constraints, a status of "I_L", "I_U", or "I_F" indicates that the "GE" (≥), "LE" (≤), or "EQ" (=) constraint, respectively, is part of the IIS. For range constraints, a status of "I_L" or "I_U" indicates that the lower or upper bound of the constraint, respectively, is needed for the IIS, and "I_F" indicates that the bounds in the constraint are conflicting. For variables, a status of "I_L", "I_U", or "I_F" indicates that the lower, upper, or both bounds of the variable, respectively, are needed for the IIS. From this information, you can identify both the names of the constraints (variables) in the IIS and the corresponding bound where infeasibility occurs.

Making any one of the constraints or variable bounds in the IIS nonbinding removes the infeasibility from the IIS. In some cases, changing a right-hand side or bound by a finite amount removes the infeasibility. However, the only way to guarantee removal of the infeasibility is to set the appropriate right-hand side or bound to ∞ or $-\infty$. Because it is possible for an LP to have multiple irreducible infeasible sets, simply removing the infeasibility from one set might not make the entire problem feasible. To make the entire problem feasible, you can specify IIS=TRUE and rerun the LP solver after removing the infeasibility from an IIS. Repeating this process until the LP solver no longer detects an IIS results in a feasible problem. This approach to infeasibility repair can produce different end problems depending on which right-hand sides and bounds you choose to relax.

The IIS= option in the LP solver uses two different methods to identify an IIS:

1. Based on the result of the initial solve, the *sensitivity filter* removes several constraints and variable bounds immediately while still maintaining infeasibility. This phase is quick and dramatically reduces the size of the IIS.

2. Next, the *deletion filter* removes each remaining constraint and variable bound one by one to check which of them are needed to obtain an infeasible system. This second phase is more time consuming,

but it ensures that the IIS set that the LP solver returns is indeed irreducible. The progress of the deletion filter is reported at regular intervals. Occasionally, the sensitivity filter might be called again during the deletion filter to improve performance.

See Example 13.4 for an example that demonstrates the use of the IIS= option in locating and removing infeasibilities. You can find more details about IIS algorithms in Chinneck (2008).

Macro Variable _OROPTMODEL_

The OPTMODEL procedure always creates and initializes a SAS macro called _OROPTMODEL_. This variable contains a character string. After each PROC OROPTMODEL run, you can examine this macro by specifying `%put &_OROPTMODEL_;` and check the execution of the most recently invoked solver from the value of the macro variable. The various terms of the variable after the LP solver is called are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data were inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, occurred.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produces the solution data in the macro variable. This term appears only when STATUS=OK. It can take one of the following values:

PS	The primal simplex algorithm produced the solution data.
DS	The dual simplex algorithm produced the solution data.
NS	The network simplex algorithm produced the solution data.
IP	The interior point algorithm produced the solution data.
DECOMP	The decomposition algorithm produced the solution data.
SIFT	The sifting algorithm produced the solution data.
SPX	The presolver produced the solution data, and the ALGORITHM=SIMPLEX option was specified.

When you run algorithms concurrently (ALGORITHM=CON), this term indicates which algorithm is the first to terminate.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The solution is optimal, but some infeasibilities (primal, dual or bound) exceed tolerances due to scaling or preprocessing.
FEASIBLE	The problem is feasible.
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
BAD_PROBLEM_TYPE	The problem type is unsupported by the solver.
ITERATION_LIMIT_REACHED	The maximum allowable number of iterations was reached.
TIME_LIMIT_REACHED	The solver reached its execution time limit.
FUNCTION_CALL_LIMIT_REACHED	The solver reached its limit on function evaluations.
INTERRUPTED	The solver was interrupted externally.
FAILED	The solver failed to converge, possibly due to numerical issues.

When SOLUTION_STATUS has a value of OPTIMAL, CONDITIONAL_OPTIMAL, ITERATION_LIMIT_REACHED, or TIME_LIMIT_REACHED, all terms of the _OROPTMODEL_ macro variable are present; for other values of SOLUTION_STATUS, some terms do not appear.

OBJECTIVE

indicates the objective value obtained by the solver at termination.

PRIMAL_INFEASIBILITY

indicates the relative violation of the primal constraints by the primal solution.

DUAL_INFEASIBILITY

indicates the relative violation of the dual constraints by the dual solution.

BOUND_INFEASIBILITY

indicates the relative violation of the lower or upper bounds (or both) by the primal solution.

DUALITY_GAP

indicates the (relative) duality gap. This term appears only if the option ALGORITHM=INTERIORPOINT is specified in the SOLVE statement.

COMPLEMENTARITY

indicates the (absolute) complementarity. This term appears only if the option ALGORITHM=INTERIORPOINT is specified in the SOLVE statement.

ITERATIONS
indicates the number of iterations taken to solve the problem. When the network simplex algorithm is used, this term indicates the number of network simplex iterations taken to solve the network relaxation. When crossover is enabled, this term indicates the number of interior point iterations taken to solve the problem.

ITERATIONS2
indicates the number of simplex iterations performed by the secondary algorithm. In network simplex, the secondary algorithm is selected automatically, unless a value has been specified for the ALGORITHM2= option. When crossover is enabled, the secondary algorithm is selected automatically. This term appears only if the network simplex algorithm is used or if crossover is enabled.

PRESOLVE_TIME
indicates the time (in seconds) used in preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

When SOLUTION_STATUS has a value of OPTIMAL, CONDITIONAL_OPTIMAL, ITERATION_LIMIT_REACHED, or TIME_LIMIT_REACHED, all terms of the _OROPTMODEL_ macro variable are present; for other values of SOLUTION_STATUS, some terms do not appear.

Examples: LP Solver

Example 13.1: Diet Problem

Consider the problem of diet optimization. There are six different foods: bread, milk, cheese, potato, fish, and yogurt. The cost and nutrition values per unit are displayed in Table 13.2.

Table 13.2 Cost and Nutrition Values

	Bread	Milk	Cheese	Potato	Fish	Yogurt
Cost	2.0	3.5	8.0	1.5	11.0	1.0
Protein, g	4.0	8.0	7.0	1.3	8.0	9.2
Fat, g	1.0	5.0	9.0	0.1	7.0	1.0
Carbohydrates, g	15.0	11.7	0.4	22.6	0.0	17.0
Calories	90	120	106	97	130	180

The following SAS code creates the data set fooddata of Table 13.2:

```
data fooddata;
   infile datalines;
   input name $  cost  prot  fat  carb  cal;
   datalines;
Bread   2     4     1    15    90
Milk    3.5   8     5    11.7  120
Cheese  8     7     9    0.4   106
Potato  1.5   1.3   0.1  22.6  97
Fish    11    8     7    0     130
Yogurt  1     9.2   1    17    180
;
```

The objective is to find a minimum-cost diet that contains at least 300 calories, not more than 10 grams of protein, not less than 10 grams of carbohydrates, and not less than 8 grams of fat. In addition, the diet should contain at least 0.5 unit of fish and no more than 1 unit of milk.

You can model the problem and solve it by using PROC OPTMODEL as follows:

```
proc optmodel;
   /* declare index set */
   set<str> FOOD;

   /* declare variables */
   var diet{FOOD} >= 0;

   /* objective function */
   num cost{FOOD};
   min f=sum{i in FOOD}cost[i]*diet[i];

   /* constraints */
   num prot{FOOD};
   num fat{FOOD};
   num carb{FOOD};
   num cal{FOOD};
   num min_cal, max_prot, min_carb, min_fat;
   con cal_con: sum{i in FOOD}cal[i]*diet[i] >= 300;
   con prot_con: sum{i in FOOD}prot[i]*diet[i] <= 10;
   con carb_con: sum{i in FOOD}carb[i]*diet[i] >= 10;
   con fat_con: sum{i in FOOD}fat[i]*diet[i] >= 8;

   /* read parameters */
   read data fooddata into FOOD=[name] cost prot fat carb cal;

   /* bounds on variables */
   diet['Fish'].lb = 0.5;
   diet['Milk'].ub = 1.0;

   /* solve and print the optimal solution */
   solve with lp/logfreq=1; /* print each iteration to log */
   print diet;
```

The optimal solution and the optimal objective value are displayed in Output 13.1.1.

Output 13.1.1 Optimal Solution to the Diet Problem

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	23

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	12.081337881
Primal Infeasibility	1.776357E-16
Dual Infeasibility	4.440892E-17
Bound Infeasibility	0
Iterations	5
Presolve Time	0.00
Solution Time	0.00

[1]	diet
Bread	0.000000
Cheese	0.449499
Fish	0.500000
Milk	0.053599
Potato	1.865168
Yogurt	0.000000

Example 13.2: Reoptimizing the Diet Problem Using BASIS=WARMSTART

After an LP is solved, you might want to change a set of the parameters of the LP and solve the problem again. This can be done efficiently in PROC OPTMODEL. The warm start technique uses the optimal solution of the solved LP as a starting point and solves the modified LP problem faster than it can be solved again from scratch. This example illustrates reoptimizing the diet problem described in Example 13.1.

Assume the optimal solution is found by the SOLVE statement. Instead of quitting the OPTMODEL procedure, you can continue to solve several variations of the original problem.

Suppose the cost of cheese increases from 8 to 10 per unit and the cost of fish decreases from 11 to 7 per serving unit. You can change the parameters and solve the modified problem by submitting the following code:

```
cost['Cheese']=10; cost['Fish']=7;
solve with lp/presolver=none
             basis=warmstart
             algorithm=ps
             logfreq=1;
print diet;
```

Note that the primal simplex algorithm is preferred because the primal solution to the last-solved LP is still feasible for the modified problem in this case. The solutions to the original diet problem and the modified problem are shown in Output 13.2.1.

Output 13.2.1 Optimal Solutions to the Original Diet Problem and the Diet Problem with Modified Objective Function

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	23

Output 13.2.1 *continued*

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	12.081337881
Primal Infeasibility	1.776357E-16
Dual Infeasibility	4.440892E-17
Bound Infeasibility	0
Iterations	5
Presolve Time	0.00
Solution Time	0.00

[1]	diet
Bread	0.000000
Cheese	0.449499
Fish	0.500000
Milk	0.053599
Potato	1.865168
Yogurt	0.000000

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	23

Output 13.2.1 *continued*

Solution Summary	
Solver	LP
Algorithm	Primal Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	10.980335514
Primal Infeasibility	1.776357E-16
Dual Infeasibility	3.94746E-16
Bound Infeasibility	0
Iterations	1
Presolve Time	0.00
Solution Time	0.00

[1]	diet
Bread	0.000000
Cheese	0.449499
Fish	0.500000
Milk	0.053599
Potato	1.865168
Yogurt	0.000000

The following iteration log indicates that it takes the LP solver no more iterations to solve the modified problem by using BASIS=WARMSTART, since the optimal solution to the original problem remains optimal after the objective function is changed.

Output 13.2.2 Log

```
NOTE: There were 6 observations read from the data set WORK.FOODDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 0 variables and 0 constraints.
NOTE: The LP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 6 variables, 4 constraints, and 23 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration       Value         Time
       D 2          1    5.500000E+00         0
       D 2          5    1.208134E+01         0
NOTE: Optimal.
NOTE: Objective = 12.081337881.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                          Objective                Entering          Leaving
      Phase Iteration       Value         Time     Variable          Variable
       P 2          1    1.098034E+01         0
NOTE: Optimal.
NOTE: Objective = 10.980335514.
NOTE: The Primal Simplex solve time is 0.00 seconds.
```

Next, restore the original coefficients of the objective function and consider the case that you need a diet that supplies at least 150 calories. You can change the parameters and solve the modified problem by submitting the following code:

```
cost['Cheese']=8; cost['Fish']=11;cal_con.lb=150;
solve with lp/presolver=none
              basis=warmstart
              algorithm=ds
              logfreq=1;
print diet;
```

Note that the dual simplex algorithm is preferred because the dual solution to the last-solved LP is still feasible for the modified problem in this case. The solution is shown in Output 13.2.3.

Output 13.2.3 Optimal Solution to the Diet Problem with Modified RHS

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	23

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	9.1744131985
Primal Infeasibility	0
Dual Infeasibility	1.97373E-16
Bound Infeasibility	0
Iterations	2
Presolve Time	0.00
Solution Time	0.00

[1]	diet
Bread	0.00000
Cheese	0.18481
Fish	0.50000
Milk	0.56440
Potato	0.14702
Yogurt	0.00000

The following iteration log indicates that it takes the LP solver just one more phase II iteration to solve the modified problem by using BASIS=WARMSTART.

Output 13.2.4 Log

```
NOTE: There were 6 observations read from the data set WORK.FOODDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering          Leaving
      Phase Iteration       Value         Time     Variable          Variable
       D 2          1    8.813205E+00         0        cal_con (S)
      carb_con (S)
       D 2          2    9.174413E+00         0
NOTE: Optimal.
NOTE: Objective = 9.1744131985.
NOTE: The Dual Simplex solve time is 0.00 seconds.
```

Next, restore the original constraint on calories and consider the case that you need a diet that supplies no more than 550 mg of sodium per day. The following row is appended to Table 13.2.

	Bread	Milk	Cheese	Potato	Fish	Yogurt
sodium, mg	148	122	337	186	56	132

You can change the parameters, add the new constraint, and solve the modified problem by submitting the following code:

```
cal_con.lb=300;
num sod{FOOD}=[148 122 337 186 56 132];
con sodium: sum{i in FOOD}sod[i]*diet[i] <= 550;
solve with lp/presolver=none
              basis=warmstart
              logfreq=1;
print diet;
```

The solution is shown in Output 13.2.5.

Output 13.2.5 Optimal Solution to the Diet Problem with Additional Constraint

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	5
Linear LE (<=)	2
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	29

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	12.081337881
Primal Infeasibility	1.776357E-16
Dual Infeasibility	4.440892E-17
Bound Infeasibility	0
Iterations	1
Presolve Time	0.00
Solution Time	0.00

[1]	diet
Bread	0.000000
Cheese	0.449499
Fish	0.500000
Milk	0.053599
Potato	1.865168
Yogurt	0.000000

The following iteration log indicates that it takes the LP solver no more iterations to solve the modified problem by using the BASIS=WARMSTART option, since the optimal solution to the original problem remains optimal after one more constraint is added.

Output 13.2.6 Log

```
NOTE: There were 6 observations read from the data set WORK.FOODDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 5 linear constraints (2 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 29 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering          Leaving
      Phase Iteration       Value         Time     Variable          Variable
       D 2          1    1.208134E+01         0
NOTE: Optimal.
NOTE: Objective = 12.081337881.
NOTE: The Dual Simplex solve time is 0.00 seconds.
```

Example 13.3: Two-Person Zero-Sum Game

Consider a two-person zero-sum game (where one person wins what the other person loses). The players make moves simultaneously, and each has a choice of actions. There is a *payoff* matrix that indicates the amount one player gives to the other under each combination of actions:

$$\begin{array}{cc} & \text{Player II plays } j \\ & \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \\ \text{Player I plays } i \begin{array}{c} 1 \\ 2 \\ 3 \end{array} & \begin{pmatrix} -5 & 3 & 1 & 8 \\ 5 & 5 & 4 & 6 \\ -4 & 6 & 0 & 5 \end{pmatrix} \end{array}$$

If player I makes move i and player II makes move j, then player I wins (and player II loses) a_{ij}. What is the best strategy for the two players to adopt? This example is simple enough to be analyzed from observation. Suppose player I plays 1 or 3; the best response of player II is to play 1. In both cases, player I loses and player II wins. So the best action for player I is to play 2. In this case, the best response for player II is to play 3, which minimizes the loss. In this case, (2, 3) is a *pure-strategy Nash equilibrium* in this game.

For illustration, consider the following mixed strategy case. Assume that player I selects i with probability p_i, $i = 1, 2, 3$, and player II selects j with probability q_j, $j = 1, 2, 3, 4$. Consider player II's problem of minimizing the maximum expected payout:

$$\min_{\mathbf{q}} \left\{ \max_i \sum_{j=1}^{4} a_{ij} q_j \right\} \quad \text{subject to} \quad \sum_{j=1}^{4} q_{ij} = 1, \quad \mathbf{q} \geq 0$$

This is equivalent to

$$\begin{aligned} \min_{\mathbf{q},v}\ v \quad \text{subject to} \quad \sum_{j=1}^{4} a_{ij} q_j &\le v \quad \forall\, i \\ \sum_{j=1}^{4} q_j &= 1 \\ \mathbf{q} &\ge 0 \end{aligned}$$

The problem can be transformed into a more standard format by making a simple change of variables: $x_j = q_j/v$. The preceding LP formulation now becomes

$$\begin{aligned} \min_{\mathbf{x},v}\ v \quad \text{subject to} \quad \sum_{j=1}^{4} a_{ij} x_j &\le 1 \quad \forall\, i \\ \sum_{j=1}^{4} x_j &= 1/v \\ \mathbf{q} &\ge 0 \end{aligned}$$

which is equivalent to

$$\max_{\mathbf{x}} \sum_{j=1}^{4} x_j \quad \text{subject to} \quad A\mathbf{x} \le \mathbf{1}, \quad \mathbf{x} \ge 0$$

where A is the payoff matrix and $\mathbf{1}$ is a vector of 1's. It turns out that the corresponding optimization problem from player I's perspective can be obtained by solving the dual problem, which can be written as

$$\min_{\mathbf{y}} \sum_{i=1}^{3} y_i \quad \text{subject to} \quad A^{\mathrm{T}}\mathbf{y} \ge \mathbf{1}, \quad \mathbf{y} \ge 0$$

You can model the problem and solve it by using PROC OPTMODEL as follows:

```
proc optmodel;
   num a{1..3, 1..4}=[-5 3 1 8
                       5 5 4 6
                      -4 6 0 5];
   var x{1..4} >= 0;
   max f = sum{i in 1..4}x[i];
   con c{i in 1..3}: sum{j in 1..4}a[i,j]*x[j] <= 1;
   solve with lp / algorithm = ps presolver = none logfreq = 1;
   print x;
   print c.dual;
quit;
```

The optimal solution is displayed in Output 13.3.1.

Output 13.3.1 Optimal Solutions to the Two-Person Zero-Sum Game

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	f
Objective Type	Linear
Number of Variables	4
Bounded Above	0
Bounded Below	4
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	3
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	11

Solution Summary	
Solver	LP
Algorithm	Primal Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	0.25
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	2
Presolve Time	0.00
Solution Time	0.00

[1]	x
1	0.00
2	0.00
3	0.25
4	0.00

[1]	c.DUAL
1	0.00
2	0.25
3	0.00

The optimal solution $\mathbf{x}^* = (0, 0, 0.25, 0)$ with an optimal value of 0.25. Therefore the optimal strategy for player II is $\mathbf{q}^* = \mathbf{x}^*/0.25 = (0, 0, 1, 0)$. You can check the optimal solution of the dual problem by using the constraint suffix ".dual". So $\mathbf{y}^* = (0, 0.25, 0)$ and player I's optimal strategy is (0, 1, 0). The solution is consistent with our intuition from observation.

Example 13.4: Finding an Irreducible Infeasible Set

This example demonstrates the use of the IIS= option to locate an irreducible infeasible set. Suppose you want to solve a linear program that has the following simple formulation:

$$
\begin{array}{rrcrcrcrl}
\text{min} & & x_1 & + & x_2 & + & x_3 & & & \text{(cost)} \\
\text{subject to} & & x_1 & + & x_2 & & & \geq & 10 & \text{(con1)} \\
 & & x_1 & & & + & x_3 & \leq & 4 & \text{(con2)} \\
 & 4 \leq & & & x_2 & + & x_3 & \leq & 5 & \text{(con3)} \\
 & & & & & x_1, & x_2 & \geq & 0 & \\
 & & & & 0 & \leq & x_3 & \leq & 3 &
\end{array}
$$

It is easy to verify that the following three constraints (or rows) and one variable (or column) bound form an IIS for this problem:

$$
\begin{array}{rcrcrcrl}
x_1 & + & x_2 & & & \geq & 10 & \text{(con1)} \\
x_1 & & & + & x_3 & \leq & 4 & \text{(con2)} \\
 & & x_2 & + & x_3 & \leq & 5 & \text{(con3)} \\
 & & & & x_3 & \geq & 0 &
\end{array}
$$

You can formulate the problem and call the LP solver by using the following statements:

```
proc optmodel presolver=none;
   /* declare variables */
   var x{1..3} >=0;

   /* upper bound on variable x[3] */
   x[3].ub = 3;

   /* objective function */
   min obj = x[1] + x[2] + x[3];

   /* constraints */
   con c1: x[1] + x[2] >= 10;
   con c2: x[1] + x[3] <= 4;
   con c3: 4 <= x[2] + x[3] <= 5;

   solve with lp / iis=true;

   print x.status;
   print c1.status c2.status c3.status;

   expand / IIS;
```

The notes printed in the log appear in Output 13.4.1.

Output 13.4.1 Finding an IIS: Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 linear constraints (1 LE, 0 EQ, 1 GE, 1 range).
NOTE: The problem has 6 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                            Objective
      Phase Iteration         Value         Time
       P 1          1    6.000000E+00         0
       P 1          3    1.000000E+00         0
NOTE: Applying the IIS sensitivity filter.
NOTE: The sensitivity filter removed 1 constraints and 3 variable bounds.
NOTE: Applying the IIS deletion filter.
NOTE: Processing constraints.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: Processing variable bounds.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: The deletion filter removed 0 constraints and 0 variable bounds.
NOTE: The IIS= option found this problem to be infeasible.
NOTE: The IIS= option found an irreducible infeasible set with 1 variables and
      3 constraints.
NOTE: The IIS solve time is 0.00 seconds.
```

There are two ways to display the rows and columns that are included in the IIS. One way is to use the PRINT statement to print the value of the .status suffix for each variable and constraint. The more straightforward approach is to use the EXPAND statement with the IIS option.

The output of both approaches appears in Output 13.4.2. The value of the .status suffix for the variables x[1] and x[2] is missing, so the variable bounds for x[1] and x[2] are not in the IIS.

Output 13.4.2 Solution Summary, Variable Status, and Constraint Status

The OPTMODEL Procedure

Solution Summary	
Solver	LP
Algorithm	IIS
Objective Function	obj
Solution Status	Infeasible
Iterations	10
Presolve Time	0.00
Solution Time	0.00

[1]	x.STATUS
1	
2	
3	I_L

c1.STATUS	c2.STATUS	c3.STATUS
I_L	I_U	I_U

```
The OPTMODEL Procedure

Var x[3] >= 0 <= 3
Constraint c1: x[1] + x[2] >= 10
Constraint c2: x[1] + x[3] <= 4
Constraint c3: 4 <= x[2] + x[3] <= 5
```

The value of c3.status is I_U, which indicates that $x_2 + x_3 \leq 5$ is an element of the IIS. The original constraint is c3, a range constraint with a lower bound of 4. If you choose to remove the constraint $x_2 + x_3 \leq 5$, you can change the value of c3.ub to the largest positive number representable in your operating environment. You can specify this number by using the CONSTANT function.

The modified LP problem is specified and solved by adding the following lines to the original PROC OPTMODEL call.

```
/* relax upper bound on constraint c3 */
c3.ub = constant('BIG');

solve with lp / iis=true;
```

Because one element of the IIS has been removed, the modified LP problem should no longer contain the infeasible set. Due to the size of this problem, there should be no additional irreducible infeasible sets.

The notes shown in Output 13.4.3 are printed to the log.

Output 13.4.3 Infeasibility Removed: Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 linear constraints (1 LE, 0 EQ, 2 GE, 0 range).
NOTE: The problem has 6 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                           Objective
      Phase Iteration        Value         Time
       P 1          1    1.400000E+01         0
       P 1          2    0.000000E+00         0
NOTE: The IIS= option found this problem to be feasible.
NOTE: The IIS solve time is 0.00 seconds.
```

The solution summary and primal solution are displayed in Output 13.4.4.

Output 13.4.4 Infeasibility Removed: Solution

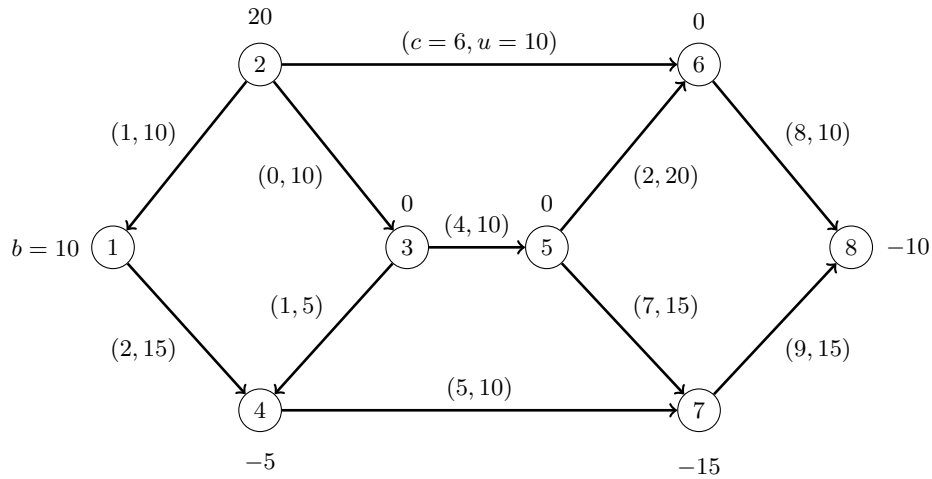
The OPTMODEL Procedure

Solution Summary	
Solver	LP
Algorithm	IIS
Objective Function	obj
Solution Status	Feasible
Iterations	2
Presolve Time	0.00
Solution Time	0.00

Example 13.5: Using the Network Simplex Algorithm

This example demonstrates how you can use the network simplex algorithm to find the minimum-cost flow in a directed graph. Consider the directed graph in Figure 13.4, which appears in Ahuja, Magnanti, and Orlin (1993).

Figure 13.4 Minimum-Cost Network Flow Problem: Data



You can use the following SAS statements to create the input data sets nodedata and arcdata:

```
data nodedata;
   input _node_ $ _sd_;
   datalines;
1    10
2    20
3     0
4    -5
5     0
6     0
7   -15
8   -10
;

data arcdata;
   input _tail_ $ _head_ $ _lo_ _capac_ _cost_;
   datalines;
1    4    0    15    2
2    1    0    10    1
2    3    0    10    0
2    6    0    10    6
3    4    0     5    1
3    5    0    10    4
4    7    0    10    5
5    6    0    20    2
5    7    0    15    7
6    8    0    10    8
7    8    0    15    9
;
```

You can use the following call to PROC OPTMODEL to find the minimum-cost flow:

```
proc optmodel;
   set <str> NODES;
   num supply_demand {NODES};

   set <str,str> ARCS;
   num arcLower  {ARCS};
   num arcUpper  {ARCS};
   num arcCost   {ARCS};

   read data arcdata into ARCS=[_tail_ _head_]
      arcLower=_lo_ arcUpper=_capac_ arcCost=_cost_;
   read data nodedata into NODES=[_node_] supply_demand=_sd_;

   var flow {<i,j> in ARCS} >= arcLower[i,j] <= arcUpper[i,j];
   min obj = sum {<i,j> in ARCS} arcCost[i,j] * flow[i,j];
   con balance {i in NODES}:
      sum {<(i),j> in ARCS} flow[i,j] - sum {<j,(i)> in ARCS} flow[j,i]
         = supply_demand[i];
   solve with lp / algorithm=ns scale=none logfreq=1;
   print flow;
quit;
%put &_OROPTMODEL_;
```

The optimal solution is displayed in Output 13.5.1.

Output 13.5.1 Network Simplex Algorithm: Primal Solution Output

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	obj
Objective Type	Linear
Number of Variables	11
Bounded Above	0
Bounded Below	0
Bounded Below and Above	11
Free	0
Fixed	0
Number of Constraints	8
Linear LE (<=)	0
Linear EQ (=)	8
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	22

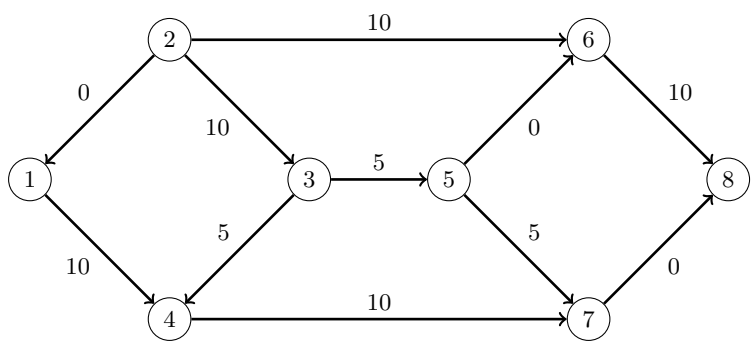
Output 13.5.1 *continued*

Solution Summary	
Solver	LP
Algorithm	Network Simplex
Objective Function	obj
Solution Status	Optimal
Objective Value	270
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	8
Iterations2	0
Presolve Time	0.00
Solution Time	0.00

[1]	[2]	flow
1	**4**	10
2	**1**	0
2	**3**	10
2	**6**	10
3	**4**	5
3	**5**	5
4	**7**	10
5	**6**	0
5	**7**	5
6	**8**	10
7	**8**	0

The optimal solution is represented graphically in Figure 13.5.

Figure 13.5 Minimum-Cost Network Flow Problem: Optimal Solution



The iteration log is displayed in Output 13.5.2.

Output 13.5.2 Log: Solution Progress

```
NOTE: There were 11 observations read from the data set WORK.ARCDATA.
NOTE: There were 8 observations read from the data set WORK.NODEDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 11 variables (0 free, 0 fixed).
NOTE: The problem has 8 linear constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 22 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem is a pure network instance; PRESOLVER=NONE is used.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Network Simplex algorithm is used.
NOTE: The network has 8 rows (100.00%), 11 columns (100.00%), and 1 component.
NOTE: The network extraction and setup time is 0.00 seconds.
                       Primal         Primal           Dual
      Iteration      Objective  Infeasibility  Infeasibility     Time
              1   0.000000E+00   2.000000E+01   8.900000E+01     0.00
              2   0.000000E+00   2.000000E+01   8.900000E+01     0.00
              3   5.000000E+00   1.500000E+01   8.400000E+01     0.00
              4   5.000000E+00   1.500000E+01   8.300000E+01     0.00
              5   7.500000E+01   1.500000E+01   8.300000E+01     0.00
              6   7.500000E+01   1.500000E+01   7.900000E+01     0.00
              7   1.300000E+02   1.000000E+01   7.600000E+01     0.00
              8   2.700000E+02   0.000000E+00   0.000000E+00     0.00
NOTE: The Network Simplex solve time is 0.00 seconds.
NOTE: The total Network Simplex solve time is 0.00 seconds.
NOTE: Optimal.
NOTE: Objective = 270.
STATUS=OK ALGORITHM=NS SOLUTION_STATUS=OPTIMAL OBJECTIVE=270
PRIMAL_INFEASIBILITY=0 DUAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0 ITERATIONS=8
ITERATIONS2=0 PRESOLVE_TIME=0.00 SOLUTION_TIME=0.00
```

Now, suppose there is a budget on the flow that comes out of arc 2: the total arc cost of flow that comes out of arc 2 cannot exceed 50. You can use the following call to PROC OPTMODEL to find the minimum-cost flow:

```
proc optmodel;
   set <str> NODES;
   num supply_demand {NODES};

   set <str,str> ARCS;
   num arcLower  {ARCS};
   num arcUpper  {ARCS};
   num arcCost   {ARCS};

   read data arcdata into ARCS=[_tail_ _head_]
      arcLower=_lo_ arcUpper=_capac_ arcCost=_cost_;
   read data nodedata into NODES=[_node_] supply_demand=_sd_;
```

```
   var flow {<i,j> in ARCS} >= arcLower[i,j] <= arcUpper[i,j];
   min obj = sum {<i,j> in ARCS} arcCost[i,j] * flow[i,j];
   con balance {i in NODES}:
      sum {<(i),j> in ARCS} flow[i,j] - sum {<j,(i)> in ARCS} flow[j,i]
         = supply_demand[i];
   con budgetOn2:
      sum {<i,j> in ARCS: i='2'} arcCost[i,j] * flow[i,j] <= 50;
   solve with lp / algorithm=ns scale=none logfreq=1;
   print flow;
quit;
%put &_OROPTMODEL_;
```

The optimal solution is displayed in Output 13.5.3.

Output 13.5.3 Network Simplex Algorithm: Primal Solution Output

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	obj
Objective Type	Linear
Number of Variables	11
Bounded Above	0
Bounded Below	0
Bounded Below and Above	11
Free	0
Fixed	0
Number of Constraints	9
Linear LE (<=)	1
Linear EQ (=)	8
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	24

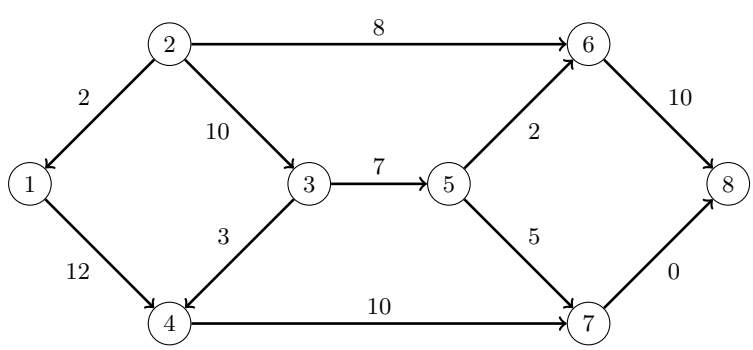
Output 13.5.3 *continued*

Solution Summary	
Solver	LP
Algorithm	Network Simplex
Objective Function	obj
Solution Status	Optimal
Objective Value	274
Primal Infeasibility	0
Dual Infeasibility	1.94289E-16
Bound Infeasibility	0
Iterations	5
Iterations2	4
Presolve Time	0.00
Solution Time	0.00

[1]	[2]	flow
1	**4**	12
2	**1**	2
2	**3**	10
2	**6**	8
3	**4**	3
3	**5**	7
4	**7**	10
5	**6**	2
5	**7**	5
6	**8**	10
7	**8**	0

The optimal solution is represented graphically in Figure 13.6.

Figure 13.6 Minimum-Cost Network Flow Problem: Optimal Solution (with Budget Constraint)



The iteration log is displayed in Output 13.5.4. Note that the network simplex algorithm extracts a subnetwork in this case.

Output 13.5.4 Log: Solution Progress

```
NOTE: There were 11 observations read from the data set WORK.ARCDATA.
NOTE: There were 8 observations read from the data set WORK.NODEDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 11 variables (0 free, 0 fixed).
NOTE: The problem has 9 linear constraints (1 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 24 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 7 variables and 7 constraints.
NOTE: The LP presolver removed 17 constraint coefficients.
NOTE: The presolved problem has 4 variables, 2 constraints, and 7 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Network Simplex algorithm is used.
NOTE: The network has 1 rows (50.00%), 4 columns (100.00%), and 1 component.
NOTE: The network extraction and setup time is 0.00 seconds.
                      Primal         Primal           Dual
      Iteration      Objective  Infeasibility  Infeasibility     Time
              1   3.364000E+02   5.450000E+00   2.400000E+01     0.00
              2   3.202000E+02   5.000000E-02   2.100000E+01     0.00
              3   3.202000E+02   0.000000E+00   2.000000E+00     0.00
              4   3.118000E+02   0.000000E+00   0.000000E+00     0.00
              5   2.716000E+02   0.000000E+00   0.000000E+00     0.00
NOTE: The Network Simplex solve time is 0.00 seconds.
NOTE: The total Network Simplex solve time is 0.00 seconds.
NOTE: The Dual Simplex algorithm is used.
                          Objective                Entering           Leaving
      Phase Iteration        Value         Time     Variable           Variable
       D 2          1    2.716000E+02         0    balance['6'] (S)
      budgetOn2 (S)
       D 2          2    2.716000E+02         0   flow['3','4']
      flow['2','3']
       D 2          3    2.740000E+02         0
       P 2          4    2.740000E+02         0
NOTE: Optimal.
NOTE: Objective = 274.
NOTE: The Simplex solve time is 0.00 seconds.
STATUS=OK ALGORITHM=NS SOLUTION_STATUS=OPTIMAL OBJECTIVE=274
PRIMAL_INFEASIBILITY=0 DUAL_INFEASIBILITY=1.94289E-16 BOUND_INFEASIBILITY=0
ITERATIONS=5 ITERATIONS2=4 PRESOLVE_TIME=0.00 SOLUTION_TIME=0.00
```

Example 13.6: Migration to OPTMODEL: Generalized Networks

The following example shows how to use PROC OPTMODEL to solve the example "Generalized Networks: Using the EXCESS= Option" in Chapter 5, "The NETFLOW Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). The input data sets are the same as in the PROC NETFLOW example.

```
title 'Generalized Networks';

data garcs;
   input _from_ $ _to_ $ _cost_ _mult_;
   datalines;
s1 d1 1 .
s1 d2 8 .
s2 d1 4 2
s2 d2 2 2
s2 d3 1 2
s3 d2 5 0.5
s3 d3 4 0.5
;

data gnodes;
   input _node_ $ _sd_ ;
   datalines;
s1 5
s2 20
s3 10
d1 -5
d2 -10
d3 -20
;
```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called GNETOUT:

```
proc optmodel;
   set <str> NODES;
   num _sd_ {NODES} init 0;
   read data gnodes into NODES=[_node_] _sd_;

   set <str,str> ARCS;
   num _lo_ {ARCS} init 0;
   num _capac_ {ARCS} init .;
   num _cost_ {ARCS};
   num _mult_ {ARCS} init 1;
   read data garcs nomiss into ARCS=[_from_ _to_] _cost_ _mult_;
   NODES = NODES union (union {<i,j> in ARCS} {i,j});

   var Flow {<i,j> in ARCS} >= _lo_[i,j];
   min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
   con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
      - sum {<j,(i)> in ARCS} _mult_[j,i] * Flow[j,i] = _sd_[i];
```

```
    num infinity = constant('BIG');
    /* change equality constraint to le constraint for supply nodes */
    for {i in NODES: _sd_[i] > 0} balance[i].lb = -infinity;

    solve;

    num _supply_ {<i,j> in ARCS} = (if _sd_[i] ne 0 then _sd_[i] else .);
    num _demand_ {<i,j> in ARCS} = (if _sd_[j] ne 0 then -_sd_[j] else .);
    num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

    create data gnetout from [_from_ _to_]
       _cost_ _capac_ _lo_ _mult_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;
```

To solve a generalized network flow problem, the usual balance constraint is altered to include the arc multiplier "_mult_[i,j]" in the second sum. The balance constraint is initially declared as an equality, but to mimic the EXCESS=SUPPLY option in PROC NETFLOW, the sense of this constraint is changed to "≤" by relaxing the constraint's lower bound for supply nodes. The output data set is displayed in Output 13.6.1.

Output 13.6.1 Optimal Solution with Excess Supply

Obs	_from_	_to_	_cost_	_capac_	_lo_	_mult_	_supply_	_demand_	_flow_	_fcost_
1	s1	d1	1	.	0	1.0	5	5	5	5
2	s1	d2	8	.	0	1.0	5	10	0	0
3	s2	d1	4	.	0	2.0	20	5	0	0
4	s2	d2	2	.	0	2.0	20	10	5	10
5	s2	d3	1	.	0	2.0	20	20	10	10
6	s3	d2	5	.	0	0.5	10	10	0	0
7	s3	d3	4	.	0	0.5	10	20	0	0

The log is displayed in Output 13.6.2.

Output 13.6.2 OPTMODEL Log

```
NOTE: There were 6 observations read from the data set WORK.GNODES.
NOTE: There were 7 observations read from the data set WORK.GARCS.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 7 variables (0 free, 0 fixed).
NOTE: The problem has 6 linear constraints (3 LE, 3 EQ, 0 GE, 0 range).
NOTE: The problem has 14 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 4 variables and 4 constraints.
NOTE: The LP presolver removed 10 constraint coefficients.
NOTE: The presolved problem has 3 variables, 2 constraints, and 4 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration        Value         Time
       D 2          1    2.500000E+01         0
NOTE: Optimal.
NOTE: Objective = 25.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The data set WORK.GNETOUT has 7 observations and 10 variables.
```

Now consider the previous example but with a slight modification to the arc multipliers, as in the PROC NETFLOW example:

```
data garcs1;
   input _from_ $ _to_ $ _cost_ _mult_;
   datalines;
s1 d1 1 0.5
s1 d2 8 0.5
s2 d1 4 .
s2 d2 2 .
s2 d3 1 .
s3 d2 5 0.5
s3 d3 4 0.5
;
```

The following PROC OPTMODEL statements are identical to the preceding example, except for the balance constraint. The balance constraint is still initially declared as an equality, but to mimic the PROC NETFLOW EXCESS=DEMAND option, the sense of this constraint is changed to "≥" by relaxing the constraint's upper bound for demand nodes.

```
proc optmodel;
   set <str> NODES;
   num _sd_ {NODES} init 0;
   read data gnodes into NODES=[_node_] _sd_;

   set <str,str> ARCS;
```

```
    num _lo_ {ARCS} init 0;
    num _capac_ {ARCS} init .;
    num _cost_ {ARCS};
    num _mult_ {ARCS} init 1;
    read data garcs1 nomiss into ARCS=[_from_ _to_] _cost_ _mult_;
    NODES = NODES union (union {<i,j> in ARCS} {i,j});

    var Flow {<i,j> in ARCS} >= _lo_[i,j];
    for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
    min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
    con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
       - sum {<j,(i)> in ARCS} _mult_[j,i] * Flow[j,i] = _sd_[i];

    num infinity = constant('BIG');
    /* change equality constraint to ge constraint */
    for {i in NODES: _sd_[i] < 0} balance[i].ub = infinity;

    solve;

    num _supply_ {<i,j> in ARCS} = (if _sd_[i] ne 0 then _sd_[i] else .);
    num _demand_ {<i,j> in ARCS} = (if _sd_[j] ne 0 then -_sd_[j] else .);
    num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

    create data gnetout1 from [_from_ _to_]
       _cost_ _capac_ _lo_ _mult_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;
```

The output data set is displayed in Output 13.6.3.

Output 13.6.3 Optimal Solution with Excess Demand

Obs	_from_	_to_	_cost_	_capac_	_lo_	_mult_	_supply_	_demand_	_flow_	_fcost_
1	s1	d1	1	.	0	0.5	5	5	5	5
2	s1	d2	8	.	0	0.5	5	10	0	0
3	s2	d1	4	.	0	1.0	20	5	0	0
4	s2	d2	2	.	0	1.0	20	10	5	10
5	s2	d3	1	.	0	1.0	20	20	15	15
6	s3	d2	5	.	0	0.5	10	10	0	0
7	s3	d3	4	.	0	0.5	10	20	10	40

The log is displayed in Output 13.6.4.

Output 13.6.4 OPTMODEL Log

```
NOTE: There were 6 observations read from the data set WORK.GNODES.
NOTE: There were 7 observations read from the data set WORK.GARCS1.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 7 variables (0 free, 0 fixed).
NOTE: The problem has 6 linear constraints (0 LE, 3 EQ, 3 GE, 0 range).
NOTE: The problem has 14 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 3 variables and 3 constraints.
NOTE: The LP presolver removed 6 constraint coefficients.
NOTE: The presolved problem has 4 variables, 3 constraints, and 8 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration       Value         Time
       D 2          1    6.500000E+01         0
       D 2          2    7.000000E+01         0
NOTE: Optimal.
NOTE: Objective = 70.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The data set WORK.GNETOUT1 has 7 observations and 10 variables.
```

Example 13.7: Migration to OPTMODEL: Maximum Flow

The following example shows how to use PROC OPTMODEL to solve the example "Maximum Flow Problem" in Chapter 5, "The NETFLOW Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). The input data set is the same as in that example.

```
title 'Maximum Flow Problem';

data arcs;
   input _from_ $ _to_ $ _cost_ _capac_;
   datalines;
S a . .
S b . .
a c 1 7
b c 2 9
a d 3 5
b d 4 8
c e 5 15
d f 6 20
e g 7 11
f g 8 6
e h 9 12
f h 10 4
g T . .
h T . .
```

```
;
```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called GOUT3:

```
proc optmodel;
   str source = 'S';
   str sink = 'T';

   set <str> NODES;
   num _supdem_ {i in NODES} = (if i in {source, sink} then . else 0);

   set <str,str> ARCS;
   num _lo_ {ARCS} init 0;
   num _capac_ {ARCS} init .;
   num _cost_ {ARCS} init 0;
   read data arcs nomiss into ARCS=[_from_ _to_] _cost_ _capac_;
   NODES = (union {<i,j> in ARCS} {i,j});

   var Flow {<i,j> in ARCS} >= _lo_[i,j];
   for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
   max obj = sum {<i,j> in ARCS: j = sink} Flow[i,j];
   con balance {i in NODES diff {source, sink}}:
      sum {<(i),j> in ARCS} Flow[i,j]
      - sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];

   solve;

   num _supply_ {<i,j> in ARCS} =
      (if _supdem_[i] ne 0 then _supdem_[i] else .);
   num _demand_ {<i,j> in ARCS} =
      (if _supdem_[j] ne 0 then -_supdem_[j] else .);
   num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

   create data gout3 from [_from_ _to_]
      _cost_ _capac_ _lo_ _supply_ _demand_ _flow_=Flow _fcost_;
quit;
```

To solve a maximum flow problem, you solve a network flow problem that has a zero supply or demand at all nodes other than the source and sink nodes, as specified in the declaration of the _SUPDEM_ numeric parameter and the balance constraint. The objective declaration uses the logical condition J = SINK to maximize the flow into the sink node. The output data set is displayed in Output 13.7.1.

Output 13.7.1 Optimal Solution

Obs	_from_	_to_	_cost_	_capac_	_lo_	_supply_	_demand_	_flow_	_fcost_
1	S	a	0	.	0	.	.	12	0
2	S	b	0	.	0	.	.	13	0
3	a	c	1	7	0	.	.	7	7
4	b	c	2	9	0	.	.	8	16
5	a	d	3	5	0	.	.	5	15
6	b	d	4	8	0	.	.	5	20
7	c	e	5	15	0	.	.	15	75
8	d	f	6	20	0	.	.	10	60
9	e	g	7	11	0	.	.	11	77
10	f	g	8	6	0	.	.	6	48
11	e	h	9	12	0	.	.	4	36
12	f	h	10	4	0	.	.	4	40
13	g	T	0	.	0	.	.	17	0
14	h	T	0	.	0	.	.	8	0

The log is displayed in Output 13.7.2.

Output 13.7.2 OPTMODEL Log

```
NOTE: There were 14 observations read from the data set WORK.ARCS.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 14 variables (0 free, 0 fixed).
NOTE: The problem has 8 linear constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 24 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The problem is a pure network instance. The ALGORITHM=NETWORK option is
      recommended for solving problems with this structure.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 9 variables and 5 constraints.
NOTE: The LP presolver removed 18 constraint coefficients.
NOTE: The presolved problem has 5 variables, 3 constraints, and 6 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                             Objective
      Phase Iteration          Value          Time
       D 2          1     3.300000E+01          0
       P 2          5     2.500000E+01          0
NOTE: Optimal.
NOTE: Objective = 25.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The data set WORK.GOUT3 has 14 observations and 9 variables.
```

Example 13.8: Migration to OPTMODEL: Production, Inventory, Distribution

The following example shows how to use PROC OPTMODEL to solve the example "Production, Inventory, Distribution Problem" in Chapter 5, "The NETFLOW Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). The input data sets are the same as in that example.

```
title 'Minimum-Cost Flow Problem';
title2 'Production Planning/Inventory/Distribution';

data node0;
   input _node_ $ _supdem_ ;
   datalines;
fact1_1 1000
fact2_1 850
fact1_2 1000
fact2_2 1500
shop1_1 -900
shop2_1 -900
shop1_2 -900
shop2_2 -1450
;

data arc0;
   input _tail_ $ _head_ $ _cost_ _capac_ _lo_
      diagonal factory key_id $10. mth_made $ _name_&$17.;
   datalines;
fact1_1  f1_mar_1 127.9   500 50 19 1 production March prod f1 19 mar
fact1_1  f1_apr_1 78.6    600 50 19 1 production April prod f1 19 apl
fact1_1  f1_may_1 95.1    400 50 19 1 production May   .
f1_mar_1 f1_apr_1 15      50  .  19 1 storage    March .
f1_apr_1 f1_may_1 12      50  .  19 1 storage    April .
f1_apr_1 f1_mar_1 28      20  .  19 1 backorder  April back f1 19 apl
f1_may_1 f1_apr_1 28      20  .  19 1 backorder  May   back f1 19 may
f1_mar_1 f2_mar_1 11      .   .  19 . f1_to_2    March .
f1_apr_1 f2_apr_1 11      .   .  19 . f1_to_2    April .
f1_may_1 f2_may_1 16      .   .  19 . f1_to_2    May   .
f1_mar_1 shop1_1  -327.65 250 .  19 1 sales      March .
f1_apr_1 shop1_1  -300    250 .  19 1 sales      April .
f1_may_1 shop1_1  -285    250 .  19 1 sales      May   .
f1_mar_1 shop2_1  -362.74 250 .  19 1 sales      March .
f1_apr_1 shop2_1  -300    250 .  19 1 sales      April .
f1_may_1 shop2_1  -245    250 .  19 1 sales      May   .
fact2_1  f2_mar_1 88.0    450 35 19 2 production March prod f2 19 mar
fact2_1  f2_apr_1 62.4    480 35 19 2 production April prod f2 19 apl
fact2_1  f2_may_1 133.8   250 35 19 2 production May   .
f2_mar_1 f2_apr_1 18      30  .  19 2 storage    March .
f2_apr_1 f2_may_1 20      30  .  19 2 storage    April .
f2_apr_1 f2_mar_1 17      15  .  19 2 backorder  April back f2 19 apl
f2_may_1 f2_apr_1 25      15  .  19 2 backorder  May   back f2 19 may
f2_mar_1 f1_mar_1 10      40  .  19 . f2_to_1    March .
f2_apr_1 f1_apr_1 11      40  .  19 . f2_to_1    April .
f2_may_1 f1_may_1 13      40  .  19 . f2_to_1    May   .
```

```
f2_mar_1 shop1_1  -297.4  250 .  19 2 sales      March .
f2_apr_1 shop1_1  -290    250 .  19 2 sales      April .
f2_may_1 shop1_1  -292    250 .  19 2 sales      May   .
f2_mar_1 shop2_1  -272.7  250 .  19 2 sales      March .
f2_apr_1 shop2_1  -312    250 .  19 2 sales      April .
f2_may_1 shop2_1  -299    250 .  19 2 sales      May   .
fact1_2  f1_mar_2 217.9   400 40 25 1 production March prod f1 25 mar
fact1_2  f1_apr_2 174.5   550 50 25 1 production April prod f1 25 apl
fact1_2  f1_may_2 133.3   350 40 25 1 production May   .
f1_mar_2 f1_apr_2 20      40  .  25 1 storage    March .
f1_apr_2 f1_may_2 18      40  .  25 1 storage    April .
f1_apr_2 f1_mar_2 32      30  .  25 1 backorder  April back f1 25 apl
f1_may_2 f1_apr_2 41      15  .  25 1 backorder  May   back f1 25 may
f1_mar_2 f2_mar_2 23      .   .  25 . f1_to_2    March .
f1_apr_2 f2_apr_2 23      .   .  25 . f1_to_2    April .
f1_may_2 f2_may_2 26      .   .  25 . f1_to_2    May   .
f1_mar_2 shop1_2  -559.76 .   .  25 1 sales      March .
f1_apr_2 shop1_2  -524.28 .   .  25 1 sales      April .
f1_may_2 shop1_2  -475.02 .   .  25 1 sales      May   .
f1_mar_2 shop2_2  -623.89 .   .  25 1 sales      March .
f1_apr_2 shop2_2  -549.68 .   .  25 1 sales      April .
f1_may_2 shop2_2  -460.00 .   .  25 1 sales      May   .
fact2_2  f2_mar_2 182.0   650 35 25 2 production March prod f2 25 mar
fact2_2  f2_apr_2 196.7   680 35 25 2 production April prod f2 25 apl
fact2_2  f2_may_2 201.4   550 35 25 2 production May   .
f2_mar_2 f2_apr_2 28      50  .  25 2 storage    March .
f2_apr_2 f2_may_2 38      50  .  25 2 storage    April .
f2_apr_2 f2_mar_2 31      15  .  25 2 backorder  April back f2 25 apl
f2_may_2 f2_apr_2 54      15  .  25 2 backorder  May   back f2 25 may
f2_mar_2 f1_mar_2 20      25  .  25 . f2_to_1    March .
f2_apr_2 f1_apr_2 21      25  .  25 . f2_to_1    April .
f2_may_2 f1_may_2 43      25  .  25 . f2_to_1    May   .
f2_mar_2 shop1_2  -567.83 500 .  25 2 sales      March .
f2_apr_2 shop1_2  -542.19 500 .  25 2 sales      April .
f2_may_2 shop1_2  -461.56 500 .  25 2 sales      May   .
f2_mar_2 shop2_2  -542.83 500 .  25 2 sales      March .
f2_apr_2 shop2_2  -559.19 500 .  25 2 sales      April .
f2_may_2 shop2_2  -489.06 500 .  25 2 sales      May   .
;
```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to SAS data sets called ARC1 and NODE2:

```
proc optmodel;
   set <str> NODES;
   num _supdem_ {NODES} init 0;
   read data node0 into NODES=[_node_] _supdem_;

   set <str,str> ARCS;
   num _lo_ {ARCS} init 0;
   num _capac_ {ARCS} init .;
   num _cost_ {ARCS};
   num diagonal {ARCS};
   num factory {ARCS};
```

```
   str key_id {ARCS};
   str mth_made {ARCS};
   str _name_ {ARCS};
   read data arc0 nomiss into ARCS=[_tail_ _head_] _lo_ _capac_ _cost_
      diagonal factory key_id mth_made _name_;
   NODES = NODES union (union {<i,j> in ARCS} {i,j});

   var Flow {<i,j> in ARCS} >= _lo_[i,j];
   for {<i,j> in ARCS: _capac_[i,j] ne .} Flow[i,j].ub = _capac_[i,j];
   min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
   con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
      - sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];

   num infinity = constant('BIG');
   num excess = sum {i in NODES} _supdem_[i];
   if (excess > 0) then do;
      /* change equality constraint to le constraint for supply nodes */
      for {i in NODES: _supdem_[i] > 0} balance[i].lb = -infinity;
   end;
   else if (excess < 0) then do;
      /* change equality constraint to ge constraint for demand nodes */
      for {i in NODES: _supdem_[i] < 0} balance[i].ub = infinity;
   end;

   solve;

   num _supply_ {<i,j> in ARCS} =
      (if _supdem_[i] ne 0 then _supdem_[i] else .);
   num _demand_ {<i,j> in ARCS} =
      (if _supdem_[j] ne 0 then -_supdem_[j] else .);
   num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

   create data arc1 from [_tail_ _head_]
      _cost_ _capac_ _lo_ _name_ _supply_ _demand_ _flow_=Flow _fcost_
      _rcost_ =
         (if Flow[_tail_,_head_].rc ne 0 then Flow[_tail_,_head_].rc else .)
      _status_ = Flow.status diagonal factory key_id mth_made;
   create data node2 from [_node_]
      _supdem_ = (if _supdem_[_node_] ne 0 then _supdem_[_node_] else .)
      _dual_ = balance.dual;
quit;
```

The PROC OPTMODEL statements use both single-dimensional (NODES) and multiple-dimensional (ARCS) index sets, which are populated from the corresponding data set variables in the READ DATA statements. The _SUPDEM_, _LO_, and _CAPAC_ parameters are given initial values, and the NOMISS option in the READ DATA statement tells PROC OPTMODEL to read only the nonmissing values from the input data set. The balance constraint is initially declared as an equality, but depending on the total supply or demand, the sense of this constraint is changed to "≤" or "≥" by relaxing the constraint's lower or upper bound, respectively. The ARC1 output data set contains most of the same information as in the NETFLOW example, including reduced cost, basis status, and dual values. The _ANUMB_ and _TNUMB_ values do not apply here.

The PROC PRINT statements are similar to the PROC NETFLOW example:

```
options ls=80 ps=54;
proc print data=arc1 heading=h width=min;
   var _tail_ _head_ _cost_ _capac_ _lo_ _name_
   _supply_ _demand_ _flow_ _fcost_;
   sum _fcost_;
run;
proc print data=arc1 heading=h width=min;
   var _rcost_ _status_ diagonal factory key_id mth_made;
run;
proc print data=node2;
run;
```

The output data sets are displayed in Output 13.8.1.

Output 13.8.1 Output Data Sets

Obs	_tail_	_head_	_cost_	_capac_	_lo_	_name_	_supply_	_demand_	_flow_	_fcost_
1	fact1_1	f1_mar_1	127.90	500	50	prod f1 19 mar	1000	.	345	44125.50
2	fact1_1	f1_apr_1	78.60	600	50	prod f1 19 apl	1000	.	600	47160.00
3	fact1_1	f1_may_1	95.10	400	50		1000	.	50	4755.00
4	f1_mar_1	f1_apr_1	15.00	50	0		.	.	0	0.00
5	f1_apr_1	f1_may_1	12.00	50	0		.	.	50	600.00
6	f1_apr_1	f1_mar_1	28.00	20	0	back f1 19 apl	.	.	20	560.00
7	f1_may_1	f1_apr_1	28.00	20	0	back f1 19 may	.	.	0	0.00
8	f1_mar_1	f2_mar_1	11.00	.	0		.	.	0	0.00
9	f1_apr_1	f2_apr_1	11.00	.	0		.	.	30	330.00
10	f1_may_1	f2_may_1	16.00	.	0		.	.	100	1600.00
11	f1_mar_1	shop1_1	-327.65	250	0		.	900	155	-50785.75
12	f1_apr_1	shop1_1	-300.00	250	0		.	900	250	-75000.00
13	f1_may_1	shop1_1	-285.00	250	0		.	900	0	0.00
14	f1_mar_1	shop2_1	-362.74	250	0		.	900	250	-90685.00
15	f1_apr_1	shop2_1	-300.00	250	0		.	900	250	-75000.00
16	f1_may_1	shop2_1	-245.00	250	0		.	900	0	0.00
17	fact2_1	f2_mar_1	88.00	450	35	prod f2 19 mar	850	.	290	25520.00
18	fact2_1	f2_apr_1	62.40	480	35	prod f2 19 apl	850	.	480	29952.00
19	fact2_1	f2_may_1	133.80	250	35		850	.	35	4683.00
20	f2_mar_1	f2_apr_1	18.00	30	0		.	.	0	0.00
21	f2_apr_1	f2_may_1	20.00	30	0		.	.	15	300.00
22	f2_apr_1	f2_mar_1	17.00	15	0	back f2 19 apl	.	.	0	0.00
23	f2_may_1	f2_apr_1	25.00	15	0	back f2 19 may	.	.	0	0.00
24	f2_mar_1	f1_mar_1	10.00	40	0		.	.	40	400.00
25	f2_apr_1	f1_apr_1	11.00	40	0		.	.	0	0.00
26	f2_may_1	f1_may_1	13.00	40	0		.	.	0	0.00
27	f2_mar_1	shop1_1	-297.40	250	0		.	900	250	-74350.00
28	f2_apr_1	shop1_1	-290.00	250	0		.	900	245	-71050.00
29	f2_may_1	shop1_1	-292.00	250	0		.	900	0	0.00
30	f2_mar_1	shop2_1	-272.70	250	0		.	900	0	0.00
31	f2_apr_1	shop2_1	-312.00	250	0		.	900	250	-78000.00
32	f2_may_1	shop2_1	-299.00	250	0		.	900	150	-44850.00
33	fact1_2	f1_mar_2	217.90	400	40	prod f1 25 mar	1000	.	400	87160.00
34	fact1_2	f1_apr_2	174.50	550	50	prod f1 25 apl	1000	.	550	95975.00
35	fact1_2	f1_may_2	133.30	350	40		1000	.	40	5332.00
36	f1_mar_2	f1_apr_2	20.00	40	0		.	.	0	0.00
37	f1_apr_2	f1_may_2	18.00	40	0		.	.	0	0.00
38	f1_apr_2	f1_mar_2	32.00	30	0	back f1 25 apl	.	.	30	960.00
39	f1_may_2	f1_apr_2	41.00	15	0	back f1 25 may	.	.	15	615.00
40	f1_mar_2	f2_mar_2	23.00	.	0		.	.	0	0.00
41	f1_apr_2	f2_apr_2	23.00	.	0		.	.	0	0.00
42	f1_may_2	f2_may_2	26.00	.	0		.	.	0	0.00
43	f1_mar_2	shop1_2	-559.76	.	0		.	900	0	0.00
44	f1_apr_2	shop1_2	-524.28	.	0		.	900	0	0.00
45	f1_may_2	shop1_2	-475.02	.	0		.	900	25	-11875.50
46	f1_mar_2	shop2_2	-623.89	.	0		.	1450	455	-283869.95
47	f1_apr_2	shop2_2	-549.68	.	0		.	1450	535	-294078.80
48	f1_may_2	shop2_2	-460.00	.	0		.	1450	0	0.00

Output 13.8.1 *continued*

Obs	_tail_	_head_	_cost_	_capac_	_lo_	_name_	_supply_	_demand_	_flow_	_fcost_
49	fact2_2	f2_mar_2	182.00	650	35	prod f2 25 mar	1500	.	645	117390.00
50	fact2_2	f2_apr_2	196.70	680	35	prod f2 25 apl	1500	.	680	133756.00
51	fact2_2	f2_may_2	201.40	550	35		1500	.	35	7049.00
52	f2_mar_2	f2_apr_2	28.00	50	0		.	.	0	0.00
53	f2_apr_2	f2_may_2	38.00	50	0		.	.	0	0.00
54	f2_apr_2	f2_mar_2	31.00	15	0	back f2 25 apl	.	.	0	0.00
55	f2_may_2	f2_apr_2	54.00	15	0	back f2 25 may	.	.	15	810.00
56	f2_mar_2	f1_mar_2	20.00	25	0		.	.	25	500.00
57	f2_apr_2	f1_apr_2	21.00	25	0		.	.	0	0.00
58	f2_may_2	f1_may_2	43.00	25	0		.	.	0	0.00
59	f2_mar_2	shop1_2	-567.83	500	0		.	900	500	-283915.00
60	f2_apr_2	shop1_2	-542.19	500	0		.	900	375	-203321.25
61	f2_may_2	shop1_2	-461.56	500	0		.	900	0	0.00
62	f2_mar_2	shop2_2	-542.83	500	0		.	1450	120	-65139.60
63	f2_apr_2	shop2_2	-559.19	500	0		.	1450	320	-178940.80
64	f2_may_2	shop2_2	-489.06	500	0		.	1450	20	-9781.20
										-1281110.35

Output 13.8.1 *continued*

Obs	_rcost_	_status_	diagonal	factory	key_id	mth_made
1	.	B	19	1	production	March
2	-0.65	U	19	1	production	April
3	0.85	L	19	1	production	May
4	63.65	L	19	1	storage	March
5	-3.00	U	19	1	storage	April
6	-20.65	U	19	1	backorder	April
7	43.00	L	19	1	backorder	May
8	50.90	L	19	.	f1_to_2	March
9	.	B	19	.	f1_to_2	April
10	.	B	19	.	f1_to_2	May
11	.	B	19	1	sales	March
12	-21.00	U	19	1	sales	April
13	9.00	L	19	1	sales	May
14	-46.09	U	19	1	sales	March
15	-32.00	U	19	1	sales	April
16	38.00	L	19	1	sales	May
17	.	B	19	2	production	March
18	-27.85	U	19	2	production	April
19	23.55	L	19	2	production	May
20	15.75	L	19	2	storage	March
21	.	B	19	2	storage	April
22	19.25	L	19	2	backorder	April
23	45.00	L	19	2	backorder	May
24	-29.90	U	19	.	f2_to_1	March
25	22.00	L	19	.	f2_to_1	April
26	29.00	L	19	.	f2_to_1	May
27	-9.65	U	19	2	sales	March
28	.	B	19	2	sales	April
29	18.00	L	19	2	sales	May
30	4.05	L	19	2	sales	March
31	-33.00	U	19	2	sales	April
32	.	B	19	2	sales	May
33	-45.16	U	25	1	production	March
34	-14.35	U	25	1	production	April
35	2.11	L	25	1	production	May
36	94.21	L	25	1	storage	March
37	75.66	L	25	1	storage	April
38	-42.21	U	25	1	backorder	April
39	-16.66	U	25	1	backorder	May
40	104.06	L	25	.	f1_to_2	March
41	13.49	L	25	.	f1_to_2	April
42	28.96	L	25	.	f1_to_2	May
43	47.13	L	25	1	sales	March
44	8.40	L	25	1	sales	April
45	.	B	25	1	sales	May
46	.	B	25	1	sales	March
47	.	B	25	1	sales	April
48	32.02	L	25	1	sales	May

Output 13.8.1 *continued*

Obs	_rcost_	_status_	diagonal	factory	key_id	mth_made
49	.	B	25	2	production	March
50	-1.66	U	25	2	production	April
51	73.17	L	25	2	production	May
52	11.64	L	25	2	storage	March
53	108.13	L	25	2	storage	April
54	47.36	L	25	2	backorder	April
55	-16.13	U	25	2	backorder	May
56	-61.06	U	25	.	f2_to_1	March
57	30.51	L	25	.	f2_to_1	April
58	40.04	L	25	.	f2_to_1	May
59	-42.00	U	25	2	sales	March
60	.	B	25	2	sales	April
61	10.50	L	25	2	sales	May
62	.	B	25	2	sales	March
63	.	B	25	2	sales	April
64	.	B	25	2	sales	May

Obs	_node_	_supdem_	_dual_
1	fact1_1	1000	0.00
2	fact2_1	850	0.00
3	fact1_2	1000	0.00
4	fact2_2	1500	0.00
5	shop1_1	-900	199.75
6	shop2_1	-900	188.75
7	shop1_2	-900	343.83
8	shop2_2	-1450	360.83
9	f1_mar_1	.	-127.90
10	f1_apr_1	.	-79.25
11	f1_may_1	.	-94.25
12	f2_mar_1	.	-88.00
13	f2_apr_1	.	-90.25
14	f2_may_1	.	-110.25
15	f1_mar_2	.	-263.06
16	f1_apr_2	.	-188.85
17	f1_may_2	.	-131.19
18	f2_mar_2	.	-182.00
19	f2_apr_2	.	-198.36
20	f2_may_2	.	-128.23

The log is displayed in Output 13.8.2.

Output 13.8.2 OPTMODEL Log

```
NOTE: There were 8 observations read from the data set WORK.NODE0.
NOTE: There were 64 observations read from the data set WORK.ARC0.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 64 variables (0 free, 0 fixed).
NOTE: The problem has 20 linear constraints (4 LE, 16 EQ, 0 GE, 0 range).
NOTE: The problem has 128 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 0 variables and 0 constraints.
NOTE: The LP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 64 variables, 20 constraints, and 128
      constraint coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration        Value         Time
       D 2          1   -4.333564E+06         0
       D 2         32   -1.281110E+06         0
NOTE: Optimal.
NOTE: Objective = -1281110.35.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The data set WORK.ARC1 has 64 observations and 16 variables.
NOTE: The data set WORK.NODE2 has 20 observations and 3 variables.
```

Example 13.9: Migration to OPTMODEL: Shortest Path

The following example shows how to use PROC OPTMODEL to solve the example "Shortest Path Problem" in Chapter 5, "The NETFLOW Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*). The input data set is the same as in that example.

```
title 'Shortest Path Problem';
title2 'How to get Hawaiian Pineapples to a London Restaurant';

data aircost1;
   input ffrom&$13. tto&$15. _cost_;
   datalines;
Honolulu       Chicago         105
Honolulu       San Francisco    75
Honolulu       Los Angeles      68
Chicago        Boston           45
Chicago        New York         56
San Francisco  Boston           71
San Francisco  New York         48
San Francisco  Atlanta          63
Los Angeles    New York         44
Los Angeles    Atlanta          57
Boston         Heathrow London  88
New York       Heathrow London  65
Atlanta        Heathrow London  76
```

```
;
```

The following PROC OPTMODEL statements read the data sets, build the linear programming model, solve the model, and output the optimal solution to a SAS data set called SPATH:

```
proc optmodel;
   str sourcenode = 'Honolulu';
   str sinknode = 'Heathrow London';

   set <str> NODES;
   num _supdem_ {i in NODES} = (if i = sourcenode then 1
      else if i = sinknode then -1 else 0);

   set <str,str> ARCS;
   num _lo_ {ARCS} init 0;
   num _capac_ {ARCS} init .;
   num _cost_ {ARCS};
   read data aircost1 into ARCS=[ffrom tto] _cost_;
   NODES = (union {<i,j> in ARCS} {i,j});

   var Flow {<i,j> in ARCS} >= _lo_[i,j];
   min obj = sum {<i,j> in ARCS} _cost_[i,j] * Flow[i,j];
   con balance {i in NODES}: sum {<(i),j> in ARCS} Flow[i,j]
      - sum {<j,(i)> in ARCS} Flow[j,i] = _supdem_[i];
   solve;

   num _supply_ {<i,j> in ARCS} =
      (if _supdem_[i] ne 0 then _supdem_[i] else .);
   num _demand_ {<i,j> in ARCS} =
      (if _supdem_[j] ne 0 then -_supdem_[j] else .);
   num _fcost_ {<i,j> in ARCS} = _cost_[i,j] * Flow[i,j].sol;

   create data spath from [ffrom tto]
      _cost_ _capac_ _lo_ _supply_ _demand_ _flow_=Flow _fcost_
      _rcost_=(if Flow[ffrom,tto].rc ne 0 then Flow[ffrom,tto].rc else .)
      _status_=Flow.status;
quit;
```

The statements use both single-dimensional (NODES) and multiple-dimensional (ARCS) index sets. The ARCS index set is populated from the ffrom and tto data set variables in the READ DATA statement. To solve a shortest path problem, you solve a minimum-cost network flow problem that has a supply of one unit at the source node, a demand of one unit at the sink node, and zero supply or demand at all other nodes, as specified in the declaration of the _SUPDEM_ numeric parameter. The SPATH output data set contains most of the same information as in the PROC NETFLOW example, including reduced cost and basis status. The _ANUMB_ and _TNUMB_ values do not apply here.

The PROC PRINT statements are similar to the PROC NETFLOW example:

```
proc print data=spath;
   sum _fcost_;
run;
```

The output is displayed in Output 13.9.1.

Output 13.9.1 Output Data Set

Obs	ffrom	tto	_cost_	_capac_	_lo_	_supply_	_demand_	_flow_	_fcost_	_rcost_	_status_
1	Honolulu	Chicago	105	.	0	1	.	0	0	.	B
2	Honolulu	San Francisco	75	.	0	1	.	0	0	.	B
3	Honolulu	Los Angeles	68	.	0	1	.	1	68	.	B
4	Chicago	Boston	45	.	0	.	.	0	0	61	L
5	Chicago	New York	56	.	0	.	.	0	0	49	L
6	San Francisco	Boston	71	.	0	.	.	0	0	57	L
7	San Francisco	New York	48	.	0	.	.	0	0	11	L
8	San Francisco	Atlanta	63	.	0	.	.	0	0	37	L
9	Los Angeles	New York	44	.	0	.	.	1	44	.	B
10	Los Angeles	Atlanta	57	.	0	.	.	0	0	24	L
11	Boston	Heathrow London	88	.	0	.	1	0	0	.	B
12	New York	Heathrow London	65	.	0	.	1	1	65	.	B
13	Atlanta	Heathrow London	76	.	0	.	1	0	0	.	B
									177		

The log is displayed in Output 13.9.2.

Output 13.9.2 OPTMODEL Log

```
NOTE: There were 13 observations read from the data set WORK.AIRCOST1.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 13 variables (0 free, 0 fixed).
NOTE: The problem has 8 linear constraints (0 LE, 8 EQ, 0 GE, 0 range).
NOTE: The problem has 26 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The problem is a pure network instance. The ALGORITHM=NETWORK option is
      recommended for solving problems with this structure.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 7 variables and 7 constraints.
NOTE: The LP presolver removed 20 constraint coefficients.
NOTE: The presolved problem has 6 variables, 1 constraints, and 6 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                            Objective
      Phase Iteration         Value         Time
       D 2          1    1.240000E+01         0
       D 2          2    1.770000E+02         0
NOTE: Optimal.
NOTE: Objective = 177.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: The data set WORK.SPATH has 13 observations and 11 variables.
```

Example 13.10: Sensitivity Analysis

In this example, consider again the diet problem from Example 13.1. Example 13.2 shows how to reoptimize the optimization problem if the input data change. This is useful if you want to investigate other scenarios or see how the optimal solution changes as a function of the input data. Sensitivity analysis automates this process by providing stability intervals for the input data.

After solving the diet problem, you can ask how much the price of each food item can change without invalidating the optimal basis that is found. You can calculate this by using the following solver call:

```
solve with lp / sensitivity=(change=(obj));
print diet.objmin diet.objmax;
```

The sensitivity analysis of the objective coefficients of the original diet problem is shown in Output 13.10.1.

Output 13.10.1 Optimal Solutions to the Original Diet Problem with Sensitivity Analysis

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear
Number of Variables	6
Bounded Above	0
Bounded Below	5
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	4
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	3
Linear Range	0
Constraint Coefficients	23

Solution Summary	
Solver	LP
Algorithm	Dual Simplex
Objective Function	f
Solution Status	Optimal
Objective Value	12.081337881
Primal Infeasibility	1.776357E-16
Dual Infeasibility	4.440892E-17
Bound Infeasibility	0
Iterations	1
Presolve Time	0.00
Solution Time	0.00

[1]	diet.OBJMIN	diet.OBJMAX
Bread	0.80934	1.7977E308
Cheese	6.82284	19.4228
Fish	5.84359	1.7977E308
Milk	-1.7977E308	4.0884
Potato	-0.19189	3.5006
Yogurt	-0.10849	1.7977E308

Note that you can combine the sensitivity analysis with the initial solve of the optimization problem. From the output, you can see that changing the price of cheese between 6.82284 and 19.4228 would result in the same optimal basis. You can easily verify this by using the warm-start technique shown in Example 13.2.

You can change the price of cheese to 15.0 and resolve the optimization problem as follows:

```
cost['Cheese'] = 15.0;
solve with lp / basis = warmstart;
```

The following iteration log indicates that it takes the LP solver no extra iterations to solve the modified problem, because the optimal basis remains optimal after the objective function is changed.

Output 13.10.2 Log

```
NOTE: There were 6 observations read from the data set WORK.FOODDATA.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver is disabled for linear problems.
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 0 variables and 0 constraints.
NOTE: The LP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 6 variables, 4 constraints, and 23 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration       Value         Time
       D 2          1    5.500000E+00         0
       D 2          5    1.208134E+01         0
NOTE: Optimal.
NOTE: Objective = 12.081337881.
NOTE: The Dual Simplex solve time is 0.00 seconds.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 4 linear constraints (1 LE, 0 EQ, 3 GE, 0 range).
NOTE: The problem has 23 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The LP presolver value AUTOMATIC is applied.
NOTE: The LP presolver time is 0.00 seconds.
NOTE: The LP presolver removed 0 variables and 0 constraints.
NOTE: The LP presolver removed 0 constraint coefficients.
NOTE: The presolved problem has 6 variables, 4 constraints, and 23 constraint
      coefficients.
NOTE: The LP solver is called.
NOTE: The Dual Simplex algorithm is used.
                          Objective
      Phase Iteration       Value         Time
       D 2          1    1.522783E+01         0
NOTE: Optimal.
NOTE: Objective = 15.227829598.
NOTE: The Dual Simplex solve time is 0.00 seconds.
```

References

Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993). *Network Flows: Theory, Algorithms, and Applications*. Englewood Cliffs, NJ: Prentice-Hall.

Andersen, E. D., and Andersen, K. D. (1995). "Presolving in Linear Programming." *Mathematical Programming* 71:221–245.

Chinneck, J. W. (2008). *Feasibility and Infeasibility in Optimization: Algorithms and Computational Methods.* Vol. 118 of International Series in Operations Research and Management Science. New York: Springer.

Dantzig, G. B. (1963). *Linear Programming and Extensions*. Princeton, NJ: Princeton University Press.

Forrest, J. J., and Goldfarb, D. (1992). "Steepest-Edge Simplex Algorithms for Linear Programming." *Mathematical Programming* 5:1–28.

Gondzio, J. (1997). "Presolve Analysis of Linear Programs Prior to Applying an Interior Point Method." *INFORMS Journal on Computing* 9:73–91.

Harris, P. M. J. (1973). "Pivot Selection Methods in the Devex LP Code." *Mathematical Programming* 57:341–374.

Maros, I. (2003). *Computational Techniques of the Simplex Method.* Boston: Kluwer Academic.

Chapter 14
The Mixed Integer Linear Programming Solver

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Overview: MILP Solver

The OPTMODEL procedure provides a framework for specifying and solving mixed integer linear programs (MILPs). A standard mixed integer linear program has the formulation

$$\begin{array}{rl} \min & \mathbf{c}^T\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \\ & \mathbf{x}_i \in \mathbb{Z} \quad \forall i \in \mathcal{S} \end{array} \qquad \text{(MILP)}$$

where

$\mathbf{x}$	$\in$	$\mathbb{R}^n$	is the vector of structural variables
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the matrix of technological coefficients
$\mathbf{c}$	$\in$	$\mathbb{R}^n$	is the vector of objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^m$	is the vector of constraints' right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^n$	is the vector of lower bounds on variables
$\mathbf{u}$	$\in$	$\mathbb{R}^n$	is the vector of upper bounds on variables
$\mathcal{S}$			is a nonempty subset of the set $\{1\ldots,n\}$ of indices

The MILP solver, available in the OPTMODEL procedure, implements a linear-programming-based branch-and-cut algorithm. This divide-and-conquer approach attempts to solve the original problem by solving linear programming relaxations of a sequence of smaller subproblems. The MILP solver also implements advanced techniques such as presolving, generating cutting planes, and applying primal heuristics to improve the efficiency of the overall algorithm.

The MILP solver provides various control options and solution strategies. In particular, you can enable, disable, or set levels for the advanced techniques previously mentioned. It is also possible to input an incumbent solution; see the section "Warm Start Option" on page 711 for details.

Getting Started: MILP Solver

The following example illustrates the use of the OPTMODEL procedure to solve mixed integer linear programs. For more examples, see the section "Examples: MILP Solver" on page 737. Suppose you want to solve the following problem:

$$\begin{array}{rrcrcrcrl} \min & 2x_1 & - & 3x_2 & - & 4x_3 & & & \\ \text{s.t.} & & - & 2x_2 & - & 3x_3 & \geq & -5 & \text{(R1)} \\ & x_1 & + & x_2 & + & 2x_3 & \leq & 4 & \text{(R2)} \\ & x_1 & + & 2x_2 & + & 3x_3 & \leq & 7 & \text{(R3)} \\ & & & x_1, & x_2, & x_3 & \geq & 0 & \\ & & & x_1, & x_2, & x_3 & \in \mathbb{Z} & & \end{array}$$

You can use the following statements to call the OPTMODEL procedure for solving mixed integer linear programs:

```
proc optmodel;
   var x{1..3} >= 0 integer;

   min f = 2*x[1] - 3*x[2] - 4*x[3];

   con r1: -2*x[2] - 3*x[3] >= -5;
   con r2: x[1] + x[2] + 2*x[3] <= 4;
   con r3: x[1] + 2*x[2] + 3*x[3] <= 7;

   solve with milp / presolver = automatic heuristics = automatic;
   print x;
quit;
```

The PRESOLVER= and HEURISTICS= options specify the levels for presolving and applying heuristics, respectively. In this example, each option is set to its default value, AUTOMATIC, meaning that the solver automatically determines the appropriate levels for presolve and heuristics.

The optimal value of x is shown in Figure 14.1.

Figure 14.1 Solution Output

The OPTMODEL Procedure

[1]	x
1	0
2	1
3	1

The solution summary stored in the macro variable _OROPTMODEL_ can be viewed by issuing the following statement:

```
%put &_OROPTMODEL_;
```

This statement produces the output shown in Figure 14.2.

Figure 14.2 Macro Output

```
STATUS=OK ALGORITHM=BAC SOLUTION_STATUS=OPTIMAL OBJECTIVE=-7 RELATIVE_GAP=0
ABSOLUTE_GAP=0 PRIMAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0
INTEGER_INFEASIBILITY=0 BEST_BOUND=-7 NODES=1 SOLUTIONS_FOUND=2 ITERATIONS=3
PRESOLVE_TIME=0.00 SOLUTION_TIME=0.03
```

Syntax: MILP Solver

The following statement is available in the OPTMODEL procedure:

SOLVE WITH MILP < / *options* > **;**

Functional Summary

Table 14.1 summarizes the options available for the SOLVE WITH MILP statement, classified by function.

Table 14.1 Options for the MILP Solver

Description	Option
Warm Start Option	
Specifies the input primal solution (warm start)	PRIMALIN
Presolve Options	
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the stopping criterion based on absolute objective gap	ABSOBJGAP=
Specifies the cutoff value for node removal	CUTOFF=
Emphasizes feasibility or optimality	EMPHASIS=
Specifies the maximum violation on variables and constraints	FEASTOL=
Enables or disables irreducible infeasible set (IIS) detection	IIS=
Specifies the maximum allowed difference between an integer variable's value and an integer	INTTOL=
Specifies the frequency of printing the node log	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of nodes to be processed	MAXNODES=
Specifies the gap criterion for the solutions that are returned when multiple solution algorithms are run	MAXPOOLGAP=
Specifies the maximum number of solutions to return from the pool	MAXPOOLSOLS=
Specifies the maximum number of solutions to be found	MAXSOLS=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the tolerance used in determining the optimality of nodes in the branch-and-bound tree	OPTTOL=
Specifies the probing level	PROBE=
Specifies the stopping criterion based on relative objective gap	RELOBJGAP=
Enables the use of scaling on the problem matrix	SCALE=
Specifies the initial seed for the random number generator	SEED=
Specifies the type of multiple solution algorithm	SOLTYPE=
Specifies the stopping criterion based on target objective value	TARGET=
Specifies whether time units are CPU time or real time	TIMETYPE=

Table 14.1 *continued*

Description	Option
Heuristics Option	
Specifies the primal heuristics level	HEURISTICS=
Search Options	
Specifies the level of conflict search	CONFLICTSEARCH=
Specifies the node selection strategy	NODESEL=
Enables use of variable priorities	PRIORITY=
Specifies the restarting strategy	RESTARTS=
Specifies the number of simplex iterations performed on each variable in the strong branching variable selection strategy	STRONGITER=
Specifies the number of candidates for the strong branching variable selection strategy	STRONGLEN=
Specifies the level of symmetry detection	SYMMETRY=
Specifies the rule for selecting the branching variable	VARSEL=
Cut Options	
Specifies the cut level for all cuts	ALLCUTS=
Specifies the clique cut level	CUTCLIQUE=
Specifies the flow cover cut level	CUTFLOWCOVER=
Specifies the flow path cut level	CUTFLOWPATH=
Specifies the Gomory cut level	CUTGOMORY=
Specifies the generalized upper bound (GUB) cover cut level	CUTGUB=
Specifies the implied bounds cut level	CUTIMPLIED=
Specifies the knapsack cover cut level	CUTKNAPSACK=
Specifies the lift-and-project cut level	CUTLAP=
Specifies the mixed lifted 0-1 cut level	CUTMILIFTED=
Specifies the mixed integer rounding (MIR) cut level	CUTMIR=
Specifies the multicommodity network flow cut level	CUTMULTICOMMODITY=
Specifies the path mixing cut level	CUTPATHMIXING=
Specifies the RLT cut level	CUTRLT=
Specifies the row multiplier factor for cuts	CUTSFACTOR=
Specifies the overall cut aggressiveness	CUTSTRATEGY=
Specifies the zero-half cut level	CUTZEROHALF=
Decomposition Algorithm Options	
Enables decomposition algorithm and specifies general control options	DECOMP=()
Specifies options for the master problem	DECOMPMASTER=()
Specifies options for the master problem solved as a MILP	DECOMPMASTERIP=()
Specifies options for the subproblem	DECOMPSUBPROB=()
Parallel Options	
Enables the MILP solver to run in concurrent mode	CONCURRENT=
Enables the MILP solver to run deterministically	DETERMINISTIC=
Enables the MILP solver to run in distributed mode	DISTRIBUTED=
Specifies the number of threads for the parallel MILP solver to use	NTHREADS=

Table 14.1 *continued*

Description	Option
Root Node Solver Options	
Specifies the root node solver and its general control options	ROOTNODE=()

MILP Solver Options

This section describes the options that are recognized by the MILP solver in PROC OPTMODEL. These options can be specified after a forward slash (/) in the SOLVE statement, provided that the MILP solver is explicitly specified using a WITH clause. For example, the following line could appear in PROC OPTMODEL statements:

```
solve with milp / allcuts=aggressive maxnodes=10000 primalin;
```

Presolve Options

FOLD=AUTOMATIC | OFF | ON

controls the folding of the problem. You can specify the following values:

AUTOMATIC specifies that the presolver use a heuristic to decide whether to fold the problem or not.

OFF disables folding. The optimization problem is not further reduced by folding.

ON specifies that the presolver try to fold the continuous part of the optimization problem.

Folding is helpful for problems that have a symmetric structure in the continuous part of the variables.

By default, FOLD=AUTOMATIC.

PRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the level of presolve processing. You can specify the following values:

AUTOMATIC applies the default level of presolve processing. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

NONE disables the presolver. Only the necessary problem transformation steps are performed.

BASIC performs minimal presolve processing. Only some very fast operations are performed.

MODERATE applies a higher level of presolve processing. Suitable limits are in place such that the presolver reduces the problem almost as much as when PRESOLVER=AGGRESSIVE, but in a reasonable time.

AGGRESSIVE applies the highest level of presolve processing. All the presolver techniques are called with no limits. This reduces the problem the most, but can take a very long time.

By default, PRESOLVER=AUTOMATIC.

Warm Start Option

PRIMALIN

enables you to input starting solutions in PROC OPTMODEL before invoking the MILP solver. When you specify this option in the SOLVE statement, the MILP solver uses the current solution and any other stored solutions as starting solutions (warm start). In particular, if the previous solver call returns multiple solutions, all these solutions are used by default. If the MILP solver finds that an input solution is feasible, then the input solution provides an incumbent solution and a bound for the branch-and-bound algorithm. If the solution is not feasible, the MILP solver tries to repair it. It is possible to set a variable value to the missing value '.' to mark a variable for repair. When it is difficult to find a good integer feasible solution for a problem, a warm start can reduce solution time significantly.

NOTE: If the MILP solver produces a feasible solution, you can use the variable values from that run as the warm start solution for a subsequent run. If the warm start solution is not feasible for the subsequent run, the solver automatically tries to repair it.

Control Options

ABSOBJGAP=*number*

ABSOLUTEOBJECTIVEGAP=*number*

specifies a stopping criterion. When the absolute difference between the best integer objective and the best bound on the objective function value becomes smaller than the value of *number*, the procedure stops. The value of *number* can be any nonnegative number; the default value is 1E–6.

CUTOFF=*number*

cuts off any nodes in a minimization (maximization) problem that have an objective value at or above (below) *number*. The value of *number* can be any number; the default value is the largest (smallest) number that can be represented by a double.

EMPHASIS=BALANCE | OPTIMAL | FEASIBLE

specifies the type of search emphasis. You can specify the following values:

BALANCE performs a balanced search.

OPTIMAL emphasizes optimality over feasibility.

FEASIBLE emphasizes feasibility over optimality.

By default, EMPHASIS=BALANCE.

FEASTOL=*number*

specifies the tolerance that the MILP solver uses to check the feasibility of a solution. This tolerance applies both to the maximum violation of bounds on variables and to the difference between the right-hand sides and left-hand sides of constraints. The value of *number* can be any value between 1E–4 and 1E–9, inclusive. However, the value of *number* cannot be larger than the integer feasibility tolerance. If the value of *number* is larger than the value of the INTTOL= option, then the solver sets FEASTOL= to the value of INTTOL=. The default value is 1E–6.

If the MILP solver fails to find a feasible solution within this tolerance but does find a solution that has some violation, then the solver stops with a solution status of OPTIMAL_COND (see the section "Macro Variable _OROPTMODEL_" on page 734).

IIS=FALSE | TRUE

specifies whether the MILP solver is to attempt to identify a set of constraints, variables, and integer restrictions that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection, and turns off certain options such as the SOLTYPE= option. If an IIS is found, information about infeasible constraints, integer restrictions, or variable bounds is written to the .status values of the constraints and variables. For more information about the .status suffix, see the section "Suffixes" on page 420.

For more information about IIS, see the section "Irreducible Infeasible Set" on page 733. By default, IIS=FALSE.

INTTOL=*number*

INTEGERTOLERANCE=*number*

specifies the amount by which an integer variable value can differ from an integer and still be considered integer feasible. The value of *number* can be any number between 1E–9 and 0.5, inclusive. The MILP solver attempts to find an optimal solution whose integer infeasibility is less than *number*. The default value is 1E–5.

If the best solution that the solver finds has an integer infeasibility larger than the value of *number*, then the solver stops with a solution status of OPTIMAL_COND (see the section "Macro Variable _OROPTMODEL_" on page 734).

LOGFREQ=*k*

PRINTFREQ=*k*

prints information in the node log every *k* seconds, where *k* is any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If *k*=0, then the node log is disabled. If *k* is positive, then the root node processing information is printed and, if possible, an entry is made every *k* seconds. An entry is also made each time a better integer solution is found.

By default, LOGFREQ=5.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that the MILP solver displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and a node log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and a node log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXNODES=*number*

specifies the maximum number of branch-and-bound nodes to be processed, where *number* can be any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you run the MILP solver in concurrent mode, CONCURRENT=TRUE, then the solver stops as soon as *number* is reached on any machine. If you run the MILP solver in distributed mode, DISTRIBUTED=TRUE, then the solver periodically checks and stops as soon as the total number of nodes that are processed by all grid nodes exceeds *number*. The default value is $2^{31} - 1$.

MAXPOOLGAP=*number*

specifies the gap criterion for the solutions to be returned when you specify a non-default SOLTYPE= option. Each of the returned solutions will have an objective value whose gap from the best integer objective value is less than or equal to *number*. The value of *number* can be any nonnegative number greater than or equal to the value of the RELOBJGAP= option. The default value is the value of the RELOBJGAP= option.

MAXPOOLSOLS=*number*

specifies the number of solutions to return from the MILP solution pool, where *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. Only feasible and unique solutions are returned, and they are returned in order of objective value, with the best solution first. The number of solutions that are found is reported in both the solution summary and the _OROPTMODEL_ macro variable. By default, MAXPOOLSOLS=10 if SOLTYPE=BEST or SOLTYPE=WITHINGAP; otherwise, MAXPOOLSOLS=1 by default.

MAXSOLS=*number*

specifies a stopping criterion, where *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If *number* of solutions have been found, then the solver stops. The default value of *number* is $2^{31} - 1$.

MAXTIME=*t*

specifies an upper limit of *t* units of time for performing the optimization process, including problem generation time and the solution time. The value of the TIMETYPE= option determines the type of units used. If you do not specify MAXTIME= option, the solver does not stop because of the amount of time elapsed. If concurrent or distributed mode of the solver is enabled, CONCURRENT=TRUE or DISTRIBUTED=TRUE, then the solver stops as soon as *t* is reached on any machine. The value of *t* can be any positive number; the default value is the largest number that can be represented by a double.

OPTTOL=*number*
specifies the tolerance that is used to determine the optimality of nodes in the branch-and-bound tree. The value of *number* can be any value between (and including) 1E–4 and 1E–9. The default value is 1E–6.

PROBE=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the probing strategy. You can specify the following values:

AUTOMATIC uses the probing strategy that is determined by the MILP solver.

NONE disables probing.

MODERATE uses probing moderately.

AGGRESSIVE uses probing aggressively.

By default, PROBE=AUTOMATIC. For more information, see the section "Presolve and Probing" on page 725.

RELOBJGAP=*number*
specifies a stopping criterion based on the best integer objective (BestInteger) and the best bound on the objective function value (BestBound). The relative objective gap is equal to

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

When this value becomes smaller than the specified gap size *number*, the solver stops. The value of *number* can be any nonnegative number; the default value is 1E–4.

SCALE=AUTOMATIC | NONE
indicates whether to scale the problem matrix. You can specify the following values:

AUTOMATIC scales the matrix as determined by the MILP solver.

NONE disables scaling.

By default, SCALE=AUTOMATIC.

SEED=*number*
specifies the initial seed of the random number generator. This option affects the perturbation in the simplex solvers; thus it might result in a different optimal solution and a different solver path. This option usually has a significant, but unpredictable, effect on the solution time. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. The default value of the seed is 100.

SOLTYPE=POOL | BEST | WITHINGAP
specifies the type of multiple solution algorithm that the MILP solver runs. You can specify this option when you need to obtain multiple optimal solutions or multiple feasible solutions within the value that is specified for the MAXPOOLGAP= option. You can specify the following values:

POOL runs the default branch-and-bound algorithm.

BEST runs the modified branch-and-bound algorithm in order to return the best (by objective value) number of solutions (as specified in the MAXPOOLSOLS= option) that have a gap value less than or equal to the value of the MAXPOOLGAP= option. If the problem has fewer solutions than the number that is specified in the MAXPOOLSOLS= option, then the solver returns all the solutions that are found within the value that is specified in the MAXPOOLGAP= option. Note that there can exist no solution better than those returned by the solver.

WITHINGAP runs the modified branch-and-bound algorithm in order to return the number of solutions (as specified in the MAXPOOLSOLS= option) that have a gap value less than or equal to the value of the MAXPOOLGAP= option. If the problem has fewer solutions than the number that is specified in the MAXPOOLSOLS= option, then the solver returns all the solutions that are found within the value that is specified in the MAXPOOLGAP= option. Note that there can exist feasible solutions that are better than the solutions returned by the solver.

By default, SOLTYPE=POOL.

NOTE: If you specify SOLTYPE=BEST or SOLTYPE=WITHINGAP, the solver turns off certain techniques (such as symmetry detection) that can reduce the search space (by pruning off feasible or alternate optimal solutions). Hence, the solver can take considerably longer to solve the problem compared to when SOLTYPE=POOL.

TARGET=*number*

specifies a stopping criterion for a minimization or maximization problem. If the best integer objective is better than or equal to *number*, the solver stops. The value of *number* can be any number; the default value is the largest (in magnitude) negative number (for a minimization problem) or the largest (in magnitude) positive number (for a maximization problem) that can be represented by a double.

TIMETYPE=CPU | REAL

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMODEL_ macro variable. You can specify the following values:

CPU specifies that units are in CPU time.

REAL specifies that units are in real time.

The “Optimization Statistics” table, an output of PROC OPTMODEL if you specify PRINTLEVEL=2 in the PROC OPTMODEL statement, also includes the same time units for Presolver Time and Solver Time. The other times (such as Problem Generation Time) in the “Optimization Statistics” table are also in the same units.

By default, TIMETYPE=REAL.

Heuristics Option

HEURISTICS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

controls the level of primal heuristics applied by the MILP solver. This level determines how frequently primal heuristics are applied during the branch-and-bound tree search. It also affects the maximum number of iterations allowed in iterative heuristics. Some computationally expensive heuristics might be disabled by the solver at less aggressive levels. You can specify the following values:

AUTOMATIC applies the default level of heuristics, similar to MODERATE.

NONE disables all primal heuristics. This value does not disable the heuristics that repair an infeasible input solution that is specified by using the PRIMALIN option.

BASIC applies basic primal heuristics at low frequency.

MODERATE applies most primal heuristics at moderate frequency.

AGGRESSIVE applies all primal heuristics at high frequency.

By default, HEURISTICS=AUTOMATIC. For more information about primal heuristics, see the section "Primal Heuristics" on page 727.

Search Options

CONFLICTSEARCH=AUTOMATIC | NONE | MODERATE | AGGRESSIVE

specifies the level of conflict search performed by the MILP solver. Conflict search is used to find clauses resulting from infeasible subproblems that arise in the search tree. You can specify the following values:

AUTOMATIC performs conflict search based on a strategy that is determined by the MILP solver.

NONE disables conflict search.

MODERATE performs a moderate conflict search.

AGGRESSIVE performs an aggressive conflict search.

By default, CONFLICTSEARCH=AUTOMATIC.

NODESEL=AUTOMATIC | BESTBOUND | BESTESTIMATE | DEPTH

specifies the node selection strategy. You can specify the following values:

AUTOMATIC uses automatic node selection.

BESTBOUND chooses the node with the best relaxed objective (best-bound-first strategy).

BESTESTIMATE chooses the node with the best estimate of the integer objective value (best-estimate-first strategy).

DEPTH chooses the most recently created node (depth-first strategy).

By default, NODESEL=AUTOMATIC. For more information about node selection, see the section "Node Selection" on page 724.

PRIORITY=TRUE | FALSE

indicates whether to use specified branching priorities for integer variables. You can specify the following values:

TRUE uses priorities when they exist.

FALSE ignores variable priorities.

By default, PRIORITY=TRUE. For more information, see the section "Branching Priorities" on page 725.

RESTARTS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the strategy for restarting the processing of the root node. You can specify the following values:

AUTOMATIC uses a restarting strategy determined by the MILP solver.

NONE disables restarting.

BASIC uses a basic restarting strategy.

MODERATE uses a moderate restarting strategy.

AGGRESSIVE uses an aggressive restarting strategy.

By default, RESTARTS=AUTOMATIC.

STRONGITER=*number* **| AUTOMATIC**

specifies the number of simplex iterations performed for each variable in the candidate list when using the strong branching variable selection strategy. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you specify the keyword AUTOMATIC, the MILP solver uses the default value; this value is calculated automatically.

STRONGLEN=*number* **| AUTOMATIC**

specifies the number of candidates used when performing the strong branching variable selection strategy. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. If you specify the keyword AUTOMATIC, the MILP solver uses the default value; this value is calculated automatically.

SYMMETRY=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies the level of symmetry detection. Symmetry detection identifies groups of equivalent decision variables and uses this information to solve the problem more efficiently. You can specify the following values:

AUTOMATIC performs symmetry detection based on a strategy that is determined by the MILP solver.

NONE disables symmetry detection.

BASIC performs a basic symmetry detection.

MODERATE performs a moderate symmetry detection.

AGGRESSIVE performs an aggressive symmetry detection.

By default, SYMMETRY=AUTOMATIC. For more information about symmetry detection, see (Ostrowski 2008).

VARSEL=AUTOMATIC | MAXINFEAS | MININFEAS | PSEUDO | STRONG
specifies the rule for selecting the branching variable. You can specify the following values:

AUTOMATIC uses automatic branching variable selection.

MAXINFEAS chooses the variable with maximum infeasibility.

MININFEAS chooses the variable with minimum infeasibility.

PSEUDO chooses a branching variable based on pseudocost.

STRONG uses a strong branching variable selection strategy.

By default, VARSEL=AUTOMATIC. For details about variable selection, see the section "Variable Selection" on page 724.

Cut Options

Table 14.2 describes the *string* values for the cut options in the OPTMODEL procedure.

Table 14.2 Values for Individual Cut Options

string	**Description**
AUTOMATIC	Generates cutting planes on the basis of a strategy that the MILP solver determines.
NONE	Disables generation of cutting planes
MODERATE	Uses a moderate cut strategy
AGGRESSIVE	Uses an aggressive cut strategy

You can specify the CUTSTRATEGY= option to set the overall aggressiveness of the cut generation in the MILP solver. Alternatively, you can use the ALLCUTS= option to set all cut types to the same level. You can override the ALLCUTS= value by using the options that correspond to particular cut types. For example, if you want the MILP solver to generate only Gomory cuts, specify ALLCUTS=NONE and CUTGOMORY=AUTOMATIC. If you want to generate all cuts aggressively but generate no lift-and-project cuts, set ALLCUTS=AGGRESSIVE and CUTLAP=NONE.

ALLCUTS=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
provides a shorthand way of setting all the cuts-related options in one setting. In other words, ALLCUTS=*string* is equivalent to setting each of the individual cuts parameters to the same value *string*. Thus, ALLCUTS=AUTOMATIC has the effect of setting CUTCLIQUE=AUTOMATIC, CUTFLOWCOVER=AUTOMATIC, . . . , and CUTZEROHALF=AUTOMATIC. Table 14.2 lists the values that can be assigned to *string*. In addition, you can override levels for individual cuts with the CUTCLIQUE=, CUTFLOWCOVER=, CUTFLOWPATH=, CUTGOMORY=, CUTGUB=, CUTIMPLIED=, CUTKNAPSACK=, CUTLAP=, CUTMILIFTED=, CUTMIR=, CUTMULTICOMMODITY=, CUTPATHMIXING=, CUTRLT=, and CUTZEROHALF= options. If the ALLCUTS= option is not specified, all the cuts-related options are either set to their individually specified values (if the corresponding option is specified) or to their default values (if that option is not specified).

CUTCLIQUE=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of clique cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTCLIQUE=AUTOMATIC.

CUTFLOWCOVER=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of flow cover cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTFLOWCOVER=AUTOMATIC.

CUTFLOWPATH=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of flow path cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTFLOWPATH=AUTOMATIC.

CUTGOMORY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of Gomory cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTGOMORY=AUTOMATIC.

CUTGUB=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of generalized upper bound (GUB) cover cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTGUB=AUTOMATIC.

CUTIMPLIED=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of implied bound cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTIMPLIED=AUTOMATIC.

CUTKNAPSACK=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of knapsack cover cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTKNAPSACK=AUTOMATIC.

CUTLAP=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of lift-and-project (LAP) cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTLAP=NONE.

CUTMILIFTED=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of mixed lifted 0-1 cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMILIFTED=AUTOMATIC.

CUTMIR=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of mixed integer rounding (MIR) cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMIR=AUTOMATIC.

CUTMULTICOMMODITY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of multicommodity network flow cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTMULTICOMMODITY=AUTOMATIC.

CUTPATHMIXING=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of path mixing cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTPATHMIXING=AUTOMATIC.

CUTRLT=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of RLT cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTRLT=AUTOMATIC.

CUTSFACTOR=*number*
specifies a row multiplier factor for cuts. The number of cuts that are added is limited to *number* times the original number of rows. The value of *number* can be any nonnegative number less than or equal to 100; the default value is automatically calculated by the MILP solver.

CUTSTRATEGY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
CUTS=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the overall aggressiveness of the cut generation in the solver. By default, CUTSTRATEGY=AUTOMATIC. Setting a nondefault value adjusts a number of cut parameters such that the cut generation is none, moderate, or aggressive compared to the default value.

CUTZEROHALF=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of zero-half cuts generated by the MILP solver. Table 14.2 describes the possible values. This option overrides the ALLCUTS= option. By default, CUTZEROHALF=AUTOMATIC.

Decomposition Algorithm Options

The following options are available for the decomposition algorithm in the MILP solver. For information about the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm."

DECOMP=(*options***)**
enables the decomposition algorithm and specifies overall control options for the algorithm. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

DECOMPMASTER=(*options***)**
specifies options for the master problem. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

DECOMPMASTERIP=(*options***)**
specifies options for the (restricted) master problem solved as a MILP with the current set of columns in an effort to obtain an integer feasible solution. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

DECOMPSUBPROB=(*options***)**
specifies option for the subproblem. For more information about this option, see Chapter 18, "The Decomposition Algorithm."

Parallel Options

CONCURRENT=TRUE | FALSE

specifies whether to run the MILP solver in concurrent mode. You can specify the following values:

TRUE runs the MILP solver in concurrent mode. The solver automatically runs the same problem on each grid node with different MILP solver options.

FALSE turns off concurrent mode for the MILP solver.

By default, CONCURRENT=FALSE.

DETERMINISTIC=TRUE | FALSE

specifies whether to enable the MILP solver to run deterministically when distributed or concurrent mode is enabled. The DETERMINISTIC= option is valid only when DISTRIBUTED=TRUE or CONCURRENT=TRUE. You can specify the following values:

TRUE runs the MILP solver in deterministic distributed or concurrent mode. The solver always returns the same solution for subsequent runs on the same grid.

FALSE runs the MILP solver in nondeterministic distributed or concurrent mode.

By default, DETERMINISTIC=FALSE when you specify CONCURRENT=TRUE, and DETERMINISTIC=TRUE when you specify DISTRIBUTED=TRUE.

DISTRIBUTED=TRUE | FALSE

specifies whether to run the MILP solver in distributed mode. For more information about this option as it relates to the standard MILP algorithm, see the section "Parallel Processing" on page 728. For more information about this option as it relates to the decomposition algorithm, see Chapter 18, "The Decomposition Algorithm." You can specify the following values:

TRUE runs the MILP solver in distributed mode.

FALSE turns off distributed mode of the MILP solver.

By default, DISTRIBUTED=FALSE.

NTHREADS=*number*

specifies the maximum number of threads for the MILP solver to use for multithreaded processing. The branch-and-cut algorithm can take advantage of multicore machines and can potentially run faster when *number* is greater than 1. The value of *number* can be any integer between 1 and 256, inclusive. The default is the value of the NTHREADS= option in PROC OPTMODEL.

Root Node Solver Options

The following options are available for choosing the root node linear programming solver in the MILP solver.

ROOTNODE=(*options*)

specifies the root node LP solver and its general control options. The available options are listed in Table 14.3 and are equivalent to the options that are used in the LP solver of the OPTMODEL procedure. For more information about these options, see Chapter 13, "The Linear Programming Solver."

Table 14.3 Options for the ROOTNODE Solver Statement

Description	Option
Solver Options	
Specifies the type of algorithm	ALGORITHM=
Presolve Option	
Controls the dualization of the problem	DUALIZE=
Controls the folding of the problem	FOLD=
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the frequency of printing solution progress	LOGFREQ=
Specifies the detail of solution progress printed in log	LOGLEVEL=
Simplex Algorithm Options	
Specifies the type of initial basis	BASIS=
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Parallel Options	
Specifies the number of threads for the parallel MILP solver to use	NTHREADS=

Details: MILP Solver

Branch-and-Bound Algorithm

The branch-and-bound algorithm, first proposed by Land and Doig (1960), is an effective approach to solving mixed integer linear programs. The following discussion outlines the approach and explains how the MILP solver enhances the basic algorithm by using several advanced techniques.

The branch-and-bound algorithm solves a mixed integer linear program by dividing the search space and generating a sequence of subproblems. The search space of a mixed integer linear program can be represented by a tree. Each node in the tree is identified with a subproblem derived from previous subproblems on the path that leads to the root of the tree. The subproblem (MILP^0) associated with the root is identical to the original problem, which is called (MILP), given in the section "Overview: MILP Solver" on page 706.

The linear programming relaxation (LP^0) of (MILP^0) can be written as

$$\begin{aligned} \min \quad & \mathbf{c}^T\mathbf{x} \\ \text{subject to} \quad & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{aligned}$$

The branch-and-bound algorithm generates subproblems along the nodes of the tree by using the following scheme. Consider $\bar{x}^0$, the optimal solution to (LP^0), which is usually obtained by using the dual simplex algorithm. If $\bar{x}_i^0$ is an integer for all $i \in \mathcal{S}$, then $\bar{x}^0$ is an optimal solution to (MILP). Suppose that for some $i \in \mathcal{S}$, $\bar{x}_i^0$ is nonintegral. In that case the algorithm defines two new subproblems (MILP^1) and (MILP^2), descendants of the parent subproblem (MILP^0). The subproblem (MILP^1) is identical to (MILP^0) except for the additional constraint

$$x_i \leq \lfloor \bar{x}_i^0 \rfloor$$

and the subproblem (MILP^2) is identical to (MILP^0) except for the additional constraint

$$x_i \geq \lceil \bar{x}_i^0 \rceil$$

The notation $\lfloor y \rfloor$ represents the largest integer that is less than or equal to y, and the notation $\lceil y \rceil$ represents the smallest integer that is greater than or equal to y. The two preceding constraints can be handled by modifying the bounds of the variable x_i rather than by explicitly adding the constraints to the constraint matrix. The two new subproblems do not have $\bar{x}^0$ as a feasible solution, but the integer solution to (MILP) must satisfy one of the preceding constraints. The two subproblems thus defined are called *active nodes* in the branch-and-bound tree, and the variable x_i is called the *branching variable*.

In the next step the branch-and-bound algorithm chooses one of the active nodes and attempts to solve the linear programming relaxation of that subproblem. The relaxation might be infeasible, in which case the subproblem is dropped (fathomed). If the subproblem can be solved and the solution is *integer feasible* (that is, x_i is an integer for all $i \in \mathcal{S}$), then its objective value provides an *upper bound* for the objective value in the minimization problem (MILP); if the solution is not integer feasible, then it defines two new subproblems. Branching continues in this manner until there are no active nodes. At this point the best integer solution found is an optimal solution for (MILP). If no integer solution has been found, then (MILP) is integer infeasible. You can specify other criteria to stop the branch-and-bound algorithm before it processes all the active nodes; see the section "Controlling the Branch-and-Bound Algorithm" on page 724 for details.

Upper bounds from integer feasible solutions can be used to *fathom* or *cut off* active nodes. Since the objective value of an optimal solution cannot be greater than an upper bound, active nodes with lower bounds higher than an existing upper bound can be safely deleted. In particular, if z is the objective value of the current best integer solution, then any active subproblems whose relaxed objective value is greater than or equal to z can be discarded.

It is important to realize that mixed integer linear programs are nondeterministic polynomial-time hard (NP-hard). Roughly speaking, this means that the effort required to solve a mixed integer linear program grows exponentially with the size of the problem. For example, a problem with 10 binary variables can generate in the worst case $2^{10} = 1{,}024$ nodes in the branch-and-bound tree. A problem with 20 binary variables can generate in the worst case $2^{20} = 1{,}048{,}576$ nodes in the branch-and-bound tree. Although it is unlikely that the branch-and-bound algorithm has to generate every single possible node, the need to explore even a small fraction of the potential number of nodes for a large problem can be resource-intensive.

A number of techniques can speed up the search progress of the branch-and-bound algorithm. Heuristics are used to find feasible solutions, which can improve the upper bounds on solutions of mixed integer linear programs. Cutting planes can reduce the search space and thus improve the lower bounds on solutions of mixed integer linear programs. When using cutting planes, the branch-and-bound algorithm is also called the *branch-and-cut algorithm*. Preprocessing can reduce problem size and improve problem solvability. The MILP solver in PROC OPTMODEL employs various heuristics, cutting planes, preprocessing, and other techniques, which you can control through corresponding options.

Controlling the Branch-and-Bound Algorithm

There are numerous strategies that can be used to control the branch-and-bound search (see Linderoth and Savelsbergh 1998, Achterberg, Koch, and Martin 2005). The MILP solver in PROC OPTMODEL implements the most widely used strategies and provides several options that enable you to direct the choice of the next active node and of the branching variable. In the discussion that follows, let (LP^k) be the linear programming relaxation of subproblem (MILP^k). Also, let

$$f_i(k) = \bar{x}_i^k - \lfloor \bar{x}_i^k \rfloor$$

where $\bar{x}^k$ is the optimal solution to the relaxation problem (LP^k) solved at node k.

Node Selection

The NODESEL= option specifies the strategy used to select the next active node. The valid keywords for this option are AUTOMATIC, BESTBOUND, BESTESTIMATE, and DEPTH. The following list describes the strategy associated with each keyword:

AUTOMATIC
: allows the MILP solver to choose the best node selection strategy based on problem characteristics and search progress. This is the default setting.

BESTBOUND
: chooses the node with the smallest (or largest, in the case of a maximization problem) relaxed objective value. The best-bound strategy tends to reduce the number of nodes to be processed and can improve lower bounds quickly. However, if there is no good upper bound, the number of active nodes can be large. This can result in the solver running out of memory.

BESTESTIMATE
: chooses the node with the smallest (or largest, in the case of a maximization problem) objective value of the estimated integer solution. Besides improving lower bounds, the best-estimate strategy also attempts to process nodes that can yield good feasible solutions.

DEPTH
: chooses the node that is deepest in the search tree. Depth-first search is effective in locating feasible solutions, since such solutions are usually deep in the search tree. Compared to the costs of the best-bound and best-estimate strategies, the cost of solving LP relaxations is less in the depth-first strategy. The number of active nodes is generally small, but it is possible that the depth-first search will remain in a portion of the search tree with no good integer solutions. This occurrence is computationally expensive.

Variable Selection

The VARSEL= option specifies the strategy used to select the next branching variable. The valid keywords for this option are AUTOMATIC, MAXINFEAS, MININFEAS, PSEUDO, and STRONG. The following list describes the action taken in each case when $\bar{x}^k$, a relaxed optimal solution of (MILP^k), is used to define two active subproblems. In the following list, "INTTOL" refers to the value assigned using the INTTOL= option. For details about the INTTOL= option, see the section "Control Options" on page 711.

AUTOMATIC enables the MILP solver to choose the best variable selection strategy based on problem characteristics and search progress. This is the default setting.

MAXINFEAS chooses as the branching variable the variable x_i such that i maximizes

$$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \mathrm{INTTOL} \leq f_i(k) \leq 1 - \mathrm{INTTOL}\}$$

MININFEAS chooses as the branching variable the variable x_i such that i minimizes

$$\{\min\{f_i(k), 1 - f_i(k)\} \mid i \in \mathcal{S} \text{ and } \mathrm{INTTOL} \leq f_i(k) \leq 1 - \mathrm{INTTOL}\}$$

PSEUDO chooses as the branching variable the variable x_i such that i maximizes the weighted up and down pseudocosts. Pseudocost branching attempts to branch on significant variables first, quickly improving lower bounds. Pseudocost branching estimates significance based on historical information; however, this approach might not be accurate for future search.

STRONG chooses as the branching variable the variable x_i such that i maximizes the estimated improvement in the objective value. Strong branching first generates a list of candidates, then branches on each candidate and records the improvement in the objective value. The candidate with the largest improvement is chosen as the branching variable. Strong branching can be effective for combinatorial problems, but it is usually computationally expensive.

Branching Priorities

In some cases, it is possible to speed up the branch-and-bound algorithm by branching on variables in a specific order. You can accomplish this in PROC OPTMODEL by attaching branching priorities to the integer variables in your model by using the .priority suffix. More information about this suffix is available in the section "Integer Variable Suffixes" on page 424 in Chapter 9. For an example in which branching priorities are used, see Example 14.3.

Presolve and Probing

The MILP solver in PROC OPTMODEL includes a variety of presolve techniques to reduce problem size, improve numerical stability, and detect infeasibility or unboundedness (Andersen and Andersen 1995; Gondzio 1997). During presolve, redundant constraints and variables are identified and removed. Presolve can further reduce the problem size by substituting variables. Variable substitution is a very effective technique, but it might occasionally increase the number of nonzero entries in the constraint matrix. Presolve might also modify the constraint coefficients to tighten the formulation of the problem.

In most cases, using presolve is very helpful in reducing solution times. You can enable presolve at different levels by specifying the PRESOLVER= option.

Probing is a technique that tentatively sets each binary variable to 0 or 1, then explores the logical consequences (Savelsbergh 1994). Probing can expedite the solution of a difficult problem by fixing variables and improving the model. However, probing is often computationally expensive and can significantly increase the solution time in some cases. You can enable probing at different levels by specifying the PROBE= option.

Cutting Planes

The feasible region of every linear program forms a *polyhedron*. Every polyhedron in n-space can be written as a finite number of half-spaces (equivalently, inequalities). In the notation used in this chapter, this polyhedron is defined by the set $\mathcal{Q} = \{x \in \mathbb{R}^n \mid Ax \leq b, l \leq x \leq u\}$. After you add the restriction that some variables must be integral, the set of feasible solutions, $\mathcal{F} = \{x \in \mathcal{Q} \mid x_i \in \mathbb{Z}\ \forall i \in \mathcal{S}\}$, no longer forms a polyhedron.

The *convex hull* of a set X is the minimal convex set that contains X. In solving a mixed integer linear program, in order to take advantage of LP-based algorithms you want to find the convex hull, $\text{conv}(\mathcal{F})$, of $\mathcal{F}$. If you can find $\text{conv}(\mathcal{F})$ and describe it compactly, then you can solve a mixed integer linear program with a linear programming solver. This is generally very difficult, so you must be satisfied with finding an approximation. Typically, the better the approximation, the more efficiently the LP-based branch-and-bound algorithm can perform.

As described in the section "Branch-and-Bound Algorithm" on page 722, the branch-and-bound algorithm begins by solving the linear programming relaxation over the polyhedron $\mathcal{Q}$. Clearly, $\mathcal{Q}$ contains the convex hull of the feasible region of the original integer program; that is, $\text{conv}(\mathcal{F}) \subseteq \mathcal{Q}$.

Cutting plane techniques are used to tighten the linear relaxation to better approximate $\text{conv}(\mathcal{F})$. Assume you are given a solution $\bar{x}$ to some intermediate linear relaxation during the branch-and-bound algorithm. A cut, or valid inequality ($\pi x \leq \pi^0$), is some half-space with the following characteristics:

- The half-space contains $\text{conv}(\mathcal{F})$; that is, every integer feasible solution is feasible for the cut ($\pi x \leq \pi^0, \forall x \in \mathcal{F}$).
- The half-space does not contain the current solution $\bar{x}$; that is, $\bar{x}$ is not feasible for the cut ($\pi \bar{x} > \pi^0$).

Cutting planes were first made popular by Dantzig, Fulkerson, and Johnson (1954) in their work on the traveling salesman problem. The two major classifications of cutting planes are *generic cuts* and *structured cuts*. Generic cuts are based solely on algebraic arguments and can be applied to any relaxation of any integer program. Structured cuts are specific to certain structures that can be found in some relaxations of the mixed integer linear program. These structures are automatically discovered during the cut initialization phase of the MILP solver. Table 14.4 lists the various types of cutting planes that are built into the MILP solver. Included in each type are algorithms for numerous variations based on different relaxations and lifting techniques. For a survey of cutting plane techniques for mixed integer programming, see Marchand et al. (1999). For a survey of lifting techniques, see Atamturk (2004).

Table 14.4 Cutting Planes in MILP Solver

Generic Cutting Planes	Structured Cutting Planes
Gomory mixed integer	Cliques
Lift-and-project	Flow cover
Mixed integer rounding	Flow path
Mixed lifted 0-1	Generalized upper bound cover
Zero-half	Implied bound
	Knapsack cover

Table 14.4 *continued*

Generic Cutting Planes	Structured Cutting Planes
	Multicommodity network flow
	Path mixing
	RLT

You can set levels for individual cuts by using the CUTCLIQUE=, CUTFLOWCOVER=, CUTFLOWPATH=, CUTGOMORY=, CUTGUB=, CUTIMPLIED=, CUTKNAPSACK=, CUTLAP=, CUTMILIFTED=, CUTMIR=, CUTMULTICOMMODITY=, CUTPATHMIXING=, CUTRLT=, and CUTZEROHALF= options. The valid levels for these options are given in Table 14.2.

The cut level determines the internal strategy used by the MILP solver for generating the cutting planes. The strategy consists of several factors, including how frequently the cut search is called, the number of cuts allowed, and the aggressiveness of the search algorithms.

Sophisticated cutting planes, such as those included in the MILP solver, can take a great deal of CPU time. Usually, the additional tightening of the relaxation helps speed up the overall process because it provides better bounds for the branch-and-bound tree and helps guide the LP solver toward integer solutions. In rare cases, shutting off cutting planes completely might lead to faster overall run times.

The default settings of the MILP solver have been tuned to work well for most instances. However, problem-specific expertise might suggest adjusting one or more of the strategies. These options give you that flexibility.

Primal Heuristics

Primal heuristics, an important component of the MILP solver in PROC OPTMODEL, are applied during the branch-and-bound algorithm. They are used to find integer feasible solutions early in the search tree, thereby improving the upper bound for a minimization problem. Primal heuristics play a role that is complementary to cutting planes in reducing the gap between the upper and lower bounds, thus reducing the size of the branch-and-bound tree.

Applying primal heuristics in the branch-and-bound algorithm assists in the following areas:

- finding a good upper bound early in the tree search (this can lead to earlier fathoming, resulting in fewer subproblems to be processed)
- locating a reasonably good feasible solution when that is sufficient (sometimes a good feasible solution is the best the solver can produce within certain time or resource limits)
- providing upper bounds for some bound-tightening techniques

The MILP solver implements several heuristic methodologies. Some algorithms, such as rounding and iterative rounding (diving) heuristics, attempt to construct an integer feasible solution by using fractional

solutions to the continuous relaxation at each node of the branch-and-cut tree. Other algorithms start with an incumbent solution and attempt to find a better solution within a neighborhood of the current best solution.

The HEURISTICS= option enables you to control the level of primal heuristics that are applied by the MILP solver. This level determines how frequently primal heuristics are applied during the tree search. Some expensive heuristics might be disabled by the solver at less aggressive levels. Setting the HEURISTICS= option to a lower level also reduces the maximum number of iterations that are allowed in iterative heuristics.

Parallel Processing

You can run the branch-and-cut algorithm in the following modes:

- In single-machine mode, the computation is executed on a single computer by multiple threads. The number of threads is specified by the NTHREADS= option.
- In distributed mode, the branch-and-cut algorithm is executed on a cluster of nodes. You disable deterministic distributed mode by setting the DETERMINISTIC= option to FALSE. By default the MILP solver is executed deterministically.
- In concurrent mode, the computation is executed on a cluster of nodes by solving the same problem across those nodes under different MILP solver settings. By default the MILP solver is executed nondeterministically.

You can run the decomposition algorithm in either single-machine or distributed mode. In distributed mode, the computation is executed on multiple computing nodes in a distributed computing environment.

Node Log

The following information about the status of the branch-and-bound algorithm is printed in the node log:

Node	indicates the sequence number of the current node in the search tree.
Active	indicates the current number of active nodes in the branch-and-bound tree.
Sols	indicates the number of feasible solutions that are found so far. You can use the MAXPOOLSOLS= option to obtain more than one solution. Note that the number printed in the node log can be different from the number of found solutions that is reported in the solution summary and in the _OROPTMODEL_ macro variable.
BestInteger	indicates the best upper bound (assuming minimization) that is found so far.
BestBound	indicates the best lower bound (assuming minimization) that is found so far.
Gap	indicates the relative gap between BestInteger and BestBound, displayed as a percentage. If the relative gap is larger than 1,000, then the absolute gap is displayed. If no active nodes remain, the value of Gap is 0.
Time	indicates the elapsed real or CPU time.

If CONCURRENT=TRUE, then the following information about the status of the branch-and-bound algorithm is printed in the node log:

Node	indicates the total number of nodes that are processed by all concurrent solves.
Active	indicates the total number of active nodes among all concurrent solves.
Sols	indicates the number of feasible solutions that are found by all concurrent solves.
BestInteger	indicates the best upper bound (assuming minimization) that is found by all concurrent solves.
BestBound	indicates the best lower bound (assuming minimization) that is found by all concurrent solves.
Gap	indicates the relative gap between BestInteger and BestBound, displayed as a percentage. If the relative gap is larger than 1,000, then the absolute gap is displayed. If no active nodes remain, the value of Gap is 0.
Time	indicates the elapsed real or CPU time.

If CONCURRENT=TRUE or DISTRIBUTED=TRUE, the node log displays the progress of the overall grid. If DETERMINISTIC=TRUE, the MILP solver returns a reproducible solution. Therefore, there might be discrepancies between the node log and the final solution that is reported by the deterministic concurrent or deterministic distributed MILP solver.

The LOGFREQ= and LOGLEVEL= options can be used to control the amount of information that is printed in the node log. By default, the root node processing information is printed and, if possible, an entry is made every five seconds. A new entry is also included each time a better integer solution is found. The LOGFREQ= option enables you to change the interval between entries in the node log. Figure 14.3 shows a sample node log.

Figure 14.3 Sample Node Log

```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 510 variables (0 free, 0 fixed).
NOTE: The problem uses 1 implicit variables.
NOTE: The problem has 510 binary and 0 integer variables.
NOTE: The problem has 560 linear constraints (510 LE, 50 EQ, 0 GE, 0 range).
NOTE: The problem has 2010 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 510 variables, 560 constraints, and 2010
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      5  24086.8916716              0    24087       0
             0        1      5  24086.8916716  19197.7909681   25.47%       0
             0        1      5  24086.8916716  19206.4233772   25.41%       0
             0        1      5  24086.8916716  19210.6350488   25.38%       0
             0        1      5  24086.8916716  19215.5729975   25.35%       0
             0        1      5  24086.8916716  19222.4722921   25.31%       0
             0        1      7  21763.2006534  19222.4722921   13.22%       0
             0        1      7  21763.2006534  19226.6966446   13.19%       0
             0        1      7  21763.2006534  19229.2373163   13.18%       0
             0        1      7  21763.2006534  19230.1316195   13.17%       0
             0        1      7  21763.2006534  19232.6824642   13.16%       0
NOTE: The MILP solver added 23 cuts with 928 cut coefficients at the root.
            12        9      8  21732.8546805  19249.1200242   12.90%       0
            29       23      9  21727.9429145  19251.5508014   12.86%       0
            74       30     12  21671.2531435  19308.8992583   12.23%       0
           123       28     14  21625.4316216  19811.6833584    9.15%       0
           208       30     16  21576.4642867  20401.2386112    5.76%       0
           212       31     17  21551.1485231  20401.2386112    5.64%       0
           246       44     18  21550.7090288  21536.4949513    0.07%       0
           312       31     19  21549.6785006  21537.1297300    0.06%       0
           326       29     20  21549.6785006  21538.7289442    0.05%       0
           433       24     21  21548.2906446  21543.2919592    0.02%       1
           516       10     22  21548.1764622  21543.2919592    0.02%       3
           537        8     23  21548.1764619  21545.1380498    0.01%       4
           548        1     23  21548.1764619  21547.3600586    0.00%       4
NOTE: Optimal within relative gap.
NOTE: Objective = 21548.176462.
```

IIS Log

If IIS=TRUE, then the following information about the status of the IIS algorithm is printed in the IIS log:

Processed	indicates the number of integer restrictions or constraints or variables that were processed for determining the IIS.
Added	indicates the number of integer restrictions or constraints or bound changes that were added to the IIS.
Time	indicates the elapsed real or CPU time.

The LOGFREQ= option enables you to change the interval between entries in the IIS log.

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTMODEL procedure causes the ODS table ProblemStatistics to be generated when the MILP solver is called. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 14.4 demonstrates the contents of the ODS table ProblemStatistics.

Figure 14.4 ODS Table ProblemStatistics

ProblemStatistics

Obs	Label1	cValue1	nValue1
1	Number of Constraint Matrix Nonzeros	8	8.000000
2	Maximum Constraint Matrix Coefficient	3	3.000000
3	Minimum Constraint Matrix Coefficient	1	1.000000
4	Average Constraint Matrix Coefficient	1.875	1.875000
5			.
6	Number of Objective Nonzeros	3	3.000000
7	Maximum Objective Coefficient	4	4.000000
8	Minimum Objective Coefficient	2	2.000000
9	Average Objective Coefficient	3	3.000000
10			.
11	Number of RHS Nonzeros	3	3.000000
12	Maximum RHS	7	7.000000
13	Minimum RHS	4	4.000000
14	Average RHS	5.3333333333	5.333333
15			.
16	Maximum Number of Nonzeros per Column	3	3.000000
17	Minimum Number of Nonzeros per Column	2	2.000000
18	Average Number of Nonzeros per Column	2.67	2.666667
19			.
20	Maximum Number of Nonzeros per Row	3	3.000000
21	Minimum Number of Nonzeros per Row	2	2.000000
22	Average Number of Nonzeros per Row	2.67	2.666667

The variable names in the ODS table ProblemStatistics are Label1, cValue1, and nValue1.

Variable and Constraint Status

If IIS=TRUE, then upon termination the MILP solver returns a .status suffix for each decision variable and constraint. The .status suffix provides the status of that variable or constraint in the IIS. For more information, see the section "Irreducible Infeasible Set" on page 733. For more information about suffixes in the OPTMODEL procedure, see the section "Suffixes" on page 420.

- The following values can appear for variable status:

  I_L The lower bound of the variable is needed for the IIS.

  I_U The upper bound of the variable is needed for the IIS.

  I_F The lower and upper bounds of the variable are needed for the IIS.

  I_LI The lower bound and integrality restriction of the variable are needed for the IIS.

  I_UI The upper bound and integrality restriction of the variable are needed for the IIS.

  I_FI The lower bound, upper bound, and integrality restriction of the variable are needed for the IIS.

I_I The integrality restriction of the variable is needed for the IIS.

- The following values can appear for constraint status:

I_L The "GE" (≥) condition of the constraint is part of the IIS.

I_U The "LE" (≤) condition of the constraint is part of the IIS.

I_F Both conditions of the constraint are part of the IIS (the constraint is an equality or a range constraint).

Irreducible Infeasible Set

For a mixed integer linear programming problem (MILP), an irreducible infeasible set (IIS) is an infeasible subset of constraints, variable bounds, and integer restrictions that becomes feasible if any single constraint, variable bound, or integer restriction is removed. It is possible to have more than one IIS in an infeasible MILP. Identifying an IIS can help isolate the structural infeasibility in a MILP.

The presolver in the MILP solver can detect infeasibility, but it identifies only the variable bound or constraint that triggers the infeasibility.

The IIS=TRUE option directs the MILP solver to search for an IIS in a specified MILP. If the MILP solver detects an IIS, it updates the .status suffix of the decision variables and constraints, and then it stops. For information about the .status suffix, see the section "Variable and Constraint Status" on page 732. From the information in the .status suffixes, you can identify both the names of the constraints (variables) in the IIS and the corresponding bound (or integrality restrictions) where infeasibility occurs. The number of iterations and nodes that are reported in the macro variable and the ODS table is the total number of iterations and nodes from all the subproblem solves during the IIS determination.

Making any one of the constraints, variable bounds, or integrality restrictions in the IIS nonbinding removes the infeasibility from the IIS. However, in the process of determining the IIS, some of the subproblems might not be solved to completion within reasonable preset limits. In such cases, the infeasible subset is not guaranteed to be irreducible, and the MILP solver prints a warning message that the infeasible subset is not irreducible. For these cases, making any one of the constraints, variable bounds, or integrality restrictions nonbinding does not eliminate the infeasibility from the IIS.

Macro Variable _OROPTMODEL_

The OPTMODEL procedure defines a macro variable named _OROPTMODEL_. This variable contains a character string that indicates the status of the MILP solver upon termination. For the MILP solver, the various terms of _OROPTMODEL_ are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data was inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the solver.
IO_ERROR	A problem occurred in reading or writing data.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produced the solution data in the macro variable. This term appears only when STATUS=OK. It can take one of the following values:

BAC	The branch-and-cut algorithm produced the solution data.
DECOMP	The decomposition algorithm produced the solution data.
IIS	The IIS detection algorithm was used to find the IIS.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
OPTIMAL_AGAP	The solution is optimal within the absolute gap specified by the ABSOBJGAP= option.

OPTIMAL_RGAP	The solution is optimal within the relative gap specified by the RELOBJGAP= option.
OPTIMAL_COND	The solution is optimal, but some infeasibilities (primal, bound, or integer) exceed tolerances due to scaling or choice of a small INTTOL= value.
TARGET	The solution is not worse than the target specified by the TARGET= option.
INFEASIBLE	The problem is infeasible.
FEASIBLE	The problem is feasible. This status is displayed when the IIS=TRUE option is specified and the problem is feasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
SOLUTION_LIM	The solver reached the maximum number of solutions specified by the MAXSOLS= option.
NODE_LIM_SOL	The solver reached the maximum number of nodes specified by the MAXNODES= option and found a solution.
NODE_LIM_NOSOL	The solver reached the maximum number of nodes specified by the MAXNODES= option and did not find a solution.
TIME_LIM_SOL	The solver reached the execution time limit specified by the MAXTIME= option and found a solution.
TIME_LIM_NOSOL	The solver reached the execution time limit specified by the MAXTIME= option and did not find a solution.
ABORT_SOL	The solver was stopped by the user but still found a solution.
ABORT_NOSOL	The solver was stopped by the user and did not find a solution.
OUTMEM_SOL	The solver ran out of memory but still found a solution.
OUTMEM_NOSOL	The solver ran out of memory and either did not find a solution or failed to output the solution due to insufficient memory.
FAIL_SOL	The solver stopped due to errors but still found a solution.
FAIL_NOSOL	The solver stopped due to errors and did not find a solution.

OBJECTIVE

indicates the objective value obtained by the solver at termination.

RELATIVE_GAP

indicates the relative gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the MILP solver. The relative gap is equal to

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

ABSOLUTE_GAP
indicates the absolute gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the MILP solver. The absolute gap is equal to |BestInteger − BestBound|.

PRIMAL_INFEASIBILITY
indicates the maximum (absolute) violation of the primal constraints by the solution.

BOUND_INFEASIBILITY
indicates the maximum (absolute) violation by the solution of the lower or upper bounds (or both).

INTEGER_INFEASIBILITY
indicates the maximum (absolute) violation of the integrality of integer variables returned by the MILP solver.

BEST_BOUND
indicates the best bound on the objective function value at termination. A missing value indicates that the MILP solver was not able to obtain such a bound.

NODES
indicates the number of nodes enumerated by the MILP solver when using the branch-and-bound algorithm.

SOLUTIONS_FOUND
indicates the number of solutions that are found by the MILP solver.

ITERATIONS
indicates the number of simplex iterations taken to solve the problem.

PRESOLVE_TIME
indicates the time (in seconds) used in preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

When SOLUTION_STATUS has a value of OPTIMAL, CONDITIONAL_OPTIMAL, ITERATION_LIMIT_REACHED, or TIME_LIMIT_REACHED, all terms of the _OROPTMODEL_ macro variable are present; for other values of SOLUTION_STATUS, some terms do not appear.

Examples: MILP Solver

This section contains examples that illustrate the options and syntax of the MILP solver in PROC OPTMODEL. Example 14.1 illustrates the use of PROC OPTMODEL to solve an employee scheduling problem. Example 14.2 discusses a multicommodity transshipment problem with fixed charges. Example 14.3 demonstrates how to warm start the MILP solver. Example 14.4 shows the solution of an instance of the traveling salesman problem in PROC OPTMODEL. Example 14.5 demonstrates the usage of some of the advanced options available in the MILP solver. Other examples of mixed integer linear programs, along with example SAS code, are given in Chapter 6.

Example 14.1: Scheduling

The following example has been adapted from the example "A Scheduling Problem" in Chapter 4, "The LP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*).

Scheduling is a common application area in which mixed integer linear programming techniques are used. In this example, you have eight one-hour time slots in each of five days. You have to assign four employees to these time slots so that each slot is covered every day. You allow the employees to specify preference data for each slot on each day. In addition, the following constraints must be satisfied:

- Each employee has some time slots for which he or she is unavailable (OneEmpPerSlot).
- Each employee must have either time slot 4 or time slot 5 off for lunch (EmpMustHaveLunch).
- Each employee can work at most two time slots in a row (AtMost2ConSlots).
- Each employee can work only a specified number of hours in the week (WeeklyHoursLimit).

To formulate this problem, let i denote a person, j denote a time slot, and k denote a day. Then, let $x_{ijk} = 1$ if person i is assigned to time slot j on day k, and 0 otherwise. Let p_{ijk} denote the preference of person i for slot j on day k. Let h_i denote the number of hours in a week that person i will work. The formulation of this problem follows:

$$
\begin{array}{llcll}
\max & \sum_{ijk} p_{ijk} x_{ijk} & & & \\
\text{s.t.} & \sum_{i} x_{ijk} & = & 1 & \forall j,k \qquad \text{(OneEmpPerSlot)} \\
 & x_{i4k} + x_{i5k} & \leq & 1 & \forall i,k \qquad \text{(EmpMustHaveLunch)} \\
 & x_{i,\ell,k} + x_{i,\ell+1,k} + x_{i,\ell+2,k} & \leq & 2 & \forall i,k, \text{and } l \leq 6 \qquad \text{(AtMost2ConSlots)} \\
 & \sum_{jk} x_{ijk} & \leq & h_i & \forall i \qquad \text{(WeeklyHoursLimit)} \\
 & x_{ijk} & = & 0 & \forall i,j,k \text{ s.t. } p_{ijk} > 0 \\
 & x_{ijk} \in \{0,1\} & & & \forall i,j,k
\end{array}
$$

The following data set preferences gives the preferences for each individual, time slot, and day. A 10 represents the most desirable time slot, and a 1 represents the least desirable time slot. In addition, a 0 indicates that the time slot is not available. The data set maxhours gives the maximum number of hours each employee can work per week.

```
data preferences;
   input name $ slot mon tue wed thu fri;
   datalines;
marc  1    10 10 10 10 10
marc  2     9  9  9  9  9
marc  3     8  8  8  8  8
marc  4     1  1  1  1  1
marc  5     1  1  1  1  1
marc  6     1  1  1  1  1
marc  7     1  1  1  1  1
marc  8     1  1  1  1  1
mike  1    10  9  8  7  6
mike  2    10  9  8  7  6
mike  3    10  9  8  7  6
mike  4    10  3  3  3  3
mike  5     1  1  1  1  1
mike  6     1  2  3  4  5
mike  7     1  2  3  4  5
mike  8     1  2  3  4  5
bill  1    10 10 10 10 10
bill  2     9  9  9  9  9
bill  3     8  8  8  8  8
bill  4     0  0  0  0  0
bill  5     1  1  1  1  1
bill  6     1  1  1  1  1
bill  7     1  1  1  1  1
bill  8     1  1  1  1  1
bob   1    10  9  8  7  6
bob   2    10  9  8  7  6
bob   3    10  9  8  7  6
bob   4    10  3  3  3  3
bob   5     1  1  1  1  1
bob   6     1  2  3  4  5
bob   7     1  2  3  4  5
bob   8     1  2  3  4  5
;

data maxhours;
   input name $ hour;
   datalines;
marc  20
mike  20
bill  20
bob   20
;
```

Using PROC OPTMODEL, you can model and solve the scheduling problem as follows:

```
proc optmodel;

   /* read in the preferences and max hours from the data sets */
   set <string,num> DailyEmployeeSlots;
```

```
set <string>     Employees;

set <num>    TimeSlots = (setof {<name,slot> in DailyEmployeeSlots} slot);
set <string> WeekDays  = {"mon","tue","wed","thu","fri"};

num WeeklyMaxHours{Employees};
num PreferenceWeights{DailyEmployeeSlots,Weekdays};
num NSlots = card(TimeSlots);

read data preferences into DailyEmployeeSlots=[name slot]
     {day in Weekdays} <PreferenceWeights[name,slot,day] = col(day)>;
read data maxhours into Employees=[name] WeeklyMaxHours=hour;

/* declare the binary assignment variable x[i,j,k] */
var Assign{<name,slot> in DailyEmployeeSlots, day in Weekdays} binary;

/* for each p[i,j,k] = 0, fix x[i,j,k] = 0 */
for {<name,slot> in DailyEmployeeSlots, day in Weekdays:
    PreferenceWeights[name,slot,day] = 0}
      fix Assign[name,slot,day] = 0;

/* declare the objective function */
max TotalPreferenceWeight =
   sum{<name,slot> in DailyEmployeeSlots, day in Weekdays}
      PreferenceWeights[name,slot,day] * Assign[name,slot,day];

/* declare the constraints */
con OneEmpPerSlot{slot in TimeSlots, day in Weekdays}:
   sum{name in Employees} Assign[name,slot,day] = 1;

con EmpMustHaveLunch{name in Employees, day in Weekdays}:
   Assign[name,4,day] + Assign[name,5,day] <= 1;

con AtMost2ConsSlots{name in Employees, start in 1..NSlots-2,
                        day in Weekdays}:
   Assign[name,start,day] + Assign[name,start+1,day]
         + Assign[name,start+2,day] <= 2 ;

con WeeklyHoursLimit{name in Employees}:
   sum{slot in TimeSlots, day in Weekdays} Assign[name,slot,day]
        <= WeeklyMaxHours[name];

/* solve the model */
solve with milp;

/* clean up the solution */
for {<name,slot> in DailyEmployeeSlots, day in Weekdays}
   Assign[name,slot,day] = round(Assign[name,slot,day],1e-6);

str assigned_employee {TimeSlots, Weekdays} init '';
for {slot in TimeSlots, day in Weekdays} do;
   for {name in Employees: Assign[name,slot,day] > 0} do;
      assigned_employee[slot,day] = name;
      leave;
```

```
      end;
   end;

   create data report from [slot]=TimeSlots
      {day in Weekdays} <col(day)=assigned_employee[slot,day]>;
quit;
```

The following statements demonstrate how to use the PRINT procedure to display a schedule that shows how the eight time slots are covered for the week:

```
/* report the solution */
title 'Reported Solution';
proc print data=report;
   id slot;
run;
```

The output from the preceding code is displayed in Output 14.1.1.

Output 14.1.1 Scheduling Reported Solution

Reported Solution

slot	mon	tue	wed	thu	fri
1	marc	marc	marc	marc	marc
2	mike	marc	marc	marc	marc
3	mike	mike	mike	bill	bill
4	bob	mike	mike	mike	mike
5	marc	marc	marc	marc	marc
6	marc	mike	mike	mike	mike
7	mike	mike	mike	mike	mike
8	marc	bob	bob	bob	bob

Example 14.2: Multicommodity Transshipment Problem with Fixed Charges

The following example has been adapted from the example "A Multicommodity Transshipment Problem with Fixed Charges" in Chapter 4, "The LP Procedure" (*SAS/OR User's Guide: Mathematical Programming Legacy Procedures*).

This example illustrates the use of PROC OPTMODEL to generate a mixed integer linear program to solve a multicommodity network flow model with fixed charges. Consider a network with nodes N, arcs A, and a set C of commodities to be shipped between the nodes. The commodities are defined in the data set COMMODITY_DATA, as follows:

```
title 'Multicommodity Transshipment Problem with Fixed Charges';

data commodity_data;
   do c = 1 to 4;
      output;
   end;
run;
```

Shipping cost s_{ijc} is for each of the four commodities c across each of the arcs (i, j). In addition, there is a fixed charge f_{ij} for the use of each arc (i, j). The shipping costs and fixed charges are defined in the data set ARC_DATA, as follows:

```
data arc_data;
   input from $ to $ c1 c2 c3 c4 fx;
   datalines;
farm-a  Chicago 20 15 17 22 100
farm-b  Chicago 15 15 15 30  75
farm-c  Chicago 30 30 10 10 100
farm-a  StLouis 30 25 27 22 150
farm-c  StLouis 10 9 11 10   75
Chicago NY      75 75 75 75 200
StLouis NY      80 80 80 80 200
;
```

The supply (positive numbers) or demand (negative numbers) d_{ic} at each of the nodes for each commodity c is shown in the data set SUPPLY_DATA, as follows:

```
data supply_data;
   input node $ sd1 sd2 sd3 sd4;
   datalines;
farm-a  100  100  40   .
farm-b  100  200  50  50
farm-c   40  100  75 100
NY     -150 -200 -50 -75
;
```

Let x_{ijc} define the flow of commodity c across arc (i, j). Let $y_{ij} = 1$ if arc (i, j) is used, and 0 otherwise. Since the total flow on an arc (i, j) must be at most the total demand across all nodes $k \in N$, you can define the trivial upper bound u_{ijc} as

$$x_{ijc} \leq u_{ijc} = \sum_{k \in N | d_{kc} < 0} (-d_{kc})$$

This model can be represented using the following mixed integer linear program:

$$\begin{array}{llllll}
\min & \displaystyle\sum_{(i,j)\in A} \sum_{c \in C} s_{ijc} x_{ijc} + \sum_{(i,j)\in A} f_{ij} y_{ij} & & & & \\
\text{s.t.} & \displaystyle\sum_{j \in N | (i,j)\in A} x_{ijc} - \sum_{j \in N | (j,i)\in A} x_{jic} & \leq & d_{ic} & \forall i \in N, c \in C & \text{(balance_con)} \\
 & x_{ijc} & \leq & u_{ijc} y_{ij} & \forall (i,j) \in A, c \in C & \text{(fixed_charge_con)} \\
 & x_{ijc} & \geq & 0 & \forall (i,j) \in A, c \in C & \\
 & y_{ij} \in \{0, 1\} & & & \forall (i,j) \in A &
\end{array}$$

Constraint (balance_con) ensures conservation of flow for both supply and demand. Constraint (fixed_charge_con) models the fixed charge cost by forcing $y_{ij} = 1$ if $x_{ijc} > 0$ for some commodity $c \in C$.

The PROC OPTMODEL statements follow:

```
proc optmodel;
   set COMMODITIES;
   read data commodity_data into COMMODITIES=[c];

   set <str,str> ARCS;
   num unit_cost {ARCS, COMMODITIES};
   num fixed_charge {ARCS};
   read data arc_data into ARCS=[from to] {c in COMMODITIES}
      <unit_cost[from,to,c]=col('c'||c)> fixed_charge=fx;
   print unit_cost fixed_charge;

   set <str> NODES = union {<i,j> in ARCS} {i,j};
   num supply {NODES, COMMODITIES} init 0;
   read data supply_data nomiss into [node] {c in COMMODITIES}
      <supply[node,c]=col('sd'||c)>;
   print supply;

   var AmountShipped {ARCS, c in COMMODITIES} >= 0 <= sum {i in NODES}
      max(supply[i,c],0);

   /* UseArc[i,j] = 1 if arc (i,j) is used, 0 otherwise */
   var UseArc {ARCS} binary;

   /* TotalCost = variable costs + fixed charges */
   min TotalCost = sum {<i,j> in ARCS, c in COMMODITIES}
      unit_cost[i,j,c] * AmountShipped[i,j,c]
```

```
      + sum {<i,j> in ARCS} fixed_charge[i,j] * UseArc[i,j];

   con flow_balance {i in NODES, c in COMMODITIES}:
      sum {<(i),j> in ARCS} AmountShipped[i,j,c] -
      sum {<j,(i)> in ARCS} AmountShipped[j,i,c] <= supply[i,c];

   /* if AmountShipped[i,j,c] > 0 then UseArc[i,j] = 1 */
   con fixed_charge_def {<i,j> in ARCS, c in COMMODITIES}:
      AmountShipped[i,j,c] <= AmountShipped[i,j,c].ub * UseArc[i,j];

   solve;

   print AmountShipped;

   create data solution from [from to commodity]={<i,j> in ARCS,
      c in COMMODITIES: AmountShipped[i,j,c].sol ne 0} amount=AmountShipped;
quit;
```

Although the PROC LP example used **M = 1.0e6** in the FIXED_CHARGE_DEF constraint that links the continuous variable to the binary variable, it is numerically preferable to use a smaller, data-dependent value. Here, the upper bound on **AmountShipped[i,j,c]** is used instead. This upper bound is calculated in the first VAR statement as the sum of all positive supplies for commodity c. The logical condition **AmountShipped[i,j,k].sol ne 0** in the CREATE DATA statement ensures that only the nonzero parts of the solution appear in the SOLUTION data set.

The problem summary, solution summary, and the output from the three PRINT statements are shown in Output 14.2.1.

Output 14.2.1 Multicommodity Transshipment Problem with Fixed Charges Solution Summary

Multicommodity Transshipment Problem with Fixed Charges

The OPTMODEL Procedure

[1]	[2]	[3]	unit_cost
Chicago	NY	1	75
Chicago	NY	2	75
Chicago	NY	3	75
Chicago	NY	4	75
StLouis	NY	1	80
StLouis	NY	2	80
StLouis	NY	3	80
StLouis	NY	4	80
farm-a	Chicago	1	20
farm-a	Chicago	2	15
farm-a	Chicago	3	17
farm-a	Chicago	4	22
farm-a	StLouis	1	30
farm-a	StLouis	2	25
farm-a	StLouis	3	27
farm-a	StLouis	4	22
farm-b	Chicago	1	15
farm-b	Chicago	2	15
farm-b	Chicago	3	15
farm-b	Chicago	4	30
farm-c	Chicago	1	30
farm-c	Chicago	2	30
farm-c	Chicago	3	10
farm-c	Chicago	4	10
farm-c	StLouis	1	10
farm-c	StLouis	2	9
farm-c	StLouis	3	11
farm-c	StLouis	4	10

[1]	[2]	fixed_charge
Chicago	NY	200
StLouis	NY	200
farm-a	Chicago	100
farm-a	StLouis	150
farm-b	Chicago	75
farm-c	Chicago	100
farm-c	StLouis	75

Output 14.2.1 *continued*

	supply			
	1	**2**	**3**	**4**
Chicago	0	0	0	0
NY	-150	-200	-50	-75
StLouis	0	0	0	0
farm-a	100	100	40	0
farm-b	100	200	50	50
farm-c	40	100	75	100

Problem Summary	
Objective Sense	Minimization
Objective Function	TotalCost
Objective Type	Linear
Number of Variables	35
Bounded Above	0
Bounded Below	0
Bounded Below and Above	35
Free	0
Fixed	0
Binary	7
Integer	0
Number of Constraints	52
Linear LE (<=)	52
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	112

Output 14.2.1 *continued*

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	TotalCost
Solution Status	Optimal
Objective Value	42825
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	42825
Nodes	1
Solutions Found	4
Iterations	41
Presolve Time	0.00
Solution Time	0.02

Output 14.2.1 *continued*

[1]	[2]	[3]	AmountShipped
Chicago	NY	1	110
Chicago	NY	2	100
Chicago	NY	3	50
Chicago	NY	4	75
StLouis	NY	1	40
StLouis	NY	2	100
StLouis	NY	3	0
StLouis	NY	4	0
farm-a	Chicago	1	10
farm-a	Chicago	2	0
farm-a	Chicago	3	0
farm-a	Chicago	4	0
farm-a	StLouis	1	0
farm-a	StLouis	2	0
farm-a	StLouis	3	0
farm-a	StLouis	4	0
farm-b	Chicago	1	100
farm-b	Chicago	2	100
farm-b	Chicago	3	0
farm-b	Chicago	4	0
farm-c	Chicago	1	0
farm-c	Chicago	2	0
farm-c	Chicago	3	50
farm-c	Chicago	4	75
farm-c	StLouis	1	40
farm-c	StLouis	2	100
farm-c	StLouis	3	0
farm-c	StLouis	4	0

Example 14.3: Facility Location

Consider the classic facility location problem. Given a set L of customer locations and a set F of candidate facility sites, you must decide on which sites to build facilities and assign coverage of customer demand to these sites so as to minimize cost. All customer demand d_i must be satisfied, and each facility has a demand capacity limit C. The total cost is the sum of the distances c_{ij} between facility j and its assigned customer i, plus a fixed charge f_j for building a facility at site j. Let $y_j = 1$ represent choosing site j to build a facility, and 0 otherwise. Also, let $x_{ij} = 1$ represent the assignment of customer i to facility j, and 0 otherwise. This model can be formulated as the following integer linear program:

$$
\begin{array}{llcll}
\min & \displaystyle\sum_{i\in L}\sum_{j\in F} c_{ij}x_{ij} + \sum_{j\in F} f_j y_j & & & \\
\text{s.t.} & \displaystyle\sum_{j\in F} x_{ij} & = & 1 & \forall i \in L \qquad \text{(assign_def)} \\
 & x_{ij} & \leq & y_j & \forall i \in L, j \in F \qquad \text{(link)} \\
 & \displaystyle\sum_{i\in L} d_i x_{ij} & \leq & Cy_j & \forall j \in F \qquad \text{(capacity)} \\
 & x_{ij} \in \{0,1\} & & & \forall i \in L, j \in F \\
 & y_j \in \{0,1\} & & & \forall j \in F
\end{array}
$$

Constraint (assign_def) ensures that each customer is assigned to exactly one site. Constraint (link) forces a facility to be built if any customer has been assigned to that facility. Finally, constraint (capacity) enforces the capacity limit at each site.

Consider also a variation of this same problem where there is no cost for building a facility. This problem is typically easier to solve than the original problem. For this variant, let the objective be

$$\min \sum_{i\in L}\sum_{j\in F} c_{ij}x_{ij}$$

First, construct a random instance of this problem by using the following DATA steps:

```
title 'Facility Location Problem';


%let NumCustomers  = 30;
%let NumSites      = 6;
%let SiteCapacity  = 35;
%let MaxDemand     = 10;
%let xmax          = 200;
%let ymax          = 100;
%let seed          = 546;

/* generate random customer locations */
data cdata(drop=i);
   call streaminit(&seed);
   length name $8;
   do i = 1 to &NumCustomers;
      name = compress('C'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      demand = rand('UNIFORM') * &MaxDemand;
      output;
   end;
run;

/* generate random site locations and fixed charge */
data sdata(drop=i);
   call streaminit(&seed);
   length name $8;
   do i = 1 to &NumSites;
```

```
      name = compress('SITE'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      fixed_charge = 30 * (abs(&xmax/2-x) + abs(&ymax/2-y));
      output;
   end;
run;
```

The following PROC OPTMODEL statements first generate and solve the model that contains the no-fixed-charge variant of the cost function. Next, they solve the fixed-charge model and demonstrate the usage of the MAXPOOLSOLS=, SOLTYPE=, and MAXPOOLGAP= options for outputting multiple solutions. Note that the solution to the model that has no fixed charge is feasible for the fixed-charge model and should provide a good starting point for the MILP solver. Use the PRIMALIN option to provide an incumbent solution (warm start).

```
proc optmodel;
   set <str> CUSTOMERS;
   set <str> SITES init {};
   /* x and y coordinates of CUSTOMERS and SITES */
   num x {CUSTOMERS union SITES};
   num y {CUSTOMERS union SITES};
   num demand {CUSTOMERS};
   num fixed_charge {SITES};
   /* distance from customer i to site j */
   num dist {i in CUSTOMERS, j in SITES}
       = sqrt((x[i] - x[j])^2 + (y[i] - y[j])^2);
   read data cdata into CUSTOMERS=[name] x y demand;
   read data sdata into SITES=[name] x y fixed_charge;
   var Assign {CUSTOMERS, SITES} binary;
   var Build {SITES} binary;
   min CostNoFixedCharge
       = sum {i in CUSTOMERS, j in SITES} dist[i,j] * Assign[i,j];
   min CostFixedCharge
       = CostNoFixedCharge + sum {j in SITES} fixed_charge[j] * Build[j];
   /* each customer assigned to exactly one site */
   con assign_def {i in CUSTOMERS}:
      sum {j in SITES} Assign[i,j] = 1;
   /* if customer i assigned to site j, then facility must be built at j */
   con link {i in CUSTOMERS, j in SITES}:
      Assign[i,j] <= Build[j];
   /* each site can handle at most &SiteCapacity demand */
   con capacity {j in SITES}:
      sum {i in CUSTOMERS} demand[i] * Assign[i,j] <=
         &SiteCapacity * Build[j];
   /* solve the MILP with no fixed charges */
   solve obj CostNoFixedCharge with milp;
   /* clean up the solution */
   for {i in CUSTOMERS, j in SITES} Assign[i,j] = round(Assign[i,j]);
   for {j in SITES} Build[j] = round(Build[j]);
   call symput('varcostNo',put(CostNoFixedCharge,6.1));
   /* create a data set for use by PROC SGPLOT */
   create data CostNoFixedCharge_Data from
     [customer site]={i in CUSTOMERS, j in SITES: Assign[i,j] = 1}
```

```
      x1=x[i] y1=y[i] x2=x[j] y2=y[j]
      function='line' drawspace='datavalue' linethickness=1 linecolor='black';
   submit;
      data csdata;
         set cdata(rename=(y=cy)) sdata(rename=(y=sy));
      run;
      title1 "Facility Location Problem";
      title2 "TotalCost = &varcostNo (Variable = &varcostNo, Fixed = 0)";
      proc sgplot data=csdata sganno=CostNoFixedCharge_Data noautolegend;
         scatter x=x y=cy / datalabel=name datalabelattrs=(size=6pt)
            markerattrs=(symbol=circlefilled color=black size=6pt);
         scatter x=x y=sy / datalabel=name datalabelattrs=(size=6pt)
            markerattrs=(symbol=diamond color=blue size=6pt);
         xaxis display=(nolabel);
         yaxis display=(nolabel);
      run;
   endsubmit;
   /* solve the MILP with fixed charges with warm start */
   solve obj CostFixedCharge with milp / primalin maxpoolsols=6 soltype=best
                                         maxpoolgap=1E-3;
   num varcost = sum {i in CUSTOMERS, j in SITES} dist[i,j] * Assign[i,j].sol;
   num fixcost = sum {j in SITES} fixed_charge[j] * Build[j].sol;
   for {s in 1.._NSOL_} do;
      /* clean up the solution */
      for {i in CUSTOMERS, j in SITES} Assign[i,j] = round(Assign[i,j].sol[s]);
      for {j in SITES} Build[j] = round(Build[j].sol[s]);
      call symput('varcost', put(varcost,6.1));
      call symput('fixcost', put(fixcost,5.1));
      call symput('totalcost', put(CostFixedCharge,6.1));
      /* create a data set for use by PROC SGPLOT */
      create data CostFixedCharge_Data from
         [customer site]={i in CUSTOMERS, j in SITES: Assign[i,j] = 1}
         x1=x[i] y1=y[i] x2=x[j] y2=y[j]
         function='line' drawspace='datavalue' linethickness=1 linecolor='black';
      submit s;
         title1 "Facility Location Problem: Solution &s";
         title2 "TotalCost = &totalcost (Variable = &varcost, Fixed = &fixcost)";
         proc sgplot data=csdata sganno=CostFixedCharge_Data noautolegend;
            scatter x=x y=cy / datalabel=name datalabelattrs=(size=6pt)
               markerattrs=(symbol=circlefilled color=black size=6pt);
            scatter x=x y=sy / datalabel=name datalabelattrs=(size=6pt)
               markerattrs=(symbol=diamond color=blue size=6pt);
            xaxis display=(nolabel);
            yaxis display=(nolabel);
         run;
      endsubmit;
   end;
quit;
```

Output 14.3.1 displays the information that is printed in the log for the facility location problem.

Output 14.3.1 OPTMODEL Log for Facility Location

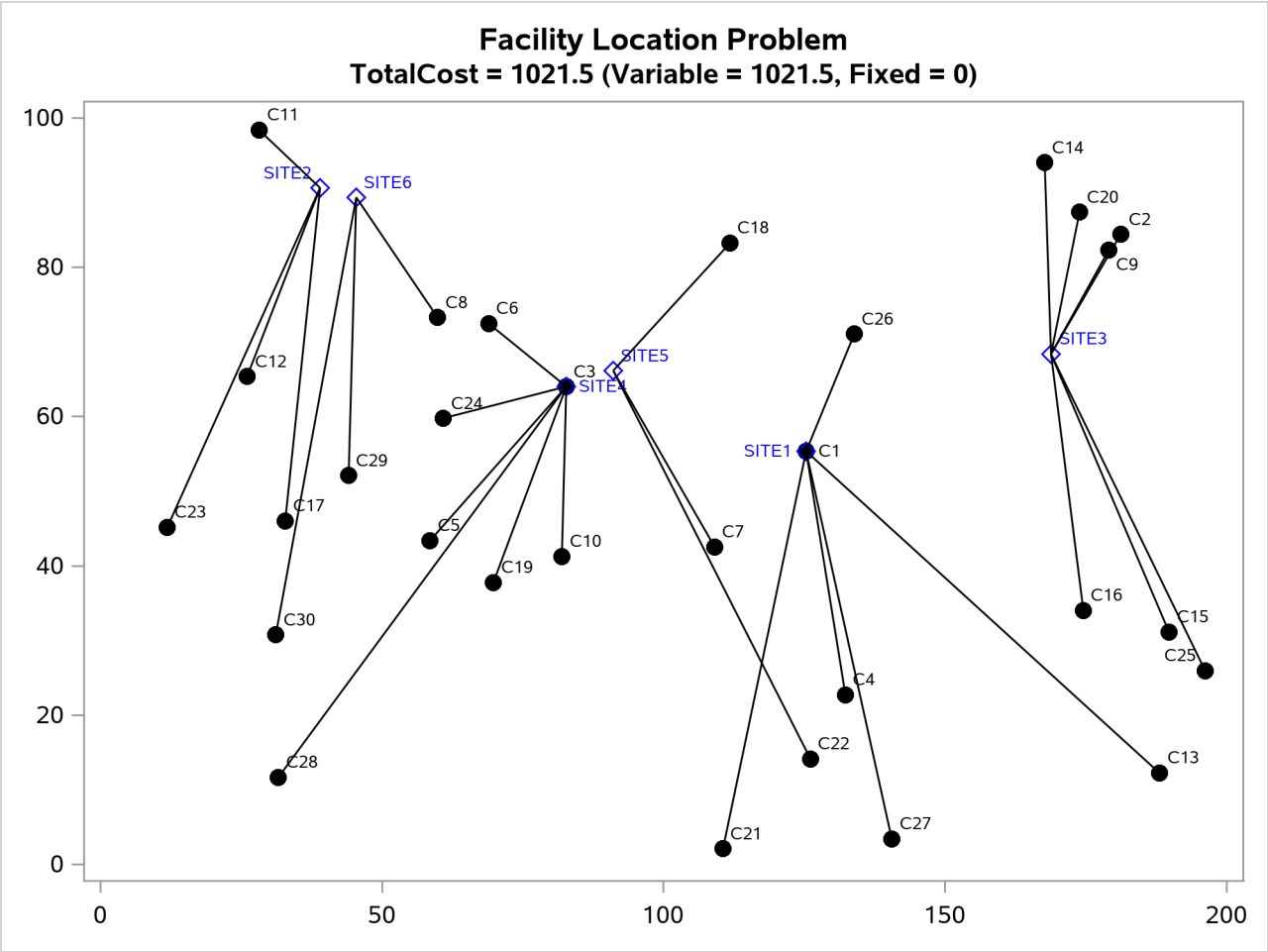
```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 186 variables (0 free, 0 fixed).
NOTE: The problem has 186 binary and 0 integer variables.
NOTE: The problem has 216 linear constraints (186 LE, 30 EQ, 0 GE, 0 range).
NOTE: The problem has 726 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 6 variables and 180 constraints.
NOTE: The MILP presolver removed 366 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 180 variables, 36 constraints, and 360
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1   1052.9414513    985.5035182    6.84%       0
NOTE: The MILP presolver is applied again.
             0        1      1   1052.9414513    985.5035182    6.84%       0
             0        1      2   1045.3217618    985.5035182    6.07%       0
             0        1      2   1045.3217618   1002.3380109    4.29%       0
             0        1      5   1025.8272473   1002.3380109    2.34%       0
             0        1      5   1025.8272473   1013.0691328    1.26%       0
NOTE: The MILP presolver is applied again.
             0        1      6   1021.5193163   1013.0691328    0.83%       0
             0        1      6   1021.5193163   1013.0691328    0.83%       0
             0        1      6   1021.5193163   1014.9738001    0.64%       0
NOTE: The MILP presolver is applied again.
             0        1      7   1021.5193163   1014.9738001    0.64%       0
NOTE: The MILP solver added 3 cuts with 17 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 1021.5193163.
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 186 variables (0 free, 0 fixed).
NOTE: The problem uses 1 implicit variables.
NOTE: The problem has 186 binary and 0 integer variables.
NOTE: The problem has 216 linear constraints (186 LE, 30 EQ, 0 GE, 0 range).
NOTE: The problem has 726 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 186 variables, 216 constraints, and 726
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
```

Output 14.3.1 *continued*

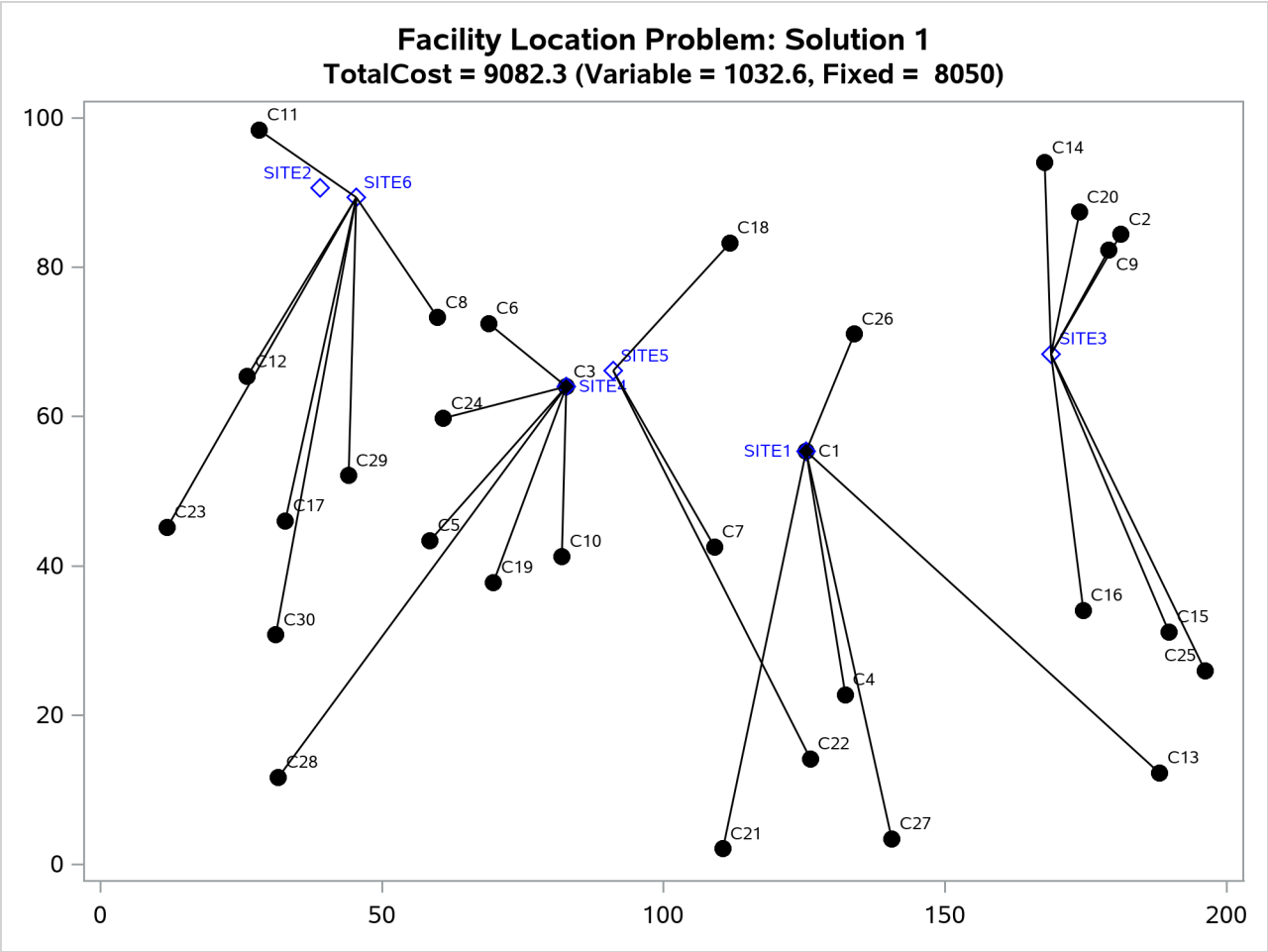
```
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      2   9113.7292152   6814.6940297   33.74%       0
             0        1      2   9113.7292152   9063.8415787    0.55%       0
             0        1      2   9113.7292152   9073.8049605    0.44%       0
             0        1      5   9082.3070802   9073.8049605    0.09%       0
             0        1      5   9082.3070802   9075.7685482    0.07%       0
             0        1      5   9082.3070802   9077.8284517    0.05%       0
             0        1      5   9082.3070802   9078.5883699    0.04%       0
             0        1      5   9082.3070802   9079.7006060    0.03%       0
NOTE: The MILP solver added 7 cuts with 103 cut coefficients at the root.
             6        0      7   9082.3070802   9082.3070802    0.00%       0
NOTE: Processing nodes for multiple solutions.
             7        5      8   9082.3070802   9082.3070802    0.00%       0
            10        5      9   9082.3070802   9082.3070802    0.00%       0
            11        5     10   9082.3070802   9082.3070802    0.00%       0
            12        5     11   9082.3070802   9082.3070802    0.00%       0
            13        4     12   9082.3070802   9082.3070802    0.00%       0
            17        4     13   9082.3070802   9082.3070802    0.00%       0
            24        4     14   9082.3070802   9082.3070802    0.00%       0
            29        6     15   9082.3070802   9082.3070802    0.00%       0
            31        6     16   9082.3070802   9082.3070802    0.00%       0
            53        0     16   9082.3070802   9082.3070802    0.00%       0
NOTE: Optimal.
NOTE: Objective = 9082.3070802.
```

The output of the program is shown in Output 14.3.2.

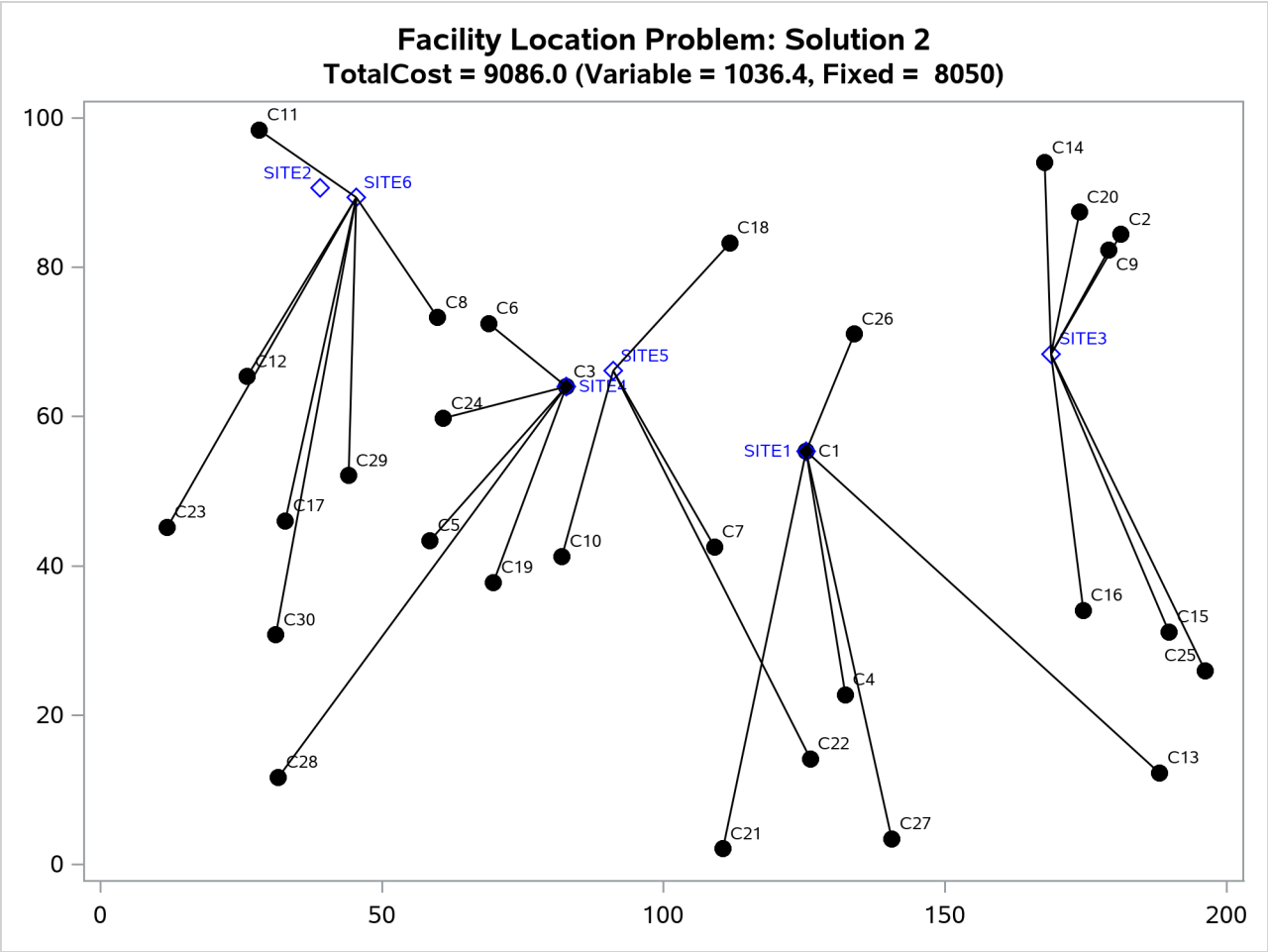
Output 14.3.2 Solution Plots for Facility Location



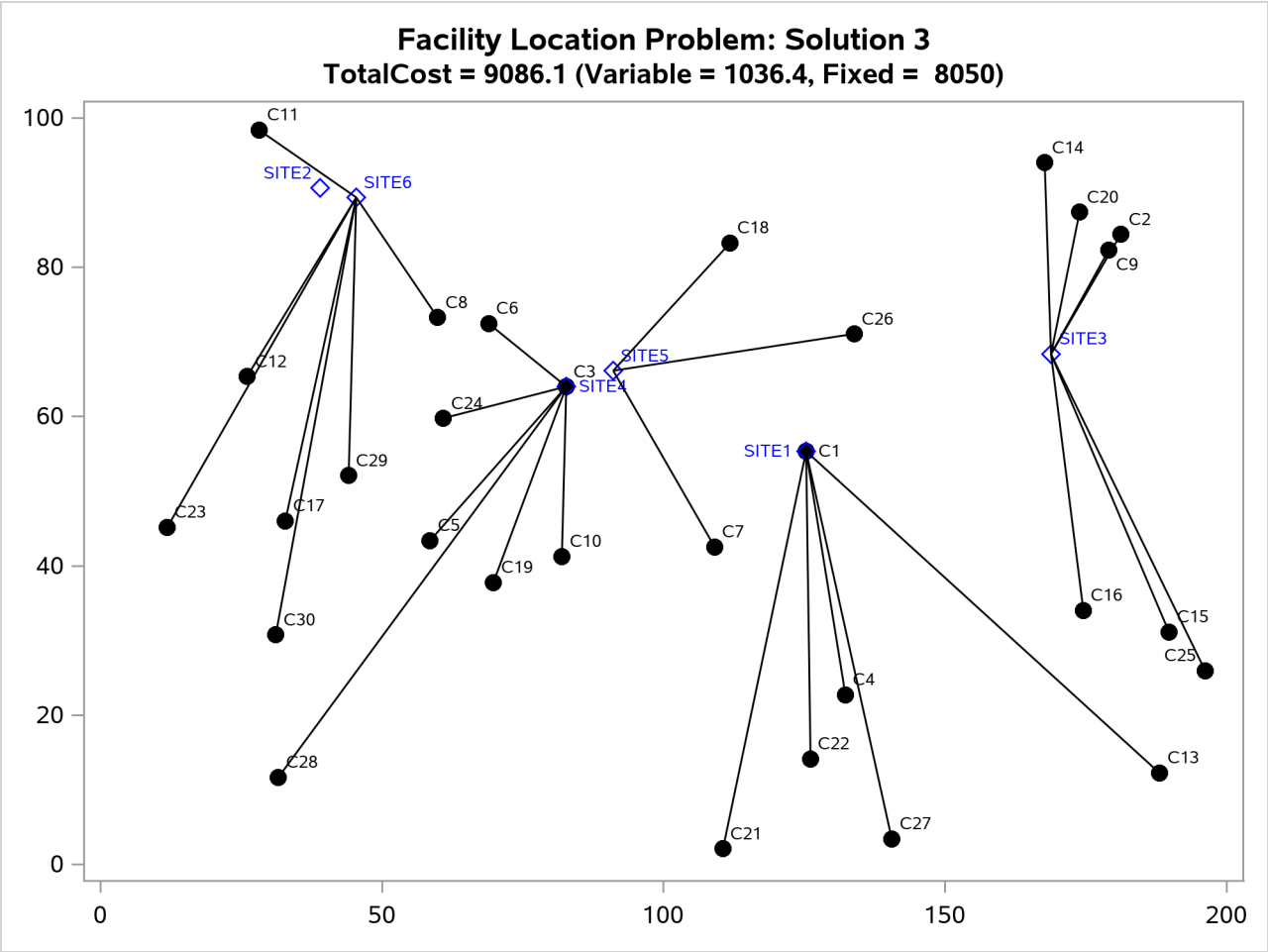
Output 14.3.2 *continued*



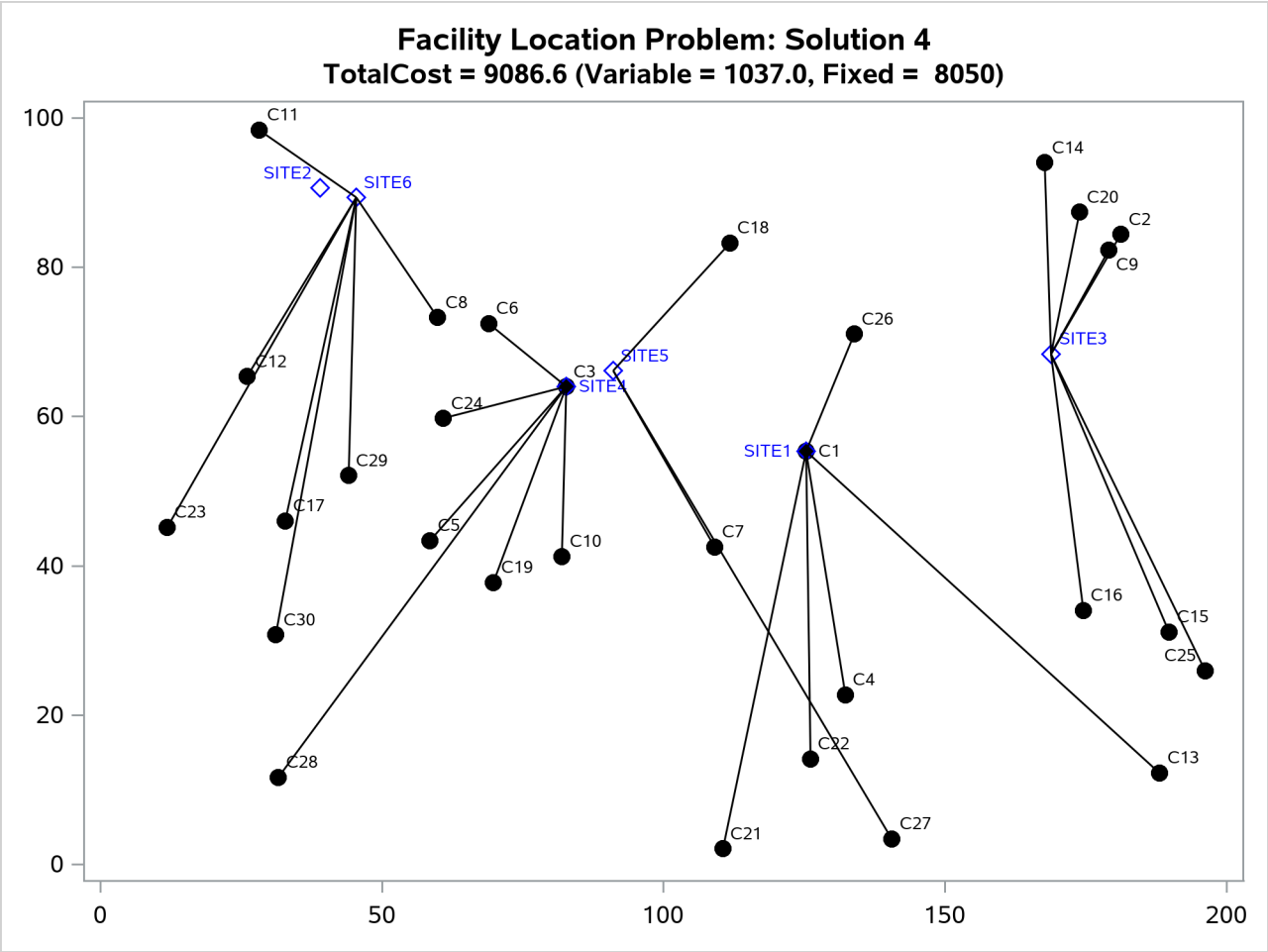
Output 14.3.2 *continued*



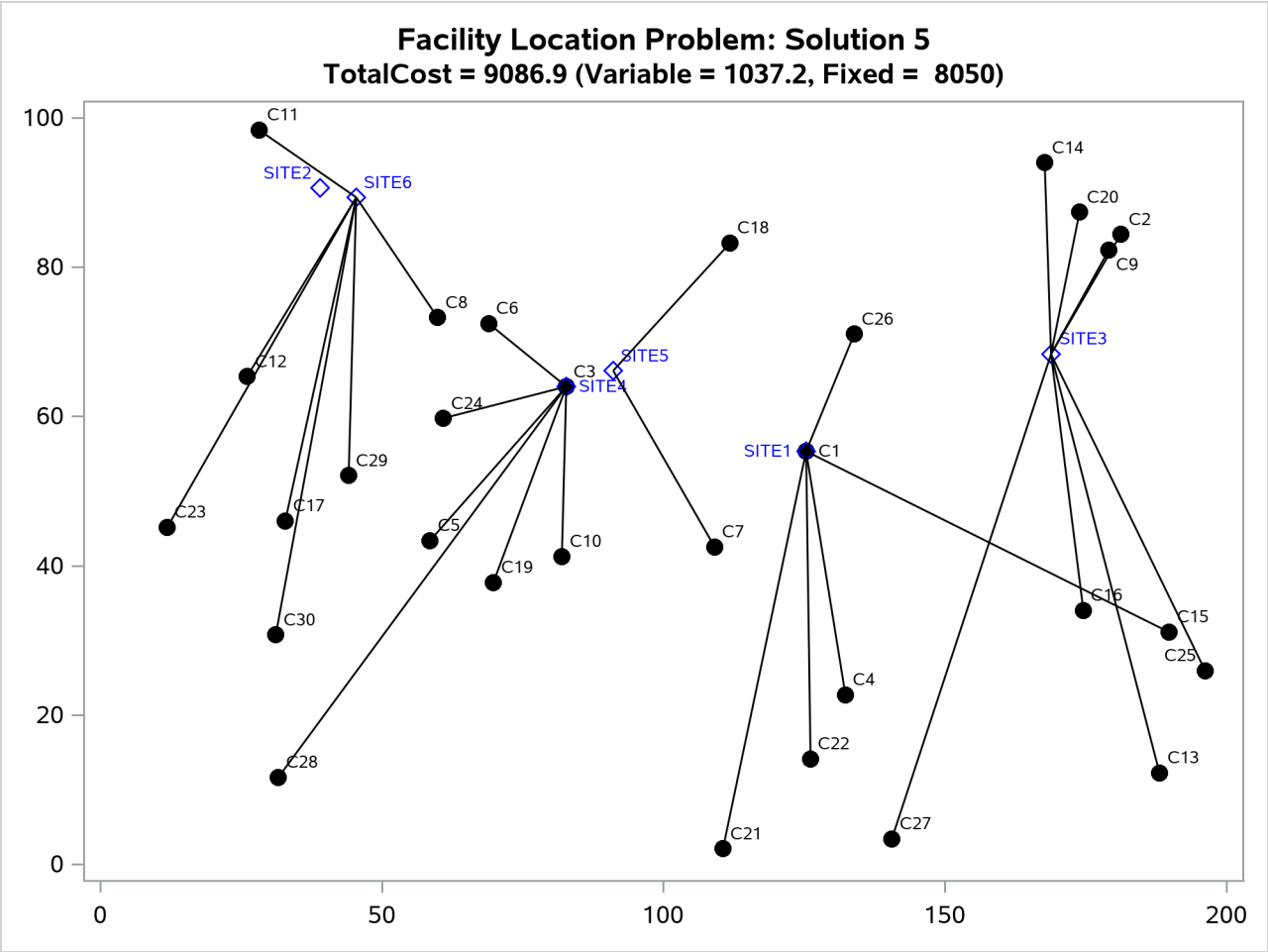
Output 14.3.2 *continued*



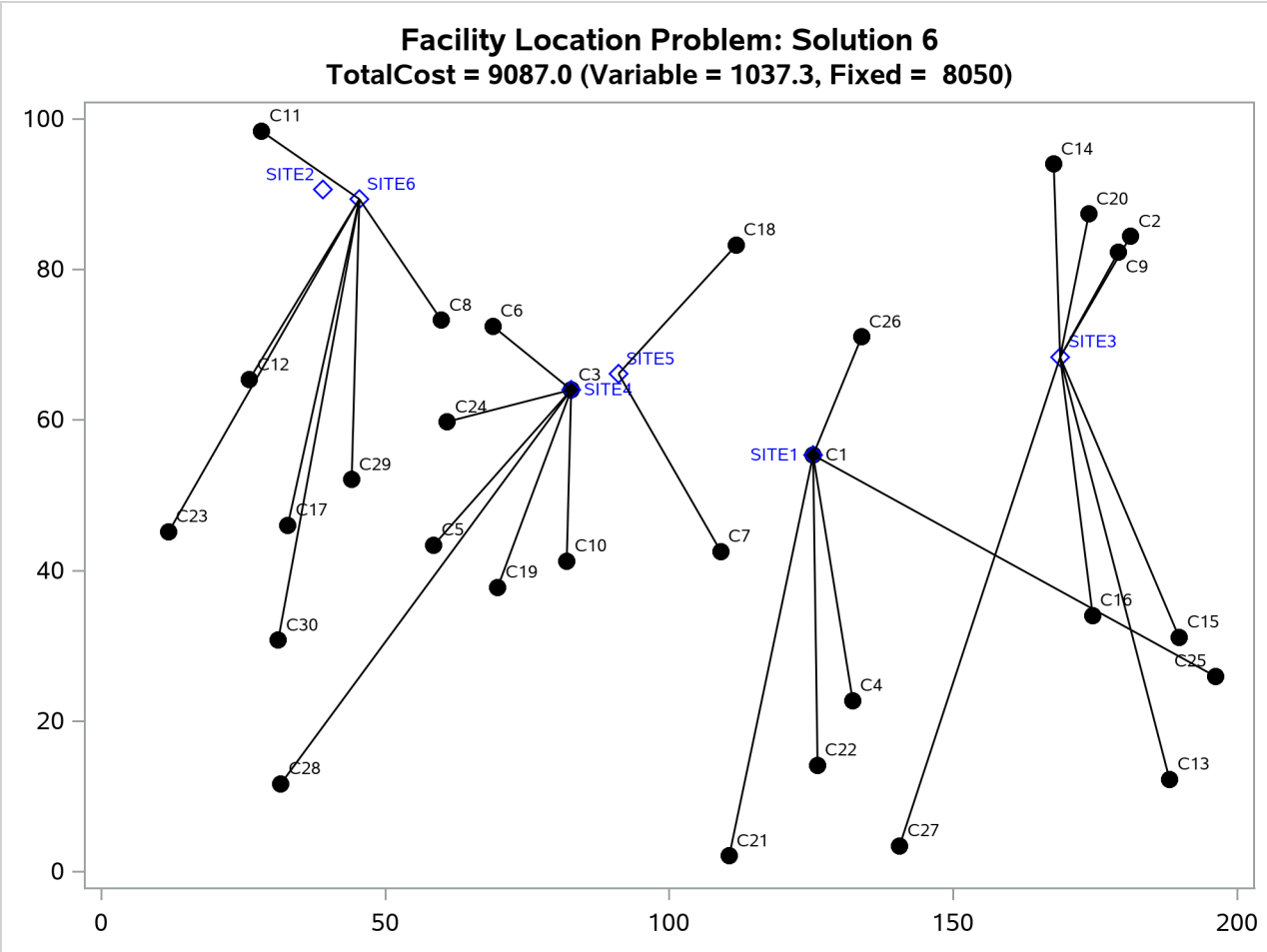
Output 14.3.2 *continued*



Output 14.3.2 *continued*



Output 14.3.2 *continued*



The economic trade-off for the fixed-charge model forces you to build fewer sites and push more demand to each site. The six different solutions are the best possible solutions that are within a 0.001 gap of the optimal solution.

It is possible to expedite the solution of the fixed-charge facility location problem by choosing appropriate branching priorities for the decision variables. Recall that for each site j, the value of the variable y_j determines whether a facility is built on that site. Suppose you decide to branch on the variables y_j before the variables x_{ij}. You can set a higher branching priority for y_j by using the .priority suffix for the Build variables in PROC OPTMODEL, as follows:

```
for{j in SITES} Build[j].priority=10;
```

Setting higher branching priorities for certain variables is not guaranteed to speed up the MILP solver, but it can be helpful in some instances. The following program creates and solves an instance of the facility location problem, giving higher priority to the variables y_j. The LOGFREQ= option is used to limit the size of the node log.

```
%let NumCustomers  = 45;
%let NumSites      = 8;
%let SiteCapacity  = 35;
%let MaxDemand     = 10;
%let xmax          = 200;
%let ymax          = 100;
%let seed          = 2345;

/* generate random customer locations */
data cdata(drop=i);
   length name $8;
   do i = 1 to &NumCustomers;
      name = compress('C'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      demand = rand('UNIFORM') * &MaxDemand;
      output;
   end;
run;

/* generate random site locations and fixed charge */
data sdata(drop=i);
length name $8;
   do i = 1 to &NumSites;
      name = compress('SITE'||put(i,best.));
      x = rand('UNIFORM') * &xmax;
      y = rand('UNIFORM') * &ymax;
      fixed_charge = (abs(&xmax/2-x) + abs(&ymax/2-y)) / 2;
      output;
   end;
run;

proc optmodel;
   set <str> CUSTOMERS;
   set <str> SITES init {};

   /* x and y coordinates of CUSTOMERS and SITES */
   num x {CUSTOMERS union SITES};
   num y {CUSTOMERS union SITES};
   num demand {CUSTOMERS};
   num fixed_charge {SITES};

   /* distance from customer i to site j */
   num dist {i in CUSTOMERS, j in SITES}
       = sqrt((x[i] - x[j])^2 + (y[i] - y[j])^2);

   read data cdata into CUSTOMERS=[name] x y demand;
   read data sdata into SITES=[name] x y fixed_charge;

   var Assign {CUSTOMERS, SITES} binary;
   var Build {SITES} binary;
```

```
    min CostFixedCharge
        = sum {i in CUSTOMERS, j in SITES} dist[i,j] * Assign[i,j]
          + sum {j in SITES} fixed_charge[j] * Build[j];

    /* each customer assigned to exactly one site */
    con assign_def {i in CUSTOMERS}:
       sum {j in SITES} Assign[i,j] = 1;

    /* if customer i assigned to site j, then facility must be built at j */
    con link {i in CUSTOMERS, j in SITES}:
       Assign[i,j] <= Build[j];

    /* each site can handle at most &SiteCapacity demand */
    con capacity {j in SITES}:
       sum {i in CUSTOMERS} demand[i] * Assign[i,j] <= &SiteCapacity * Build[j];

    /* assign priority to Build variables (y) */
    for{j in SITES} Build[j].priority=10;

    /* solve the MILP with fixed charges, using branching priorities */
    solve obj CostFixedCharge with milp / logfreq=1000;
  quit;
```

The resulting output is shown in Output 14.3.3.

Output 14.3.3 PROC OPTMODEL Log for Facility Location with Branching Priorities

```
NOTE: There were 45 observations read from the data set WORK.CDATA.
NOTE: There were 8 observations read from the data set WORK.SDATA.
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 368 variables (0 free, 0 fixed).
NOTE: The problem has 368 binary and 0 integer variables.
NOTE: The problem has 413 linear constraints (368 LE, 45 EQ, 0 GE, 0 range).
NOTE: The problem has 1448 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 368 variables, 413 constraints, and 1448
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      3   1760.2751189   1677.3196849    4.95%       0
NOTE: The MILP presolver is applied again.
             0        1      3   1760.2751189   1677.3196849    4.95%       0
             0        1      3   1760.2751189   1682.1823495    4.64%       0
             0        1      4   1696.2311955   1682.1823495    0.84%       0
             0        1      4   1696.2311955   1689.4445102    0.40%       0
NOTE: The MILP presolver is applied again.
             0        1      5   1696.2311955   1689.4445102    0.40%       0
             0        1      5   1696.2311955   1689.4445102    0.40%       0
             0        1      5   1696.2311955   1689.4445102    0.40%       0
             0        1      6   1690.4317599   1690.4317599    0.00%       0
NOTE: The MILP solver added 5 cuts with 30 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 1690.4317599.
```

Example 14.4: Traveling Salesman Problem

NOTE: This example shows how to use the MILP solver to solve the TSP. For an example of how to use a specialized algorithm to solve the TSP, see the "Examples" section in Chapter 15, "The Network Solver."

The traveling salesman problem (TSP) is that of finding a minimum cost *tour* in an undirected graph G with vertex set $V = \{1, \ldots, |V|\}$ and edge set E. A tour is a connected subgraph for which each vertex has degree two. The goal is then to find a tour of minimum total cost, where the total cost is the sum of the costs of the edges in the tour. Associated with each edge $e \in E$ are a binary variable x_e, which indicates whether edge e is part of the tour, and a cost $c_e \in \mathbb{R}$. Let $\delta(S) = \{\{i, j\} \in E \mid i \in S,\ j \notin S\}$. Then an integer linear programming (ILP) formulation of the TSP is as follows:

$$
\begin{array}{llll}
\min & \sum_{e \in E} c_e x_e & & \\
\text{s.t.} & \sum_{e \in \delta(i)} x_e = 2 & \forall i \in V & \text{(two_match)} \\
& \sum_{e \in \delta(S)} x_e \geq 2 & \forall S \subset V,\ 2 \leq |S| \leq |V|-1 & \text{(subtour_elim)} \\
& x_e \in \{0,1\} & \forall e \in E &
\end{array}
$$

The equations (two_match) are the *matching constraints*, which ensure that each vertex has degree two in the subgraph, while the inequalities (subtour_elim) are known as the *subtour elimination constraints* (SECs) and enforce connectivity.

Since there is an exponential number $O(2^{|V|})$ of SECs, it is impossible to explicitly construct the full TSP formulation for large graphs. An alternative formulation of polynomial size was introduced by Miller, Tucker, and Zemlin (1960) (MTZ):

$$
\begin{array}{llll}
\min & \sum_{(i,j) \in E} c_{ij} x_{ij} & & \\
\text{s.t.} & \sum_{j \in V} x_{ij} = 1 & \forall i \in V & \text{(assign_i)} \\
& \sum_{i \in V} x_{ij} = 1 & \forall j \in V & \text{(assign_j)} \\
& u_i - u_j + 1 \leq (|V|-1)(1-x_{ij}) & \forall (i,j) \in V, i \neq 1, j \neq 1 & \text{(mtz)} \\
& 2 \leq u_i \leq |V| & \forall i \in \{2,..,|V|\}, & \\
& x_{ij} \in \{0,1\} & \forall (i,j) \in E &
\end{array}
$$

This formulation uses a directed graph. Constraints (assign_i) and (assign_j) now enforce that each vertex has degree two (one edge in, one edge out). The MTZ constraints (mtz) enforce that no subtours exist.

TSPLIB is a set of benchmark instances for the TSP. For more information about TSPLIB, see https://pubsonline.informs.org/doi/abs/10.1287/ijoc.3.4.376. The following DATA step converts a TSPLIB instance of type EUC_2D into a SAS data set that contains the coordinates of the vertices:

```
/* convert the TSPLIB instance into a data set */
data tspData(drop=H);
   infile "st70.tsp";
   input H $1. @;
   if H not in ('N','T','C','D','E');
   input @1 var1-var3;
run;
```

The following PROC OPTMODEL statements attempt to solve the TSPLIB instance st70.tsp by using the MTZ formulation:

```
/* direct solution using the MTZ formulation */
proc optmodel;
   set VERTICES;
   set EDGES = {i in VERTICES, j in VERTICES: i ne j};
   num xc {VERTICES};
   num yc {VERTICES};
```

```
   /* read in the instance and customer coordinates (xc, yc) */
   read data tspData into VERTICES=[_n_] xc=var2 yc=var3;

   /* the cost is the Euclidean distance rounded to the nearest integer */
   num c {<i,j> in EDGES}
      init floor( sqrt( ((xc[i]-xc[j])**2 + (yc[i]-yc[j])**2)) + 0.5);

   var x {EDGES} binary;
   var u {i in 2..card(VERTICES)} >= 2 <= card(VERTICES);

   /* each vertex has exactly one in-edge and one out-edge */
   con assign_i {i in VERTICES}:
      sum {j in VERTICES: i ne j} x[i,j] = 1;
   con assign_j {j in VERTICES}:
      sum {i in VERTICES: i ne j} x[i,j] = 1;

   /* minimize the total cost */
   min obj
      = sum {<i,j> in EDGES} (if i > j then c[i,j] else c[j,i]) * x[i,j];

   /* no subtours */
   con mtz {<i,j> in EDGES : (i ne 1) and (j ne 1)}:
      u[i] - u[j] + 1 <= (card(VERTICES) - 1) * (1 - x[i,j]);

   solve with milp / maxtime = 600;
quit;
```

It is well known that the MTZ formulation is much weaker than the subtour formulation. The exponential number of SECs makes it impossible, at least in large instances, to use a direct call to the MILP solver with the subtour formulation. For this reason, if you want to solve the TSP with one SOLVE statement, you must use the MTZ formulation and rely strictly on generic cuts and heuristics. Except for very small instances, this is unlikely to be a good approach.

A much more efficient way to tackle the TSP is to dynamically generate the subtour inequalities as *cuts*. Typically this is done by solving the LP relaxation of the two-matching problem, finding violated subtour cuts, and adding them iteratively. The problem of finding violated cuts is known as the *separation problem*. In this case, the separation problem takes the form of a minimum cut problem, which is nontrivial to implement efficiently. Therefore, for the sake of illustration, an integer program is solved at each step of the process.

The initial formulation of the TSP is the integral two-matching problem. You solve this by using PROC OPTMODEL to obtain an integral matching, which is not necessarily a tour. In this case, the separation problem is trivial. If the solution is a connected graph, then it is a tour, so the problem is solved. If the solution is a disconnected graph, then each component forms a violated subtour constraint. These constraints are added to the formulation, and the integer program is solved again. This process is repeated until the solution defines a tour.

The following PROC OPTMODEL statements solve the TSP by using the subtour formulation and iteratively adding subtour constraints:

```
/* iterative solution using the subtour formulation */
proc optmodel;
   set VERTICES;
   set EDGES = {i in VERTICES, j in VERTICES: i > j};
   num xc {VERTICES};
```

```
num yc {VERTICES};

num numsubtour init 0;
set SUBTOUR {1..numsubtour};

/* read in the instance and customer coordinates (xc, yc) */
read data tspData into VERTICES=[var1] xc=var2 yc=var3;

/* the cost is the Euclidean distance rounded to the nearest integer */
num c {<i,j> in EDGES}
   init floor( sqrt( ((xc[i]-xc[j])**2 + (yc[i]-yc[j])**2)) + 0.5);

var x {EDGES} binary;

/* minimize the total cost */
min obj =
   sum {<i,j> in EDGES} c[i,j] * x[i,j];

/* each vertex has exactly one in-edge and one out-edge */
con two_match {i in VERTICES}:
   sum {j in VERTICES: i > j} x[i,j]
   + sum {j in VERTICES: i < j} x[j,i] = 2;

/* no subtours (these constraints are generated dynamically) */
con subtour_elim {s in 1..numsubtour}:
   sum {<i,j> in EDGES: (i in SUBTOUR[s] and j not in SUBTOUR[s])
   or (i not in SUBTOUR[s] and j in SUBTOUR[s])} x[i,j] >= 2;

/* this starts the algorithm to find violated subtours */
set <num,num> EDGES1;
set VERTICES1 = union{<i,j> in EDGES1} {i, j};
num component {VERTICES1};
num numcomp  init 2;
num iter     init 1;
num numiters init 1;
set ITERS = 1..numiters;
num sol {ITERS, EDGES};

/* initial solve with just matching constraints */
solve;
call symput(compress('obj'||put(iter,best.)),
   trim(left(put(round(obj),best.))));
for {<i,j> in EDGES} sol[iter,i,j] = round(x[i,j]);

/* while the solution is disconnected, continue */
do while (numcomp > 1);
   iter = iter + 1;

   /* find connected components of support graph   */
   EDGES1 = {<i,j> in EDGES: round(x[i,j].sol) = 1};
   solve with network /
      links   = (include=EDGES1)
      nodes   = (include=VERTICES1)
      concomp
```

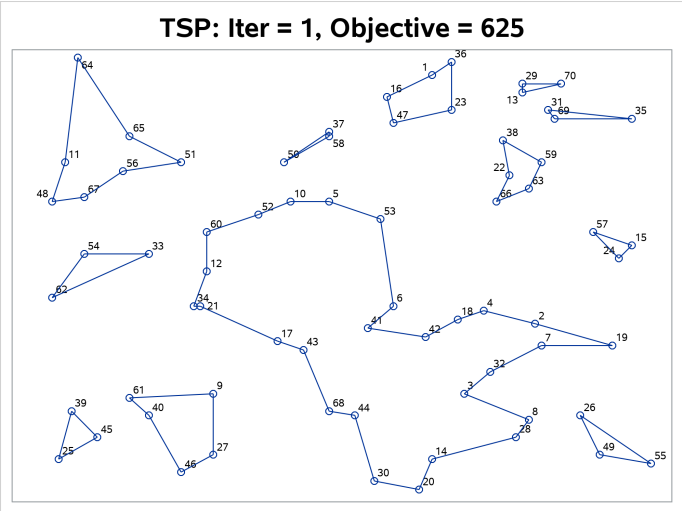
```
            out     = (concomp=component);

         numcomp = _oroptmodel_num_["NUM_COMPONENTS"];
         if numcomp = 1 then leave;
         numiters = iter;
         numsubtour = numsubtour + numcomp;
         for {comp in 1..numcomp} do;
            SUBTOUR[numsubtour-numcomp+comp]
            = {i in VERTICES: component[i] = comp};
         end;

         solve;
         call symput(compress('obj'||put(iter,best.)),
            trim(left(put(round(obj),best.))));
         for {<i,j> in EDGES} sol[iter,i,j] = round(x[i,j]);
      end;

      /* create a data set for use by PROC SGPLOT */
      create data solData from
         [iter i j]={it in ITERS, <i,j> in EDGES: sol[it,i,j] = 1}
         x1=xc[i] y1=yc[i] x2=xc[j] y2=yc[j];
      call symput('numiters',put(numiters,best.));
   quit;
```

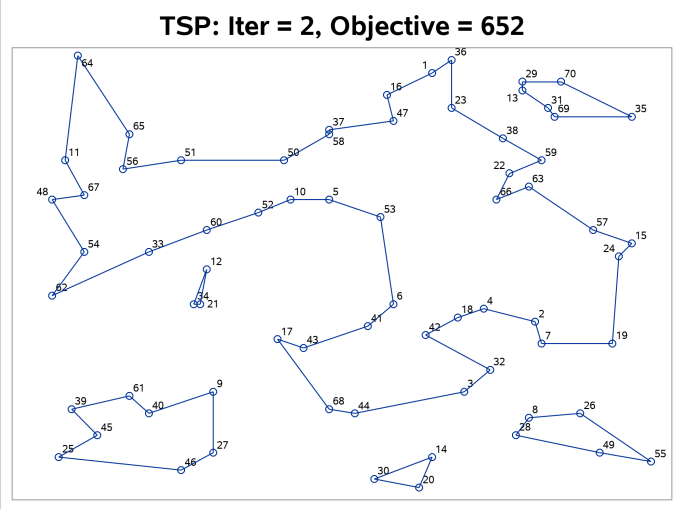
You can generate plots of the solution and objective value at each stage by using the following statements:

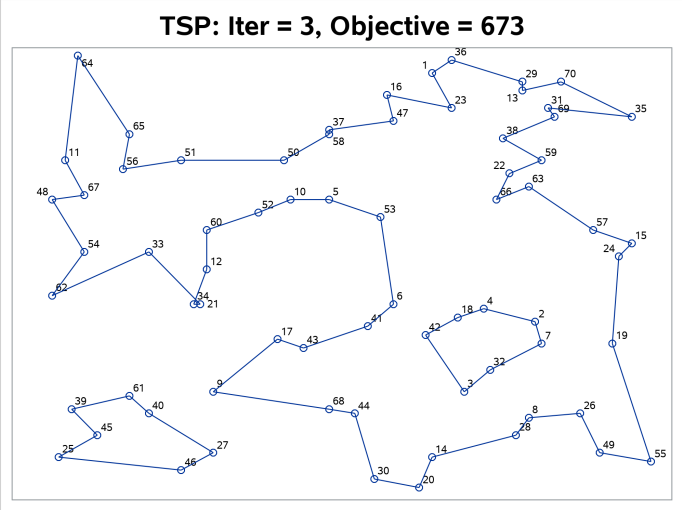
```
   %macro plotTSP;
      %do i = 1 %to &numiters;
         /* create annotate data set to draw subtours */
         data anno(drop=iter);
            retain drawspace 'datavalue' linethickness 1 function 'line';
            set solData;
            where iter = &i;
         run;

         title1 h=2 "TSP: Iter = &i, Objective = &&obj&i";
         title2;

         proc sgplot data=tspData sganno=anno;
            scatter x=var2 y=var3 / datalabel=var1;
            xaxis display=none;
            yaxis display=none;
         run;
      %end;
   %mend plotTSP;

   %plotTSP;
```

The plot in Output 14.4.1 shows the solution and objective value at each stage. Notice that each stage restricts some subset of subtours. When you reach the final stage, you have a valid tour.

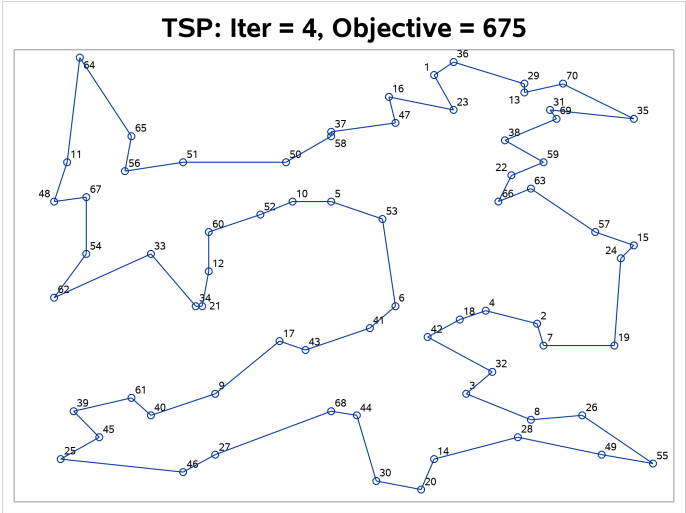
Output 14.4.1 Traveling Salesman Problem Iterative Solution







Output 14.4.1 *continued*



Example 14.5: Advanced Options

This example demonstrates some of the advanced algorithmic options that are available in the MILP solver on some simple integer linear programming models.

The following PROC OPTMODEL statements generate and solve a simple integer programming model in order to demonstrate the usage of the SOLTYPE= option. Specifying SOLTYPE=BEST enables you to obtain a maximum of 10 best (if available) solutions of the model whose gap from the best integer solution is less than or equal to the default value of the MAXPOOLGAP= option.

```
proc optmodel;
   var a >= 0 <= 2 integer, b >= 0 <= 2 integer,
       c >= 0 <= 2 integer;
   con a - b = 0;
   max f = a-b+c;
   solve with milp/ maxpoolsols=10 soltype=best presolver=0;
%put &_oroptmodel_;
quit;
```

Output 14.5.1 displays the information that is printed in the log for demonstrating the SOLTYPE= option. Since the model has only three unique best solutions that fall within the default value of the MAXPOOLGAP= option, all three solutions are returned to the user.

Output 14.5.1 OPTMODEL Log That Demonstrates the SOLTYPE= Option

```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 0 binary and 3 integer variables.
NOTE: The problem has 1 linear constraints (0 LE, 1 EQ, 0 GE, 0 range).
NOTE: The problem has 2 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      2      2.0000000      2.9990000   33.31%       0
             2        0      2      2.0000000      2.0000000    0.00%       0
NOTE: Processing nodes for multiple solutions.
             3        1      3      2.0000000      2.0000000    0.00%       0
             4        0      4      2.0000000      2.0000000    0.00%       0
NOTE: Optimal.
NOTE: Objective = 2.
STATUS=OK ALGORITHM=BAC SOLUTION_STATUS=OPTIMAL OBJECTIVE=2 RELATIVE_GAP=0
ABSOLUTE_GAP=0 PRIMAL_INFEASIBILITY=0 BOUND_INFEASIBILITY=0
INTEGER_INFEASIBILITY=0 BEST_BOUND=2 NODES=5 SOLUTIONS_FOUND=3 ITERATIONS=19
PRESOLVE_TIME=0.00 SOLUTION_TIME=0.01
```

You can choose the root node LP solver by specifying the ROOTNODE= option in the MILP solver. The following PROC OPTMODEL statements generate and solve a simple integer programming model by choosing the primal simplex algorithm for solving the root node LP, and they display the progress log of the primal simplex algorithm.

```
proc optmodel;
   var x{1..3} >= 0 integer;
   min f = 2*x[1] - 3*x[2] - 4*x[3];
   con r1: -2*x[2] - 3*x[3] >= -5;
   con r2: x[1] + x[2] + 2*x[3] <= 4;
   con r3: x[1] + 2*x[2] + 3*x[3] <= 7;
   x[1] = .;
   solve with milp / primalin
   rootnode=(algorithm=ps loglevel=2);
quit;
```

The resulting output is shown in Output 14.5.2.

Output 14.5.2 PROC OPTMODEL Log That Demonstrates the Usage of the ROOTNODE= Option

```
NOTE: Problem generation will use 16 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 0 binary and 3 integer variables.
NOTE: The problem has 3 linear constraints (2 LE, 0 EQ, 1 GE, 0 range).
NOTE: The problem has 8 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The value of variable x[1] is missing.
NOTE: The input solution is infeasible or incomplete. Repair heuristics are
      applied.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 1 variables and 2 constraints.
NOTE: The MILP presolver removed 6 constraint coefficients.
NOTE: The MILP presolver modified 2 constraint coefficients.
NOTE: The presolved problem has 2 variables, 1 constraints, and 2 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 16 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
NOTE: The LP relaxation log follows.
NOTE: ----------------------------------------------------------
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Primal Simplex algorithm is used.
                            Objective
      Phase Iteration         Value         Time
       P 2          1   -6.000000E+00         0
       D 2          4   -7.000000E+00         0
NOTE: The Primal Simplex solve time is 0.00 seconds.
NOTE: ----------------------------------------------------------
             0        1      2     -7.0000000     -7.9990000   12.49%       0
             0        0      2     -7.0000000     -7.0000000    0.00%       0
NOTE: Optimal.
NOTE: Objective = -7.
```

References

Achterberg, T., Koch, T., and Martin, A. (2005). "Branching Rules Revisited." *Operations Research Letters* 33:42–54.

Andersen, E. D., and Andersen, K. D. (1995). "Presolving in Linear Programming." *Mathematical Programming* 71:221–245.

Atamturk, A. (2004). "Sequence Independent Lifting for Mixed-Integer Programming." *Operations Research* 52:487–490.

Dantzig, G. B., Fulkerson, R., and Johnson, S. M. (1954). "Solution of a Large-Scale Traveling Salesman Problem." *Operations Research* 2:393–410.

Gondzio, J. (1997). "Presolve Analysis of Linear Programs Prior to Applying an Interior Point Method." *INFORMS Journal on Computing* 9:73–91.

Land, A. H., and Doig, A. G. (1960). "An Automatic Method for Solving Discrete Programming Problems." *Econometrica* 28:497–520.

Linderoth, J. T., and Savelsbergh, M. W. P. (1998). "A Computational Study of Search Strategies for Mixed Integer Programming." *INFORMS Journal on Computing* 11:173–187.

Marchand, H., Martin, A., Weismantel, R., and Wolsey, L. (1999). "Cutting Planes in Integer and Mixed Integer Programming." DP 9953, CORE, Université Catholique de Louvain.

Miller, C. E., Tucker, A. W., and Zemlin, R. A. (1960). "Integer Programming Formulation of Traveling Salesman Problems." *Journal of the Association for Computing Machinery* 7:326–329.

Ostrowski, J. (2008). "Symmetry in Integer Programming." Ph.D. diss., Lehigh University.

Savelsbergh, M. W. P. (1994). "Preprocessing and Probing Techniques for Mixed Integer Programming Problems." *ORSA Journal on Computing* 6:445–454.

Chapter 15
The Network Solver

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Overview: Network Solver

The network solver includes a number of graph theory, combinatorial optimization, and network analysis algorithms. The algorithm classes are listed in Table 15.1.

Table 15.1 Algorithm Classes in the Network Solver

Algorithm Class	SOLVE WITH NETWORK Option
Biconnected components	BICONNECTEDCOMPONENTS
Maximal cliques	CLIQUE=
Connected components	CONNECTEDCOMPONENTS=
Cycle detection	CYCLE=
Linear assignment (matching)	LINEARASSIGNMENT
Maximum flow	MAXFLOW=
Minimum-cost network flow	MINCOSTFLOW
Minimum cut	MINCUT=
Minimum spanning tree	MINSPANTREE=
Path enumeration	PATH=
Shortest path	SHORTESTPATH=
Topological sort	TOPOLOGICALSORT
Transitive closure	TRANSITIVECLOSURE
Traveling salesman	TSP=
Vehicle routing	VRP=

You can use the network solver to analyze relationships between entities. These relationships are typically defined by using a *graph*. A graph, $G = (N, E)$, is defined over a set N of nodes, and a set E of links. A *node* is an abstract representation of some entity (or object), and a *link* defines some relationship (or connection) between two nodes. The terms *node* and *vertex* are often interchanged in describing an entity. The term *link* is often interchanged with the term *edge* or *arc* in describing a relationship. Similarly, the terms *graph* and *network* are interchangeable.

Unlike other solvers that PROC OPTMODEL uses, the network solver operates directly on arrays and sets. You do not need to explicitly define variables, constraints, and objectives to use the network solver. PROC OPTMODEL declares the appropriate objects internally as needed. You specify the names of arrays and sets that define your inputs and outputs as options in the SOLVE WITH NETWORK statement.

Getting Started: Network Solver

This section shows an introductory example for getting started with the network solver. For more information about the expected input formats and the various algorithms available, see the sections "Details: Network Solver" on page 804 and "Examples: Network Solver" on page 902.

Consider the following road network between a SAS employee's home in Raleigh, NC, and the SAS headquarters in Cary, NC.

In this road network (graph), the links are the roads and the nodes are intersections between roads. For each road, you assign a *link attribute* in the parameter time_to_travel to describe the number of minutes that it takes to drive from one node to another. The following data were collected using Google Maps (Google 2011):

```
data LinkSetInRoadNC10am;
   input start_inter $1-20 end_inter $21-40 miles miles_per_hour;
   datalines;
614CapitalBlvd      Capital/WadeAve      0.6  25
614CapitalBlvd      Capital/US70W        0.6  25
614CapitalBlvd      Capital/US440W       3.0  45
Capital/WadeAve     WadeAve/RaleighExpy  3.0  40
Capital/US70W       US70W/US440W         3.2  60
US70W/US440W        US440W/RaleighExpy   2.7  60
Capital/US440W      US440W/RaleighExpy   6.7  60
US440W/RaleighExpy  RaleighExpy/US40W    3.0  60
WadeAve/RaleighExpy RaleighExpy/US40W    3.0  60
RaleighExpy/US40W   US40W/HarrisonAve    1.3  55
US40W/HarrisonAve   SASCampusDrive       0.5  25
;
```

Using the network solver, you want to find the route that yields the shortest path between home (614 Capital Blvd) and the SAS headquarters (SAS Campus Drive). This can be done by using the SHORTESTPATH= option as follows:

```
proc optmodel;
   set<str,str> LINKS;
   num miles{LINKS};
   num miles_per_hour{LINKS};
   num time_to_travel{<i,j> in LINKS} = miles[i,j]/ miles_per_hour[i,j] * 60;
   read data LinkSetInRoadNC10am into
      LINKS=[start_inter end_inter]
      miles miles_per_hour
   ;
   /* You can compute paths between many pairs of source and destination,
      so these parameters are declared as sets */
   set HOME = /"614CapitalBlvd"/;
   set WORK = /"SASCampusDrive"/;

   /* The path is stored as a set of: Start, End, Sequence, Tail, Head */
   set<str,str,num,str,str> PATH;

   solve with network /
```

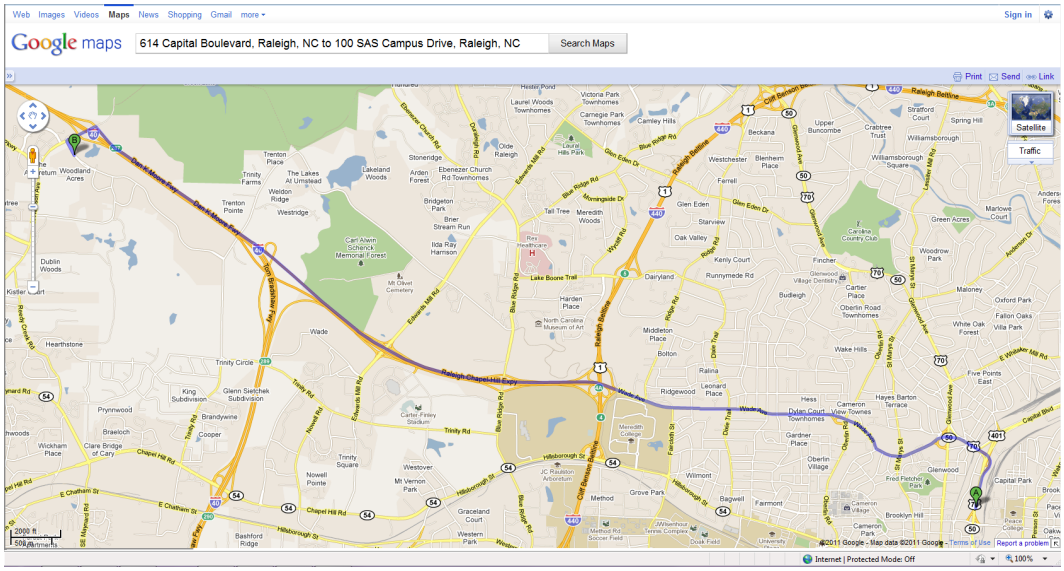
```
      links     = ( weight = time_to_travel )
      shortpath = ( source = HOME
                    sink   = WORK )
      out       = ( sppaths = PATH )
   ;
   create data ShortPath from [s t order start_inter end_inter]=PATH
      time_to_travel[start_inter,end_inter];
quit;
```

For more information about shortest path algorithms in the network solver, see the section "Shortest Path" on page 856. Figure 15.1 displays the output data set ShortPath, which shows the best route to take to minimize travel time at 10:00 a.m. This route is also shown in Google Maps in Figure 15.2.

Figure 15.1 Shortest Path for Road Network at 10:00 A.M.

order	start_inter	end_inter	time_to_travel
1	614CapitalBlvd	Capital/WadeAve	1.4400
2	Capital/WadeAve	WadeAve/RaleighExpy	4.5000
3	WadeAve/RaleighExpy	RaleighExpy/US40W	3.0000
4	RaleighExpy/US40W	US40W/HarrisonAve	1.4182
5	US40W/HarrisonAve	SASCampusDrive	1.2000
			11.5582

Figure 15.2 Shortest Path for Road Network at 10:00 A.M. in Google Maps



Now suppose that it is rush hour (5:00 p.m.) and the time to traverse the roads has changed because of traffic patterns. You want to find the route that is the shortest path for going home from SAS headquarters under different speed assumptions due to traffic.

The following statements are similar to the first network solver run, except that one *miles_per_hour* value is modified and the SOURCE= and SINK= option values are reversed:

```
proc optmodel;
   set<str,str> LINKS;
   num miles{LINKS};
   num miles_per_hour{LINKS};
   num time_to_travel{<i,j> in LINKS} = miles[i,j]/ miles_per_hour[i,j] * 60;
   read data LinkSetInRoadNC10am into
      LINKS=[start_inter end_inter]
      miles miles_per_hour
   ;
   /* high traffic */
   miles_per_hour['Capital/WadeAve','WadeAve/RaleighExpy'] = 25;

   /* You can compute paths between many pairs of source and destination,
      so these parameters are declared as sets */
   set HOME = /"614CapitalBlvd"/;
   set WORK = /"SASCampusDrive"/;

   /* The path is stored as a set of: Start, End, Sequence, Tail, Head */
   set<str,str,num,str,str> PATH;

   solve with network /
      links     = ( weight = time_to_travel )
      shortpath = ( source = WORK
                    sink   = HOME )
      out       = ( sppaths = PATH )
   ;
   create data ShortPath from [s t order start_inter end_inter]=PATH
      time_to_travel[start_inter,end_inter];
quit;
```

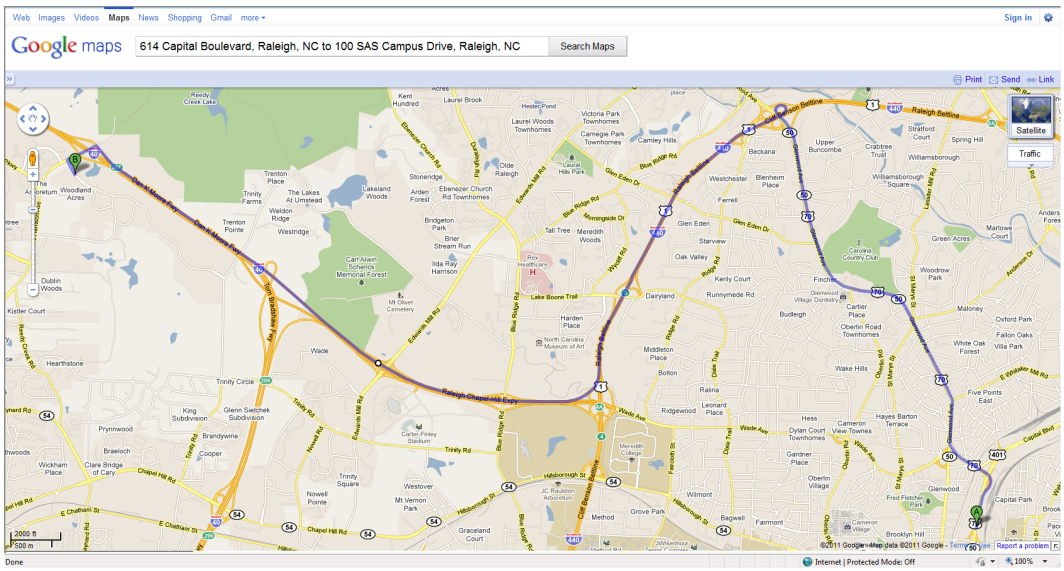
Now, the output data set ShortPath, shown in Figure 15.3, shows the best route for going home at 5:00 p.m. Because the traffic on Wade Avenue is usually heavy at this time of day, the route home is different from the route to work.

Figure 15.3 Shortest Path for Road Network at 5:00 P.M.

order	start_inter	end_inter	time_to_travel
1	US40W/HarrisonAve	SASCampusDrive	1.2000
2	RaleighExpy/US40W	US40W/HarrisonAve	1.4182
3	US440W/RaleighExpy	RaleighExpy/US40W	3.0000
4	US70W/US440W	US440W/RaleighExpy	2.7000
5	Capital/US70W	US70W/US440W	3.2000
6	614CapitalBlvd	Capital/US70W	1.4400
			12.9582

This new route is shown in Google Maps in Figure 15.4.

Figure 15.4 Shortest Path for Road Network at 5:00 P.M. in Google Maps


Web Images Videos Maps News Shopping Gmail more
Sign in
Google maps
614 Capital Boulevard, Raleigh, NC to 100 SAS Campus Drive, Raleigh, NC
Search Maps
Print Send Link
Satellite
Traffic
Raleigh Beltline
Raleigh-Chapel Hill Expy
Blue Ridge Rd
Lake Boone Trail
Wade Ave
Hillsborough St
Capital Blvd
Trinity Rd
Edwards Mill Rd
Glenwood
Brooklyn Hill
Fairmont
Bagwell
Wilmont
Method
Grove Park
Graceland Court
Chapel Hill Rd
Trinity Square
Westover
Mt Vernon Park
Nowell Pointe
Cartier-Finley Stadium
Meredith College
JC Raulston Arboretum
North Carolina Museum of Art
Mt Olivet Cemetery
Carl Alvin Schenck Memorial Forest
Lake Johnson
Reedy Creek Lake
Hearthstone
Wade
Trinity Circle
King Subdivision
Glenn Sletchek Subdivision
Prynnwood
Braeloch
Cooper
Brandywine
Wickham Place
Clare Bridge of Cary
Dublin Woods
Kistler Court
Woodland Acres
Trenton Place
Trinity Farms
The Lakes At Umstead
Weldon Ridge
Westridge
Trenton Pointe
Lakeland Woods
Stoneridge
Arden Forest
Ebenezer Church Rd Townhomes
Bridgeton Park
Brier Stream Run
Ilda Ray Harrison
Kent Hundred
Laurel Brook
Hester Pond
Laurel Woods Townhomes
Victoria Park Townhomes
Carnegie Park Townhomes
Camley Hills
Olde Raleigh
Laurel Hills Park
Glen Eden Dr
Blue Ridge Rd
Hillsborough St
Tall Tree
Meredith Woods
Harden Place
Rex HealthCare
Oak Valley
Starview
Glen Eden
Westchester
Ferrell
Beckana
Blenheim Place
Upper Buncombe
Crabtree Trust
Stratford Court
Spring Hill
Williamsborough
Williamsborough Square
Green Acres
Marlowe Court
Carolina Country Club
Woodrow Park
Anderson Dr
Kenly Court
Runnymede Rd
Daryland
Budleigh
Finch
Glenwood Village Dentistry
Cartier Place
Oberlin Road Townhomes
Maloney
Oxford Park
Fallon Oaks Villa Park
White Oak Forest
E Whitaker Mill Rd
Five Points East
Wake Hills
Middleton Place
Bolton
Raina
Ridgewood
Leonard Place
Hess
Dylan Court Townhomes
Cameron View Townhomes
Hayes Barton Terrace
Gardner Place
Oberlin Village
Cameron Village
Fred Fletcher Park
Glenwood
Capital Park
St Mary's St
Oberlin Rd
Wade Ave
Dean Trail
Ridge Rd
Pine Rd
Fairoaks St
Meredith College
Cliff Dawson Parkway
Blue Ridge Rd
Edwards Mill Rd
Trinity Rd
Nowell Rd
Chapel Hill Rd
E Chatham St
Hearthstone
Kistler Court
Dublin Woods
Woodland Acres
Wade
Trinity Circle
Prynnwood
Braeloch
Cooper
Brandywine
Wickham Place
Clare Bridge of Cary
Trinity Square
Westover
Mt Vernon Park
Nowell Pointe
Graceland Court
Grove Park
Method
Wilmont
Bagwell
Fairmont
Glenwood
Brooklyn Hill
Capital Park
Fred Fletcher Park
Oberlin Village
Cameron Village
Gardner Place
Hayes Barton Terrace
Five Points East
Oxford Park
Maloney
Woodrow Park
Green Acres
Marlowe Court
Carolina Country Club
Budleigh
Finch
Runnymede Rd
Kenly Court
Starview
Glen Eden
Oak Valley
Westchester
Ferrell
Beckana
Blenheim Place
Upper Buncombe
Crabtree Trust
Stratford Court
Spring Hill
Williamsborough
Williamsborough Square

Syntax: Network Solver

SOLVE WITH NETWORK /

General and Diagnostic Options:
< **GRAPH_DIRECTION=DIRECTED** | **UNDIRECTED** >
< **INCLUDE_SELFLINK** >
< **LOGFREQ=***number* >
< **LOGLEVEL=***number* | *string* >
< **MAXTIME=***number* >
< **NTHREADS=***number* >
< **TIMETYPE=***number* | *string* >

Data Input and Output Options:
< **LINKS=(** *suboptions* **)** >
< **NODES=(** *suboptions* **)** >
< **OUT=(** *suboptions* **)** >
< **SUBGRAPH=(** *suboptions* **)** >

Algorithm Options:
< **BICONNECTEDCOMPONENTS** < **=()** > >
< **CLIQUE** < **=(** *suboptions* **)** > >
< **CONNECTEDCOMPONENTS** < **=(** *suboption* **)** > >
< **CYCLE** < **=(** *suboptions* **)** > >
< **LINEARASSIGNMENT** < **=()** > >
< **MAXFLOW** < **=(** *suboptions* **)** > >
< **MINCOSTFLOW** < **=()** > >
< **MINCUT** < **=(** *suboptions* **)** > >
< **MINSPANTREE** < **=(** *suboptions* **)** > >
< **PATH** < **=(** *suboptions* **)** > >
< **SHORTESTPATH** < **=(** *suboptions* **)** > >
< **TOPOLOGICALSORT** < **=()** > >
< **TRANSITIVECLOSURE** < **=()** > >
< **TSP** < **=(** *suboptions* **)** > >
< **VRP=(** *suboptions* **)** > **;**

There are three types of SOLVE WITH NETWORK statement options:

- General and diagnostic options have the same meaning for multiple algorithms.
- Data input and output options, such as the LINKS=, NODES=, and OUT= options, control the names of the sets and variables that the network solver uses to build the graph and that the algorithms use for output.
- Algorithm options select an algorithm to run, and where available, provide further algorithm-specific configuration directives.

The section "Functional Summary" on page 780 provides a quick reference for each of the suboptions for each option. Each option is then described in more detail in its own section, in alphabetical order.

Functional Summary

Table 15.2 summarizes the options and suboptions available in the SOLVE WITH NETWORK statement.

Table 15.2 Functional Summary of SOLVE WITH NETWORK Options

Description	Option Suboption
General Options	
Specifies directed or undirected graphs	GRAPH_DIRECTION=
Includes self links in the graph definition	INCLUDE_SELFLINK=
Specifies the iteration log frequency	LOGFREQ=
Controls the amount of information that is displayed in the SAS log	LOGLEVEL=
Specifies the maximum time spent calculating results	MAXTIME=
Specifies the number for threads to use for threaded processing	NTHREADS=
Specifies whether time units are in CPU time or real time	TIMETYPE=
Input and Output Options	
Groups link-indexed data	LINKS=()
Names a set of links to include in the graph definition even if no weights or bounds are available for them	INCLUDE=
Specifies the flow lower bound for each link	LOWER=
Specifies the flow upper bound for each link	UPPER=
Specifies link weights	WEIGHT=
Groups node-indexed data	NODES=()
Names a set of nodes to include in the graph definition even if no weights are available for them	INCLUDE=
Specifies node supply lower bounds in the minimum-cost network flow problem	LOWER=
Specifies node supply upper bounds in the minimum-cost network flow problem	UPPER=
Specifies node weights	WEIGHT=
Specifies the input sets that enable you to solve a problem over a subgraph	SUBGRAPH=()
Specifies the subset of links to use	LINKS=
Specifies the subset of nodes to use	NODES=
Specifies the output sets or arrays for each algorithm (see Table 15.4 for which OUT= suboptions you can specify for each algorithm)	OUT=()
Specifies the output array for the arrival times of vehicles to the nodes	ARRIVAL=
Specifies the output set for articulation points	ARTPOINTS=
Specifies the output set for linear assignment	ASSIGNMENTS=
Specifies the array to contain the biconnected component of each link	BICONCOMP=
Specifies the output set for cliques	CLIQUES=
Specifies the set to contain the pairs (u, v) of nodes where v is reachable from u	CLOSURE=

Table 15.2 *(continued)*

Description	Option Suboption
Specifies the output array for connected components	CONCOMP=
Specifies the output set for the cut sets for minimum cuts	CUTSETS=
Specifies the output set for nodes in cycles	CYCLES=
Specifies the output set for links in cycles	CYCLESLINKS=
Specifies the output array for the dual values of node constraints	DUAL=
Specifies the output array for the flow on each link	FLOW=
Specifies the output set for the minimum spanning tree (forest)	FOREST=
Specifies the output set for the links that remain after the SUBGRAPH= option is applied	LINKS=
Specifies the array to contain the node clique number of each node	NODECLIQUE=
Specifies the output set for the nodes that remain after the SUBGRAPH= option is applied	NODES=
Specifies the output array for the node order	ORDER=
Specifies the output set for the partitions for minimum cuts	PARTITIONS=
Specifies the output set for path link sequences	PATHSLINKS=
Specifies the output set for path node sequences	PATHSNODES=
Specifies the output set for path weights	PATHSWEIGHTS=
Specifies the output array for the reduced costs of link flow variables	RC=
Specifies the output array for the vehicle routing assignments	ROUTE=
Specifies the set to contain the link sequence for each path	SPPATHS=
Specifies the numeric array to contain the path weight for each source and sink node pair	SPWEIGHTS=
Specifies the output set for the tour in the traveling salesman problem	TOUR=
Specifies the output set for the vehicle routing links	VRPLINKS=
Algorithm Options and Suboptions	
Finds biconnected components and articulation points of an undirected input graph	BICONNECTEDCOMPONENTS
Finds maximal cliques in the input graph	CLIQUE=
Specifies the maximum number of cliques to return	MAXCLIQUES=
Specifies the maximum link weight for the cliques found	MAXLINKWEIGHT=
Specifies the maximum node weight for the cliques found	MAXNODEWEIGHT=
Specifies the maximum size for the cliques found	MAXSIZE=
Specifies the minimum link weight for the cliques found	MINLINKWEIGHT=
Specifies the minimum node weight for the cliques found	MINNODEWEIGHT=
Specifies the minimum size for the cliques found	MINSIZE=
Finds the connected components of the input graph	CONNECTEDCOMPONENTS=
Specifies the algorithm to use for calculating connected components	ALGORITHM=
Finds the cycles (or the existence of a cycle) in the input graph	CYCLE=
Specifies the algorithm to use in enumerating cycles	ALGORITHM=
Specifies the maximum number of cycles to return	MAXCYCLES=

Table 15.2 *(continued)*

Description	Option Suboption
Specifies the maximum link count to allow in a cycle	MAXLENGTH=
Specifies the maximum sum of link weights to allow in a cycle	MAXLINKWEIGHT=
Specifies the maximum sum of node weights to allow in a cycle	MAXNODEWEIGHT=
Specifies the minimum link count to allow in a cycle	MINLENGTH=
Specifies the minimum sum of link weights to allow in a cycle	MINLINKWEIGHT=
Specifies the minimum sum of node weights to allow in a cycle	MINNODEWEIGHT=
Solves the minimal-cost linear assignment problem	LINEARASSIGNMENT
Finds the maximum flow in an input graph	MAXFLOW=
Specifies the single-element set that consists of the sink node	SINK=
Specifies the single-element set that consists of the source node	SOURCE=
Solves the minimum-cost network flow problem	MINCOSTFLOW
Finds the minimum link-weighted cut of an input graph	MINCUT=
Specifies the maximum number of cuts to return from the algorithm	MAXCUTS=
Specifies the maximum weight of each cut to return from the algorithm	MAXWEIGHT=
Specifies the single-element set that consists of the sink node	SINK=
Specifies the single-element set that consists of the source node	SOURCE=
Solves the minimum link-weighted spanning tree problem on an input graph	MINSPANTREE=
Specifies the single-element set that consists of the source node	SOURCE=
Finds the paths between sets of nodes on the input graph	PATH=
Specifies the maximum link count to allow in a path	MAXLENGTH=
Specifies the maximum sum of link weights to allow in a path	MAXLINKWEIGHT=
Specifies the maximum sum of node weights to allow in a path	MAXNODEWEIGHT=
Specifies the minimum link count to allow in a path	MINLENGTH=
Specifies the minimum sum of link weights to allow in a path	MINLINKWEIGHT=
Specifies the minimum sum of node weights to allow in a path	MINNODEWEIGHT=
Specifies the set of sink nodes	SINK=
Specifies the set of source nodes	SOURCE=
Calculates shortest paths between sets of nodes on the input graph	SHORTESTPATH=
Specifies the maximum absolute objective gap for the paths found	MAXABSOBJGAP=
Specifies the maximum sum of link weights to allow in a shortest path	MAXLINKWEIGHT=
Specifies the maximum number of ranked paths to find for each pair	MAXPATHSPERPAIR=
Specifies the maximum relative objective gap for the paths found	MAXRELOBJGAP=
Specifies the minimum sum of link weights to allow in a shortest path	MINLINKWEIGHT=
Specifies a sequence of nodes to be visited in the shortest path	SEQUENCE=
Specifies the set of sink nodes	SINK=
Specifies the set of source nodes	SOURCE=
Finds a topological sort of an input graph	TOPOLOGICALSORT
Calculates the transitive closure of an input graph	TRANSITIVECLOSURE

Table 15.2 *(continued)*

Description	Option Suboption
Solves the traveling salesman problem	TSP=
Requests that the stopping criterion be based on the absolute objective gap	ABSOBJGAP=
Specifies the cutoff value for branch-and-bound node removal	CUTOFF=
Specifies the level of cutting planes to be generated by the network solver	CUTSTRATEGY=
Specifies the primal heuristics level	HEURISTICS=
Specifies the maximum number of branch-and-bound nodes to be processed	MAXNODES=
Specifies the maximum number of feasible tours to be identified	MAXSOLS=
Specifies whether to use a mixed integer linear programming solver	MILP=
Requests that the stopping criterion be based on the relative objective gap	RELOBJGAP=
Requests that the stopping criterion be based on the target objective value	TARGET=
Solves the vehicle routing problem	VRP=
Requests that the stopping criterion be based on the absolute objective gap	ABSOBJGAP=
Specifies the capacity of each vehicle	CAPACITY=
Specifies the cutoff value for branch-and-bound node removal	CUTOFF=
Specifies the level of cutting planes to be generated by the network solver	CUTSTRATEGY=
Specifies the name of the array that contains the node demands	DEMAND=
Specifies the name of the single-element set that consists of the depot node	DEPOT=
Specifies the primal heuristics level	HEURISTICS=
Specifies the maximum number of branch-and-bound nodes to be processed	MAXNODES=
Specifies the maximum number of routes to be allowed to service demand	MAXROUTES=
Specifies the maximum number of feasible solutions to be identified	MAXSOLS=
Specifies whether to use a mixed integer linear programming solver	MILP=
Specifies the minimum number of routes to be allowed to service demand	MINROUTES=
Requests that the stopping criterion be based on the relative objective gap	RELOBJGAP=
Specifies the name of the array that contains the service time for the nodes—that is, how long the vehicle must stay at the node; this suboption is used only for a vehicle routing problem with time windows.	SERVICETIME=
Requests that the stopping criterion be based on the target objective value	TARGET=

Table 15.2 *(continued)*

Description	Option Suboption
Specifies the name of the array that contains the earliest time when a vehicle can start to serve a node (though it might arrive earlier); this suboption is used only for a vehicle routing problem with time windows.	TIMEWINDOWLOWER=
Specifies the name of the array that contains the latest time when a vehicle can arrive at a node; this suboption is used only for a vehicle routing problem with time windows.	TIMEWINDOWUPPER=
Specifies the name of the array that contains the travel time for the links; this suboption is used only for a vehicle routing problem with time windows.	TRAVELTIME=

Table 15.3 lists the valid GRAPH_DIRECTION= values for each algorithm option in the SOLVE WITH NETWORK statement.

Table 15.3 Supported Graph Directions by Algorithm

	Direction	
Algorithm	Undirected	Directed
BICONNECTEDCOMPONENTS	x	
CLIQUE	x	
CONNECTEDCOMPONENTS		
AFFOREST	x	
DFS	x	x
UNIONFIND	x	
CYCLE	x	x
LINEARASSIGNMENT		x
MAXFLOW		
SINK=, SOURCE=		x
MINCOSTFLOW		x
MINCUT		
SINK=, SOURCE=	x	x
Otherwise	x	
MINSPANTREE	x	x
PATH	x	x
SHORTESTPATH	x	x
TOPOLOGICALSORT		x
TRANSITIVECLOSURE	x	x
TSP	x	x
VRP	x	x

Table 15.4 indicates, for each algorithm option in the SOLVE WITH NETWORK statement, which output options you can specify and what their types can be. The types vary depending on whether nodes are of type

STRING or NUMBER.

Table 15.4 Output Suboptions and Types by Algorithm

Algorithm Option OUT= Suboption	OPTMODEL Type
BICONNECTEDCOMPONENTS	
ARTPOINTS=	SET<STRING> or SET<NUMBER>
BICONCOMP=	NUMBER indexed over links (<NUMBER,NUMBER> or <STRING,STRING>)
CLIQUE=	
CLIQUES=	SET<NUMBER,NUMBER> or SET<NUMBER,STRING>
NODECLIQUE=	NUMBER indexed over nodes (NUMBER or STRING)
CONNECTEDCOMPONENTS=	
CONCOMP=	NUMBER indexed over nodes (NUMBER or STRING)
CYCLE=	
CYCLES=	SET<NUMBER,NUMBER,NUMBER> or SET<NUMBER,NUMBER,STRING>
CYCLESLINKS=	SET<NUMBER,NUMBER,NUMBER,NUMBER> or SET<NUMBER,NUMBER,STRING,STRING>
LINEARASSIGNMENT	
ASSIGNMENTS=	SET<NUMBER,NUMBER> or SET<STRING,STRING>
MAXFLOW=	
FLOW=	NUMBER indexed over links (<NUMBER,NUMBER> or <STRING,STRING>)
MINCOSTFLOW	
DUAL=	NUMBER indexed over nodes (NUMBER or STRING)
FLOW=	NUMBER indexed over links (<NUMBER,NUMBER> or <STRING,STRING>)
RC=	NUMBER indexed over links (<NUMBER,NUMBER> or <STRING,STRING>)
MINCUT=	
CUTSETS=	SET<NUMBER,NUMBER,NUMBER> or SET<NUMBER,STRING,STRING>
PARTITIONS=	SET<NUMBER,NUMBER> or SET<NUMBER,STRING>
MINSPANTREE	
FOREST=	SET<NUMBER,NUMBER> or SET<STRING,STRING>
PATH=	
PATHSLINKS=	SET<NUMBER,NUMBER,NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,NUMBER,STRING,STRING>
PATHSNODES=	SET<NUMBER,NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,NUMBER,STRING>

Table 15.4 *(continued)*

Algorithm Option OUT= Suboption	OPTMODEL Type
SHORTESTPATH=	
PATHSLINKS=	SET<NUMBER,NUMBER,NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,NUMBER,STRING,STRING>
PATHSNODES=	SET<NUMBER,NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,NUMBER,STRING>
PATHSWEIGHTS=	SET<NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,NUMBER>
SPPATHS=	SET<NUMBER,NUMBER,NUMBER,NUMBER,NUMBER> or SET<STRING,STRING,NUMBER,STRING,STRING>
SPWEIGHTS=	NUMBER indexed over sink and source node pairs (<NUMBER,NUMBER> or <STRING,STRING>)
TOPOLOGICALSORT	
ORDER=	NUMBER indexed over nodes (NUMBER or STRING)
TRANSITIVECLOSURE	
CLOSURE=	SET<NUMBER,NUMBER> or SET<STRING,STRING>
TSP=	
ORDER=	NUMBER indexed over nodes (NUMBER or STRING)
TOUR=	SET<NUMBER,NUMBER> or SET<STRING,STRING>
VRP=	
ARRIVAL=	NUMBER indexed over nodes (NUMBER or STRING)
ORDER=	NUMBER indexed over nodes (NUMBER or STRING)
ROUTE=	NUMBER indexed over nodes (NUMBER or STRING)
VRPLINKS=	SET<NUMBER,NUMBER,NUMBER,NUMBER> or SET<NUMBER,NUMBER,STRING,STRING>

SOLVE WITH NETWORK Statement

SOLVE WITH NETWORK */ < options >* **;**

The SOLVE WITH NETWORK statement invokes the network solver. You can specify the following *options* to define various processing and diagnostic controls, the graph input and output, and the algorithm to run:

General Options

You can specify the following general options, which have the same meaning for multiple algorithms.

GRAPH_DIRECTION=DIRECTED | UNDIRECTED
DIRECTION=DIRECTED | UNDIRECTED
specifies directed or undirected graphs.

Table 15.5 Values for the GRAPH_DIRECTION= Option

Option Value	Description
DIRECTED	Requests a directed graph. In a directed graph, each link (i, j) has a direction that defines how something (for example, information) might flow over that link. In link (i, j), information flows from node i to node j ($i \rightarrow j$). The node i is called the *source* (*tail*) node, and node j is called the *sink* (*head*) node.
UNDIRECTED	Requests an undirected graph. In an undirected graph, each link $\{i, j\}$ has no direction and information can flow in either direction. That is, $\{i, j\} = \{j, i\}$.

By default, GRAPH_DIRECTION=UNDIRECTED.

INCLUDE_SELFLINK
includes self links in the graph definition—for example, (i, i)—when an input graph is read. By default, when the network solver reads the LINKS= data, it removes all self links.

LOGFREQ=*number*
controls the frequency with which an algorithm reports progress from its underlying solver. This setting is recognized by the traveling salesman problem, vehicle routing problem, and minimum-cost network flow problem algorithms. You can set *number* to 0 to turn off log updates from underlying algorithms.

LOGLEVEL=*number* | *string*
controls the amount of information that is displayed in the SAS log. This setting sets the log level for all algorithms. Table 15.6 describes the valid values for this option.

Table 15.6 Values for LOGLEVEL= Option

number	*string*	Description
0	NONE	Turns off all procedure-related messages in the SAS log
1	BASIC	Displays a basic summary of the input, output, and algorithmic processing
2	MODERATE	Displays a summary of the input, output, and algorithmic processing
3	AGGRESSIVE	Displays a detailed summary of the input, output, and algorithmic processing

By default, LOGLEVEL=BASIC.

MAXTIME=*number*

specifies the maximum time spent calculating results. The type of time (either CPU time or real time) is determined by the value of the TIMETYPE= option. The value of *number* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment. The clique, cycle, linear assignment problem, minimum-cost network flow, path enumeration, traveling salesman problem, and vehicle routing problem algorithms recognize the MAXTIME= option.

NTHREADS=*number*

specifies the number for threads to use for threaded processing. Algorithms that are specified by the CLIQUE, CYCLE (with the ALGORITHM=BUILD suboption), PATH, or SHORTESTPATH options can use threaded processing. The value of *number* must be an integer between 1 and 256, inclusive. The default is the value of the OPTMODEL NTHREADS= option.

TIMETYPE=*number* | *string*

specifies whether CPU time or real time is used for measuring solution times. This affects the MAXTIME= option for each applicable algorithm. Table 15.7 describes the valid values of the TIMETYPE= option.

Table 15.7 Values for TIMETYPE= Option

number	*string*	**Description**
0	CPU	Specifies units of CPU time
1	REAL	Specifies units of real time

By default, TIMETYPE=REAL.

Input and Output Options

The following options enable you to specify the graph to run algorithms on. These options take array and set names. They are known as *identifier expressions* in Chapter 9, "The OPTMODEL Procedure." Also see Table 15.4 for semantic requirements and the section "Input Data for the Network Solver" on page 804 for use cases.

LINKS=(*suboptions* **)**

groups link-indexed data. For more information, see the section "Input Data for the Network Solver" on page 804.

You can specify the following *suboptions*:

INCLUDE=*set-name*

names a set of links to include in the graph definition even if no weights or bounds are available for them. Each pair of the set represents a tail node and a head node for a link in the graph.

LOWER=*array-name*
specifies the flow lower bound for each link. The array must be numeric, and it must be indexed over a subset of the links of the graph.

UPPER=*array-name*
specifies the flow upper bound for each link. The array must be numeric, and it must be indexed over a subset of the links of the graph.

WEIGHT=*array-name*
specifies link weights. The array must be numeric, and it must be indexed over a subset of the links of the graph. If you specify this suboption, then any link that does not appear in the index set of the WEIGHT= array has weight 0. If you do not specify this suboption, then every link has weight 1.

NODES=(*suboptions* **)**
groups node-indexed data. For more information, see the section "Input Data for the Network Solver" on page 804.

You can specify the following *suboptions*:

INCLUDE=*set-name*
names a set of nodes to include in the graph definition even if no weights are available for them. For an example, see the section "Connected Components" on page 821

LOWER=*array-name*
specifies node supply lower bounds in the minimum-cost network flow problem. The array must be numeric, and it must be indexed over a subset of the nodes of the graph. For more information, see the section "Minimum-Cost Network Flow" on page 836.

UPPER=*array-name*
specifies node supply upper bounds in the minimum-cost network flow problem. The array must be numeric, and it must be indexed over a subset of the nodes of the graph. For more information, see the section "Minimum-Cost Network Flow" on page 836.

WEIGHT=*array-name*
specifies node weights. The array must be numeric, and it must be indexed over a subset of the nodes of the graph. If you specify this suboption, then any node that does not appear in the index set of the WEIGHT= array has weight 0. If you do not specify this suboption, then every node has weight 1.

OUT=(*suboptions* **)**
specifies the output sets or arrays for each algorithm (see Table 15.4 for which OUT= suboptions you can specify for each algorithm). You can use some of these options (even if you do not invoke any algorithm) to see the filtering outcome that is produced by the SUBGRAPH= option.

If you do not specify a *suboption* that matches the algorithm option in the statement, the algorithm runs and only updates the objective.

If you specify a suboption that does not match the algorithm option in the statement, OPTMODEL issues a warning.

When you declare arrays that are indexed over nodes, over links, or over sets of nodes or links, you must use the same type you used in your node definition.

See the various algorithm sections for examples of the use of these OUT= *suboptions*.

ARRIVAL=*array-name*
specifies the output array for the arrival times of vehicles to the nodes. This suboption is used with the VRP= algorithm option.

ARTPOINTS=*set-name*
specifies the output set for articulation points. Each element of the set represents a node ID. This suboption is used with the BICONNECTEDCOMPONENTS algorithm option.

ASSIGNMENTS=*set-name*
specifies the output set for linear assignment. This suboption is used with the LINEARASSIGNMENT algorithm option.

BICONCOMP=*array-name*
specifies the array to contain the biconnected component of each link. This suboption is used with the BICONNECTEDCOMPONENTS algorithm option.

CLIQUES=*set-name*
specifies the output set for cliques. Each tuple of the set represents clique ID and node ID. This suboption is used with the CLIQUE= algorithm option.

CLOSURE=*set-name*
specifies the set to contain the pairs (u, v) of nodes where v is reachable from u. This suboption is used with the TRANSITIVECLOSURE algorithm option.

CONCOMP=*array-name*
specifies the output array for connected components. This suboption is used with the CONNECTEDCOMPONENTS= algorithm option.

CUTSETS=*set-name*
specifies the output set for the cut sets for minimum cuts. Each tuple of the set represents the cut ID, the tail node ID, and the head node ID. This suboption is used with the MINCUT= algorithm option.

CYCLES=*set-name*
specifies the output set for nodes in cycles. Each tuple of the set represents a cycle ID, the order within that cycle, and the node ID. This suboption is used with the CYCLE= algorithm option.

CYCLESLINKS=*set-name*
specifies the output set for links in cycles. Each tuple of the set represents a cycle ID, the order within that cycle, the tail node ID, and the head node ID. This suboption is used with the CYCLE= algorithm option.

DUAL=*array-name*
specifies the output array for the dual values of node constraints. For information about dual values, see the section "Dual Values" on page 425. This suboption is used with the MINCOSTFLOW algorithm option.

FLOW=*array-name*
specifies the output array for the flow on each link. This suboption is used with the MAXFLOW= and MINCOSTFLOW algorithm options.

FOREST=*set-name*
specifies the output set for the minimum spanning tree (forest). This suboption is used with the MINSPANTREE algorithm option.

LINKS=*set-name*
specifies the output set for the links that remain after the SUBGRAPH= option is applied. Each tuple of the set represents tail and head nodes, followed by a sequence of numbers that correspond to the attributes that you provide in the LINKS= suboptions. The length of the tuples must be the number of attributes that you specify plus 2 (for the tail and head node information). The options that you specify in the LINKS= option will appear in the output in the following order: WEIGHT=, LOWER=, and UPPER=. For an example, see Figure 15.12 in "Solving over Subsets of Nodes and Links (Filters)" on page 808.

NODECLIQUE=*array-name*
specifies the array to contain the node clique number of each node. Each element of the array represents the node clique number of a node. This suboption is used with the CLIQUE= algorithm option.

NODES=*set-name*
specifies the output set for the nodes that remain after the SUBGRAPH= option is applied. Each tuple of the set represents a node, followed by a sequence of numbers that correspond to the attributes that you provide in the NODES= suboptions. The length of the tuples must be the number of attributes that you specify plus 1 (for node information). The options that you specify in the NODES= option will appear in the output in the following order: WEIGHT=, LOWER=, and UPPER=. For an example, see the section "Minimum-Cost Network Flow with Flexible Supply and Demand" on page 840.

ORDER=*array-name*
specifies the output array for the node order. This suboption is used with the TOPOLOGICALSORT, TSP=, and VRP= algorithm options.

PARTITIONS=*set-name*
specifies the output set for the partitions for minimum cuts. The set contains, for each partition, the node IDs in the smaller of the two subsets. Each tuple of the set represents a cut ID and a node ID. This suboption is used with the MINCUT= algorithm option.

PATHSLINKS=*set-name*
specifies the output set for path link sequences. Each tuple of the set represents a source node ID, a sink node ID, a path ID, the order within the path, a tail node ID, and a head node ID. This suboption is used with the PATH= and SHORTESTPATH= algorithm options.

PATHSNODES=*set-name*
specifies the output set for path node sequences. Each tuple of the set represents a source node ID, a sink node ID, a path ID, the order within the path, and a node ID. This suboption is used with the PATH= and SHORTESTPATH= algorithm options.

PATHSWEIGHTS=*set-name*
specifies the output set for path weights. Each tuple of the set represents a source node ID, a sink node ID, a path ID, the order within the path, and the sum of link weights on the path. This suboption is used with the SHORTESTPATH= algorithm option.

RC=*array-name*
specifies the output array for the reduced costs of link flow variables. For information about reduced costs, see the section "Reduced Costs" on page 431. This suboption is used with the MINCOSTFLOW algorithm option.

ROUTE=*array-name*
specifies the output array for the vehicle routing assignments. This suboption is used with the VRP= algorithm option.

SPPATHS=*set-name*
specifies the set to contain the link sequence for each path. Each tuple of the set represents a source node ID, a sink node ID, a sequence number, a tail node ID, and a head node ID. This suboption is used with the SHORTESTPATH= algorithm option.

SPWEIGHTS=*array-name*
specifies the numeric array to contain the path weight for each source and sink node pair. This suboption is used with the SHORTESTPATH= algorithm option.

TOUR=*set-name*
specifies the output set for the tour in the traveling salesman problem. This suboption is used with the TSP= algorithm option.

VRPLINKS=*set-name*
specifies the output set for the vehicle routing links. This suboption is used with the VRP= algorithm option.

SUBGRAPH=(*suboptions* **)**
specifies the input sets that enable you to solve a problem over a subgraph. For more information, see the section "Input Data for the Network Solver" on page 804.

You can specify the following *suboptions*:

LINKS=*set-name*
specifies the subset of links to use. If you specify a node pair that is not referenced in any of the suboptions of the LINKS= option, then the network solver returns an error.

NODES=*set-name*
specifies the subset of nodes to use. If you specify a node that is not referenced in any of the suboptions of the LINKS= option or the NODES= option, then the network solver returns an error.

Algorithm Options

BICONNECTEDCOMPONENTS< =() >

BICONCOMP< =() >

finds biconnected components and articulation points of an undirected input graph. For more information, see the section "Biconnected Components and Articulation Points" on page 813.

CLIQUE< =(*suboptions* **) >**

finds maximal cliques in the input graph. For more information, see the section "Clique" on page 817.

You can specify the following *suboptions*:

MAXCLIQUES=*number* **| ALL**

specifies the maximum number of cliques to return. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. ALL represents the maximum value, $2^{31} - 1$. The default is 1.

MAXLINKWEIGHT=*number*

specifies the maximum sum of link weights in a clique. Any clique whose sum of link weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment. By default, no cliques are removed from the results.

MAXNODEWEIGHT=*number*

specifies the maximum sum of node weights in a clique. Any clique whose sum of node weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment. By default, no cliques are removed from the results.

MAXSIZE=*number*

specifies the maximum number of nodes in a clique. Any clique whose size is greater than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. The default is the maximum value, $2^{31} - 1$. By default, no cliques are removed from the results.

MINLINKWEIGHT=*number*

specifies the minimum sum of link weights in a clique. Any clique whose sum of link weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment. By default, no cliques are removed from the results.

MINNODEWEIGHT=*number*

specifies the minimum sum of node weights in a clique. Any clique whose sum of node weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment. By default, no cliques are removed from the results.

MINSIZE=*number*
specifies the minimum number of nodes in a clique. Any clique that has fewer nodes than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. By default, MINSIZE=1 and no cliques are removed from the results.

CONNECTEDCOMPONENTS< =(*suboption* **) >**
CONCOMP< =(*suboption* **) >**
finds the connected components of the input graph. For more information, see the section "Connected Components" on page 821.

You can specify the following *suboption*:

ALGORITHM=AUTOMATIC | AFFOREST | DFS | UNIONFIND
specifies the algorithm to use for calculating connected components. Table 15.8 describes the valid values for this option.

Table 15.8 Values for the ALGORITHM= Option

Option Value	Description
AUTOMATIC	Automatically determines the algorithm for connected components
AFFOREST	Uses the afforest algorithm for connected components. You can specify ALGORITHM=AFFOREST only with undirected graphs.
DFS	Uses the depth-first search algorithm for connected components
UNIONFIND	Uses the union-find algorithm for connected components. You can specify ALGORITHM=UNIONFIND only with undirected graphs.

By default, ALGORITHM=AUTOMATIC.

CYCLE< =(*suboptions* **) >**
finds the cycles (or the existence of a cycle) in the input graph. For more information, see the section "Cycle" on page 826.

You can specify the following *suboptions* in the CYCLE= option:

ALGORITHM=BACKTRACK | BUILD
specifies the algorithm to use in enumerating cycles. Table 15.9 lists the valid values for this option.

Table 15.9 Values for the ALGORITHM= Option

Option Value	Description
BACKTRACK	Uses a backtracking algorithm based on Johnson (1975)
BUILD	Uses a building algorithm based on Liu and Wang (2006)

By default, ALGORITHM=BACKTRACK for MAXLENGTH= values greater than 20; otherwise, ALGORITHM=BUILD.

MAXCYCLES=*number* | **ALL**
specifies the maximum number of cycles to return. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. ALL represents the maximum value, $2^{31} - 1$. The default is 1.

MAXLENGTH=*number*
specifies the maximum number of links to allow in a cycle. Any cycle whose length is greater than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. The default is the maximum value, $2^{31} - 1$. By default, nothing is removed from the results.

MAXLINKWEIGHT=*number*
specifies the maximum sum of link weights to allow in a cycle. Any cycle whose sum of link weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment. By default, nothing is filtered.

MAXNODEWEIGHT=*number*
specifies the maximum sum of node weights to allow in a cycle. Any cycle whose sum of node weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment. By default, nothing is filtered.

MINLENGTH=*number*
specifies the minimum number of links to allow in a cycle. Any cycle that has fewer links than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. The default is 1. By default, only self-loops are filtered.

MINLINKWEIGHT=*number*
specifies the minimum sum of link weights to allow in a cycle. Any cycle whose sum of link weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment. By default, nothing is filtered.

MINNODEWEIGHT=*number*
specifies the minimum sum of node weights to allow in a cycle. Any cycle whose sum of node weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment. By default, nothing is filtered.

LINEARASSIGNMENT< =() >

LAP< =() >
solves the minimal-cost linear assignment problem. In graph terms, this problem is also known as the minimum link-weighted matching problem on a bipartite directed graph. The input data (the cost matrix) are defined as a directed graph by specifying the LINKS= option in the SOLVE WITH NETWORK statement, where the costs are defined as link weights. Internally, the graph is treated as a bipartite directed graph.

For more information, see the section "Linear Assignment (Matching)" on page 832.

MAXFLOW< =(*suboptions* **) >**

finds the maximum flow in an input graph. For more information, see the section "Maximum Flow" on page 833. You can specify the following *suboptions* in the MAXFLOW= option:

SINK=*set-name*

specifies the single-element set that consists of the sink node.

SOURCE=*set-name*

specifies the single-element set that consists of the source node.

MINCOSTFLOW< =() >

MCF< =() >

solves the minimum-cost network flow problem.

For more information, see the section "Minimum-Cost Network Flow" on page 836.

MINCUT< =(*suboptions* **) >**

finds the minimum link-weighted cut of an input graph. For more information, see the section "Minimum Cut" on page 842. You can specify the following *suboptions* in the MINCUT= option:

MAXCUTS=*number*

specifies the maximum number of cuts to return from the algorithm. A minimum cut and any other cuts (possibly not minimum) that the algorithm finds during the search, up to *number*, are returned. By default, MAXCUTS=1.

MAXWEIGHT=*number*

specifies the maximum weight of the cuts to return from the algorithm. Only cuts that have weight less than or equal to *number* are returned. The default is the positive number that has the largest absolute value that can be represented in your operating environment.

SINK=*set-name*

specifies the single-element set that consists of the sink node.

SOURCE=*set-name*

specifies the single-element set that consists of the source node.

MINSPANTREE< =(*suboptions* **) >**

MST< =(*suboptions* **) >**

solves the minimum link-weighted spanning tree problem on an input graph. For more information, see the section "Minimum Spanning Tree" on page 848. You can specify the following *suboption* in the MINSPANTREE= option:

SOURCE=*set-name*

specifies the single-element set that consists of the source node.

PATH< =(*suboptions* **) >**

finds the paths between sets of nodes on the input graph. You can specify the following *suboptions*:

MAXLENGTH=*number*
specifies the maximum number of links to allow in a path. Any path whose length is greater than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. The default is the maximum value, $2^{31} - 1$, which causes nothing to be removed from the results.

MAXLINKWEIGHT=*number*
specifies the maximum sum of link weights to allow in a path. Any path whose sum of link weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment, which causes nothing to be removed from the results.

MAXNODEWEIGHT=*number*
specifies the maximum sum of node weights to allow in a path. Any path whose sum of node weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment, which causes nothing to be removed from the results.

MINLENGTH=*number*
specifies the minimum number of links to allow in a path. Any path whose length is less than *number* is removed from the results. You can specify *number* as an integer in the range 1 to $2^{31} - 1$, inclusive. The default is 1, which causes nothing to be removed from the results.

MINLINKWEIGHT=*number*
specifies the minimum sum of link weights to allow in a path. Any path whose sum of link weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment, which causes nothing to be removed from the results.

MINNODEWEIGHT=*number*
specifies the minimum sum of node weights to allow in a path. Any path whose sum of node weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment, which causes nothing to be removed from the results.

SINK=*set-name*
specifies the set of sink nodes.

SOURCE=*set-name*
specifies the set of source nodes.

For more information, see the section "Path Enumeration" on page 853.

SHORTESTPATH< =(*suboptions* **) >**
SHORTPATH< =(*suboptions* **) >**
calculates shortest paths between sets of nodes on the input graph. For more information, see the section "Shortest Path" on page 856.

You can specify the following suboptions:

MAXABSOBJGAP=*number*

MAXABSOLUTEOBJECTIVEGAP=*number*

specifies an acceptance criterion for the sum of link weights (CandidatePath) in paths relative to the sum of link weights in the shortest path (ShortestPath). The absolute objective gap is equal to

$$|\text{CandidatePath} - \text{ShortestPath}|$$

Any path whose absolute objective gap is greater than *number* is removed from the results. The value of *number* can be any nonnegative number. The default is the positive number that has the largest absolute value that can be represented in your operating environment, which causes no paths to be removed from the results.

MAXLINKWEIGHT=*number*

MAXPATHWEIGHT=*number*

specifies the maximum sum of link weights to allow in a shortest path.

Any shortest path whose sum of link weights is greater than *number* is removed from the results. The default is the positive number that has the largest absolute value that can be represented in your operating environment, which causes no paths to be removed from the results.

MAXPATHSPERPAIR=*number* | **ALL**

specifies the maximum number of ranked paths to find for each pair. The algorithm finds at most *number* best paths between each source-sink pair. ALL represents the maximum value, $2^{31} - 1$. The paths that are returned are arranged in ascending order in the sum of link weights for each path. By default, MAXPATHSPERPAIR=1 and the algorithm finds one shortest path between each source-sink pair.

MAXRELOBJGAP=*number*

MAXRELATIVEOBJECTIVEGAP=*number*

specifies an acceptance criterion for the sum of link weights (CandidatePath) in paths relative to the sum of link weights in the shortest path (ShortestPath). The relative objective gap is equal to

$$\frac{|\text{CandidatePath} - \text{ShortestPath}|}{|\text{ShortestPath}| + 1\text{E}{-10}}$$

Any path whose relative objective gap is greater than *number* is removed from the results. The value of *number* can be any nonnegative number. The default is the positive number that has the largest absolute value that can be represented in your operating environment, which causes no paths to be removed from the results.

MINLINKWEIGHT=*number*

MINPATHWEIGHT=*number*

specifies the minimum sum of link weights to allow in a shortest path.

Any shortest path whose sum of link weights is less than *number* is removed from the results. The default is the negative number that has the largest absolute value that can be represented in your operating environment, which causes no paths to be removed from the results.

SEQUENCE=*array-name*
specifies a sequence of nodes to be visited in the shortest path.

SINK=*set-name*
specifies the set of sink nodes.

SOURCE=*set-name*
specifies the set of source nodes.

TOPOLOGICALSORT< =() >
TOPSORT< =() >
finds a topological sort of an input graph. For more information, see the section "Topological Sort" on page 877.

TRANSITIVECLOSURE< =() >
TRANSCL< =() >
calculates the transitive closure of an input graph. For more information, see the section "Transitive Closure" on page 879.

TSP< =(*suboptions* **) >**
solves the traveling salesman problem. For more information, see the section "Traveling Salesman Problem" on page 882.

The algorithm that is used to solve this problem is built around the same method that is used in PROC OPTMILP: a branch-and-cut algorithm. Many of the following *suboptions* are the same as those described for the OPTMILP procedure in Chapter 6, "The OPTMILP Procedure."

You can specify the following *suboptions*:

ABSOBJGAP=*number*
specifies a stopping criterion. When the absolute difference between the best integer objective and the objective of the best remaining branch-and-bound node becomes less than the value of *number*, the solver stops. The value of *number* can be any nonnegative number. By default, ABSOBJGAP=1E–6.

CUTOFF=*number*
cuts off any branch-and-bound nodes in a minimization problem that has an objective value greater than *number*. The value of *number* can be any number.

The default value is the positive number that has the largest absolute value that can be represented in your operating environment.

CUTSTRATEGY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of cutting planes to be generated by the network solver. TSP-specific cutting planes are always generated. You can specify the following values:

AUTOMATIC generates cutting planes according to a strategy determined by the mixed integer linear programming solver.

NONE disables the generation of mixed integer linear programming cutting planes (some TSP-specific cutting planes are still active for validity).

MODERATE uses a moderate cutting strategy.

AGGRESSIVE uses an aggressive cutting strategy.

By default, CUTSTRATEGY=NONE.

HEURISTICS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
controls the level of primal heuristics that the network solver applies. This level determines how frequently the network solver applies primal heuristics during the branch-and-bound tree search. It also affects the maximum number of iterations that are allowed in iterative heuristics. Some computationally expensive heuristics might be disabled by the solver at less aggressive levels. You can specify the following values:

AUTOMATIC applies the default level of heuristics.

NONE disables all primal heuristics.

BASIC applies basic primal heuristics at low frequency.

MODERATE applies most primal heuristics at moderate frequency.

AGGRESSIVE applies all primal heuristics at high frequency.

By default, HEURISTICS=AUTOMATIC.

MAXNODES=*number*
specifies the maximum number of branch-and-bound nodes to be processed. The value of *number* can be any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MAXNODES=$2^{31} - 1$.

MAXSOLS=*number*
specifies the maximum number of feasible tours to be identified. If *number* solutions have been found, then the solver stops. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MAXSOLS=$2^{31} - 1$.

MILP=TRUE | FALSE
specifies whether to use a mixed integer linear programming (MILP) solver to solve the traveling salesman problem. The MILP solver attempts to find the overall best TSP tour by using a branch-and-bound-based algorithm. This algorithm can be expensive for large-scale problems. If MILP=FALSE, then the network solver uses its initial heuristics to find a feasible, but not necessarily optimal, tour as quickly as possible. You can specify the following values:

TRUE uses a mixed integer linear programming solver.

FALSE does not use a mixed integer linear programming solver.

By default, MILP=TRUE.

RELOBJGAP=*number*

specifies a stopping criterion that is based on the best integer objective (BestInteger) and the objective of the best remaining node (BestBound). The value of the relative objective gap is

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

When this value becomes less than the specified gap size *number*, the solver stops. The value of *number* can be any nonnegative number.

By default, RELOBJGAP=1E–4.

TARGET=*number*

specifies a stopping criterion for minimization problems. If the best integer objective value is greater than or equal to *number*, the solver stops. The value of *number* can be any number.

The default value is the negative number that has the largest absolute value that can be represented in your operating environment.

VRP=(*suboptions* **)**

solves the vehicle routing problem. For more information, see the section "Vehicle Routing Problem" on page 889.

The algorithm that is used to solve this problem is built around the same method that the OPTMILP procedure uses: a branch-and-cut algorithm. Many of the following *suboptions* are the same as those described for the OPTMILP procedure in Chapter 6, "The OPTMILP Procedure."

You can specify the following *suboptions*:

ABSOBJGAP=*number*

specifies a stopping criterion. When the absolute difference between the best integer objective and the objective of the best remaining branch-and-bound node becomes less than the value of *number*, the solver stops. The value of *number* can be any nonnegative number. By default, ABSOBJGAP=1E–6.

CAPACITY=*number*

specifies the capacity of each vehicle. The capacity is the maximum amount of goods that a vehicle can pick up from the depot to be delivered to customers. The value of number can be any nonnegative number.

The default value is the positive number that has the largest absolute value that can be represented in your operating environment.

CUTOFF=*number*

cuts off any branch-and-bound nodes in a minimization problem that has an objective value greater than *number*. The value of *number* can be any number.

The default value is the positive number that has the largest absolute value that can be represented in your operating environment.

CUTSTRATEGY=AUTOMATIC | NONE | MODERATE | AGGRESSIVE
specifies the level of cutting planes to be generated by the network solver. VRP-specific cutting planes are always generated. You can specify the following values:

AUTOMATIC generates cutting planes according to a strategy that is determined by the mixed integer linear programming solver.

NONE disables the generation of mixed integer linear programming cutting planes (some VRP-specific cutting planes are still active for validity).

MODERATE uses a moderate cutting strategy.

AGGRESSIVE uses an aggressive cutting strategy.

By default, CUTSTRATEGY=NONE.

DEMAND=*array-name*
specifies the name of the array that contains the node demands. The array must be numeric, and it must be indexed over a subset of the nodes of the graph.

By default, node demand is 0 for the nodes not in the subset.

DEPOT=*set-name*
specifies the name of the single-element set that consists of the depot node. This suboption is required.

HEURISTICS=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
controls the level of primal heuristics that the network solver applies. This level determines how frequently the network solver applies primal heuristics during the branch-and-bound tree search. It also affects the maximum number of iterations that are allowed in iterative heuristics. Some computationally expensive heuristics might be disabled by the solver at less aggressive levels. You can specify the following values:

AUTOMATIC applies the default level of heuristics.

NONE disables all primal heuristics.

BASIC applies basic primal heuristics at low frequency.

MODERATE applies most primal heuristics at moderate frequency.

AGGRESSIVE applies all primal heuristics at high frequency.

By default, HEURISTICS=AUTOMATIC.

MAXNODES=*number*
specifies the maximum number of branch-and-bound nodes to be processed. The value of *number* can be any nonnegative integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MAXNODES=$2^{31} - 1$.

MAXROUTES=*number*

specifies the maximum number of routes to be allowed to service demand. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MAXROUTES=$2^{31} - 1$.

MAXSOLS=*number*

specifies the maximum number of feasible solutions to be identified. If *number* solutions have been found, then the solver stops. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MAXSOLS=$2^{31} - 1$.

MILP=TRUE | FALSE

specifies whether to use a mixed integer linear programming (MILP) solver to solve the vehicle routing problem. The MILP solver attempts to find the overall best VRP tour by using a branch-and-bound-based algorithm. This algorithm can be expensive for large-scale problems. If MILP=FALSE, then the network solver uses its initial heuristics to find a feasible, but not necessarily optimal, solution as quickly as possible. You can specify the following values:

TRUE uses a mixed integer linear programming solver.

FALSE does not use a mixed integer linear programming solver.

By default, MILP=TRUE, unless you specify a time-related suboption. For more information, see the section "Vehicle Routing Problem with Time Windows" on page 895.

MINROUTES=*number*

specifies the minimum number of routes to be allowed to service demand. The value of *number* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$.

By default, MINROUTES=1.

RELOBJGAP=*number*

specifies a stopping criterion that is based on the best integer objective (BestInteger) and the objective of the best remaining node (BestBound). The value of the relative objective gap is

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

When this value becomes less than the specified gap size *number*, the solver stops. The value of *number* can be any nonnegative number.

By default, RELOBJGAP=1E–4.

SERVICETIME=*array-name*

specifies the name of the array that contains the service time for the nodes—that is, how long the vehicle must stay at the node; this suboption is used only for a vehicle routing problem with time windows. The array must be numeric, and it must be indexed over a subset of the nodes of the graph.

By default, the service time value is 0 for the nodes not in the subset.

TARGET=*number*

specifies a stopping criterion for minimization problems. If the best integer objective value is greater than or equal to *number*, the solver stops. The value of *number* can be any number.

The default value is the negative number that has the largest absolute value that can be represented in your operating environment.

TIMEWINDOWLOWER=*array-name*

specifies the name of the array that contains the earliest time when a vehicle can start to serve a node (though it might arrive earlier); this suboption is used only for a vehicle routing problem with time windows. The array must be numeric, and it must be indexed over a subset of the nodes of the graph.

By default, the lower limit on the time window is 0 for the nodes not in the subset.

TIMEWINDOWUPPER=*array-name*

specifies the name of the array that contains the latest time when a vehicle can arrive at a node; this suboption is used only for a vehicle routing problem with time windows. The array must be numeric, and it must be indexed over a subset of the nodes of the graph.

By default, the upper limit on the time window is $2^{31} - 1$ for the nodes not in the subset.

TRAVELTIME=*array-name*

specifies the name of the array that contains the travel time for the links; this suboption is used only for a vehicle routing problem with time windows. The array must be numeric, and it must be indexed over a subset of the links of the graph.

By default, the travel time is assumed to be the same as the weight for links not in the subset.

Details: Network Solver

The network solver uses a collection of specialized algorithms that optimize specific types of common problems. When you use the network solver, you specify variable arrays, numeric arrays, and sets, both to define an instance and to get solutions, without explicitly formulating objectives and constraints.

Input Data for the Network Solver

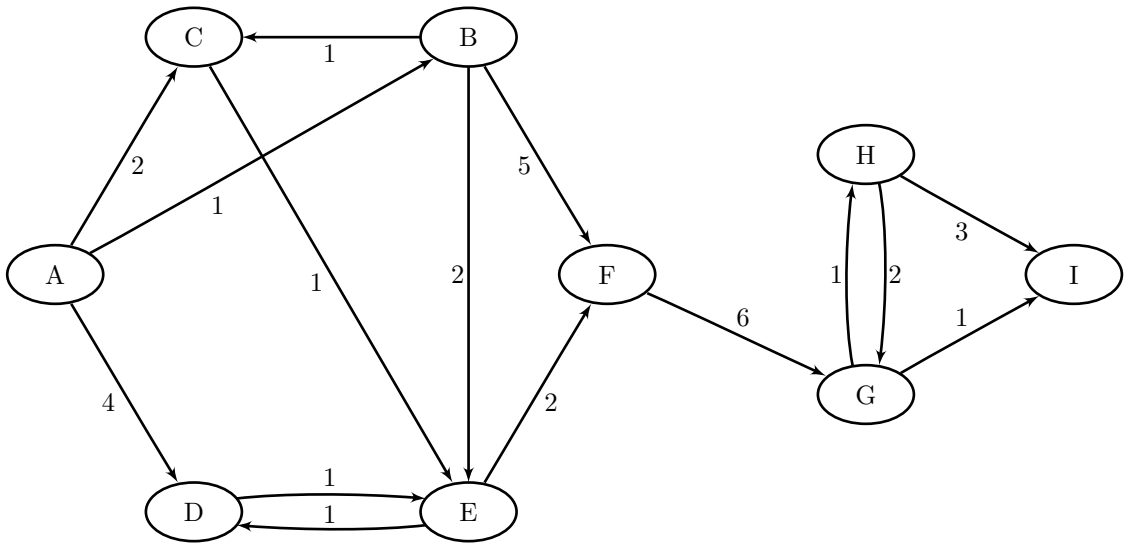
This section describes how you can import and export node, link, and problem data from and to SAS data sets and how you can solve problems over a subgraph without changing your original sets. The section "Graph Input Data" on page 805 describes how to load node and link data in some common formats. The section "Solving over Subsets of Nodes and Links (Filters)" on page 808 describes subgraphs and how to access the objective value of a network problem.

Graph Input Data

This section describes how to input a graph for analysis by the network solver. Because PROC OPTMODEL uses node and link attributes that are indexed over the sets of nodes and links, you need to provide only node and link attributes. PROC OPTMODEL infers the graph from the attributes you provide. When a documented default value exists for the attribute of a link or a node, you need to provide only the values that differ from the default. For example, the section "Minimum-Cost Network Flow" on page 836 assumes that the link flow upper bound is ∞. You need to specify only the finite upper bounds.

Consider the directed graph shown in Figure 15.5.

Figure 15.5 A Simple Directed Graph



Each node and link has associated attributes: a node label and a link weight.

None of the algorithms in PROC OPTMODEL support Null Graphs, i.e., graphs with 0 nodes. PROC OPTMODEL will usually raise a semantic error and stop processing any remaining statements in a block if after processing its inputs it determines that the graph is null. If the graph definition itself is not null, but the graph to be passed to the solver after applying the SUBGRAPH= option is null, then the predeclared parameter _SOLUTION_STATUS_ will be set to NULL_GRAPH. For more information, see "Solving over Subsets of Nodes and Links (Filters)" on page 808.

Data Indexed by Nodes or Links

Nodes often represent entities, and links represent relationships between these entities. Therefore, it is common to store a graph as a link-indexed table. When nodes have attributes beyond their name (label), these attributes are stored in a node-indexed table. This section covers the more complex link-indexed case. The node-indexed case is essentially identical to this one, except that the PROC OPTMODEL set has tuple length of one when node-indexed data are read, whereas the PROC OPTMODEL set has tuple length two when link-indexed data are read.

Let $G = (N, E)$ define a graph with a set N of nodes and a set E of links. A link is an ordered pair of nodes. Each node is defined by using either numeric or string labels.

The directed graph G shown in Figure 15.5 can be represented by the following links data set LinkSetIn:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 1   A C 2   A D 4   B C 1   B E 2
B F 5   C E 1   D E 1   E D 1   E F 2
F G 6   G H 1   G I 1   H G 2   H I 3
;
```

The following statements read in this graph and print the resulting links and nodes sets. These statements do not run any algorithms, so the resulting output contains only the input graph.

```
proc optmodel;
   set<str,str> LINKS;
   set NODES = union{<ni,nj> in LINKS} {ni,nj};
   num weight{LINKS};

   read data LinkSetIn into LINKS=[from to] weight;

   print weight;
   put NODES=; /* computed automatically by OPTMODEL */
quit;
```

The network solver preserves the node order of each link that you provide, even in cases where the link is traversed in the opposite order, such as in paths or tours. For an example, see the tour $(1, 4, 2, 3, 5)$ in Figure 15.8.

The log output in Figure 15.6 shows the nodes that are read from the input link data set. In this example PROC OPTMODEL computed the node set N (NODES) from its definition when it was needed. The ODS output in Figure 15.7 shows the weights that are read from the input link data set, which is indexed by link. PUT is used for NODES because PROC OPTMODEL sets are basic types such as number and string. Thus, you use PUT to quickly inspect a set value. In contrast, you use PRINT to inspect an array, such as weight.

Figure 15.6 Node Set Printout of a Simple Directed Graph

```
NOTE: There were 15 observations read from the data set WORK.LINKSETIN.
NODES={'A','B','C','D','E','F','G','H','I'}
```

Figure 15.7 Link Set of a Simple Directed Graph That Includes Weights

The OPTMODEL Procedure

[1]	[2]	weight
A	B	1
A	C	2
A	D	4
B	C	1
B	E	2
B	F	5
C	E	1
D	E	1
E	D	1
E	F	2
F	G	6
G	H	1
G	I	1
H	G	2
H	I	3

As described in the GRAPH_DIRECTION= option, if the graph is undirected, the *from* and *to* labels are interchangeable. If you define this graph as undirected, then reciprocal links (for example, $D \rightarrow E$ and $E \rightarrow D$) are treated as the same link, and duplicates are removed. The network solver takes the first occurrence of the link and ignores the others. By default, GRAPH_DIRECTION=UNDIRECTED, so to declare the graph as undirected you can just omit this option.

After you read the data into PROC OPTMODEL sets, you pass link information to the solver by using the LINKS= option. Node input is analogous to link input. You pass node information to the solver by using the NODES= option.

The INCLUDE= suboption is especially useful for algorithms that depend only on the graph topology, (such as the connected components algorithm). If an algorithm requires a node or link property and that property is not defined for a node or link that is added by the INCLUDE= suboption, the algorithm will not run.

Matrix Input Data

The contents of a table can be represented as a graph. The relationships between two sets of nodes, N_1 and N_2, can be represented by a $|N_1|$ by $|N_2|$ incidence matrix A, in which N_1 is the set of rows and N_2 is the set of columns.

To read a matrix that is stored in a data set into PROC OPTMODEL, you need to take two extra steps:

1. Determine the name of each numeric variable that you want to use. PROC CONTENTS can be useful for this task.
2. Use an iterated READ DATA statement.

For more information, see "Example 15.3: Linear Assignment Problem for Minimizing Relay Times" on page 909.

Solving over Subsets of Nodes and Links (Filters)

You can solve a problem over a subgraph without declaring new link and node sets. You can specify the LINKS= and NODES= suboptions of the SUBGRAPH= option to filter nodes and links before PROC OPTMODEL builds and solves the instance. If you want to see the resulting subgraph, you can specify the LINKS= and NODES= suboptions of the OUT= option. If you just want to produce a subgraph, you do not need to invoke an algorithm.

You can keep all the input and output arrays defined over the original graph and define a subgraph by providing any combination of the LINKS= and NODES= suboptions of the SUBGRAPH= option. If you specify either of the suboptions of the SUBGRAPH= option, then union semantics apply. PROC OPTMODEL uses the following rules:

- Only the links that are included in the set named in the LINKS= option are used to create the instance.
- Only the nodes that appear either in the NODES= suboption of the SUBGRAPH= option or that appear as the head or tail of a link in the LINKS= suboption are used to create the instance.
- A node or a link that appears only in the SUBGRAPH= option, but not in the original graph, is discarded. To add nodes or links that do not have attributes, see the INCLUDE= suboption of the LINKS= and NODE= options.

If the value of the LOGLEVEL= suboption is equal to or greater than 3, PROC OPTMODEL issues a message for each of the nodes and links that it discards until the number of messages issued during problem generation reaches the value of the MSGLIMIT= option in the PROC OPTMODEL statement. If the value of the LOGLEVEL= suboption is greater than 0, PROC OPTMODEL also issues a summary that shows the total count of discarded nodes and links from each input array or set.

The following statements call PROC OPTMODEL and declare a five-node complete undirected graph; a subset of links that contains all links between nodes 1, 2, 3, and 4; and a subset of nodes that contains nodes 3, 4, and 5:

```
proc optmodel;
   set NODES = 1..5;
   set LINKS = {vi in NODES, vj in NODES: vi < vj};
   num distance {<vi,vj> in LINKS} = 10*vi + vj;

   set <num,num> TOUR;

   /* Build a link set using only nodes 1..4 nodes */
   set <num,num> LINKS_BETWEEN_1234 = {vi in 1..3, vj in (vi+1)..4};
   /* Build a node subset consisting of nodes 3..5 */
   set NODES_345 = 3..5;
```

After the sets are declared, the statements in the following steps solve several traveling salesman problems (TSPs) on subgraphs. For more information about TSPs, see the section “Traveling Salesman Problem” on page 882.

1. The first SOLVE statement solves a TSP on the original graph. Note that the links in the tour (see Figure 15.8) are returned with the same orientation that you provide in the input. For example, the

second step on the tour goes from node 4 to node 2 using link (2, 4). This guarantees that you do not need to do extra processing of output to check for link orientation. You can just use the output directly.

```
/* Implicit network 1: solve over nodes 1..5 -- The original network*/
solve with NETWORK /
   links=( weight=distance )
   out=( tour=TOUR )
   tsp
;
put TOUR=;
```

As shown in Figure 15.8, all links implied by the WEIGHT= suboption of the LINKS= option become part of the graph.

Figure 15.8 SOLVE WITH NETWORK Log: Traveling Salesman Tour of an Unfiltered Graph

```
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 10.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 111 using 0.03 (cpu:
      0.00) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
NOTE: Optimal.
NOTE: Objective = 111.
NOTE: Processing the traveling salesman problem used 0.03 (cpu: 0.01) seconds.
TOUR={<1,4>,<2,4>,<2,3>,<3,5>,<1,5>}
```

To access the objective value of a network problem, use the _OROPTMODEL_NUM_ predefined array. The network solver ignores the _OBJ_ predefined symbol, which is part of the current named problem. The current named problem is independent of the network solver, because the network solver uses sets and numeric arrays for input and output. For more information, see the sections "Multiple Subproblems" on page 454 and "Solver Status Parameters" on page 467 in Chapter 9, "The OPTMODEL Procedure."

```
put _OROPTMODEL_NUM_['OBJECTIVE']=;
```

2. The next SOLVE statement solves a TSP on the subgraph that is defined by the link set LINKS_BETWEEN_1234.

```
/* Filter on LINKS: solve over nodes 1..4 */
solve with NETWORK /
   links=( weight=distance )
   subgraph=( links=LINKS_BETWEEN_1234 )
   out=( tour=TOUR )
   tsp
;
put TOUR=;
```

As shown in Figure 15.9, the network solver now ignores node 5.

Figure 15.9 SOLVE WITH NETWORK Log: Traveling Salesman Tour over Nodes $N = \{1, 2, 3, 4\}$

```
_OROPTMODEL_NUM_[OBJECTIVE]=111
NOTE: The SUBGRAPH= option filtered 4 elements from 'distance.'
NOTE: The number of nodes in the input graph is 4.
NOTE: The number of links in the input graph is 6.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 74 using 0.00 (cpu:
      0.00) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
NOTE: Optimal.
NOTE: Objective = 74.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
TOUR={<1,3>,<2,3>,<2,4>,<1,4>}
```

3. The next SOLVE statement solves a TSP on the subgraph that is defined by the node set NODES_345.

```
/* Filter on NODES: solve over nodes 3..5 */
solve with NETWORK /
   links=( weight=distance )
   subgraph=( nodes=NODES_345 )
   out=( tour=TOUR )
   tsp
;
put TOUR=;
```

As shown in Figure 15.10, the network solver now ignores nodes 1 and 2, along with any links incident to them.

Figure 15.10 SOLVE WITH NETWORK Log: Traveling Salesman Tour over Nodes $N = \{3, 4, 5\}$

```
NOTE: The SUBGRAPH= option filtered 7 elements from 'distance.'
NOTE: The number of nodes in the input graph is 3.
NOTE: The number of links in the input graph is 3.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 114 using 0.00 (cpu:
      0.00) seconds.
NOTE: Optimal.
NOTE: Objective = 114.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
TOUR={<3,4>,<4,5>,<3,5>}
```

4. The next SOLVE statement attempts to solve a TSP on the subgraph that is defined by the node set NODES_345 and the link set that is defined by the links on the nodes $\{1, 2, 3, 4\}$. This subgraph creates

an infeasible instance because the links $\{(1,5),(2,5),(3,5),(4,5)\}$ that were defined in the original graph have been filtered out. Thus, node 5 is disconnected and no tour can exist.

```
/* Explicit nodes and links: semantic error over nodes 1..5
 * Links <u,5> are undefined and no documented default exists. */
solve with NETWORK /
   links=( weight=distance )
   subgraph=( nodes=NODES_345 links=LINKS_BETWEEN_1234 )
   out=( tour=TOUR )
   tsp
;
```

As shown in Figure 15.11, the network solver identifies that no tour exists over the surviving nodes and links.

Figure 15.11 SOLVE WITH NETWORK Log: Infeasible Traveling Salesman Problem after Filtering

```
NOTE: The SUBGRAPH= option filtered 4 elements from 'distance.'
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 6.
NOTE: The number of singleton nodes in the input graph is 1.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: Infeasible.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
```

5. The last SOLVE statement uses the LINKS= suboption of the OUT= option to capture exactly which nodes and links were generated and with which attributes. In this case, because the only attribute defined is link weight, the set LINKS_OUT has tuples of length three.

```
   /* make room for tail, head, and weight */
   set<num,num,num> LINKS_OUT;
   solve with NETWORK /
      links=( weight=distance )
      subgraph=( nodes=NODES_345 links=LINKS_BETWEEN_1234 )
      out=( tour=TOUR links=LINKS_OUT )
      tsp
   ;
   put LINKS_OUT=;
quit;
```

As shown in Figure 15.12, the network solver can return the graph after filtering. This feature can sometimes help you identify why you might get counterintuitive results.

Figure 15.12 SOLVE WITH NETWORK Log: Remaining Links after Filtering

```
NOTE: The SUBGRAPH= option filtered 4 elements from 'distance.'
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 6.
NOTE: The number of singleton nodes in the input graph is 1.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: Infeasible.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
LINKS_OUT={<1,2,12>,<1,3,13>,<1,4,14>,<2,3,23>,<2,4,24>,<3,4,34>}
```

Numeric Limitations

Extremely large or extremely small numerical values might cause computational difficulties for some of the algorithms in the network solver. For this reason, each algorithm restricts the magnitude of the data values to a particular threshold number. If the user data values exceed this threshold, the network solver issues an error message. The value of the threshold limit is different for each algorithm and depends on the operating environment. The threshold limits are listed in Table 15.10, where M is defined as the largest absolute value representable in your operating environment.

Table 15.10 Threshold Limits by Algorithm

	Graph Links			Graph Nodes		
Algorithm	weight	lower	upper	weight	lower	upper
CLIQUE	$\sqrt{M}$			$\sqrt{M}$		
CYCLE	$\sqrt{M}$			$\sqrt{M}$		
LINEARASSIGNMENT	$\sqrt{M}$					
MAXFLOW			1e15			
MINCOSTFLOW	1e15	1e15	1e15		1e15	1e15
MINCUT	$\sqrt{M}$					
MINSPANTREE	$\sqrt{M}$					
PATH	$\sqrt{M}$			$\sqrt{M}$		
SHORTESTPATH	$\sqrt{M}$					
TSP	1e20					
VRP	1e20				1e20	

To obtain these limits, use the SAS CONSTANT function. For example, the following PROC OPTMODEL code assigns $\sqrt{M}$ to a variable c and prints that value to the log:

```
proc optmodel;
   num c = constant('SQRTBIG');
   put c=;
quit;
```

Missing Values

A missing value has no valid interpretation for most of the algorithms in the network solver. If the user data contain a missing value, the network solver issues an error message. There is only one exception: the minimum-cost network flow algorithm interprets a missing value in the lower or upper bound option as the default bound value. For more information about this algorithm, see the section "Minimum-Cost Network Flow" on page 836.

Negative Link Weights

For certain algorithms in the network solver, a negative link weight is not allowed. The following algorithm issues an error message if a negative link weight is provided:

- MINCUT

Biconnected Components and Articulation Points

A *biconnected component* (or *block*) of a graph $G = (N, E)$ is a connected subgraph that you cannot break into disconnected pieces by deleting any single node (and its incident links). An *articulation point* (or *cut point*) of a graph is a node whose removal would cause an increase in the number of connected components. Articulation points can be important when you analyze any graph that represents a communications network. Consider an articulation point $i \in N$ that, if removed, breaks the graph into two components, C^1 and C^2. All paths in G between some nodes in C^1 and some nodes in C^2 must pass through node i. In this sense, articulation points are critical to communication. Examples where articulation points are important include airline hubs, electric circuits, network wires, protein bonds, traffic routers, and many other industrial applications.

In the network solver, you can find biconnected components and articulation points of an input graph by invoking the BICONNECTEDCOMPONENTS option. This algorithm works only with undirected graphs.

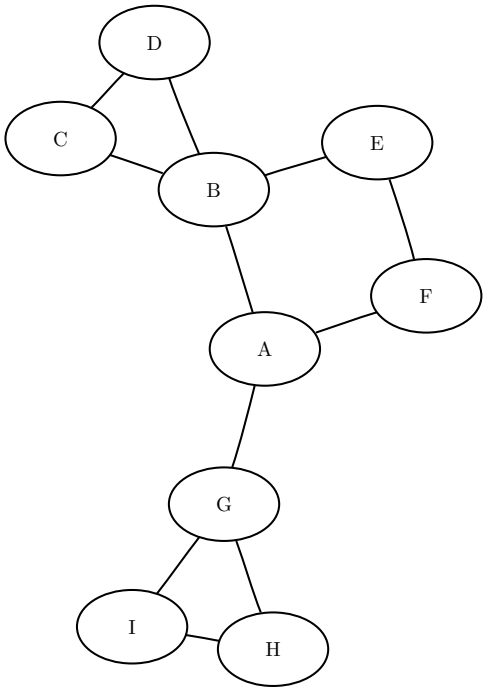
The results for the biconnected components algorithm are written to the link-indexed numeric array that is specified in the BICONCOMP= suboption of the OUT= option. For each link in the links array, the value in this array identifies its component. The component identifiers are numbered sequentially starting from 1. The articulation points are written to the set that is specified in the ARTPOINTS= suboption of the OUT= option.

The algorithm that the network solver uses to compute biconnected components is a variant of depth-first search (Tarjan 1972). This algorithm runs in time $O(|N| + |E|)$ and therefore should scale to very large graphs.

Biconnected Components of a Simple Undirected Graph

This section illustrates the use of the biconnected components algorithm on the simple undirected graph G that is shown in Figure 15.13.

Figure 15.13 A Simple Undirected Graph G



The undirected graph G can be represented by the links data set LinkSetInBiCC as follows:

```
data LinkSetInBiCC;
   input from $ to $ @@;
   datalines;
A B  A F  A G  B C  B D
B E  C D  E F  G I  G H
H I
;
```

The following statements calculate the biconnected components and articulation points and output the results in the data sets LinkSetOut and NodeSetOut:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetInBiCC into LINKS=[from to];
   set NODES = union{<i,j> in LINKS} {i,j};
   num bicomponent{LINKS};
   set<str> ARTPOINTS;

   solve with NETWORK /
      loglevel  = moderate
      links     = (include=LINKS)
      biconcomp
      out       = (biconcomp=bicomponent artpoints=ARTPOINTS)
   ;

   print bicomponent;
   put ARTPOINTS;
   create data LinkSetOut from [from to] biconcomp=bicomponent;
```

```
   create data NodeSetOut from [node]=ARTPOINTS artpoint=1;
quit;
```

The data set LinkSetOut now contains the biconnected components of the input graph, as shown in Figure 15.14.

Figure 15.14 Biconnected Components of a Simple Undirected Graph

from	to	biconcomp
A	B	2
A	F	2
A	G	4
B	C	1
B	D	1
B	E	2
C	D	1
E	F	2
G	I	3
G	H	3
H	I	3

In addition, the data set NodeSetOut contains the articulation points of the input graph, as shown in Figure 15.15.

Figure 15.15 Articulation Points of a Simple Undirected Graph

node	artpoint
A	1
B	1
G	1

The biconnected components are shown graphically in Figure 15.16 and Figure 15.17.

Figure 15.16 Biconnected Components C^1 and C^2

$C^1 = \{B, C, D\}$ $C^2 = \{A, B, E, F\}$

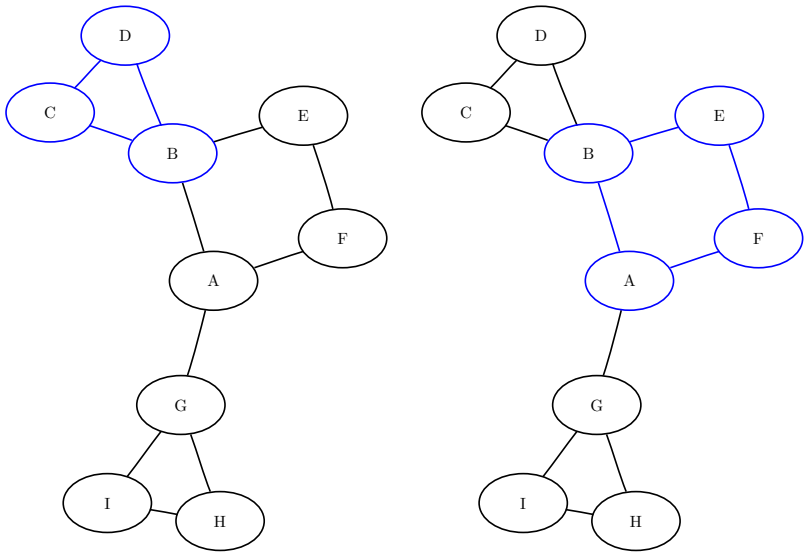
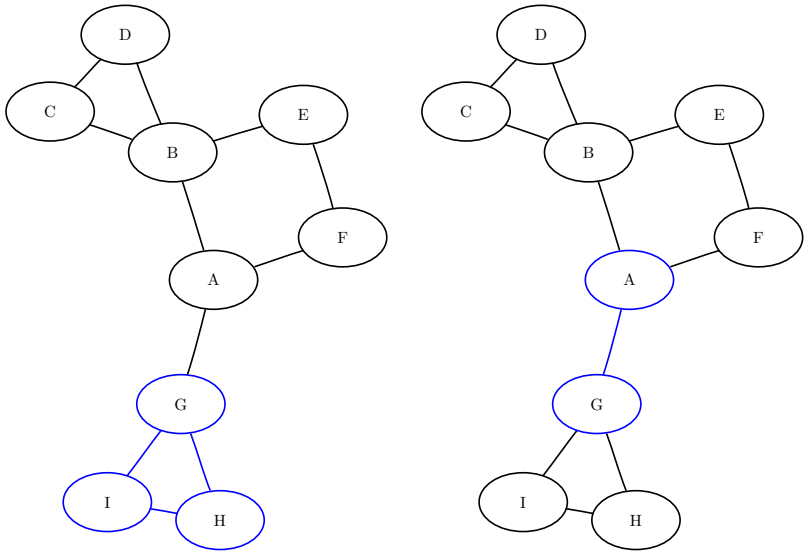


Figure 15.17 Biconnected Components C^3 and C^4

$C^3 = \{G, H, I\}$ $C^4 = \{A, G\}$



For a more detailed example, see "Example 15.1: Articulation Points in a Terrorist Network" on page 902.

Clique

A *clique* of a graph $G = (N, E)$ is an induced subgraph that is a complete graph. Every node in a clique is connected to every other node in that clique. A *maximal clique* is a clique that is not a subset of the nodes of any larger clique. That is, it is a set C of nodes such that every pair of nodes in C is connected by a link and every node not in C is missing a link to at least one node in C. The number of maximal cliques in a particular graph can be very large and can grow exponentially with every node that is added. Finding cliques in graphs has applications in many industries, including bioinformatics, social networks, electrical engineering, and chemistry.

You can find the maximal cliques of an input graph by invoking the CLIQUE= option. The clique algorithm works only with undirected graphs.

The clique algorithm has two kinds of output:

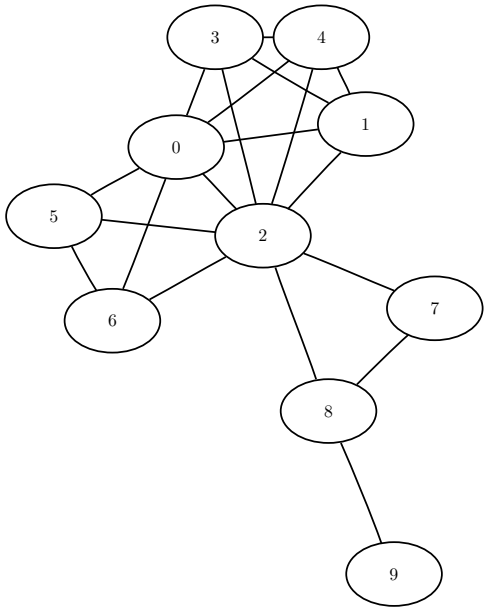
- If you specify the CLIQUES= suboption of the OUT= option, then the results for the clique algorithm are written to the set that is specified in the CLIQUES= suboption. Each node of each clique is listed in the set along with a clique ID (the first argument of the tuple) to identify the clique to which it belongs. A node can appear multiple times in this set if it belongs to multiple cliques.
- If you specify the NODECLIQUE= suboption of the OUT= option, then the clique algorithm automatically sets the MAXCLIQUES= option to ALL, computes the node clique number of each node (the largest clique size of the cliques that contain the node), and stores the result in the array that is specified in the NODECLIQUE= suboption.

The algorithm that the network solver uses to compute maximal cliques is a variant of the Bron-Kerbosch algorithm (Bron and Kerbosch 1973; Harley 2003). Enumerating all maximal cliques is NP-hard, so this algorithm typically does not scale to very large graphs.

Maximal Cliques of a Simple Undirected Graph

This section illustrates the use of the clique algorithm on the simple undirected graph G that is shown in Figure 15.18.

Figure 15.18 A Simple Undirected Graph G



The undirected graph G can be represented by the following links data set LinkSetIn:

```
data LinkSetIn;
   input from to @@;
   datalines;
0 1  0 2  0 3  0 4  0 5
0 6  1 2  1 3  1 4  2 3
2 4  2 5  2 6  2 7  2 8
3 4  5 6  7 8  8 9
;
```

The following statements calculate the maximal cliques, output the results in the data set Cliques, and use the CARD function and SLICE operator as a convenient way to compute the clique sizes, which are output to a data set called CliqueSizes:

```
proc optmodel;
   set<num,num> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num,num> CLIQUES;

   solve with NETWORK /
      links  = (include=LINKS)
      clique = (maxcliques=all)
      out    = (cliques=CLIQUES)
   ;

   put CLIQUES;
   create data Cliques from [clique node]=CLIQUES;
   num num_cliques = card(setof {<cid,node> in CLIQUES} cid);
   set CLIQUE_IDS = 1..num_cliques;
   num size {cid in CLIQUE_IDS} = card(slice(<cid,*>, CLIQUES));
   create data CliqueSizes from [clique] size;
```

```
quit;
```

The data set Cliques now contains the maximal cliques of the input graph; it is shown in Figure 15.19.

Figure 15.19 Maximal Cliques of a Simple Undirected Graph

clique	node
1	0
1	2
1	1
1	3
1	4
2	0
2	2
2	5
2	6
3	2
3	8
3	7
4	8
4	9

In addition, the data set CliqueSizes contains the number of nodes in each clique; it is shown in Figure 15.20.

Figure 15.20 Sizes of Maximal Cliques of a Simple Undirected Graph

clique	size
1	5
2	4
3	3
4	2

The maximal cliques are shown graphically in Figure 15.21 and Figure 15.22.

Figure 15.21 Maximal Cliques C^1 and C^2

$C^1 = \{0, 1, 2, 3, 4\}$ $C^2 = \{0, 2, 5, 6\}$

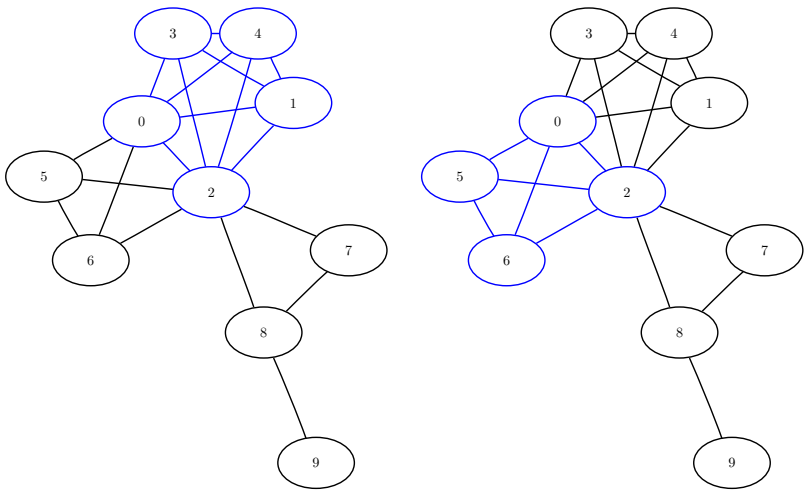
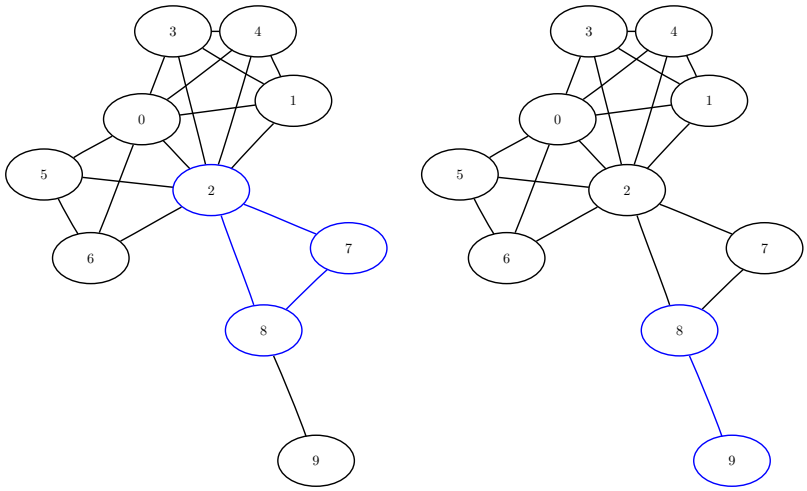


Figure 15.22 Maximal Cliques C^3 and C^4

$C^3 = \{2, 7, 8\}$ $C^4 = \{8, 9\}$



The following statements calculate the node clique number for each node, save the results in the NodeCliqueNumber array, and convert the array into the data set NodeClique:

```
proc optmodel;
   set<num,num> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num> NODES;
   NODES=(union {<i,j> in LINKS} {i,j});
   num NodeCliqueNumber{NODES};

   solve with NETWORK /
      links  = (include=LINKS)
```

```
      clique
      out    = (nodeclique=NodeCliqueNumber)
   ;
   create data NodeClique from [node] NodeCliqueNumber;
quit;
```

The NodeClique data set now contains the node clique number for each node of the input graph; it is shown in Figure 15.23.

Figure 15.23 Node Clique Numbers for Nodes of a Simple Undirected Graph

node	NodeCliqueNumber
0	5
1	5
2	5
3	5
4	5
5	4
6	4
7	3
8	3
9	2

Connected Components

A *connected component* of a graph is a set of nodes that are all reachable from each other. That is, if two nodes are in the same component, then there is a path between them.

In the network solver, you can invoke connected components by using the CONNECTEDCOMPONENTS= option.

There are three main algorithms that you can use to find connected components in an undirected graph: the depth-first search algorithm (ALGORITHM=DFS), the union-find algorithm (ALGORITHM=UNIONFIND), and the afforest algorithm (ALGORITHM=AFFOREST). For a graph $G = (N, E)$, all algorithms run in time $O(|N| + |E|)$ and can usually scale to very large graphs. By default, ALGORITHM=AUTOMATIC, in which case the connected components solver automatically determines the algorithm to be used.

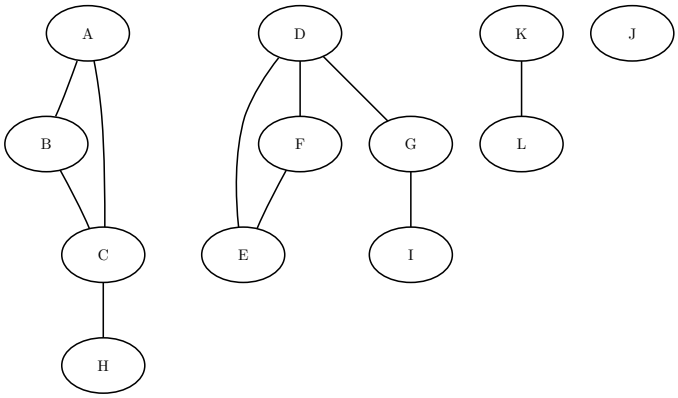
For directed graphs, you can compute strongly connected components by specifying the GRAPH_DIRECTION=DIRECTED option in the SOLVE WITH NETWORK statement. To compute weakly connected components, you can ignore the edge directions by specifying GRAPH_DIRECTION= UNDIRECTED.

The results of the connected components algorithm are written to the node-indexed numeric array that you specify in the CONCOMP= suboption of the OUT= option. For each node in the set, the value of this array identifies its component. The component identifiers are numbered sequentially starting from 1.

Connected Components of a Simple Undirected Graph

This section illustrates the use of the connected components algorithm on the simple undirected graph *G* that is shown in Figure 15.24.

Figure 15.24 A Simple Undirected Graph *G*



The undirected graph *G* can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ @@;
   datalines;
A B  A C  B C  C H  D E  D F  D G  F E  G I  K L
;
```

The following statements calculate the connected components and output the results in the data set NodeSetOut:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set NODES = union {<i,j> in LINKS} {i,j};
   num component{NODES};

   solve with NETWORK /
      links   = (include=LINKS)
      concomp
      out     = (concomp=component)
   ;

   print component;
   create data NodeSetOut from [node] concomp=component;
quit;
```

The data set NodeSetOut contains the connected components of the input graph and is shown in Figure 15.25.

Figure 15.25 Connected Components of a Simple Undirected Graph

node	concomp
A	1
B	1
C	1
H	1
D	2
E	2
F	2
G	2
I	2
K	3
L	3

Notice that the graph is defined by using only the links array. As seen in Figure 15.24, this graph also contains a singleton node labeled J, which has no associated links. By definition, this node defines its own component. But because the input graph was defined by using only the links array, node J did not show up in the results data set. To define a graph by using nodes that have no associated links, you should also define the input nodes set. In this case, you can define a nodes data set NodeSetIn as follows:

```
data NodeSetIn;
   input node $ @@;
   datalines;
A  B  C  D  E  F  G  H  I  J  K  L
;
```

You could also have defined the set directly in PROC OPTMODEL, but in this case, a separate data set nicely preserves the independence between the model and the data.

Now, when you calculate the connected components, you define the input graph by using both the nodes input data set and the links input data set:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<str> NODES;
   read data NodeSetIn into NODES=[node];
   num component{NODES};

   solve with NETWORK /
      links   = (include=LINKS)
      nodes   = (include=NODES)
      concomp
      out     = (concomp=component)
   ;

   print component;
   create data NodeSetOut from [node] concomp=component;
quit;
```

The resulting data set, NodeSetOut, includes the singleton node J as its own component, as shown in Figure 15.26.

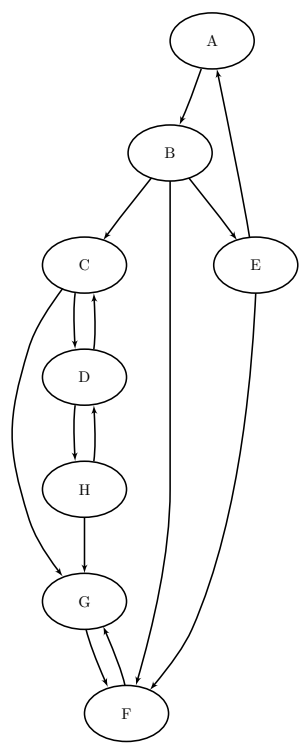
Figure 15.26 Connected Components of a Simple Undirected Graph

node	concomp
A	1
B	1
C	1
D	2
E	2
F	2
G	2
H	1
I	2
J	3
K	4
L	4

Connected Components of a Simple Directed Graph

This section illustrates the use of the connected components algorithm on the simple directed graph G that is shown in Figure 15.27.

Figure 15.27 A Simple Directed Graph G



The directed graph G can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ @@;
   datalines;
A B  B C  B E  B F  C G
C D  D C  D H  E A  E F
F G  G F  H G  H D
;
```

The following statements calculate the connected components and output the results in the data set NodeSetOut:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set NODES = union {<i,j> in LINKS} {i,j};
   num component{NODES};

   solve with NETWORK /
      graph_direction = directed
      links           = (include=LINKS)
      concomp
      out             = (concomp=component)
   ;

   print component;
   create data NodeSetOut from [node] concomp=component;
quit;
```

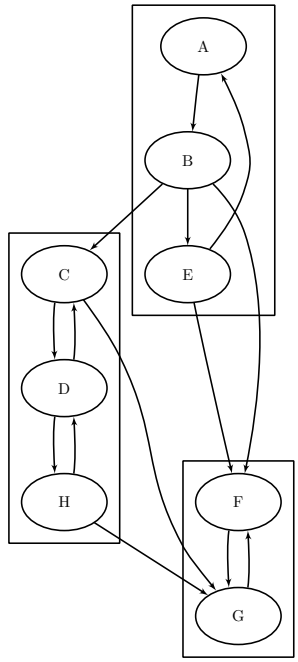
The data set NodeSetOut, shown in Figure 15.28, now contains the connected components of the input graph.

Figure 15.28 Connected Components of a Simple Directed Graph

node	concomp
A	3
B	3
C	2
E	3
F	1
G	1
D	2
H	2

The connected components are represented graphically in Figure 15.29.

Figure 15.29 Strongly Connected Components of Graph G



Cycle

A *path* in a graph is a sequence of links such that the *to* node of each link is the *from* node of the next link. An *elementary cycle* is a path in which the starting node and the ending node are the same and no node appears more than twice in the sequence.

In the network solver, you can find (or just count) the elementary cycles of an input graph by invoking the CYCLE= algorithm option. To find the cycles and report them in a set, use the CYCLES= or CYCLESLINKS= suboption in the OUT= option. You do not need to use the CYCLES= or CYCLESLINKS= suboption to simply count the cycles.

For undirected graphs, each link represents two directed links. For this reason, the following cycles are filtered out: trivial cycles ($A \rightarrow B \rightarrow A$) and duplicate cycles that are found by traversing a cycle in both directions ($A \rightarrow B \rightarrow C \rightarrow A$ and $A \rightarrow C \rightarrow B \rightarrow A$).

The results of the cycle detection algorithm are written to the set that you specify in the CYCLES= or CYCLESLINKS= suboption in the OUT= option. The CYCLES= set lists each node of each cycle (in the third argument of the tuple) along with a cycle ID (in the first argument) to identify the cycle to which it belongs, and the order (sequence) of the node in the cycle (in the second argument). The CYCLESLINKS= set lists each link (in the third and fourth arguments of the tuple) along with a cycle ID (the first argument) and the order of the link in the cycle (the second argument).

The algorithm that the network solver uses to compute all cycles when the value of the MAXLENGTH= option is greater than 20 is a variant of the algorithm in Johnson (1975) (ALGORITHM=BACKTRACK). This algorithm runs in time $O((|N| + |E|)(c + 1))$, where c is the number of elementary cycles in the graph. So the algorithm should scale to large graphs that contain few cycles. However, some graphs can have a very large number of cycles, so the algorithm might not scale. The default when the value of the MAXLENGTH=

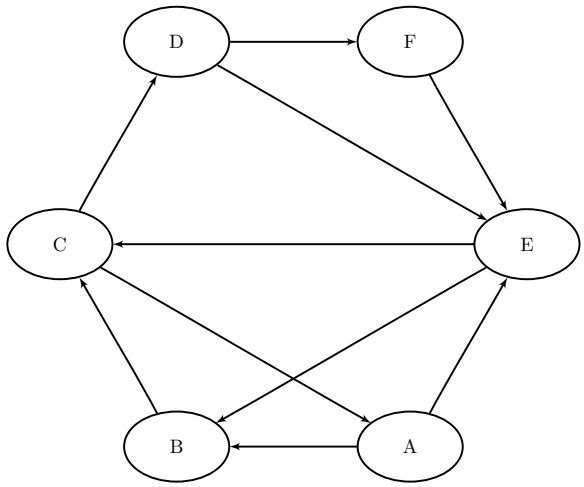
option is less than or equal to 20 is described in Liu and Wang (2006) (ALGORITHM=BUILD). This algorithm is typically much faster than the backtracking algorithm when the length of the cycles is sufficiently restricted.

If MAXCYCLES=ALL and there are many cycles, the CYCLES= or CYCLESLINKS= set can become very large. It might be beneficial to check the number of cycles before you try to create the CYCLES= or CYCLESLINKS= set. By default, MAXCYCLES=1, so the algorithm returns the first cycle that it finds and stops processing. This should run relatively quickly. For large-scale graphs, the MINLINKWEIGHT= and MAXLINKWEIGHT= suboptions might increase the computation time.

Cycle Detection of a Simple Directed Graph

This section provides a simple example of using the cycle detection algorithm on the simple directed graph *G* that is shown in Figure 15.30. Two other examples are "Example 15.2: Cycle Detection for Kidney Donor Exchange" on page 905, which shows the use of cycle detection for optimizing a kidney donor exchange, and "Example 15.6: Transitive Closure for Identification of Circular Dependencies in a Bug Tracking System" on page 917, which shows an application of cycle detection to dependencies between bug reports.

Figure 15.30 A Simple Directed Graph *G*



The directed graph *G* can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ @@;
   datalines;
A B  A E  B C  C A  C D
D E  D F  E B  E C  F E
;
```

The following statements check whether the graph has a cycle:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num,num,str> CYCLES;

   solve with NETWORK /
```

```
      graph_direction = directed
      links           = (include=LINKS)
      cycle           = (maxcycles=1)
   ;
quit;
```

The result is written to the log of the procedure, as shown in Figure 15.31.

Figure 15.31 Network Solver Log: Check the Existence of a Cycle in a Simple Directed Graph

```
NOTE: There were 10 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 6.
NOTE: The number of links in the input graph is 10.
NOTE: The network solver is called.
NOTE: Processing cycle enumeration using 1 threads across 1 machines.
NOTE: Required number of cycles found.
NOTE: The algorithm found 1 cycles.
NOTE: Processing cycle enumeration used 0.00 (cpu: 0.00) seconds.
```

The following statements count the number of cycles in the graph:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num,num,str> CYCLES;

   solve with NETWORK /
      graph_direction = directed
      links           = (include=LINKS)
      cycle           = (maxcycles=all)
   ;
quit;
```

The result is written to the log of the procedure, as shown in Figure 15.32.

Figure 15.32 Network Solver Log: Count the Number of Cycles in a Simple Directed Graph

```
NOTE: There were 10 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 6.
NOTE: The number of links in the input graph is 10.
NOTE: The network solver is called.
NOTE: Processing cycle enumeration using 1 threads across 1 machines.
NOTE: The algorithm found 7 cycles.
NOTE: Processing cycle enumeration used 0.00 (cpu: 0.00) seconds.
```

The following statements return the first cycle found in the graph:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num,num,str> CYCLES;
```

```
   solve with NETWORK /
      graph_direction = directed
      links           = (include=LINKS)
      cycle           = (maxcycles=1)
      out             = (cycles=CYCLES)
   ;

   put CYCLES;
   create data Cycles from [cycle order node]=CYCLES;
quit;
```

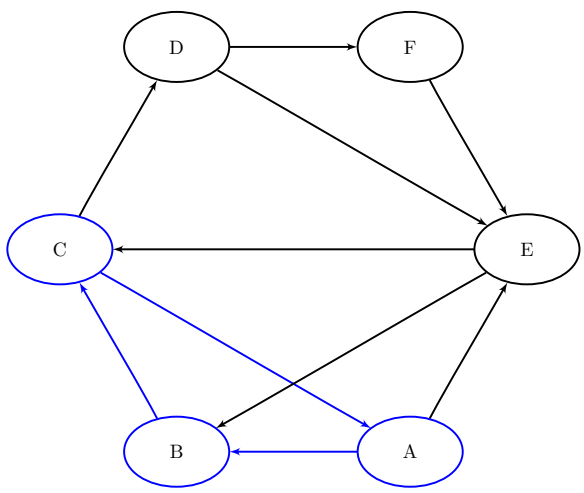
The data set Cycles now contains the first cycle found in the input graph; it is shown in Figure 15.33.

Figure 15.33 First Cycle Found in a Simple Directed Graph

cycle	order	node
1	1	A
1	2	B
1	3	C
1	4	A

The first cycle that is found in the input graph is shown graphically in Figure 15.34.

Figure 15.34 $A \rightarrow B \rightarrow C \rightarrow A$



The following statements return all the cycles in the graph:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<num,num,str> CYCLES;

   solve with NETWORK /
      graph_direction = directed
      links           = (include=LINKS)
      cycle           = (maxcycles=all)
      out             = (cycles=CYCLES)
```

```
    ;

    put CYCLES;
    create data Cycles from [cycle order node]=CYCLES;
quit;
```

The data set Cycles now contains all the cycles in the input graph; it is shown in Figure 15.35.

Figure 15.35 All Cycles in a Simple Directed Graph

cycle	order	node
1	1	A
1	2	B
1	3	C
1	4	A
2	1	A
2	2	E
2	3	B
2	4	C
2	5	A

cycle	order	node
3	1	A
3	2	E
3	3	C
3	4	A
4	1	B
4	2	C
4	3	D
4	4	E
4	5	B

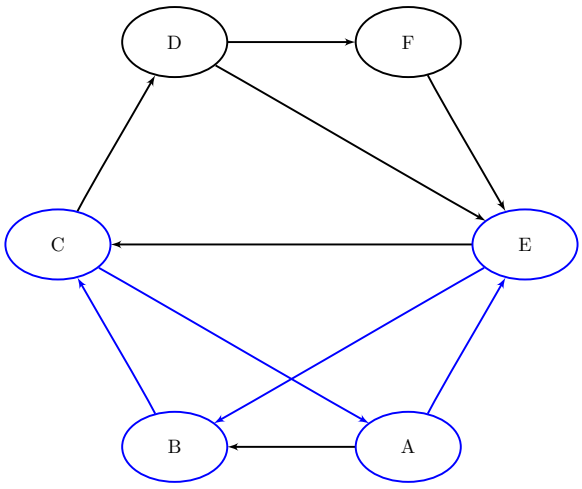
cycle	order	node
5	1	B
5	2	C
5	3	D
5	4	F
5	5	E
5	6	B
6	1	E
6	2	C
6	3	D

cycle	order	node
6	4	E
7	1	E
7	2	C
7	3	D
7	4	F
7	5	E

The six additional cycles are shown graphically in Figure 15.36 through Figure 15.38.

Figure 15.36 Cycles

$A \rightarrow E \rightarrow B \rightarrow C \rightarrow A$



$A \rightarrow E \rightarrow C \rightarrow A$

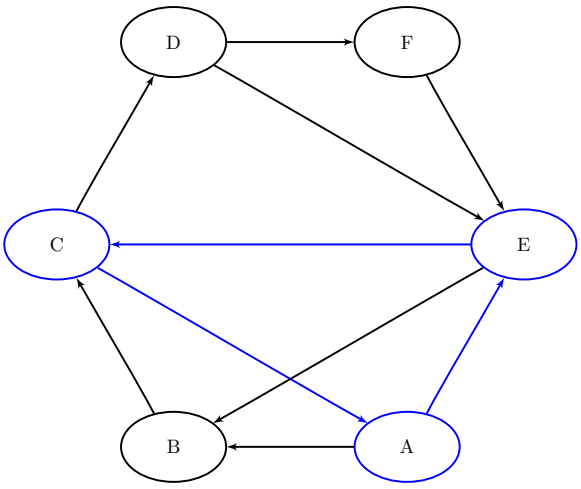
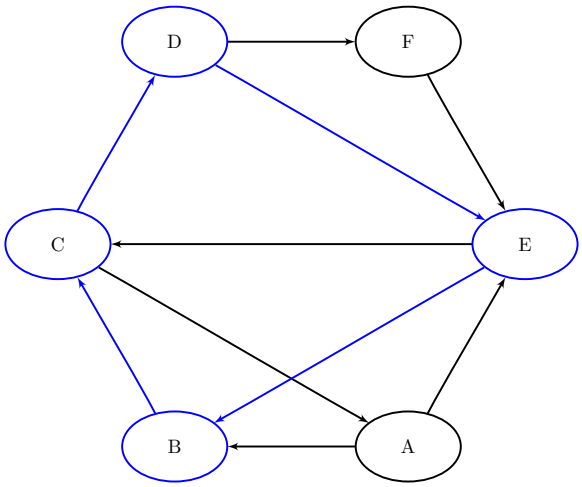


Figure 15.37 Cycles

$B \to C \to D \to E \to B$



$B \to C \to D \to F \to E \to B$

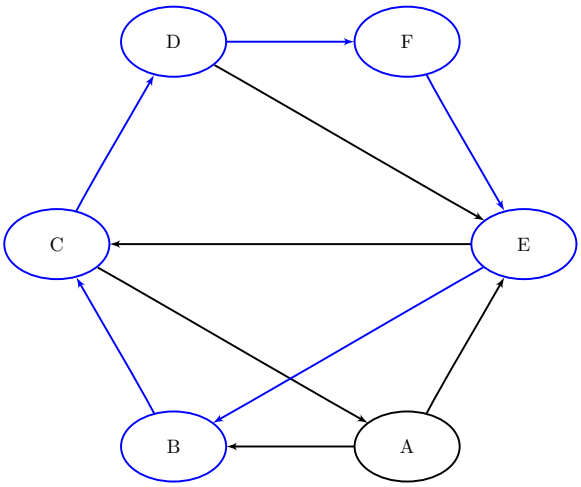
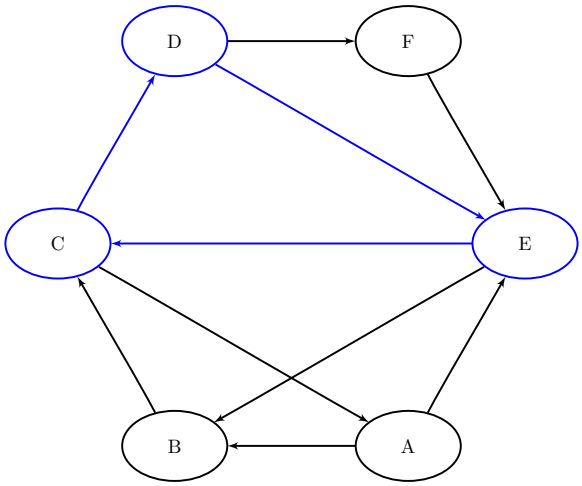
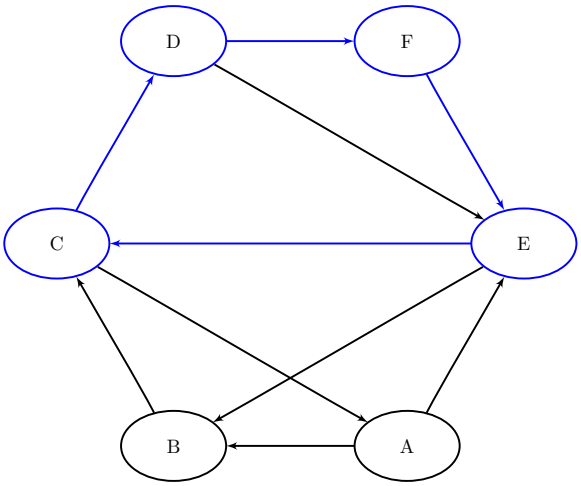


Figure 15.38 Cycles

$E \to C \to D \to E$



$E \to C \to D \to F \to E$



Linear Assignment (Matching)

The *linear assignment problem* (LAP) is a fundamental problem in combinatorial optimization that involves assigning workers to tasks at minimal costs. In graph theoretic terms, LAP is equivalent to finding a minimum-weight matching in a weighted bipartite directed graph. In a *bipartite graph*, the nodes can be divided into two disjoint sets, S (workers) and T (tasks), such that every link connects a node in S to a node in T. That is, the node sets S and T are independent. The concept of assigning workers to tasks can be generalized to the assignment of any abstract object in one group to an abstract object in a second group.

The linear assignment problem can be formulated as an integer programming optimization problem. The form of the problem depends on the sizes of the two input sets, S and T. Let E represent the set of possible assignments between sets S and T. In the bipartite graph, these assignments are the links. If $|S| \geq |T|$, then the following optimization problem is solved:

$$\begin{aligned}
\text{minimize} \quad & \sum_{e \in E} c_e x_e \\
\text{subject to} \quad & \sum_{e \in \delta_i^{\text{out}}} x_e \leq 1 \quad i \in S \\
& \sum_{e \in \delta_j^{\text{in}}} x_e = 1 \quad j \in T \\
& x_e \in \{0, 1\} \quad e \in E
\end{aligned}$$

where δ_i^{out} represents the set of outgoing links that are connected from node i and δ_j^{in} represents the set of incoming links that are connected to node j.

This model allows for some elements of set S (workers) to go unassigned (if $|S| > |T|$). However, if $|S| < |T|$, then the following optimization problem is solved:

$$\begin{aligned}
\text{minimize} \quad & \sum_{e \in E} c_e x_e \\
\text{subject to} \quad & \sum_{e \in \delta_i^{\text{out}}} x_e = 1 \quad i \in S \\
& \sum_{e \in \delta_j^{\text{in}}} x_e \leq 1 \quad j \in T \\
& x_e \in \{0, 1\} \quad e \in E
\end{aligned}$$

This model allows for some elements of set T (tasks) to go unassigned.

In the network solver, you can invoke the linear assignment problem solver by using the LINEARASSIGNMENT option. The algorithm that the network solver uses for solving a LAP is based on augmentation of shortest paths (Jonker and Volgenant 1987). This algorithm can be applied as long as the graph is bipartite.

The resulting assignment (or matching) is contained in the set that is specified in the ASSIGNMENTS= suboption of the OUT= option.

For a detailed example, see "Example 15.3: Linear Assignment Problem for Minimizing Relay Times" on page 909.

Maximum Flow

The *maximum network flow* problem involves finding the maximum possible flow through a network from a source node s to a sink node t, given that each link has a capacity limiting the amount of flow along that link. Let $G = (N, E)$ be a directed graph. For each link $e \in E$, define a nonnegative capacity u_e that specifies the maximum flow that link e can carry. Define decision variables x_e that denote the amount of flow sent across link e. The problem can be modeled as a linear programming problem as

$$\begin{aligned} \text{maximize} \quad & \sum_{e \in \delta_s^{\text{out}}} x_e \\ \text{subject to} \quad & \sum_{e \in \delta_i^{\text{out}}} x_e = \sum_{e \in \delta_i^{\text{in}}} x_e \qquad i \in N \setminus \{s, t\} \\ & 0 \le x_e \le u_e \qquad\qquad e \in E \end{aligned}$$

where δ_i^{out} represents the set of outgoing links that are connected from node i and δ_i^{in} represents the set of incoming links that are connected to node i.

In the network solver, you can invoke the maximum flow algorithm by using the MAXFLOW= option. You can use this algorithm only on directed graphs, and you must specify the SOURCE=*s* and SINK=*t* suboptions.

The network solver uses the Boykov-Kolmogorov algorithm (Boykov and Kolmogorov 2004) to compute the maximum flow. This algorithm runs in time $O(|N|^2|E||C|)$, where N is the set of nodes, E is the set of edges in the graph, and C is the value of the maximum flow in the graph.

The input for the network is the standard graph input, which is described in the section "Input Data for the Network Solver" on page 804. The MAXFLOW= option uses the following suboption of the LINKS= input option that specifies a link-indexed numeric array:

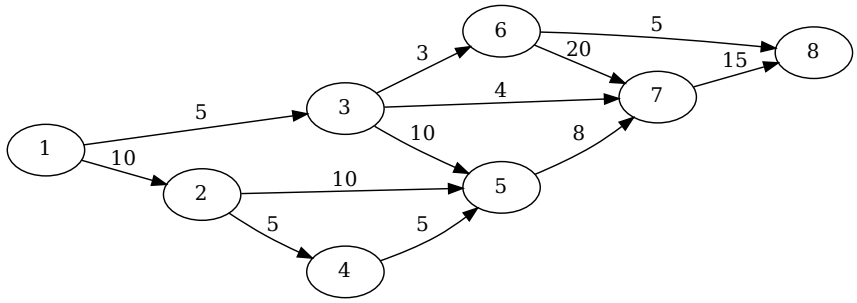
- The UPPER= suboption defines the link flow upper bound u_e. (The default is ∞.)

The resulting optimal flow through the network is written to the link-indexed numeric array that is specified in the FLOW= suboption of the OUT= option in the SOLVE WITH NETWORK statement.

Maximum Network Flow for a Directed Graph

This example demonstrates how to find the maximum flow in a directed graph. Consider the directed graph with link capacities shown in Figure 15.39.

Figure 15.39 Maximum Network Flow Problem: Data



The directed graph *G* can be represented by the links data table, LinkSetIn, that is created by the following DATA step:

```
data LinkSetIn;
   input from to upper;
   datalines;
1 2 10
1 3 5
2 4 5
2 5 10
3 5 10
3 6 3
3 7 4
4 5 5
5 7 8
6 7 20
6 8 5
7 8 15
;
```

You can use the following call to the network solver to find a maximum flow from node 1 to node 8:

```
proc optmodel;
   set <num,num> LINKS;
   num upper{LINKS};
   read data LinkSetIn into LINKS=[from to] upper;
   set SOURCE = {1};
   set SINK = {8};
   num flow{LINKS};

   solve with network /
      loglevel        = moderate
      graph_direction = directed
      links           = (upper=upper)
      maxFlow         = (source=SOURCE sink=SINK)
      out             = (flow=flow)
   ;
```

```
    print flow;
    create data LinkSetOut from [from to] upper flow;
  quit;
```

The progress of the procedure is shown in Figure 15.40.

Figure 15.40 Network Solver Log for Maximum Network Flow

```
NOTE: There were 12 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 12.
NOTE: The network solver is called.
NOTE: Processing the maximum flow problem using 1 threads across 1 machines.
NOTE: Objective = 13.
NOTE: Processing the maximum flow problem used 0.00 (cpu: 0.00) seconds.
NOTE: The data set WORK.LINKSETOUT has 12 observations and 4 variables.
```

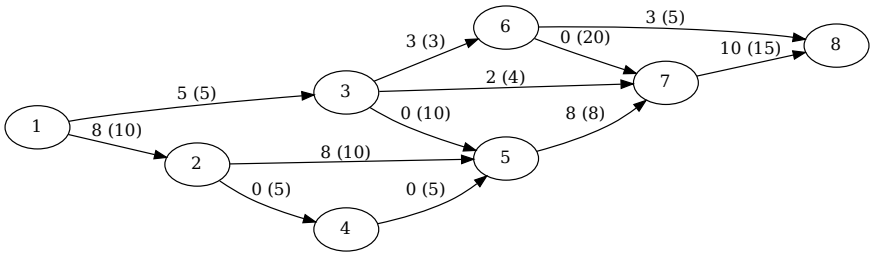
The optimal flows are displayed in Figure 15.41.

Figure 15.41 Maximum Network Flow Problem: Optimal Flows

Obs	from	to	upper	flow
1	1	2	10	8
2	1	3	5	5
3	2	4	5	0
4	2	5	10	8
5	3	5	10	0
6	3	6	3	3
7	3	7	4	2
8	4	5	5	0
9	5	7	8	8
10	6	7	20	0
11	6	8	5	3
12	7	8	15	10

The optimal flow (with link capacities in parentheses) is represented graphically in Figure 15.42.

Figure 15.42 Maximum Network Flow Problem: Optimal Flows



Minimum-Cost Network Flow

The *minimum-cost network flow* (MCF) problem is a fundamental problem in network analysis that involves sending flow through a network at minimal cost. Let $G = (N, E)$ be a directed graph. For each link $e \in E$, associate a cost per unit of flow, designated as c_e. The demand (or supply) at each node $i \in N$ is designated as b_i, where $b_i \geq 0$ denotes a supply node and $b_i < 0$ denotes a demand node. These values must be within $[b_i^l, b_i^u]$. Define decision variables x_e that denote the amount of flow sent across link e. The amount of flow that can be sent across each link is bounded to be within $[l_e, u_e]$. The problem can be modeled as a linear programming problem as

$$\begin{aligned} \text{minimize} \quad & \sum_{e \in E} c_e x_e \\ \text{subject to} \quad & b_i^l \leq \sum_{e \in \delta_i^{\text{out}}} x_e - \sum_{e \in \delta_i^{\text{in}}} x_e \leq b_i^u \qquad i \in N \\ & l_e \leq x_e \leq u_e \qquad\qquad\qquad\qquad e \in E \end{aligned}$$

where δ_i^{out} represents the set of outgoing links that are connected from node i and δ_i^{in} represents the set of incoming links that are connected to node i. When $b_i = b_i^l = b_i^u$ for all nodes $i \in N$, the problem is called a *standard network flow* problem. For these problems, the sum of the supply and demand values must be equal to 0 to ensure that a feasible solution exists.

In the network solver, you can invoke the minimum-cost network flow solver by using the MINCOSTFLOW option.

The algorithm that the network solver uses for solving MCF is a variant of the primal network simplex algorithm (Ahuja, Magnanti, and Orlin 1993). Sometimes the directed graph G is disconnected. In this case, the problem is first decomposed into its weakly connected components, and then each minimum-cost flow problem is solved separately.

The input for the network is the standard graph input, which is described in the section "Input Data for the Network Solver" on page 804. The MCF option uses the following suboptions of the LINKS= input option that specify link-indexed numeric arrays:

- The WEIGHT= suboption defines the link cost c_e per unit of flow. (The default is 0, but if the WEIGHT= suboption is not specified, then the default is 1.)
- The LOWER= suboption defines the link flow lower bound l_e. (The default is 0.)
- The UPPER= suboption defines the link flow upper bound u_e. (The default is ∞.)

The MCF option uses the following suboptions of the NODES= option. The parameter of each suboption is a numeric array that is positive for supply nodes and negative for demand nodes. To specify fixed node supplies and demands, use only the LOWER= suboption.

- The LOWER= suboption defines the node supply lower bounds. (The default is 0.)
- The UPPER= suboption defines the node supply upper bounds. (The default is ∞, but if the UPPER= option is not specified, then the upper bounds are set equal to the lower bounds).

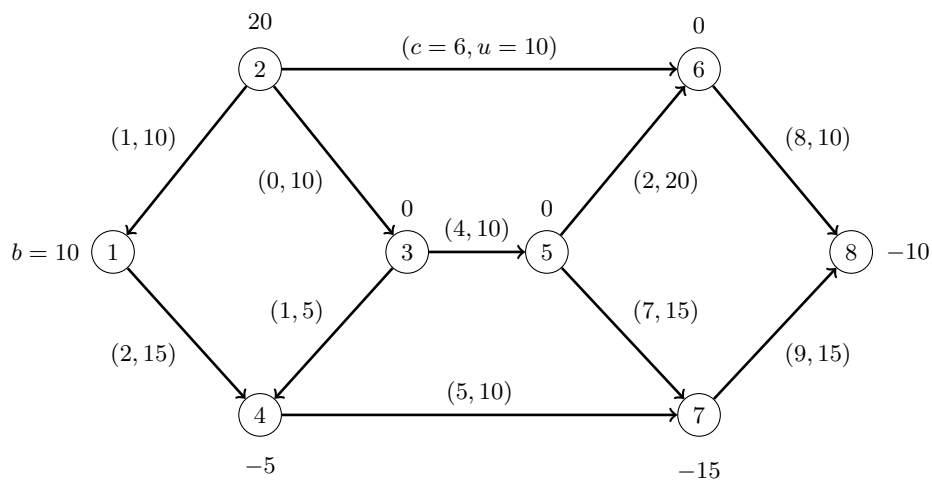
The resulting optimal flow through the network is written to the link-indexed numeric array that is specified in the FLOW= suboption of the OUT= option in the SOLVE WITH NETWORK statement.

You can also retrieve the dual and reduced cost values that are associated with the optimal solution to the linear program. The dual values for the node balance constraints are written to the node-indexed numeric array that you specify in the DUAL= suboption of the OUT= option. Similarly, the reduced costs for the link flow variables are written to the link-indexed numeric array that you specify in the RC= suboption of the OUT= option.

Minimum Cost Network Flow for a Simple Directed Graph

The following example demonstrates how to use the network simplex algorithm to find a minimum-cost flow in a directed graph. Consider the directed graph in Figure 15.43, which appears in Ahuja, Magnanti, and Orlin (1993).

Figure 15.43 Minimum-Cost Network Flow Problem: Data



The directed graph G can be represented by the following links data set LinkSetIn and nodes data set NodeSetIn:

```
data LinkSetIn;
   input from to weight upper;
   datalines;
1 4 2 15
2 1 1 10
2 3 0 10
2 6 6 10
3 4 1  5
3 5 4 10
4 7 5 10
5 6 2 20
5 7 7 15
6 8 8 10
7 8 9 15
;
```

```
data NodeSetIn;
   input node supply;
   datalines;
1  10
2  20
4  -5
7 -15
8 -10
;
```

You can use the following call to the network solver to find a minimum-cost flow:

```
proc optmodel;
   set <num,num> LINKS;
   num cost{LINKS};
   num upper{LINKS};
   read data LinkSetIn into LINKS=[from to] cost=weight upper;
   set NODES = union {<i,j> in LINKS} {i,j};
   num supply{NODES} init 0;
   read data NodeSetIn into [node] supply;
   num flow{LINKS};
   num flow_rc{LINKS};
   num dual{NODES};

   solve with network /
      loglevel        = moderate
      logfreq         = 1
      graph_direction = directed
      links           = (upper=upper weight=cost)
      nodes           = (lower=supply)
      mcf
      out             = (flow=flow rc=flow_rc dual=dual)
   ;

   print flow;
   create data LinkSetOut from [from to] upper cost flow flow_rc;
   create data NodeSetOut from [node] dual;
quit;
```

The progress of the procedure is shown in Figure 15.44.

Figure 15.44 Network Solver Log for Minimum-Cost Network Flow

```
NOTE: There were 11 observations read from the data set WORK.LINKSETIN.
NOTE: There were 5 observations read from the data set WORK.NODESETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 11.
NOTE: The network solver is called.
NOTE: Processing the minimum-cost network flow problem using 1 threads across 1
      machines.
NOTE: The network has 1 connected component.
                        Primal         Primal           Dual
      Iteration      Objective  Infeasibility  Infeasibility     Time
              1   0.000000E+00   2.000000E+01   8.900000E+01     0.00
              2   0.000000E+00   2.000000E+01   8.900000E+01     0.00
              3   5.000000E+00   1.500000E+01   2.666667E+01     0.00
              4   5.000000E+00   1.500000E+01   2.766667E+01     0.00
              5   7.500000E+01   1.500000E+01   2.666667E+01     0.00
              6   7.500000E+01   1.500000E+01   1.580000E+01     0.00
              7   1.300000E+02   1.000000E+01   2.533333E+01     0.00
              8   2.700000E+02   0.000000E+00   0.000000E+00     0.00
NOTE: The Network Simplex solve time is 0.00 seconds.
NOTE: Objective = 270.
NOTE: Processing the minimum-cost network flow problem used 0.00 (cpu: 0.00)
      seconds.
NOTE: The data set WORK.LINKSETOUT has 11 observations and 6 variables.
NOTE: The data set WORK.NODESETOUT has 8 observations and 2 variables.
```

The optimal solution is displayed in Figure 15.45.

Figure 15.45 Minimum-Cost Network Flow Problem: Optimal Solution

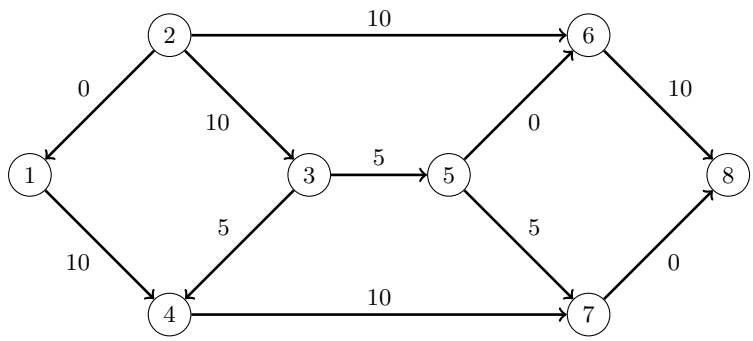
Obs	from	to	upper	cost	flow	flow_rc
1	1	4	15	2	10	0
2	2	1	10	1	0	1
3	2	3	10	0	10	0
4	2	6	10	6	10	0
5	3	4	5	1	5	-1
6	3	5	10	4	5	0
7	4	7	10	5	10	-4
8	5	6	20	2	0	0
9	5	7	15	7	5	0
10	6	8	10	8	10	0
11	7	8	15	9	0	6

Figure 15.45 *continued*

node	dual
1	0
4	-2
2	0
3	0
6	-6
5	-4
7	-11
8	-14

The optimal solution is represented graphically in Figure 15.46.

Figure 15.46 Minimum-Cost Network Flow Problem: Optimal Solution



Minimum-Cost Network Flow with Flexible Supply and Demand

Using the same directed graph shown in Figure 15.43, this example demonstrates a network that has a flexible supply and demand. Consider the following adjustments to the node bounds:

- Node 1 has an infinite supply, but it still requires at least 10 units to be sent.
- Node 4 is a throughput node that can now handle an infinite amount of demand.
- Node 8 has a flexible demand. It requires between 6 and 10 units.

You use the special missing values (.I) to represent infinity and (.M) to represent minus infinity. The adjusted node bounds can be represented by the following nodes data set:

```
data NodeSetIn;
   input node lower upper;
   datalines;
1  10  .I
2  20  20
4  .M  -5
7 -15 -15
8 -10  -6
;
```

You can use the following call to PROC OPTMODEL to find a minimum-cost flow:

```
proc optmodel;
   set <num,num> LINKS;
   num cost{LINKS};
   num upper{LINKS};
      read data LinkSetIn into LINKS=[from to] cost=weight upper;
   set <num> NODES;
   num supply{NODES};
   num supplyUB{NODES}; /* also demand lower bound, if negative */
      read data NodeSetIn into NODES=[node] supply=lower supplyUB=upper;
   num flow{LINKS};

   solve with NETWORK /
      direction = directed
      links     = ( upper = upper weight = cost )
      nodes     = ( lower = supply upper = supplyUB )
      mcf
      out       = ( flow = flow )
   ;
   print flow;
   create data LinkSetOut from [from to] upper cost flow;
quit;
```

The progress of the procedure is shown in Figure 15.47.

Figure 15.47 PROC OPTMODEL Log for Minimum-Cost Network Flow

```
NOTE: There were 11 observations read from the data set WORK.LINKSETIN.
NOTE: There were 5 observations read from the data set WORK.NODESETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 11.
NOTE: The network solver is called.
NOTE: Processing the minimum-cost network flow problem using 1 threads across 1
      machines.
NOTE: Objective = 226.
NOTE: Processing the minimum-cost network flow problem used 0.00 (cpu: 0.00)
      seconds.
NOTE: The data set WORK.LINKSETOUT has 11 observations and 5 variables.
```

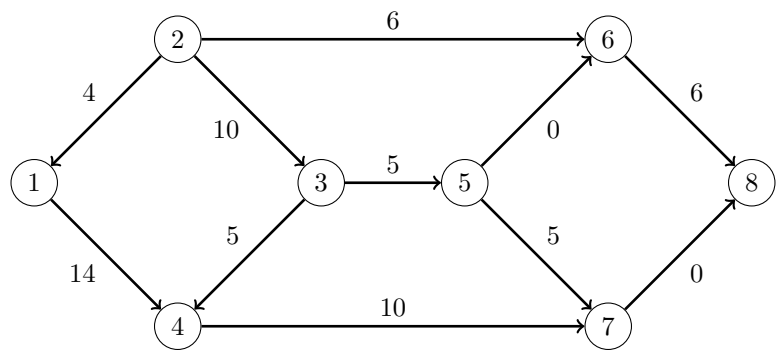
The optimal solution is displayed in Figure 15.48.

Figure 15.48 Minimum-Cost Network Flow Problem: Optimal Solution

Obs	from	to	upper	cost	flow
1	1	4	15	2	14
2	2	1	10	1	4
3	2	3	10	0	10
4	2	6	10	6	6
5	3	4	5	1	5
6	3	5	10	4	5
7	4	7	10	5	10
8	5	6	20	2	0
9	5	7	15	7	5
10	6	8	10	8	6
11	7	8	15	9	0

The optimal solution is represented graphically in Figure 15.49.

Figure 15.49 Minimum-Cost Network Flow Problem: Optimal Solution



Minimum Cut

A *cut* is a partition of the nodes N of a graph into two disjoint subsets S and $T = N \setminus S$. A *cut set* is the set of links that join a node in S to a node in T. A *minimum cut* of a graph is a cut whose cut set has the smallest link metric, which is measured as follows: For an unweighted graph, the link metric is the number of links in the cut set. For a weighted graph, the link metric is the sum of the link weights in the cut set.

In the network solver, you can invoke the minimum-cut algorithm by using the MINCUT= option. Unless you specify the SOURCE= and SINK= suboptions, you can use this algorithm only on undirected graphs.

If the value of the MAXCUTS= suboption is greater than 1, then the algorithm can return more than one set of cuts (a minimum cut and other cuts that are possibly not minimum). The resulting cuts can be described in terms of the links or partitions of the nodes of the graph in the cut sets. The example in the next section illustrates several ways to manipulate the output from the minimum-cut algorithm. The node partition is specified in the PARTITIONS= suboption of the OUT= option in the SOLVE WITH NETWORK statement. Each tuple in this set has a cut ID and a node. PROC OPTMODEL provides only the smaller of the two subsets that form each partition. You can use the DIFF set operator to get the complement of each partition. The cut set is specified in the CUTSETS= suboption of the OUT= option. This set contains the cut ID and the corresponding list of links.

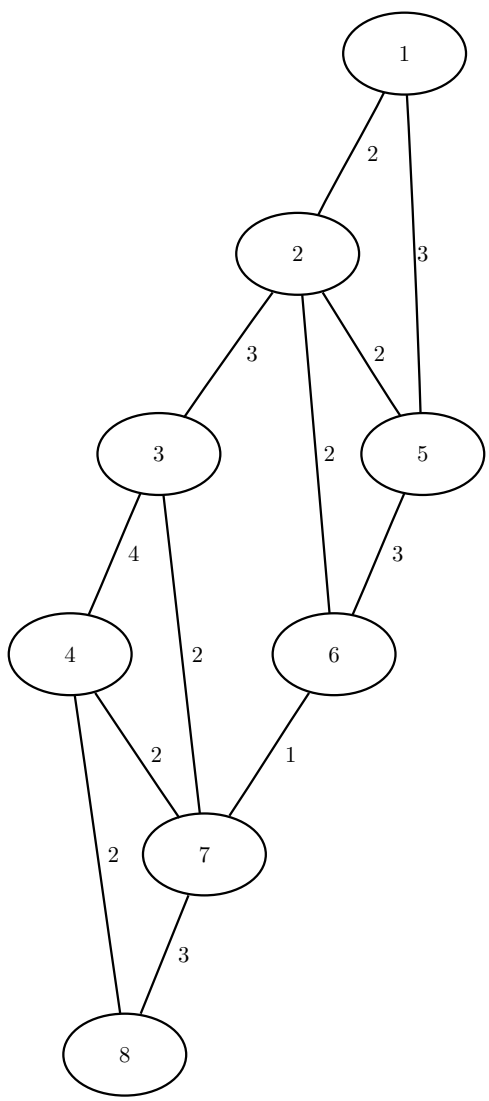
The network solver uses the Stoer-Wagner algorithm (Stoer and Wagner 1997) to compute the minimum cuts. This algorithm runs in time $O(|N||E| + |N|^2 \log |N|)$.

When you specify the SOURCE=*s* and SINK=*t* suboptions of the MINCUT= option, the network solver solves the *minimum s-t cut* problem, which is to find a minimum cut such that $s \in S$ and $t \in T$. The cut set for this cut intersects every path from the source node *s* to the sink node *t*. If you specify either the SOURCE= suboption or the SINK= suboption, the other is also required. Only one cut is returned by the minimum *s-t* cut algorithm, so the MAXCUTS= suboption is ignored when the SOURCE= and SINK= suboptions are specified.

Minimum Cut for a Simple Undirected Graph

As a simple example, consider the weighted undirected graph in Figure 15.50.

Figure 15.50 A Simple Undirected Graph



The links data set can be represented as follows:

```
data LinkSetIn;
   input from to weight @@;
   datalines;
1 2 2  1 5 3  2 3 3  2 5 2  2 6 2
3 4 4  3 7 2  4 7 2  4 8 2  5 6 3
6 7 1  7 8 3
;
```

The following statements calculate minimum cuts in the graph and output the results in the data set MinCut:

```
proc optmodel;
   set<num,num> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set<num> NODES = union {<i,j> in LINKS} {i,j};
   set<num,num> PARTITIONS;
   set<num,num,num> CUTSETS;

   solve with NETWORK /
      loglevel = moderate
      links    = (weight=weight)
      mincut   = (maxcuts=3)
      out      = (partitions=PARTITIONS cutsets=CUTSETS)
   ;
   set CUTS = setof {<cut,i,j> in CUTSETS} cut;
   num minCutWeight {cut in CUTS} = sum {<(cut),i,j> in CUTSETS} weight[i,j];
   print minCutWeight;

   for { cut in CUTS }
      put "Cut ID: "    cut
          "Partition: " ( slice( <cut,*>, PARTITIONS ) )
          "and "        ( NODES diff slice( <cut,*>, PARTITIONS ) )
          "Cut: "       ( slice( <cut,*,*>, CUTSETS ) )
          "Weight: "    minCutWeight[cut];

   create data MinCut from [mincut from to]=CUTSETS weight[from,to];
   num partition {cut in CUTS, node in NODES} =
      if <cut,node> in PARTITIONS then 0 else 1;
   create data NodeSetOut from [cut node]={CUTS, NODES} partition;
quit;
```

The progress of the procedure is shown in Figure 15.51.

Figure 15.51 Network Solver Log for Minimum Cut

```
NOTE: There were 12 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 12.
NOTE: The network solver is called.
NOTE: Processing the minimum-cut problem using 1 threads across 1 machines.
NOTE: The minimum-cut algorithm found 3 cuts.
NOTE: Objective = 4.
NOTE: Processing the minimum-cut problem used 0.00 (cpu: 0.00) seconds.
Cut ID: 1 Partition: {3,4,7,8} and {1,2,5,6} Cut: {<2,3>,<6,7>} Weight: 4
Cut ID: 2 Partition: {8} and {1,2,5,3,6,4,7} Cut: {<4,8>,<7,8>} Weight: 5
Cut ID: 3 Partition: {1} and {2,5,3,6,4,7,8} Cut: {<1,2>,<1,5>} Weight: 5
NOTE: The data set WORK.MINCUT has 6 observations and 4 variables.
NOTE: The data set WORK.NODESETOUT has 24 observations and 3 variables.
```

The data set NodeSetOut now contains the partition of the nodes for each cut, shown in Figure 15.52.

Figure 15.52 Minimum Cut Node Partition

cut	node	partition
1	1	1
1	2	1
1	5	1
1	3	0
1	6	1
1	4	0
1	7	0
1	8	0
2	1	1
2	2	1
2	5	1
2	3	1
2	6	1
2	4	1
2	7	1
2	8	0
3	1	0
3	2	1
3	5	1
3	3	1
3	6	1
3	4	1
3	7	1
3	8	1

The data set MinCut contains the links in the cut sets for each cut. This data set is shown in Figure 15.53, which also shows each cut separately.

Figure 15.53 Minimum Cut Sets

mincut	from	to	weight
1	2	3	3
1	6	7	1
2	4	8	2
2	7	8	3
3	1	2	2
3	1	5	3

mincut=1

from	to	weight
2	3	3
6	7	1
mincut		**4**

mincut=2

from	to	weight
4	8	2
7	8	3
mincut		**5**

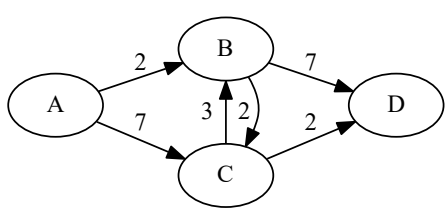
mincut=3

from	to	weight
1	2	2
1	5	3
mincut		**5**
		14

Minimum *s*-*t* Cut for a Directed Graph

As an example of the minimum *s*-*t* cut algorithm, consider the weighted directed graph in Figure 15.54.

Figure 15.54 Directed Graph



The links data set can be represented as follows:

```
data LinkSetIn;
   input from $ to $ weight;
   datalines;
A B 2
A C 7
B C 2
B D 7
C B 3
C D 2
;
```

The following statements calculate a minimum cut in the graph that intersects all paths from A to D, and they output the results in the data set MinCut:

```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set<str> NODES = union {<i,j> in LINKS} {i,j};
   set<num,str> PARTITIONS;
   set<num,str,str> CUTSETS;
   set<str> SOURCE = {"A"};
   set<str> SINK = {"D"};

   solve with NETWORK /
      direction = directed
      loglevel  = moderate
      links     = (weight=weight)
      mincut    = (source=SOURCE sink=SINK)
      out       = (partitions=PARTITIONS cutsets=CUTSETS)
   ;
   set CUTS = setof {<cut,i,j> in CUTSETS} cut;
   num minCutWeight {cut in CUTS} = sum {<(cut),i,j> in CUTSETS} weight[i,j];
   print minCutWeight;

   for { cut in CUTS }
      put "Cut ID: "    cut
          "Partition: " ( slice( <cut,*>, PARTITIONS ) )
          "and "        ( NODES diff slice( <cut,*>, PARTITIONS ) )
          "Cut: "       ( slice( <cut,*,*>, CUTSETS ) )
          "Weight: "    minCutWeight[cut];

   create data MinCut from [mincut from to]=CUTSETS weight[from,to];
   num partition {cut in CUTS, node in NODES} =
      if <cut,node> in PARTITIONS then 0 else 1;
   create data NodeSetOut from [cut node]={CUTS, NODES} partition;
quit;
```

The progress of the procedure is shown in Figure 15.55.

Figure 15.55 Network Solver Log for Minimum Cut

```
NOTE: There were 6 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 4.
NOTE: The number of links in the input graph is 6.
NOTE: The network solver is called.
NOTE: Processing the minimum-cut problem using 1 threads across 1 machines.
NOTE: The minimum-cut algorithm found 1 cuts.
NOTE: Objective = 7.
NOTE: Processing the minimum-cut problem used 0.00 (cpu: 0.00) seconds.
Cut ID: 1 Partition: {'A','C'} and {'B','D'} Cut: {<'A','B'>,<'C','B'>,<'C','D'>
} Weight: 7
NOTE: The data set WORK.MINCUT has 3 observations and 4 variables.
NOTE: The data set WORK.NODESETOUT has 4 observations and 3 variables.
```

The data set NodeSetOut now contains the partition of the nodes and is shown in Figure 15.56.

Figure 15.56 Minimum Cut Node Partition

cut	node	partition
1	A	0
1	B	1
1	C	0
1	D	1

The data set MinCut contains the links in the minimum cut and is shown in Figure 15.57.

Figure 15.57 Minimum Cut Sets

mincut	from	to	weight
1	A	B	2
1	C	B	3
1	C	D	2

Minimum Spanning Tree

A *spanning tree* of a connected graph is a subgraph that is a tree that connects all the nodes together. A *minimum spanning tree* (MST) of a connected and link-weighted graph is a spanning tree whose sum of link weights is less than or equal to the sum of link weights of every other spanning tree. More generally, a *spanning forest* is a union of disjoint tree subgraphs that collectively span the nodes of the graph. A *minimum spanning forest* is a spanning forest that has the minimum possible number of trees and whose sum of link weights is less than or equal to the sum of link weights of every other spanning forest that has the minimum possible number of trees.

In the network solver, you can invoke the minimum spanning tree algorithm by using the MINSPANTREE option.

The resulting minimum spanning tree is contained in the set that is specified in the FOREST= suboption of the OUT= option in the SOLVE WITH NETWORK statement.

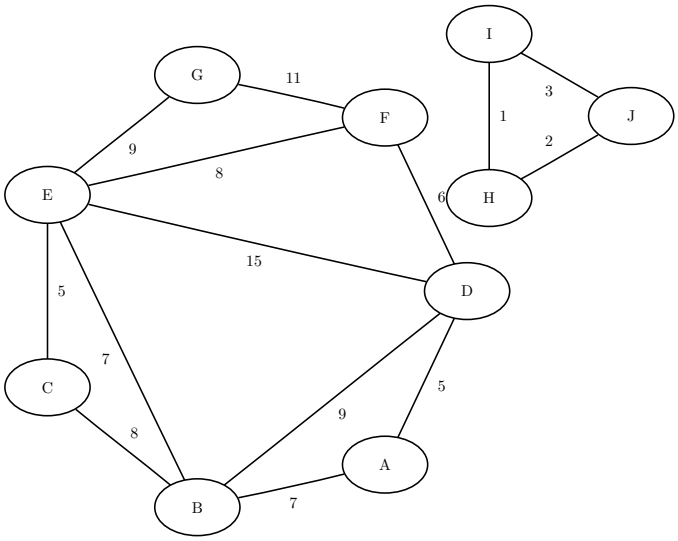
Minimum Spanning Tree for a Simple Undirected Graph

For undirected graphs, each connected component has a minimum spanning tree, and the minimum spanning forest for the graph is the union of the minimum spanning trees of its connected components.

The network solver uses Kruskal's algorithm (Kruskal 1956) to compute the minimum spanning tree. This algorithm runs in time $O(|E| \log |N|)$ and therefore should scale to very large graphs.

As a simple example, consider the weighted undirected graph in Figure 15.58.

Figure 15.58 A Simple Undirected Graph



The links data set can be represented as follows:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B  7  A D  5  B C 8  B D 9  B E 7
C E  5  D E 15  D F 6  E F 8  E G 9
F G 11  H I  1  I J 3  H J 2
;
```

The following statements calculate a minimum spanning forest and output the results in the data set MinSpanForest:

```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set<str,str> FOREST;

   solve with NETWORK /
      links       = (weight=weight)
```

```
      minspantree
      out          = (forest=FOREST)
   ;

   put FOREST;
   create data MinSpanForest from [from to]=FOREST weight;
quit;
```

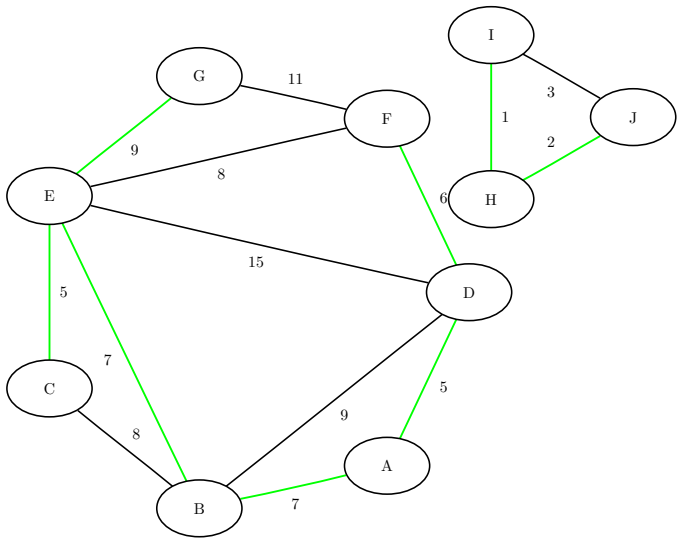
The MinSpanForest data set now contains the links that belong to a minimum spanning forest, which is shown in Figure 15.59.

Figure 15.59 Minimum Spanning Forest

from	to	weight
H	I	1
H	J	2
A	D	5
C	E	5
D	F	6
A	B	7
B	E	7
E	G	9
		42

The minimal-cost links are shown in green in Figure 15.60.

Figure 15.60 Minimum Spanning Forest



For a more detailed example, see "Example 15.5: Minimum Spanning Tree for Computer Network Topology" on page 915.

Minimum Spanning Tree for a Directed Graph

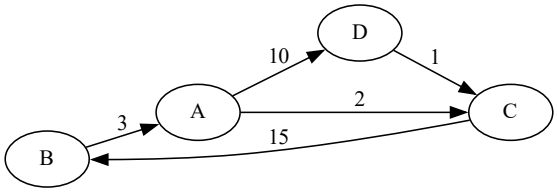
In the MST problem on directed graphs, each tree subgraph in the solution has the extra restriction that it must be an *arborescence* (also called a *branching*). That is, each tree has a source (or root) node with zero incoming links, and every other node in the tree has exactly one incoming link. A minimum spanning forest in a strongly connected directed graph always consists of a single tree, but a weakly connected directed graph might require additional trees to span all nodes.

In the SOLVE WITH NETWORK statement, for directed graphs you can use the SOURCE= suboption to specify a source node. If a spanning tree exists that has the designated source node, the output solution is a spanning tree that is rooted at that source node and has the smallest total link weight among all such trees. If no such tree exists, the output solution is a forest that consists of the smallest number of trees that are needed to span the nodes of the graph, such that one tree is rooted at the specified source node; the solution has the smallest total link weight among all such forests. If no source node is specified, the algorithm outputs a spanning forest that has the smallest total link weight among all spanning forests that have the minimum possible number of trees.

The network solver uses the Tarjan (1977) variant of an algorithm that was independently introduced by Chu and Liu (1965) and Edmonds (1967) to compute the minimum spanning tree in directed graphs. This algorithm runs in time $O(|N|^2)$.

As a simple example, consider the weighted directed graph in Figure 15.61.

Figure 15.61 A Simple Directed Graph



The links data set can be represented as follows:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A C  2   A D 10   B A  3
C B 15   D C  1
;
```

The following statements calculate a minimum spanning forest and output the results in the data set MinSpanForest:

```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set<str,str> FOREST;
```

```
   solve with NETWORK /
      graph_direction = directed
      links       = (weight=weight)
      minspantree
      out         = (forest=FOREST);

   put FOREST;
   create data MinSpanForest from [from to]=FOREST weight;
quit;
```

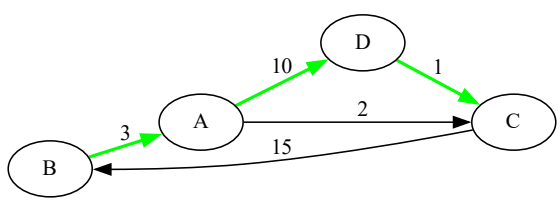
The MinSpanForest data set now contains the links that belong to a minimum spanning forest, which is shown in Figure 15.62.

Figure 15.62 Minimum Spanning Forest

from	to	weight
B	A	3
D	C	1
A	D	10
		14

The minimal-cost links are shown in green in Figure 15.63.

Figure 15.63 Minimum Spanning Forest



The following statements calculate a minimum spanning forest for the same input graph, with the additional specification that node *A* be a source node:

```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set<str,str> FOREST;
   set ROOT = /A/;

   solve with NETWORK /
      graph_direction = directed
      links       = (weight=weight)
      minspantree = (source=ROOT)
      out         = (forest=FOREST);

   put FOREST;
```

```
    create data MinSpanForest from [from to]=FOREST weight;
  quit;
```

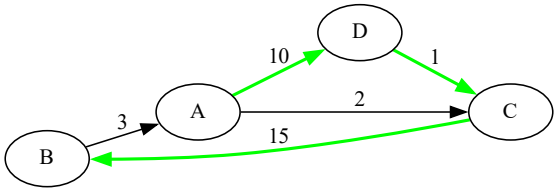
The MinSpanForest data set now contains the links that belong to a minimum spanning forest with source node *A*, which is shown in Figure 15.64.

Figure 15.64 Minimum Spanning Forest

from	to	weight
D	C	1
A	D	10
C	B	15
		26

The minimal-cost links are shown in green in Figure 15.65.

Figure 15.65 Minimum Spanning Forest



Path Enumeration

A *path* in a graph is a sequence of links such that the *to* node of each link is the *from* node of the next link. An *elementary path* is a path in which no node is visited more than once. A path between two nodes, *i* and *j*, in a graph is a path that starts at *i* and ends at *j*. The starting node is called the *source node*, and the ending node is called the *sink node*.

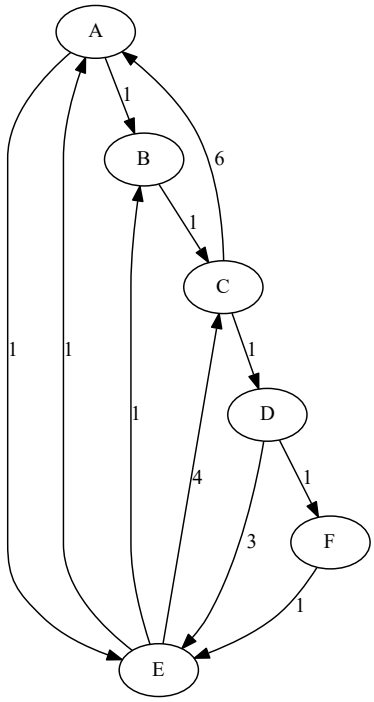
In the network solver, you can find the elementary paths of an input graph by using the PATH= option.

By default, the network solver finds paths for all pairs of nodes in the input graph. That is, it finds all paths for each possible combination of source nodes and sink nodes. Alternatively, you can use the SOURCE= suboption to specify a particular source node and find all paths from the specified source node to all possible sink nodes. Conversely, by using the SINK= option, you can specify a sink node and find all paths from all possible source nodes to the specified sink node. By using both options together, you can request all paths for a specific source-sink pair. In addition, you can use the SOURCE= and SINK= suboptions to define a list of source-sink pairs to process. The following subsection provides an example of how to use these options.

Path Enumeration for One Source-Sink Pair

This section provides a simple example of using the SOURCE= and SINK= options and the path enumeration algorithm on the simple directed graph *G* shown in Figure 15.66 to find all paths between one source-sink pair.

Figure 15.66 A Simple Directed Graph *G*



The directed graph *G* can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 1 A E 1 B C 1 C A 6 C D 1
D E 3 D F 1 E B 1 E C 4 F E 1
E A 1
;
```

The following statements find all paths from node *D* to node *A* whose path link weight is less than or equal to 10:

```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set SOURCE = {'D'};
   set SINK   = {'A'};
```

```
    /* source, sink, path, order, from, to */
    set<str,str,num,num,str,str> PATHLINKS;

    /* source, sink, path, order, node */
    set<str,str,num,num,str> PATHNODES;

    solve with network /
       direction     = directed
       links         = (weight=weight)
       path          = (source=SOURCE sink=SINK maxlinkweight=10)
       out           = (pathslinks=PATHLINKS pathsnodes=PATHNODES)
    ;
    create data PathLinks from [source sink path order from to]=PATHLINKS;
    create data PathNodes from [source sink path order node]=PATHNODES;
  quit;
```

The output data set PathLinks contains the links of the three paths from *D* to *A* whose path link weight is less than or equal to 10, as shown in Figure 15.67.

Figure 15.67 Links for All (Short) Paths in a Simple Directed Graph

source	sink	path	order	from	to
D	A	1	1	D	E
D	A	1	2	E	A
D	A	2	1	D	F
D	A	2	2	F	E
D	A	2	3	E	A
D	A	3	1	D	F
D	A	3	2	F	E
D	A	3	3	E	B
D	A	3	4	B	C
D	A	3	5	C	A

The output data set PathNodes contains the nodes of the three paths, as shown in Figure 15.68.

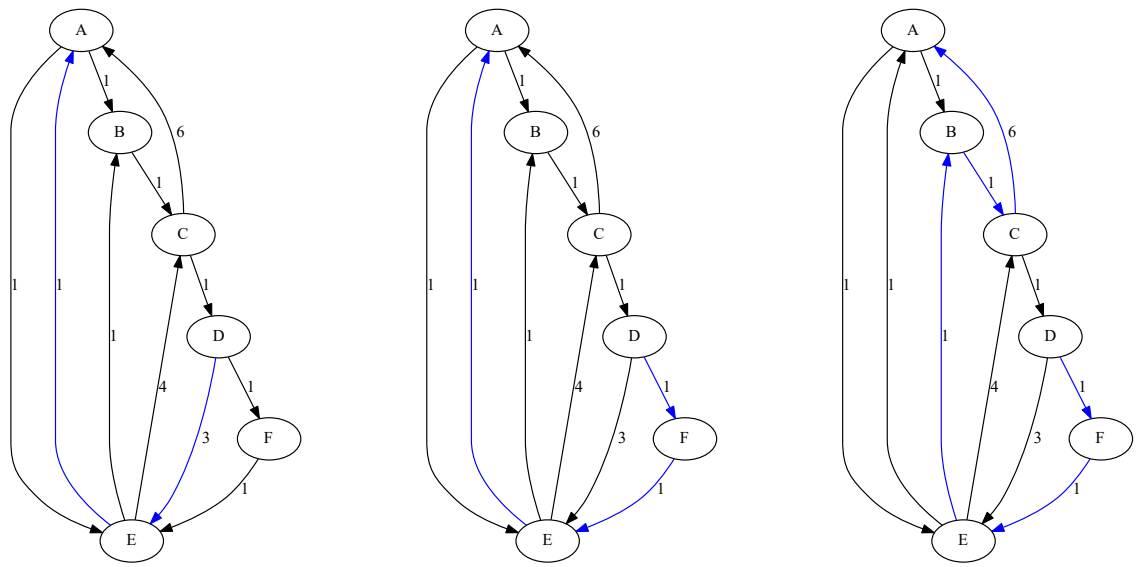
Figure 15.68 Nodes for All (Short) Paths in a Simple Directed Graph

source	sink	path	order	node
D	A	1	1	D
D	A	1	2	E
D	A	1	3	A
D	A	2	1	D
D	A	2	2	F
D	A	2	3	E
D	A	2	4	A
D	A	3	1	D
D	A	3	2	F
D	A	3	3	E
D	A	3	4	B
D	A	3	5	C
D	A	3	6	A

The three (short) paths are shown graphically in Figure 15.69.

Figure 15.69 Paths

$D \rightarrow E \rightarrow A$ $\qquad$ $D \rightarrow F \rightarrow E \rightarrow A$ $\qquad$ $D \rightarrow F \rightarrow E \rightarrow B \rightarrow C \rightarrow A$



Shortest Path

A *shortest path* between two nodes, *i* and *j*, in a graph is a path that starts at *i* and ends at *j* and has the lowest total link weight. The starting node is called the *source node*, and the ending node is called the *sink node*.

In the network solver, you can calculate shortest paths by using the SHORTESTPATH= option.

By default, the network solver finds shortest paths for all pairs. That is, it finds a shortest path for each possible combination of source and sink nodes. Alternatively, you can use the SOURCE= suboption to fix a particular source node and find shortest paths from the fixed source node to all possible sink nodes. Conversely, by using the SINK= suboption, you can fix a sink node and find shortest paths from all possible source nodes to the fixed sink node. By using both suboptions together, you can request one particular shortest path for a specific source-sink pair. In addition, you can use the SOURCE= and SINK= suboptions to define a list of source-sink pairs to process. The following sections show examples of these suboptions.

Which algorithm the network solver uses to find shortest paths depends on the data. The algorithm and run-time complexity for each graph type is shown in Table 15.11.

Table 15.11 Algorithms for Shortest Paths

Graph Type	Algorithm	Complexity (per Source Node)
Unweighted	Breadth-first search	$O(\|N\| + \|E\|)$
Weighted (nonnegative)	Dijkstra's algorithm	$O(\|N\| \log \|N\| + \|E\|)$
Weighted (positive and negative allowed)	Bellman-Ford algorithm	$O(\|N\|\|E\|)$

Details for each algorithm can be found in Ahuja, Magnanti, and Orlin (1993).

By default, MAXPATHSPERPAIR=1 and the algorithm returns one shortest path for each source-sink pair. If you set the MAXPATHSPERPAIR= suboption to a value K greater than 1, the network solver finds up to K paths for each source-sink pair, arranged in ascending order in the sum of link weights for each path. In this case, the algorithm that is used is a variant of Yen's algorithm (Yen 1971). The run-time complexity of Yen's algorithm for each link type is shown in Table 15.12.

Table 15.12 Algorithm Complexity for Ranked Paths

Link Type	Complexity (per Source-Sink Pair)
Weighted (nonnegative)	$O(K\|N\|(\|N\|\log\|N\| + \|E\|))$
Weighted (positive and negative allowed)	$O(K\|N\|^2\|E\|)$

For weighted graphs, the algorithm uses the parameter that is specified in the WEIGHT= suboption of the LINKS= option to evaluate a path's total weight (cost).

Outputs

The shortest path algorithm produces up to five outputs that describe the shortest paths found for each source-sink pair. Up to K paths can be output per source-sink pair, where K is the value of the MAXPATHSPERPAIR= suboption. The outputs are shown in Table 15.13.

Table 15.13 Output Options for Shortest Paths

OUT= Suboption	Type	Maximum Paths per Source-Sink Pair	Description
PATHSLINKS=	Set	K	Link sequences
PATHSNODES=	Set	K	Node sequences
PATHSWEIGHTS=	Set	K	Total weights
SPPATHS=	Set	1	Link sequences
SPWEIGHTS=	Parameter	1	Total weights

When an output supports K paths per source-sink pair, the paths are ranked by ascending total weight, with the shortest path given rank 1. The outputs that support a single path per source-sink pair include only the shortest path found for each pair.

SPPATHS= and PATHSLINKS= Sets

The SPPATHS= and PATHSLINKS= sets contain the links present in the shortest path for each source-sink pair. The SPPATHS= set contains only the shortest path for each source-sink pair.

The individual links in these sets always appear in the order that you provide. If you provide link (u, v) and solve a shortest path problem on an undirected graph, and that path visits node v before node u, then this set will contain link (u, v), not link (v, u), which is not part of the network. This approach simplifies indexing throughout your model.

For large graphs and a large requested number of source-sink pairs, these sets can be extremely large. For extremely large graphs, generating the output can sometimes take longer than computing the shortest paths.

For example, using the US road network data for the state of New York, the data contain a directed graph that has 264,346 nodes. Finding the shortest path for all pairs from only one source node results in 140,969,120 observations, which is a set of size 11 GB. Finding shortest paths for all pairs from all nodes would produce an enormous set.

The SPPATHS= set contains the following tuple members:

1. the source node of this shortest path
2. the sink node of this shortest path
3. for this source-sink pair, the order of this link in a shortest path
4. the *tail* node of this link in a shortest path
5. the *head* node of this link in a shortest path

The PATHSLINKS= set contains the following tuple members:

1. the source node of this shortest path
2. the sink node of this shortest path
3. the rank of this path among all shortest paths for the source-sink pair
4. the order of this link in a shortest path
5. the *tail* node of this link in a shortest path
6. the *head* node of this link in a shortest path

PATHSNODES= Set

The PATHSNODES= set contains the nodes present in the shortest paths for each source-sink pair.

The PATHSNODES= set contains the following tuple members:

1. the source node of this shortest path
2. the sink node of this shortest path
3. the rank of this path among all shortest paths for the source-sink pair
4. the order of a node in a shortest path
5. the node in a shortest path

Like the SPPATHS= and PATHSLINKS= sets, the PATHSNODES= set can be extremely large when you have a large graph and a large requested number of source-sink pairs.

SPWEIGHTS= Array

The SPWEIGHTS= array contains the total weight for the shortest path for each of the source-sink pairs.

PATHSWEIGHTS= Set

The PATHSWEIGHTS= set contains the total weights of the shortest paths for each source-sink pair.

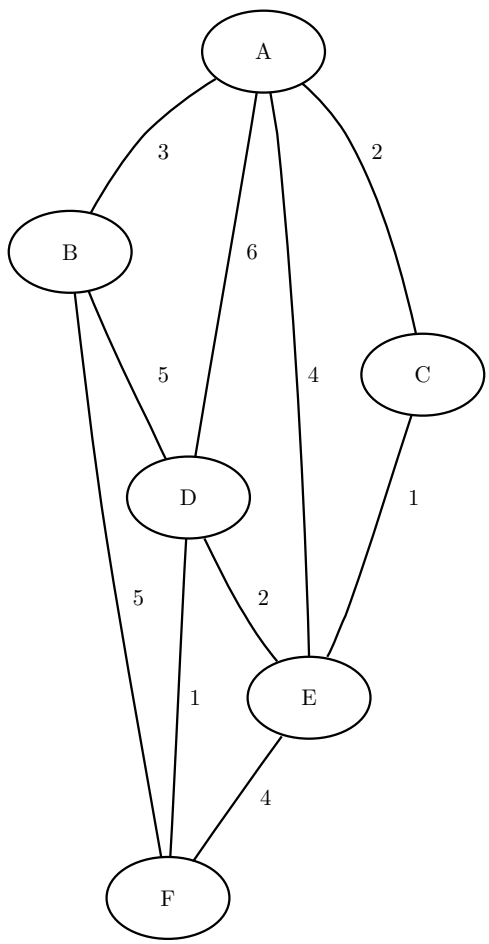
The PATHSWEIGHTS= set contains the following tuple members:

1. the source node of this shortest path
2. the sink node of this shortest path
3. the rank of this path among all shortest paths for the source-sink pair
4. the sum of link weights in a shortest path

Shortest Paths for All Pairs

This example illustrates the use of the shortest path algorithm for all source-sink pairs on the simple undirected graph G that is shown in Figure 15.70.

Figure 15.70 A Simple Undirected Graph G



The undirected graph G can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 3  A C 2  A D 6  A E 4  B D 5
B F 5  C E 1  D E 2  D F 1  E F 4
;
```

The following statements calculate shortest paths for all source-sink pairs:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set NODES = union{<i,j> in LINKS} {i,j};
   num path_length{NODES, NODES};

   solve with NETWORK /
      links     = (weight=weight)
      shortpath
      out       = (sppaths=PATHS spweights=path_length)
   ;

   put PATHS;
   print path_length;
   create data ShortPathP from [source sink order from to]=PATHS
      weight[from,to];
   create data ShortPathW from [source sink]
      path_weight=path_length;
quit;
```

The data set ShortPathP contains the shortest paths and is shown in Figure 15.71.

Figure 15.71 All-Pairs Shortest Paths

ShortPathP

source	sink	order	from	to	weight
A	B	1	A	B	3
A	C	1	A	C	2
A	D	1	A	C	2
A	D	2	C	E	1
A	D	3	D	E	2
A	E	1	A	C	2
A	E	2	C	E	1
A	F	1	A	C	2
A	F	2	C	E	1
A	F	3	D	E	2
A	F	4	D	F	1
B	A	1	A	B	3
B	C	1	A	B	3
B	C	2	A	C	2
B	D	1	B	D	5
B	E	1	A	B	3
B	E	2	A	C	2
B	E	3	C	E	1
B	F	1	B	F	5
C	A	1	A	C	2
C	B	1	A	C	2
C	B	2	A	B	3
C	D	1	C	E	1
C	D	2	D	E	2
C	E	1	C	E	1
C	F	1	C	E	1
C	F	2	D	E	2
C	F	3	D	F	1

source	sink	order	from	to	weight
D	A	1	D	E	2
D	A	2	C	E	1
D	A	3	A	C	2
D	B	1	B	D	5
D	C	1	D	E	2
D	C	2	C	E	1
D	E	1	D	E	2
D	F	1	D	F	1
E	A	1	C	E	1
E	A	2	A	C	2
E	B	1	C	E	1
E	B	2	A	C	2
E	B	3	A	B	3
E	C	1	C	E	1
E	D	1	D	E	2
E	F	1	D	E	2
E	F	2	D	F	1
F	A	1	D	F	1
F	A	2	D	E	2
F	A	3	C	E	1
F	A	4	A	C	2
F	B	1	B	F	5
F	C	1	D	F	1
F	C	2	D	E	2
F	C	3	C	E	1
F	D	1	D	F	1
F	E	1	D	F	1
F	E	2	D	E	2

The data set ShortPathW contains the path weight for the shortest paths of each source-sink pair and is shown in Figure 15.72.

Figure 15.72 All-Pairs Shortest Paths Summary

ShortPathW

source	sink	path_weight
A	A	.
A	B	3
A	C	2
A	D	5
A	E	3
A	F	6
B	A	3
B	B	.
B	C	5
B	D	5
B	E	6
B	F	5
C	A	2
C	B	5
C	C	.
C	D	3
C	E	1
C	F	4

source	sink	path_weight
D	A	5
D	B	5
D	C	3
D	D	.
D	E	2
D	F	1
E	A	3
E	B	6
E	C	1
E	D	2
E	E	.
E	F	3
F	A	6
F	B	5
F	C	4
F	D	1
F	E	3
F	F	.

Shortest Paths for a Subset of Source-Sink Pairs

This section illustrates the use of the SOURCE= and SINK= suboptions and the shortest path algorithm to calculate shortest paths for a subset of source-sink pairs. If S denotes the nodes in the SOURCE= set and T denotes the nodes in the SINK= set, the network solver calculates all the source-sink pairs in the crossproduct of these two sets.

For example, the following statements calculate a shortest path for the four combinations of source-sink pairs in $S \times T = \{A, C\} \times \{B, F\}$:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set SOURCES = / A C /;
   set SINKS   = / B F /;

   solve with NETWORK /
      links     = (weight=weight)
      shortpath = (source=SOURCES sink=SINKS)
      out       = (sppaths=PATHS)
   ;

   put PATHS;
   create data ShortPath from [source sink order from to]=PATHS weight[from,to];
quit;
```

The data set ShortPath contains the shortest paths and is shown in Figure 15.73.

Figure 15.73 Shortest Paths for a Subset of Source-Sink Pairs

ShortPath

source	sink	order	from	to	weight
A	B	1	A	B	3
A	F	1	A	C	2
A	F	2	C	E	1
A	F	3	D	E	2
A	F	4	D	F	1
C	B	1	A	C	2
C	B	2	A	B	3
C	F	1	C	E	1
C	F	2	D	E	2
C	F	3	D	F	1

Shortest Paths for a Subset of Source or Sink Pairs

This section illustrates the use of the shortest path algorithm to calculate shortest paths between a subset of source (or sink) nodes and all other sink (or source) nodes.

In this case, you designate the subset of source (or sink) nodes in the node set by specifying the SOURCE= (or SINK=) suboption. By specifying only one of the suboptions, you indicate that you want the network solver to calculate all pairs from a subset of source nodes (or to calculate all pairs to a subset of sink nodes).

For example, the following statements calculate all the shortest paths from nodes B and E:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set SOURCES = / B E /;

   solve with NETWORK /
      links     = (weight=weight)
      shortpath = (source=SOURCES)
      out       = (sppaths=PATHS)
   ;

   put PATHS;
   create data ShortPath from [source sink order from to]=PATHS weight[from,to];
quit;
```

The data set ShortPath contains the shortest paths and is shown in Figure 15.74.

Figure 15.74 Shortest Paths for a Subset of Source Pairs

ShortPath

source	sink	order	from	to	weight
B	A	1	A	B	3
B	C	1	A	B	3
B	C	2	A	C	2
B	D	1	B	D	5
B	E	1	A	B	3
B	E	2	A	C	2
B	E	3	C	E	1
B	F	1	B	F	5
E	A	1	C	E	1
E	A	2	A	C	2
E	B	1	C	E	1
E	B	2	A	C	2
E	B	3	A	B	3
E	C	1	C	E	1
E	D	1	D	E	2
E	F	1	D	E	2
E	F	2	D	F	1

Conversely, the following statements calculate all the shortest paths to nodes B and E:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set SINKS = / B E /;

   solve with NETWORK /
      links     = (weight=weight)
      shortpath = (sink=SINKS)
      out       = (sppaths=PATHS)
   ;

   put PATHS;
   create data ShortPath from [source sink order from to]=PATHS weight[from,to];
quit;
```

The data set ShortPath contains the shortest paths and is shown in Figure 15.75.

Figure 15.75 Shortest Paths for a Subset of Sink Pairs

ShortPath

source	sink	order	from	to	weight
A	B	1	A	B	3
A	E	1	A	C	2
A	E	2	C	E	1
B	E	1	A	B	3
B	E	2	A	C	2
B	E	3	C	E	1
C	B	1	A	C	2
C	B	2	A	B	3
C	E	1	C	E	1
D	B	1	B	D	5
D	E	1	D	E	2
E	B	1	C	E	1
E	B	2	A	C	2
E	B	3	A	B	3
F	B	1	B	F	5
F	E	1	D	F	1
F	E	2	D	E	2

Shortest Paths for One Source-Sink Pair

This section illustrates the use of the shortest path algorithm to calculate shortest paths between one source-sink pair by using the SOURCE= and SINK= suboptions.

The following statements calculate a shortest path between node *C* and node *F*:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set SOURCES = / C /;
   set SINKS   = / F /;

   solve with NETWORK /
      links     = (weight=weight)
      shortpath = (source=SOURCES sink=SINKS)
      out       = (sppaths=PATHS)
   ;

   put PATHS;
   create data ShortPath from [source sink order from to]=PATHS weight[from,to];
quit;
```

The data set ShortPath contains this shortest path and is shown in Figure 15.76.

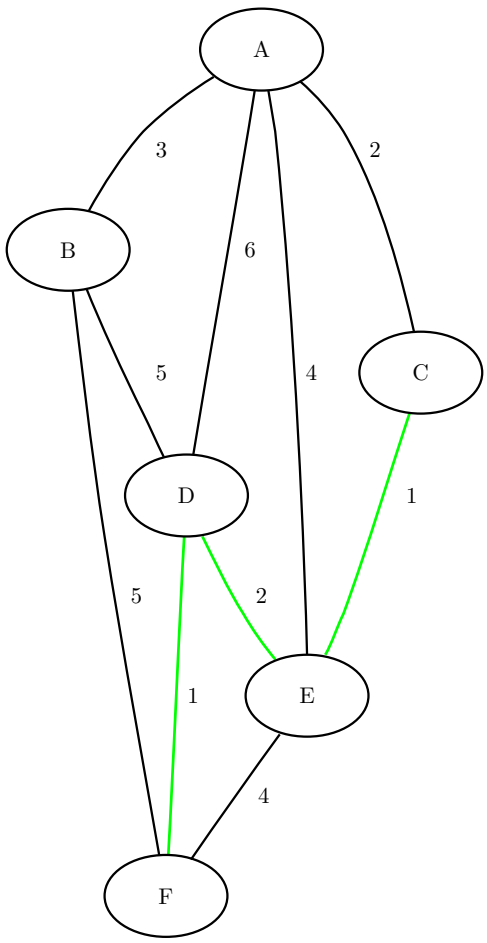
Figure 15.76 Shortest Paths for One Source-Sink Pair

ShortPath

source	sink	order	from	to	weight
C	F	1	C	E	1
C	F	2	D	E	2
C	F	3	D	F	1

The shortest path is shown graphically in Figure 15.77.

Figure 15.77 Shortest Path between Nodes C and F



Shortest Paths with Auxiliary Weight Calculation

This section illustrates the use of the shortest path algorithm, where auxiliary weights are used to calculate the shortest paths between all source-sink pairs.

Consider a links data set in which the auxiliary weight is a counter for each link:

```
data LinkSetIn;
   input from $ to $ weight count @@;
   datalines;
A B 3 1  A C 2 1  A D 6 1  A E 4 1  B D 5 1
B F 5 1  C E 1 1  D E 2 1  D F 1 1  E F 4 1
;
```

The following statements calculate shortest paths for all source-sink pairs:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   num count{LINKS};
   read data LinkSetIn into LINKS=[from to] weight count;
   set <str,str,num,str,str> PATHS; /* source, sink, order, from, to */
   set NODES = union{<i,j> in LINKS} {i,j};
   num path_length{i in NODES, j in NODES: i ~= j};

   solve with NETWORK /
      links     = (weight=weight)
      shortpath
      out       = (sppaths=PATHS spweights=path_length)
   ;

   put PATHS;
   num path_weight2{source in NODES, sink in NODES: source ~= sink} =
      sum {<(source),(sink),order,from,to> in PATHS} count[from,to];
   print path_length path_weight2;
   create data ShortPathW from [source sink]
      path_weight=path_length path_weight2;
quit;
```

The data set ShortPathW contains the total path weight for shortest paths in each source-sink pair and is shown in Figure 15.78. Because the variable count in LinkSetIn has a value of 1 for all links, the value in the output data set variable path_weights2 contains the number of links in each shortest path.

Figure 15.78 Shortest Paths Including Auxiliary Weights in Calculation

ShortPathW

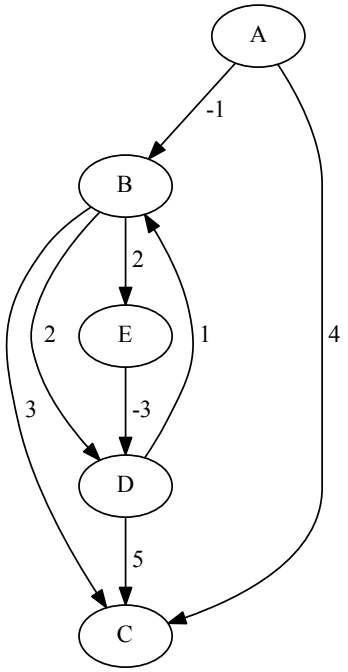
source	sink	path_weight	path_weight2
A	B	3	1
A	C	2	1
A	D	5	3
A	E	3	2
A	F	6	4
B	A	3	1
B	C	5	2
B	D	5	1
B	E	6	3
B	F	5	1
C	A	2	1
C	B	5	2
C	D	3	2
C	E	1	1
C	F	4	3
D	A	5	3
D	B	5	1
D	C	3	2
D	E	2	1
D	F	1	1
E	A	3	2
E	B	6	3
E	C	1	1
E	D	2	1
E	F	3	2
F	A	6	4
F	B	5	1
F	C	4	3
F	D	1	1
F	E	3	2

The section "Getting Started: Network Solver" on page 775 shows an example of using the shortest path algorithm to minimize travel to and from work based on traffic conditions.

Shortest Paths with Negative Link Weights

This section illustrates the use of the shortest path algorithm on a simple directed graph G with negative link weights, shown in Figure 15.79.

Figure 15.79 A Simple Directed Graph *G* with Negative Link Weights



The following statements call PROC OPTMODEL and declare the directed graph *G* by using set and array literals. For more information about literals, see the section "NUMBER, STRING, and SET Parameter Declarations" on page 325 in Chapter 9, "The OPTMODEL Procedure."

```
proc optmodel;
   set LINKS            = / <A B> <A C> <B C> <B D> <B E> <D B> <D C> <E D> /;
   num weight{LINKS} init [   -1     4     3     2     2     1     5    -3  ];
```

The next statements declare a set of the correct type for path output and calculate the shortest paths between source node *E* and sink node *B*:

```
   set NODES = union{<i,j> in LINKS} {i,j};
   /* Use the type (in this case, STRING) of NODES but leave PATHS empty */
   set PATHS init {NODES,NODES,/0/,NODES,NODES:0};
   set SOURCE = /E/, SINK = /B/;
   solve with NETWORK /
      links     = ( weight = weight )
      direction = directed
      shortpath = ( source = SOURCE sink = SINK )
      out       = ( sppaths = PATHS )
   ;
   put "Path and Weight: " (setof{<s,t,i,u,v> in PATHS} <u,v,weight[u,v]> );
```

As shown in Figure 15.80, the network solver identifies a shortest path that has negative weights.

Figure 15.80 SOLVE WITH NETWORK Log: Shortest Paths with Negative Link Weights

```
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 8.
NOTE: The network solver is called.
NOTE: Processing the shortest paths problem using 1 threads across 1 machines.
NOTE: Processing the shortest paths problem used 0.00 (cpu: 0.00) seconds.
Path and Weight: {<'E','D',-3>,<'D','B',1>}
```

If you reduce the weight on link (B, E) from 2 units to 1 unit, there is a negative weight cycle $(E \rightarrow D \rightarrow B \rightarrow E)$. The Bellman-Ford algorithm catches this and produces an error, as shown in Figure 15.81.

```
   weight['B','E'] = 1;
   solve with NETWORK /
      links     = (weight=weight)
      direction = directed
      shortpath = ( source = SOURCE sink = SINK )
      out       = ( sppaths = PATHS )
   ;
   put _SOLUTION_STATUS_=;
quit;
```

Figure 15.81 SOLVE WITH NETWORK Log: Negative Weight Cycle

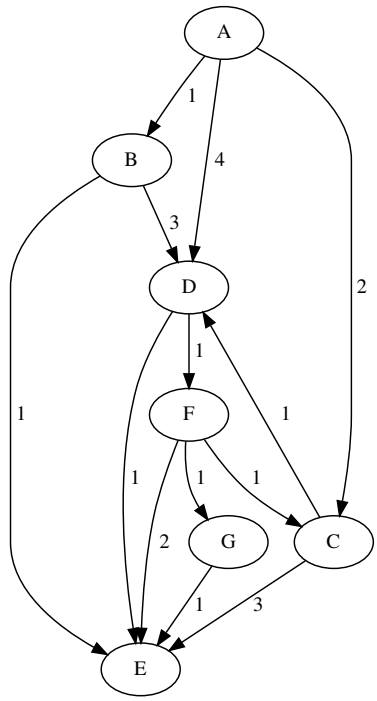
```
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 8.
NOTE: The network solver is called.
NOTE: Processing the shortest paths problem using 1 threads across 1 machines.
ERROR: The graph contains a negative weight cycle.
NOTE: Processing the shortest paths problem used 0.00 (cpu: 0.01) seconds.
_SOLUTION_STATUS_=BAD_PROBLEM_TYPE
```

Ranked Paths

This section illustrates the use of the shortest path algorithm to find ranked paths that are arranged in ascending order in the sum of link weights for each path. The MAXPATHSPERPAIR= suboption defines the maximum number of ranked paths per source-sink pair to return.

Consider the directed graph G shown in Figure 15.82.

Figure 15.82 Directed Graph G



You can represent the directed graph G by using the following links data table, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 1  A D 4  A C 2  B E 1  B D 3
D E 1  C D 1  C E 3  D F 1  F C 1
F E 2  F G 1  G E 1
;
```

The following statements find the four shortest paths between the source node A and the sink node E:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,num,str,str> PATHS;
   set <str,str,num,num> PWEIGHTS;
   set SOURCE = / A /;
   set SINK   = / E /;

   solve with network /
      links     = (weight=weight)
      direction = directed
      shortpath = (source=SOURCE sink=SINK maxpathsperpair=4)
      out       = (pathslinks=PATHS pathsweights=PWEIGHTS);
```

```
    create data ShortPathP from [source sink rank order from to]=PATHS
                               weight[from,to];
    create data ShortPathW from [source sink rank path_weight]=PWEIGHTS;
  quit;
```

The output data table ShortPathW contains the path weights of the ranked paths, as shown in Figure 15.83.

Figure 15.83 Path Weights of Ranked Paths for One Source-Sink Pair

source	sink	rank	path_weight
A	E	1	2
A	E	2	4
A	E	3	5
A	E	4	5

The output data table ShortPathP contains the ranked paths (displayed by rank), as shown in Figure 15.84.

Figure 15.84 Ranked Paths for One Source-Sink Pair by Rank

rank=1

source	sink	order	from	to	weight
A	E	1	A	B	1
A	E	2	B	E	1

rank=2

source	sink	order	from	to	weight
A	E	1	A	C	2
A	E	2	C	D	1
A	E	3	D	E	1

rank=3

source	sink	order	from	to	weight
A	E	1	A	B	1
A	E	2	B	D	3
A	E	3	D	E	1

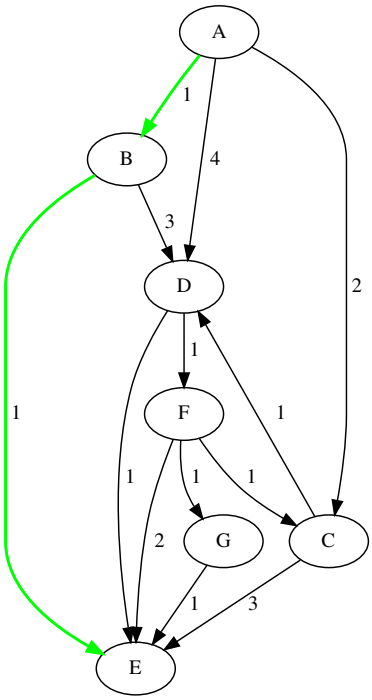
rank=4

source	sink	order	from	to	weight
A	E	1	A	D	4
A	E	2	D	E	1

The ranked paths are shown graphically in Figure 15.85 and Figure 15.86.

Figure 15.85 Rank 1 and 2 Paths from A to E

$A \rightarrow B \rightarrow E$
path_weight=2



$A \rightarrow C \rightarrow D \rightarrow E$
path_weight=4

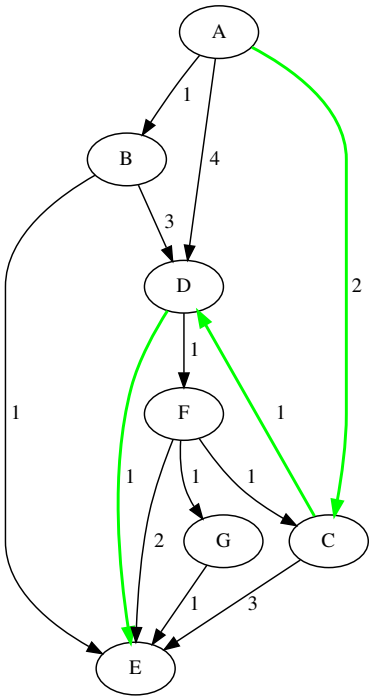
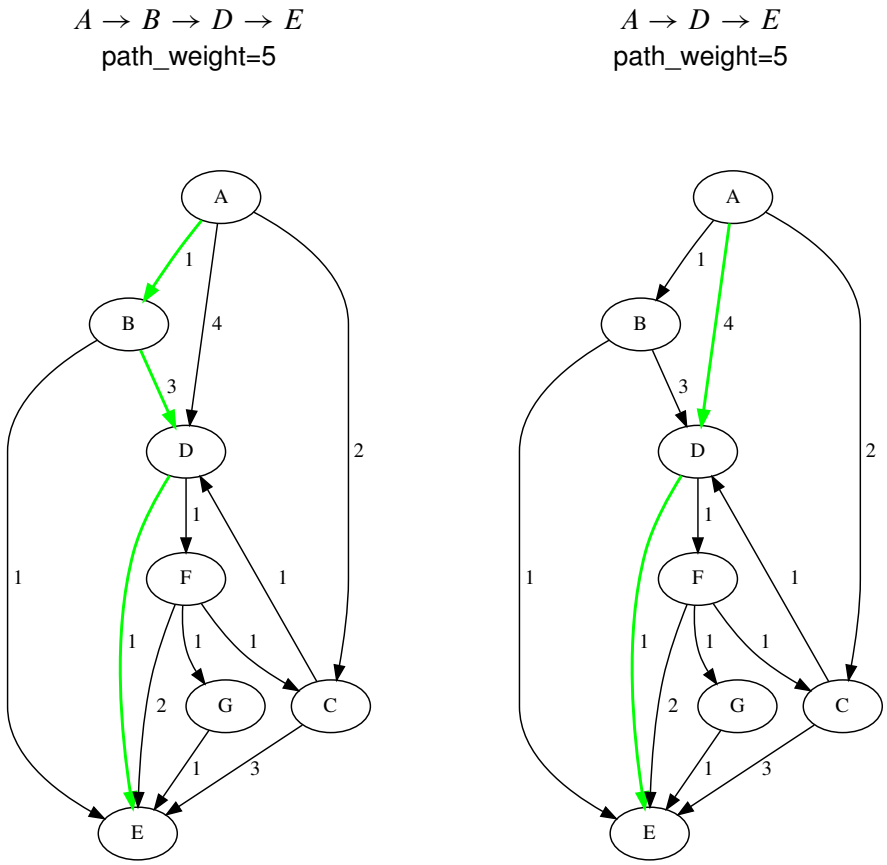


Figure 15.86 Rank 3 and 4 Paths from A to E



The MAXRELOBJGAP= suboption specifies the maximum acceptable relative difference between the sum of link weights in the shortest path and the sum of link weights in each alternative path. In the previous example, you found the four shortest paths between nodes A and E with respect to the sum of link weights. For the shortest path, path_weight=2. Specifying MAXRELOBJGAP=1.0 removes any paths that are more than 100% worse than the shortest path.

The following statements find the (at most) four shortest paths between the source node A and the sink node E such that each path is within 100% of the shortest path:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str,str,num,num> PWEIGHTS; /* source, sink, rank, weight */
   set SOURCE = / A /;
   set SINK   = / E /;

   solve with network /
      links     = (weight=weight)
      direction = directed
      shortpath = (source=SOURCE sink=SINK
```

```
                    maxpathsperpair=4 maxrelobjgap=1.0)
      out       = (pathsweights=PWEIGHTS);

   create data ShortPathW from [source sink rank path_weight]=PWEIGHTS;
quit;
```

The output data table ShortPathW contains the path weights of the acceptable ranked paths, as shown in Figure 15.87.

Figure 15.87 Path Weights of Acceptable Ranked Paths for One Source-Sink Pair

source	sink	rank	path_weight
A	E	1	2
A	E	2	4

Shortest Paths through a Sequence of Nodes

This section illustrates how to use the shortest path algorithm to find the shortest path through a sequence of nodes. The SEQUENCE= suboption defines the sequence of nodes to be visited.

Consider again the directed graph G shown in Figure 15.82. In the example in the section "Shortest Paths for One Source-Sink Pair" on page 865, you calculate the shortest path from A to E. Consider the case where you start at A and need to visit F and then D before ending at E.

You can represent the sequence of nodes to visit by using the following nodes subset data table, NodeSubSetIn:

```
data NodeSubSetIn;
   input node $ sequence;
   datalines;
A 1
F 2
D 3
E 4
;
```

NOTE: The observations in this table can be in any order, and the nodes are visited in ascending order of the sequence order values. Also, the sequence order values do not need to be 1 through the number of observations; only their relative order is important. Observations whose sequence order number is missing are discarded.

NOTE: The node that has the lowest sequence order value is the source of the path, and the node that has the highest sequence order value is the sink of the path. Therefore the SEQUENCE= suboption is incompatible with the SOURCE= and SINK= suboptions.

NOTE: The SEQUENCE= suboption is compatible with the MAXPATHSPERPAIR= suboption.

The following statements find the two shortest paths through the sequence of nodes A, F, D, E:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <str> NODESUBSET;
   num sequence{NODESUBSET};
```

```
read data NodeSubSetIn into NODESUBSET=[node] sequence;
set <str,str,num,num,str,str> PATHSLINKS;
set <str,str,num,num,str> PATHSNODES;
set <str,str,num,num> PWEIGHTS;

solve with network /
   loglevel        = moderate
   graph_direction = directed
   links           = (weight=weight)
   shortPath       = (sequence=sequence maxpathsperpair=2)
   out             = (pathslinks=PATHSLINKS
                      pathsnodes=PATHSNODES
                      pathsweights=PWEIGHTS
                     );

create data ShortPathP from [source sink rank order from to]=PATHSLINKS
                           weight[from,to];
create data ShortPathN from [source sink rank order node]=PATHSNODES;
create data ShortPathW from [source sink rank path_weight]=PWEIGHTS;

run;
```

The output data table ShortPathP contains the links of these shortest paths (including the rank of the path that they are part of), as shown in Figure 15.88.

Figure 15.88 Shortest Path Links through a Sequence of Nodes

source	sink	rank	order	from	to	weight
A	E	1	1	A	C	2
A	E	1	2	C	D	1
A	E	1	3	D	F	1
A	E	1	4	F	C	1
A	E	1	5	C	D	1
A	E	1	6	D	E	1
A	E	2	1	A	D	4
A	E	2	2	D	F	1
A	E	2	3	F	C	1
A	E	2	4	C	D	1
A	E	2	5	D	E	1

The output data table ShortPathN contains the nodes of these shortest paths (including the rank of the path that they are part of and their position on that path), as shown in Figure 15.89.

Figure 15.89 Shortest Path Nodes through a Sequence of Nodes

source	sink	rank	order	node
A	E	1	1	A
A	E	1	2	C
A	E	1	3	D
A	E	1	4	F
A	E	1	5	C
A	E	1	6	D
A	E	1	7	E
A	E	2	1	A
A	E	2	2	D
A	E	2	3	F
A	E	2	4	C
A	E	2	5	D
A	E	2	6	E

The output data table ShortPathW contains only the path weights of these shortest paths, as shown in Figure 15.90.

Figure 15.90 Path Weights of Shortest Paths through a Sequence of Nodes

source	sink	rank	path_weight
A	E	1	7
A	E	2	8

Topological Sort

A *topological ordering* of a directed graph $G = (N, E)$ is a linear ordering of its nodes such that, for every directed link $(i, j) \in E$, node i comes before node j in the ordering. A topological ordering is commonly used to handle workflow dependencies. For example, consider scheduling a set of tasks that have dependencies. You can build a directed graph in which each node represents a task and each link (i, j) represents the requirement that task i be completed before task j. A topological ordering of this graph would give you a valid sequence of tasks.

A topological ordering exists if and only if the graph contains no directed cycles.

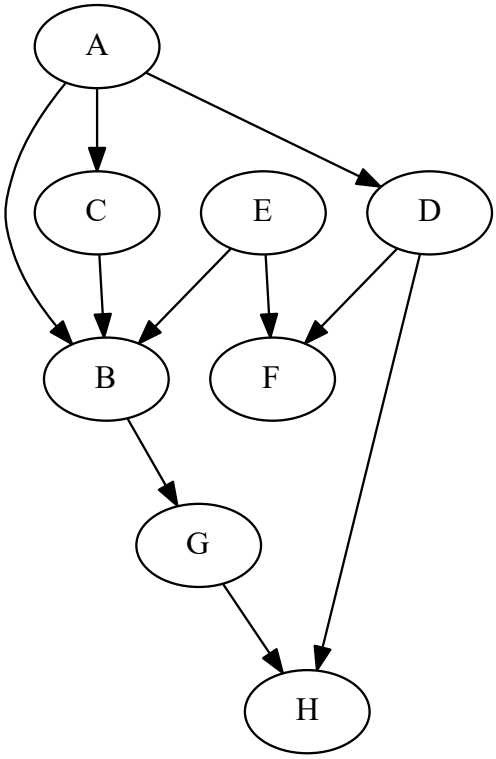
In the network solver, you can invoke topological sort by using the TOPOLOGICALSORT option.

The results of the topological sort algorithm are written to the node-indexed numeric array that you specify in the ORDER= suboption of the OUT= option. For each node in the set, the value of this array identifies the position of the node in the topological sort. The positions are numbered sequentially, starting from 1.

Topological Sort in a Directed Graph

This section illustrates the use of the topological sort algorithm on the simple directed graph *G* shown in Figure 15.91.

Figure 15.91 A Simple Directed Graph *G*



The directed graph *G* can be represented by the following links data set, LinkSetIn:

```
data LinkSetIn;
   input from $ to $ @@;
   datalines;
A B  A C  A D  E B  D F
E F  C B  B G  G H  D H
;
```

The following statements calculate the topological sort and output the results in the data set NodeOrder:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set NODES = union {<i,j> in LINKS} {i,j};
   num order{NODES};
```

```
   solve with NETWORK /
      links           = (include=LINKS)
      loglevel        = moderate
      graph_direction = directed
      topologicalsort
      out             = (order=order)
   ;

   print order;
   create data NodeOrder from [node] top_order=order;
quit;
```

The data set NodeOrder contains the position of every node in a topological sort of the input graph and is shown (after ordering by node position) in Figure 15.92.

Figure 15.92 Topological Sort Order of a Simple Directed Graph

node	top_order
E	1
A	2
D	3
F	4
C	5
B	6
G	7
H	8

Transitive Closure

The *transitive closure* of a graph G is a graph $G^T = (N, E^T)$ such that for all $i, j \in N$ there is a link $(i, j) \in E^T$ if and only if there is a path from i to j in G.

The transitive closure of a graph can help efficiently answer questions about reachability. Suppose you want to find out whether you can get from node i to node j in the original graph G. Given the transitive closure G^T of G, you can simply check for the existence of link (i, j). Transitive closure has many applications, including speeding up the processing of structured query languages, which are often used in databases.

In the network solver, you can invoke the transitive closure algorithm by using the TRANSITIVECLOSURE option.

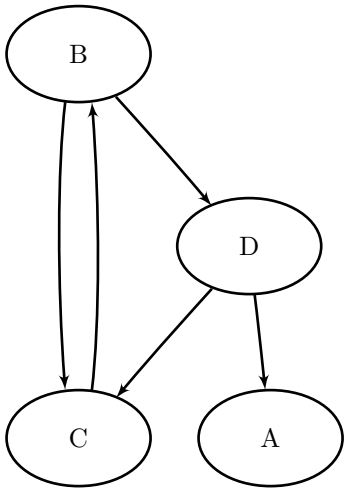
The results for the transitive closure algorithm are written to the set that is specified in the CLOSURE= suboption of the OUT= option.

The algorithm that the network solver uses to compute transitive closure is a sparse version of the Floyd-Warshall algorithm (Cormen, Leiserson, and Rivest 1990). This algorithm runs in time $O(|N|^3)$ and therefore might not scale to very large graphs.

Transitive Closure of a Simple Directed Graph

This example illustrates the use of the transitive closure algorithm on the simple directed graph *G* that is shown in Figure 15.93.

Figure 15.93 A Simple Directed Graph *G*



The directed graph *G* can be represented by the links data set LinkSetIn as follows:

```
data LinkSetIn;
   input from $ to $ @@;
   datalines;
B C  B D  C B  D A  D C
;
```

The following statements calculate the transitive closure and output the results in the data set TransClosure:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetIn into LINKS=[from to];
   set<str,str> CAN_REACH;

   solve with NETWORK /
      graph_direction = directed
      links = ( include = LINKS )
      transcl
      out = ( closure = CAN_REACH )
   ;

   put CAN_REACH;
   create data TransClosure from [from to]=CAN_REACH;
quit;
```

The data set TransClosure contains the transitive closure of *G* and is shown in Figure 15.94.

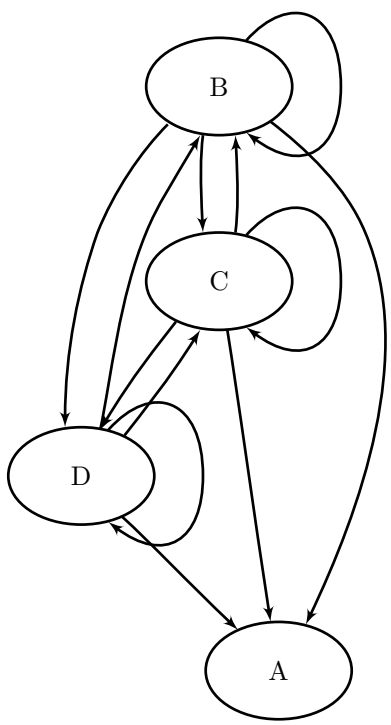
Figure 15.94 Transitive Closure of a Simple Directed Graph

Transitive Closure

from	to
B	B
B	C
B	D
B	A
C	B
C	C
C	D
C	A
D	B
D	C
D	D
D	A

The transitive closure of G is shown graphically in Figure 15.95.

Figure 15.95 Transitive Closure of G



For a more detailed example, see Example 15.6.

Traveling Salesman Problem

The *traveling salesman problem* (TSP) finds a minimum-cost tour in a graph (G) that has a node set (N) and a link set (E). A *path* in a graph is a sequence of nodes, each of which has a link to the next node in the sequence. An *elementary cycle* is a path in which the starting node and ending node are the same and otherwise no node appears more than once in the sequence. A *Hamiltonian cycle* (or *tour*) is an elementary cycle that visits every node. In solving the TSP, then, the goal is to find a Hamiltonian cycle of minimum total cost, where the total cost is the sum of the costs of the links in the tour. Associated with each link $e \in E$ are a binary variable x_e, which indicates whether link e is part of the tour, and a cost c_e. Then an integer linear programming formulation of the TSP (for an undirected graph G) is as follows:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{e \in E} c_e x_e & & \\
\text{subject to} & \displaystyle\sum_{e \in \delta(i)} x_e = 2 & i \in N & \text{(TwoMatch)} \\
 & \displaystyle\sum_{e \in \delta(S)} x_e \geq 2 & S \subset N,\ 2 \leq |S| \leq |N| - 1 & \text{(Subtour)} \\
 & x_e \in \{0, 1\} & e \in E &
\end{array}
$$

where for each subset S of nodes $\delta(S)$ represents the set of links (i, j), with $i \in S$ and $j \notin S$.

The TwoMatch equations represent the *matching constraints*, which ensure that each node has degree 2 in the subgraph. The Subtour inequalities represent the *subtour elimination constraints* (SECs), which enforce connectivity.

For a directed graph, G, the same formulation and solution approach is used on an expanded graph G', as described in Kumar and Li (1994). The network solver takes care of the construction of the expanded graph and returns the solution in terms of the original input graph.

In practical terms, you can think of the TSP in the context of a routing problem in which each node is a city and the links are roads that connect those cities. If you know the distance between each pair of cities, the goal is to find the shortest possible route that visits each city exactly once and returns to the starting city. The TSP has applications in planning, logistics, manufacturing, genomics, and many other areas.

In the network solver, you can invoke the traveling salesman problem solver by using the TSP= option.

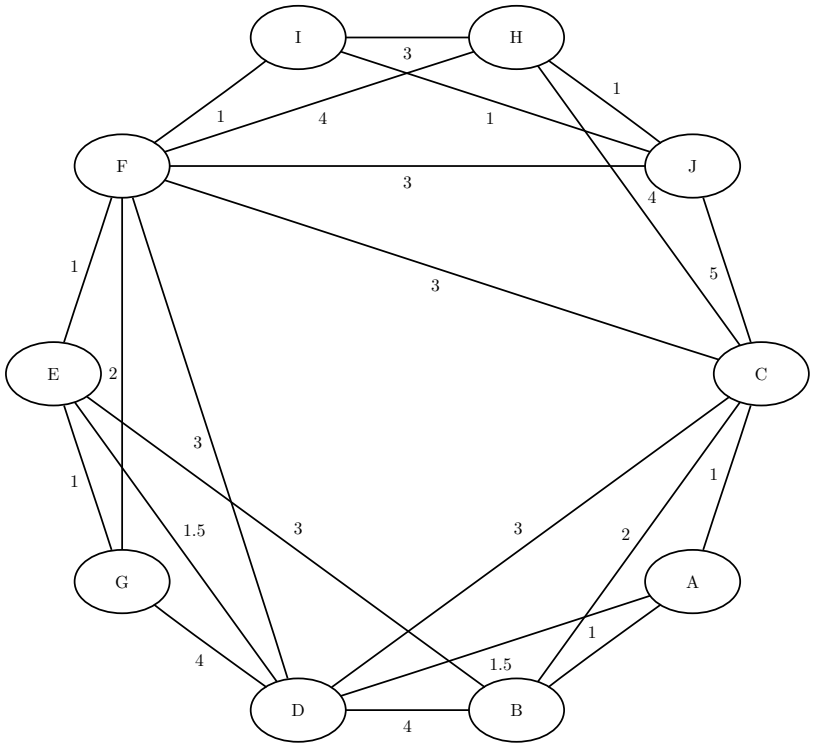
The algorithm that the network solver uses for solving a TSP is based on a variant of the branch-and-cut process described in Applegate et al. (2006).

The resulting tour is represented in two ways: in the numeric array that is specified in the ORDER= suboption of the OUT= option, the tour is specified as a sequence of nodes; in the set that is specified in the TOUR= suboption of the OUT= option, the tour is specified as a list of links in the optimal tour.

Traveling Salesman Problem Applied to a Simple Undirected Graph

As a simple example, consider the weighted undirected graph in Figure 15.96.

Figure 15.96 A Simple Undirected Graph



You can represent the links data set as follows:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 1.0   A C 1.0   A D 1.5   B C 2.0   B D 4.0
B E 3.0   C D 3.0   C F 3.0   C H 4.0   D E 1.5
D F 3.0   D G 4.0   E F 1.0   E G 1.0   F G 2.0
F H 4.0   H I 3.0   I J 1.0   C J 5.0   F J 3.0
F I 1.0   H J 1.0
;
```

The following statements calculate an optimal traveling salesman tour and output the results in the data sets TSPTour and NodeSetOut:

```
proc optmodel;
   set<str,str> EDGES;
   set<str> NODES = union{<i,j> in EDGES} {i,j};
   num weight{EDGES};
   read data LinkSetIn into EDGES=[from to] weight;
   num tsp_order{NODES};
   set<str,str> TOUR;

   solve with NETWORK /
```

```
      loglevel = moderate
      links    = (weight=weight)
      tsp
      out      = (order=tsp_order tour=TOUR)
   ;

   put TOUR;
   print {<i,j> in TOUR} weight;
   print tsp_order;
   create data NodeSetOut from [node]         tsp_order;
   create data TSPTour    from [from to]=TOUR weight;
quit;
```

The progress of the procedure is shown in Figure 15.97.

Figure 15.97 Network Solver Log: Optimal Traveling Salesman Tour of a Simple Undirected Graph

```
NOTE: There were 22 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 10.
NOTE: The number of links in the input graph is 22.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 16 using 0.00 (cpu:
      0.00) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1     16.0000000     15.5005000    3.22%       0
             0        0      1     16.0000000     16.0000000    0.00%       0
NOTE: Optimal.
NOTE: Objective = 16.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
{<'A','B'>,<'B','C'>,<'C','H'>,<'H','J'>,<'I','J'>,<'F','I'>,<'F','G'>,<'E','G'>
,<'D','E'>,<'A','D'>}
NOTE: The data set WORK.NODESETOUT has 10 observations and 2 variables.
NOTE: The data set WORK.TSPTOUR has 10 observations and 3 variables.
```

The data set NodeSetOut now contains a sequence of nodes in the optimal tour and is shown in Figure 15.98.

Figure 15.98 Nodes in the Optimal Traveling Salesman Tour

Traveling Salesman Problem

node	tsp_order
A	1
B	2
C	3
H	4
J	5
I	6
F	7
G	8
E	9
D	10

The data set TSPTour now contains the links in the optimal tour and is shown in Figure 15.99.

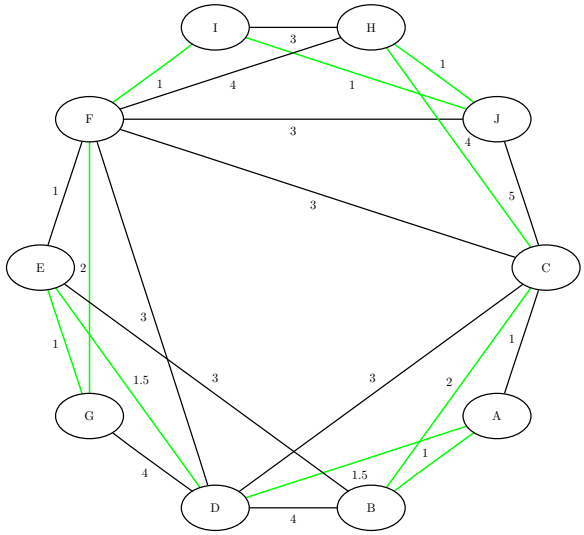
Figure 15.99 Links in the Optimal Traveling Salesman Tour

Traveling Salesman Problem

from	to	weight
A	B	1.0
B	C	2.0
C	H	4.0
H	J	1.0
I	J	1.0
F	I	1.0
F	G	2.0
E	G	1.0
D	E	1.5
A	D	1.5
		16.0

The minimum-cost links are shown in green in Figure 15.100.

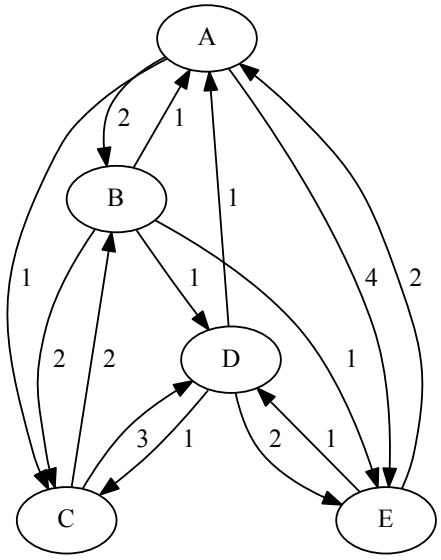
Figure 15.100 Optimal Traveling Salesman Tour



Traveling Salesman Problem Applied to a Simple Directed Graph

As another simple example, consider the weighted directed graph in Figure 15.101. In this graph it might not be possible to travel directly between a pair of nodes in both directions, or the cost of traveling directly between two nodes might depend on the direction of travel.

Figure 15.101 A Simple Directed Graph



You can represent the links data set as follows:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
A B 2.0   A C 1.0   A E 4.0
B A 1.0   B C 2.0   B D 1.0   B E 1.0
C B 2.0   C D 3.0
D A 1.0   D C 1.0   D E 2.0
E A 2.0   E D 1.0
;
```

The following statements, which are identical to those in the undirected example above except for the SOLVE statement clause DIRECTION=DIRECTED, calculate an optimal traveling salesman tour (on a directed graph) and output the results in the data sets TSPTour and NodeSetOut:

```
proc optmodel;
   set<str,str> EDGES;
   set<str> NODES = union{<i,j> in EDGES} {i,j};
   num weight{EDGES};
   read data LinkSetIn into EDGES=[from to] weight;
   num tsp_order{NODES};
   set<str,str> TOUR;

   solve with NETWORK /
      loglevel  = moderate
      links     = (weight=weight)
      direction = directed
      tsp
      out       = (order=tsp_order tour=TOUR)
   ;

   put TOUR;
   print {<i,j> in TOUR} weight;
   print tsp_order;
   create data NodeSetOut from [node]         tsp_order;
   create data TSPTour    from [from to]=TOUR weight;
quit;
```

The progress of the procedure is shown in Figure 15.102.

Figure 15.102 Network Solver Log: Optimal Traveling Salesman Tour of a Simple Directed Graph

```
NOTE: There were 14 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 5.
NOTE: The number of links in the input graph is 14.
NOTE: The network solver is called.
NOTE: The TSP solver is starting using an augmented symmetric graph with 10
      nodes and 19 links.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 6 using 0.00 (cpu:
      0.00) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1      6.0000000      5.9001000    1.69%       0
             0        0      1      6.0000000      6.0000000    0.00%       0
NOTE: Optimal.
NOTE: Objective = 6.
NOTE: Processing the traveling salesman problem used 0.00 (cpu: 0.00) seconds.
{<'A','C'>,<'C','B'>,<'B','E'>,<'E','D'>,<'D','A'>}
NOTE: The data set WORK.NODESETOUT has 5 observations and 2 variables.
NOTE: The data set WORK.TSPTOUR has 5 observations and 3 variables.
```

The data set NodeSetOut now contains a sequence of nodes in the optimal tour and is shown in Figure 15.103.

Figure 15.103 Nodes in the Optimal Traveling Salesman Tour

node	tsp_order
A	1
C	2
B	3
E	4
D	5

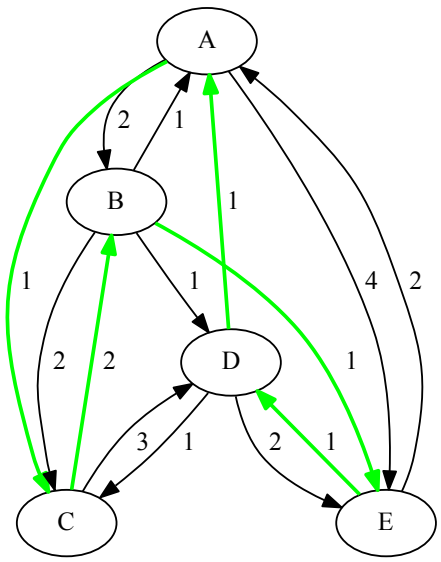
The data set TSPTour now contains the links in the optimal tour and is shown in Figure 15.104.

Figure 15.104 Links in the Optimal Traveling Salesman Tour

from	to	weight
A	C	1
C	B	2
B	E	1
E	D	1
D	A	1
		6

The minimum-cost links are shown in green in Figure 15.105.

Figure 15.105 Optimal Traveling Salesman Tour



Vehicle Routing Problem

The *vehicle routing problem* (VRP) finds a set of elementary cycles in a graph $G = (N, E)$ that start and end at a common depot, visit all customer nodes once, and satisfy vehicle capacity limits at minimum cost. The node set ($N = C \cup \{1\}$) consists of a set of customers (C) and a depot node (1). A *route* is an elementary cycle that starts and ends at the depot. A route is serviced by a vehicle that picks up goods at the depot node and delivers them to its assigned set of customers. Each customer has a demand d_i, and each vehicle has a capacity Q. The number of routes (K) that are used varies and, depending on the vehicle fleet configuration, is restricted to be greater than or equal to K_l and less than or equal to K_u.

Associated with each link $e \in E$ are a binary variable x_e, which indicates whether link e is part of the prescribed routes, and a cost c_e. In addition, an integer variable K indicates the number of routes to be used.

Then an integer linear programming formulation of the VRP (for a directed graph G) is as follows:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{e \in E} c_e x_e & & \\
\text{subject to} & \displaystyle\sum_{e \in \delta_i^{\text{out}}} x_e = 1 & i \in C & \text{(LeaveNode)} \\
& \displaystyle\sum_{e \in \delta_j^{\text{in}}} x_e = 1 & j \in C & \text{(EnterNode)} \\
& \displaystyle\sum_{e \in \delta_1^{\text{out}}} x_e = K & & \text{(LeaveDepot)} \\
& \displaystyle\sum_{e \in \delta_1^{\text{in}}} x_e = K & & \text{(EnterDepot)} \\
& \displaystyle\sum_{e \in \delta(S)} x_e \geq r(S) & S \subseteq C, S \neq \emptyset & \text{(Capacity/Subtour)} \\
& K_l \leq K \leq K_u & & \\
& x_e \in \{0, 1\} & e \in E &
\end{array}
$$

where for each subset of S of customers, $\delta(S)$ represents the set of links (i, j), with $i \in S$ and $j \notin S$; δ_i^{out} represents the set of outgoing links that are connected from node i; δ_i^{in} represents the set of incoming links that are connected to node i; and $r(S) = \lceil \sum_{i \in S} d_i / Q \rceil$ is a lower bound on the number of vehicles needed in order to service customers S.

The LeaveNode and EnterNode equations ensure that each node is visited exactly once. The LeaveDepot and EnterDepot equations ensure that the depot node is visited K times (once for each route). The Capacity/Subtour inequalities enforce connectivity and the vehicle capacity restriction.

In practical terms, you can think of the VRP in the context of a package delivery system in which each node is a customer (location) that demands a certain quantity of goods and the links are roads that connect those locations. The goods start out in the depot (or warehouse) node, must be loaded into the servicing vehicles (which have a capacity limit), and must be delivered to the customers in the least amount of time (or distance). The VRP has many applications, most prominently in logistics.

In the network solver, you can invoke the vehicle routing problem solver by using the VRP= option.

The algorithm that the network solver uses for solving the VRP is based on a variant of the branch-and-cut process described in Lysgaard, Letchford, and Eglese (2004). The VRP solver internally uses modified versions of two pieces of open source software. The first package, VRPH, is used to generate primal feasible solutions; the original† source code can be found at `https://github.com/skinkie/VRPH`. The second package, CVRPSEP, is used to generate cutting planes to improve the dual bound; the original† source code can be found at `https://econ.au.dk/research/researcher-websites/jens-lysgaard/cvrpsep/`.

† Bug fixes and modifications of the following open source packages used by the network solver are hosted at the sites listed:

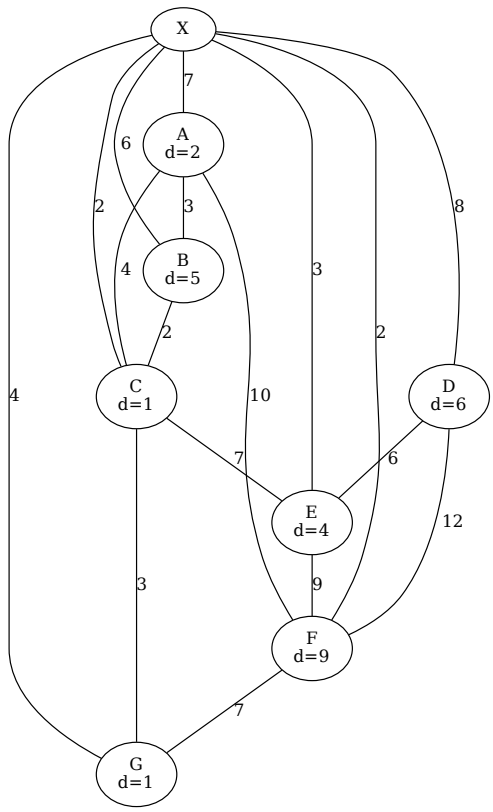
- VRPH: `https://github.com/sassoftware/VRPH`
- CVRPSEP: `https://github.com/sassoftware/cvrpsep`

The resulting routes are represented in two ways. The node-oriented representation is stored in the numeric arrays specified by the ROUTE= and ORDER= suboptions of the OUT= option. The link-oriented representation is stored in the set specified by the VRPLINKS= suboption of the OUT= option.

Vehicle Routing Problem Applied to an Undirected Graph

As a simple example, consider the weighted undirected graph in Figure 15.106 with depot node X and vehicle capacity $Q = 10$.

Figure 15.106 Undirected Graph



You can represent the links and nodes data tables as follows:

```
data LinkSetIn;
   input from $ to $ weight @@;
   datalines;
X A 7 X B 6 X C 2 X E 3 X D 8
X F 2 X G 4 A B 3 A C 4 A F 10
B C 2 C E 7 C G 3 D E 6 D F 12
E F 9 F G 7
;

data NodeSetIn;
   input node $ demand @@;
   datalines;
A 2 B 5 C 1 D 6 E 4 F 9 G 1
;
```

The following statements calculate the optimal routes and output the results in the data sets RoutesNodes and RoutesLinks:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <num,num,str,str> VRPLINKS; /* route, order, from, to */
   set NODES = union{<i,j> in LINKS} {i, j};
   num demand{NODES};
   read data NodeSetIn into [node] demand;
   set DEPOT = /X/;
   num route{NODES};
   num route_order{NODES};

   solve with network /
      loglevel = aggressive
      links    = (weight=weight)
      vrp      = (depot=DEPOT demand=demand capacity=10)
      out      = (route=route order=route_order vrplinks=VRPLINKS)
   ;

   create data RoutesNodes
      from [node] demand route route_order;
   create data RoutesLinks
      from [route route_order from to]=VRPLINKS weight[from, to];
quit;
```

The progress of the procedure is shown in Figure 15.107.

Figure 15.107 Network Solver Log: Vehicle Routing Problem for an Undirected Graph

```
NOTE: There were 17 observations read from the data set WORK.LINKSETIN.
NOTE: There were 7 observations read from the data set WORK.NODESETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 17.
NOTE: The network solver is called.
NOTE: Processing the vehicle routing problem using 1 threads across 1 machines.
NOTE: The initial VRP heuristics found a solution with cost 40 using 0.03 (cpu:
      0.02) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1     40.0000000     38.0000000    5.26%       0
             0        0      1     40.0000000     40.0000000    0.00%       0
NOTE: The MILP solver added 2 cuts with 10 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 40.
NOTE: Processing the vehicle routing problem used 0.03 (cpu: 0.02) seconds.
NOTE: The data set WORK.ROUTESNODES has 8 observations and 4 variables.
NOTE: The data set WORK.ROUTESLINKS has 10 observations and 5 variables.
```

The output data set RoutesNodes now contains the nodes of the optimal routes. The following statements sort the resulting data and display each route along with the sum of the customer demands serviced by that route, as shown in Figure 15.108:

```
proc sort data=RoutesNodes;
   by route route_order;
run;
proc print data=RoutesNodes;
   by route;
   sum demand;
run;
```

Figure 15.108 Nodes in the Optimal Routes

route=.

Obs	node	demand	route_order
1	X	.	1

route=1

Obs	node	demand	route_order
2	A	2	2
3	B	5	3
4	C	1	4
5	G	1	5
route		**9**	

route=2

Obs	node	demand	route_order
6	E	4	2
7	D	6	3
route		**10**	

route=3

Obs	node	demand	route_order
8	F	9	2
		28	

The output data set RoutesLinks now contains the links of the optimal routes as a sequence of links. The following statements sort the resulting data and display each route along with the sum of the link weights for that route, as shown in Figure 15.109:

```
proc sort data=RoutesLinks;
   by route route_order;
run;
proc print data=RoutesLinks;
   by route;
   sum weight;
run;
```

Figure 15.109 Links in the Optimal Routes

route=1

Obs	route_order	from	to	weight
1	1	X	A	7
2	2	A	B	3
3	3	B	C	2
4	4	C	G	3
5	5	X	G	4
route				**19**

route=2

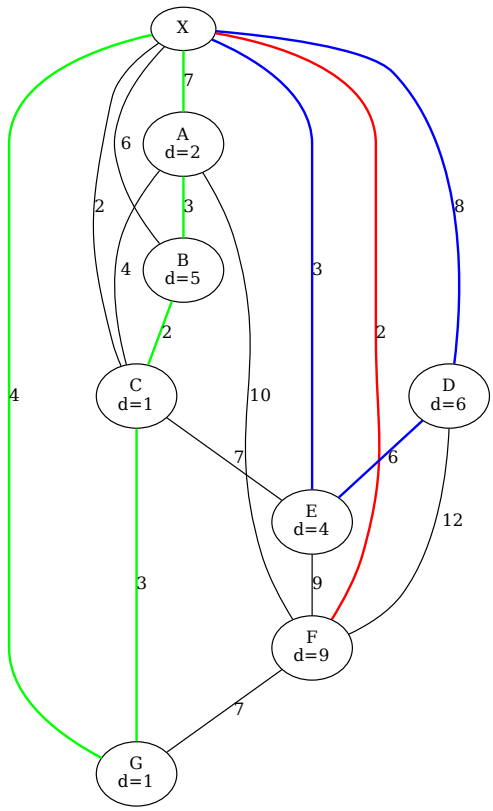
Obs	route_order	from	to	weight
6	1	X	E	3
7	2	D	E	6
8	3	X	D	8
route				**17**

route=3

Obs	route_order	from	to	weight
9	1	X	F	2
10	2	X	F	2
route				**4**
				40

The optimal routes are highlighted in Figure 15.110.

Figure 15.110 Optimal Routes



For a more detailed example, see "Example 15.8: Vehicle Routing Problem (CVRPLIB)" on page 925.

Vehicle Routing Problem with Time Windows

If you specify any time variables by using at least one of the SERVICETIME=, TRAVELTIME=, TIMEWINDOWLOWER=, or TIMEWINDOWUPPER= options, then the network solver treats the problem as a vehicle routing problem with time windows (VRPTW). In this case, the value of the MILP=TRUE option is ignored and a heuristic algorithm is used.

VRPTW is an extension to the traditional VRP problem in which the time variables must be respected while minimizing link cost. In this scenario, each link $e \in E$ has an associated travel time t_e (which might be different from the cost), and the depot and each customer $i \in N$ have a nonnegative service time s_i and a nonnegative time window $[l_i, u_i]$. The time window dictates when a vehicle is allowed to deliver goods to the customer: A vehicle must not arrive past time u_i, but it is allowed to arrive before the time window and wait until time l_i to deliver. For the depot node, l_i determines the starting time of the vehicle, and u_i determines the latest time when the vehicle can arrive back at the depot. If a_i is the time when a vehicle arrives at node i, then these constraints can be represented as follows:

$$x_e(a_i + s_i + t_e - a_j) \le 0 \qquad i = \text{from}(e), j = \text{to}(e), e \in E \qquad \text{(SeqTime)}$$

$$l_i \le a_i \le u_i \qquad i \in C \qquad \text{(TimeWindow)}$$

The SeqTime constraint ensures that departure times at one node and arrival times at a subsequent node are valid. The TimeWindow constraint ensures that deliveries are performed within the time windows.

As an example, consider again the weighted undirected graph in Figure 15.106 with depot node X and vehicle capacity $Q = 10$, but now with time windows given by the following nodes data table:

```
data NodeSetIn;
   input node $ demand twl twu @@;
   datalines;
A 2 0 7
B 5 0 20
C 1 0 20
D 6 0 20
E 4 9 20
F 9 0 20
G 1 0 4
;
```

The following statements calculate the optimal routes that respect the time windows at the nodes and output the results in the data sets RoutesNodes and RoutesLinks:

```
proc optmodel;
   set <str,str> LINKS;
   num weight{LINKS};
   read data LinkSetIn into LINKS=[from to] weight;
   set <num,num,str,str> VRPLINKS; /* route, order, from, to */
   set NODES = union{<i,j> in LINKS} {i, j};
   num demand{NODES};
   num twl{NODES};
   num twu{NODES};
   read data NodeSetIn into [node] demand twl twu;
   set DEPOT = /X/;
   num route{NODES};
   num route_order{NODES};
   num delivery_time{NODES};

   solve with network /
      loglevel = aggressive
      links    = (weight=weight)
      vrp      = (depot=DEPOT
                  capacity=10
                  demand=demand
                  timeWindowLower=twl
                  timeWindowUpper=twu
                  milp=FALSE)
      out      = (route=route
                  order=route_order
                  arrival=delivery_time
                  vrplinks=VRPLINKS);

   create data RoutesNodes
      from [node] demand twl twu route route_order delivery_time;
   create data RoutesLinks
      from [route route_order from to]=VRPLINKS weight[from, to];
```

```
quit;
```

The progress of the procedure is shown in Figure 15.111.

Figure 15.111 Network Solver Log: VRPTW for an Undirected Graph

```
NOTE: There were 17 observations read from the data set WORK.LINKSETIN.
NOTE: There were 7 observations read from the data set WORK.NODESETIN.
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 17.
NOTE: The network solver is called.
NOTE: Processing the vehicle routing problem with time windows using 1 threads
      across 1 machines.
NOTE: The initial VRP heuristics found a solution with cost 43 using 0.01 (cpu:
      0.01) seconds.
NOTE: Processing the vehicle routing problem used 0.01 (cpu: 0.01) seconds.
NOTE: The data set WORK.ROUTESNODES has 8 observations and 7 variables.
NOTE: The data set WORK.ROUTESLINKS has 11 observations and 5 variables.
```

The output data set RoutesNodes now contains the nodes of the optimal routes, the variables that are related to the time windows, and the time when the vehicles arrive at the nodes. The following statements sort and display the resulting data by the route and the order within the route. Figure 15.112 shows the results.

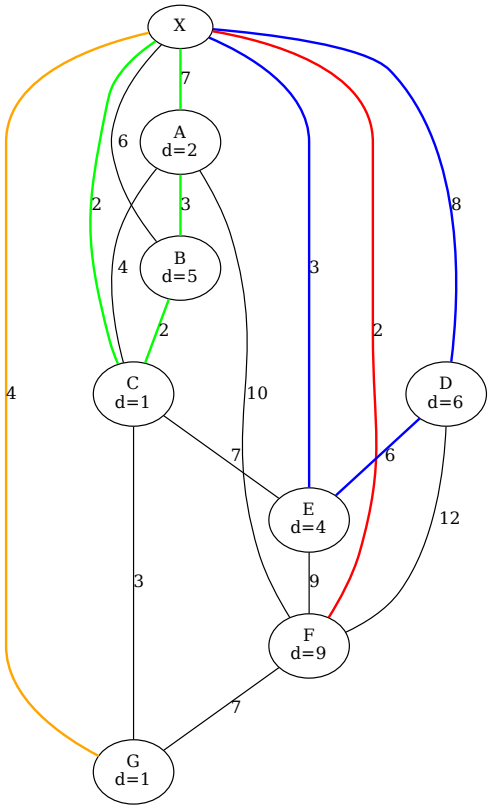
```
proc sort data=RoutesNodes;
   by route route_order;
run;
proc print data=RoutesNodes;
run;
```

Figure 15.112 Nodes in the Optimal Routes

Obs	node	demand	twl	twu	route	route_order	delivery_time
1	X	.	.	.	.	1	23
2	F	9	0	20	1	2	2
3	E	4	9	20	2	2	9
4	D	6	0	20	2	3	15
5	C	1	0	20	3	2	2
6	B	5	0	20	3	3	4
7	A	2	0	7	3	4	7
8	G	1	0	4	4	2	4

The optimal routes are highlighted in Figure 15.113.

Figure 15.113 Optimal Routes



Macro Variable _OROPTMODEL_

PROC OPTMODEL always creates and initializes a SAS macro variable called _OROPTMODEL_, which contains a character string. After each PROC OPTMODEL run, you can examine this macro variable by specifying **`%put &_OROPTMODEL_;`** and check the execution of the most recently invoked solver from the value of the macro variable.

Each keyword and value pair in _OROPTMODEL_ also appears in two other places: the PROC OPTMODEL automatic arrays _OROPTMODEL_NUM_ and _OROPTMODEL_STR_; and the ODS tables ProblemSummary and SolutionSummary, which appear after a SOLVE statement, unless you set the PRINTLEVEL= option to NONE. You can use these variables to obtain details about the solution even if you do not specify an output destination in the OUT= option.

After the solver is called, the various keywords in the variable are interpreted as follows:

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	The use of syntax is incorrect.
DATA_ERROR	The input data is inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem in reading or writing of data has occurred.
SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, has occurred.
ERROR	The status cannot be classified into any of the preceding categories.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

ABORT_NOSOL	The solver was stopped by the user and did not find a solution.
ABORT_SOL	The solver was stopped by the user but still found a solution.
BAD_PROBLEM_TYPE	The problem type is not supported by the solver.
CONDITIONAL_OPTIMAL	The optimality of the solution cannot be proven.
ERROR	The algorithm encountered an error.
FAIL_NOSOL	The solver stopped due to errors and did not find a solution.
FAIL_SOL	The solver stopped due to errors but still found a solution.
FAILED	The solver failed to converge, possibly due to numerical issues.
HEURISTIC_NOSOL	The solver used only heuristics and did not find a solution.
HEURISTIC_SOL	The solver used only heuristics and found a solution.
INFEASIBLE	The problem is infeasible.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
INTERRUPTED	The solver was interrupted by the system or the user before completing its work.
NODE_LIM_NOSOL	The solver reached the maximum number of nodes specified in the MAXNODES= option and did not find a solution.
NODE_LIM_SOL	The solver reached the maximum number of nodes specified in the MAXNODES= option and found a solution.
NULL_GRAPH	The graph was null (it had 0 nodes) after PROC OPTMODEL processed the SUBGRAPH= option.
OK	The algorithm terminated normally.
OPTIMAL	The solution is optimal.

OPTIMAL_AGAP	The solution is optimal within the absolute gap that is specified in the ABSOBJGAP= option.
OPTIMAL_COND	The solution is optimal, but some infeasibilities (primal, bound, or integer) exceed tolerances because of scaling.
OPTIMAL_RGAP	The solution is optimal within the relative gap that is specified in the RELOBJGAP= option.
OUTMEM_NOSOL	The solver ran out of memory and either did not find a solution or failed to output the solution due to insufficient memory.
OUTMEM_SOL	The solver ran out of memory but still found a solution.
SOLUTION_LIM	The solver reached the maximum number of solutions specified in the MAXCLIQUES=, MAXCYCLES=, or MAXSOLS= option.
TARGET	The solution is not worse than the target that is specified in the TARGET= option.
TIME_LIM_NOSOL	The solver reached the execution time limit specified in the MAXTIME= option and did not find a solution.
TIME_LIM_SOL	The solver reached the execution time limit specified in the MAXTIME= option and found a solution.
TIME_LIMIT_REACHED	The solver reached its execution time limit.
UNBOUNDED	The problem is unbounded.

PROBLEM_TYPE

indicates the type of problem solved. It can take one of the following values:

BICONCOMP	Biconnected components
CLIQUE	Maximal cliques
CONCOMP	Connected components
CYCLE	Cycle detection
LAP	Linear assignment (matching)
MAXFLOW	Maximum flow
MCF	Minimum-cost network flow
MINCUT	Minimum cut
MST	Minimum spanning tree
PATH	Path enumeration
SHORTPATH	Shortest path
TRANSCL	Transitive closure
TSP	Traveling salesman
VRP	Vehicle routing
NONE	This value is used when you do not specify an algorithm to run.

OBJECTIVE
indicates the objective value that is obtained by the solver at termination. For problem classes that do not have an explicit objective, such as cycle, the value of this keyword within the _OROPTMODEL_ macro variable is missing (.).

PRESOLVE_TIME
indicates the time (in seconds) used in preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

When SOLUTION_STATUS has a value of OK or the algorithm finds a solution, all terms of the _OROPTMODEL_ macro variable are present; otherwise, some terms might not appear.

The following keywords within the _OROPTMODEL_ macro variable appear only with certain algorithms. The keywords convey information about the number of solutions each algorithm found:

NUM_ARTICULATION_POINTS
indicates the number of articulation points found. This term appears only for biconnected components.

NUM_CLIQUES
indicates the number of cliques found. This term appears only for clique.

NUM_COMPONENTS
indicates the number of components that match the definitions of the corresponding problem class. This term appears only for connected components and biconnected components.

NUM_CYCLES
indicates the number of cycles found that satisfy the criteria you provide. This term appears only for cycles.

NUM_PATHS
indicates the number of paths found that satisfy the criteria you provide. This term appears only for path enumeration and shortest path.

The following keywords within the _OROPTMODEL_ macro variable appear only with the TSP algorithm:

RELATIVE_GAP
indicates the relative gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the MILP solver. The relative gap is equal to

$$|\text{BestInteger} - \text{BestBound}| / (1\text{E}{-10} + |\text{BestBound}|)$$

ABSOLUTE_GAP
indicates the absolute gap between the best integer objective (BestInteger) and the best bound on the objective function value (BestBound) upon termination of the MILP solver. The absolute gap is equal to |BestInteger − BestBound|.

PRIMAL_INFEASIBILITY
indicates the maximum (absolute) violation of the primal constraints by the solution.

BOUND_INFEASIBILITY
indicates the maximum (absolute) violation by the solution of the lower or upper bounds (or both).

INTEGER_INFEASIBILITY
indicates the maximum (absolute) violation of the integrality of integer variables returned by the MILP solver.

BEST_BOUND
indicates the best bound on the objective function value at termination. A missing value indicates that the MILP solver was not able to obtain such a bound.

NODES
indicates the number of nodes enumerated by the MILP solver by using the branch-and-bound algorithm.

ITERATIONS
indicates the number of simplex iterations taken to solve the problem.

Examples: Network Solver

Example 15.1: Articulation Points in a Terrorist Network

This example considers the terrorist communications network from the attacks on the United States on September 11, 2001, described in Krebs 2002. Figure 15.114 shows this network, which was constructed after the attacks, based on collected intelligence information.

Figure 15.114 Terrorist Communications Network from 9/11

The full network data include 153 links. The following statements show a small subset to illustrate the use of the BICONNECTEDCOMPONENTS option in this context:

```
data LinkSetInTerror911;
   input from & $32. to & $32.;
   datalines;
Abu Zubeida                Djamal Beghal
Jean-Marc Grandvisir       Djamal Beghal
Nizar Trabelsi             Djamal Beghal
Abu Walid                  Djamal Beghal
Abu Qatada                 Djamal Beghal
Zacarias Moussaoui         Djamal Beghal
Jerome Courtaillier        Djamal Beghal
Kamel Daoudi               Djamal Beghal
Abu Walid                  Kamel Daoudi
Abu Walid                  Abu Qatada
Kamel Daoudi               Zacarias Moussaoui
Kamel Daoudi               Jerome Courtaillier
```

```
   ... more lines ...

Nawaf Alhazmi              Khalid Al-Mihdhar
Osama Awadallah            Khalid Al-Mihdhar
Abdussattar Shaikh         Khalid Al-Mihdhar
Abdussattar Shaikh         Osama Awadallah
;
```

Suppose that this communications network had been discovered before the attack on 9/11. If the investigators' goal was to disrupt the flow of communication between different groups within the organization, then they would want to focus on the people who are articulation points in the network.

To find the articulation points, use the following statements:

```
proc optmodel;
   set<str,str> LINKS;
   read data LinkSetInTerror911 into LINKS=[from to];
   set NODES = union{<i,j> in LINKS} {i,j};
   set<str> ARTPOINTS;

   solve with NETWORK /
      links     = (include=LINKS)
      biconcomp
      out       = (artpoints=ARTPOINTS)
   ;

   put ARTPOINTS;
   create data ArtPoints from [node]=ARTPOINTS artpoint=1;
quit;
```

The data set ArtPoints contains members of the network who are articulation points. Focusing investigations on cutting off these particular members could have caused a great deal of disruption in the terrorists' ability to communicate when formulating the attack.

Output 15.1.1 Articulation Points of Terrorist Communications Network from 9/11

node	artpoint
Djamal Beghal	1
Zacarias Moussaoui	1
Essid Sami Ben Khemais	1
Mohamed Atta	1
Mamoun Darkazanli	1
Nawaf Alhazmi	1

Example 15.2: Cycle Detection for Kidney Donor Exchange

This example looks at an application of cycle detection to help create a kidney donor exchange. Suppose someone needs a kidney transplant and a family member is willing to donate one. If the donor and recipient are incompatible (because of blood types, tissue mismatch, and so on), the transplant cannot happen. Now suppose two donor-recipient pairs i and j are in this situation, but donor i is compatible with recipient j and donor j is compatible with recipient i. Then two transplants can take place in a two-way swap, shown graphically in Figure 15.115. More generally, an n-way swap can be performed involving n donors and n recipients (CNN 2012).

Figure 15.115 Kidney Donor Exchange Two-Way Swap

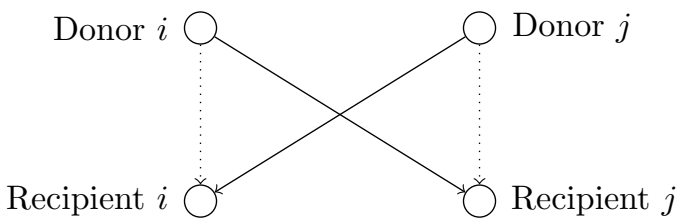
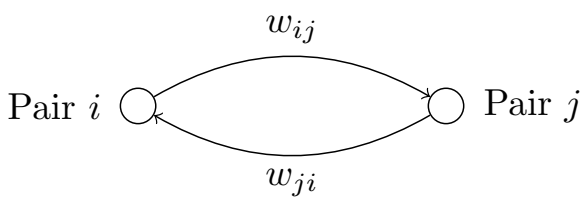


Figure 15.116 Kidney Donor Exchange Network



To model this problem, define a directed graph as follows. Each node is an incompatible donor-recipient pair. Link (i, j) exists if the donor from node i is compatible with the recipient from node j, as shown in Figure 15.116. The link weight is a measure of the quality of the match. By introducing dummy links whose weight is 0, you can also include altruistic donors who have no recipients or recipients who have no donors. The idea is to find a maximum-weight node-disjoint union of directed cycles. You want the union to be node-disjoint so that no kidney is donated more than once, and you want cycles so that the donor from node i donates a kidney if and only if the recipient from node i receives a kidney.

Without any other constraints, the problem could be solved as a linear assignment problem, as described in the section "Linear Assignment (Matching)" on page 832. But doing so would allow arbitrarily long cycles in the solution. Because of practical considerations (such as travel) and to mitigate risk, each cycle must have no more than L links. The kidney exchange problem is to find a maximum-weight node-disjoint union of short directed cycles.

One way to solve this problem is to explicitly generate all cycles whose length is at most L and then solve a set packing problem. You can use PROC OPTMODEL to generate the cycles, formulate the set packing problem, call the mixed integer linear programming solver, and output the optimal solution.

The following DATA step sets up the problem, first creating a random graph on n nodes with link probability p and Uniform(0,1) weight:

```
/* create random graph on n nodes with arc probability p
   and uniform(0,1) weight */
%let n = 100;
%let p = 0.02;
data LinkSetIn;
   call streaminit(1);
   do from = 0 to &n - 1;
      do to = 0 to &n - 1;
         if from eq to then continue;
         else if rand('UNIFORM') < &p then do;
            weight = rand('UNIFORM');
            output;
         end;
      end;
   end;
run;
```

The following statements declare parameters and then read the input data:

```
%let max_length = 10;
proc optmodel;
   /* declare index sets and parameters, and read data */
   set <num,num> ARCS;
   num weight {ARCS};
   read data LinkSetIn into ARCS=[from to] weight;
   set<num,num,num> ID_ORDER_NODE;
```

The following statements use the network solver to generate all cycles whose length is greater than or equal to 2 and less than or equal to 10:

```
   /* generate all cycles with 2 <= length <= max_length */
   solve with NETWORK /
      loglevel        = moderate
      graph_direction = directed
      links           = (include=ARCS)
      cycle           = (maxcycles=all minlength=2 maxlength=&max_length)
      out             = (cycles=ID_ORDER_NODE)
   ;
```

The network solver finds 395 cycles of the appropriate length, as shown in Output 15.2.1.

Output 15.2.1 Cycles for Kidney Donor Exchange Network Solver Log

```
NOTE: There were 208 observations read from the data set WORK.LINKSETIN.
NOTE: The number of nodes in the input graph is 98.
NOTE: The number of links in the input graph is 208.
NOTE: The network solver is called.
NOTE: Processing cycle enumeration using 12 threads across 1 machines.
NOTE: Processing cycle enumeration using the build algorithm.
NOTE: The algorithm found 395 cycles.
NOTE: Processing cycle enumeration used 0.00 (cpu: 0.01) seconds.
```

From the resulting set ID_ORDER_NODE, use the following statements to convert to one tuple per cycle-arc combination:

```
/* extract <cid,from,to> triples from <cid,order,node> triples */
set <num,num,num> ID_FROM_TO init {};
num last init ., from, to;
for {<cid,order,node> in ID_ORDER_NODE} do;
   from = last;
   to   = node;
   last = to;
   if order ne 1 then ID_FROM_TO = ID_FROM_TO union {<cid,from,to>};
end;
```

Alternatively, you can use the CYCLESLINKS= suboption to get the cycle-arc tuples directly from the solver:

```
/* generate cycles as <cid,order,from,to> quadruples */
/* rather than <cid,order,node> triples */
set <num,num,num,num> ID_ORDER_FROM_TO;
solve with NETWORK /
   loglevel        = moderate
   graph_direction = directed
   links           = (include=ARCS)
   cycle           = (maxcycles=all minlength=2 maxlength=&max_length)
   out             = (cycleslinks=ID_ORDER_FROM_TO)
;
```

Given the set of cycles, you can now formulate a mixed integer linear program (MILP) to maximize the total cycle weight. Let C be the set of cycles of appropriate length, N_c be the set of nodes in cycle c, A_c be the set of links in cycle c, and w_{ij} be the link weight for link (i, j). Define a binary decision variable x_c. Set x_c to 1 if cycle c is used in the solution; otherwise, set it to 0. Then, the following MILP defines the problem that you want to solve (to maximize the quality of the kidney exchange):

$$
\begin{array}{llll}
\text{maximize} & \displaystyle\sum_{c \in C} \left(\sum_{(i,j) \in A_c} w_{ij} \right) x_c & & \\
\text{subject to} & \displaystyle\sum_{c \in C : i \in N_c} x_c \leq 1 & i \in N & \text{(incomp_pair)} \\
& x_c \in \{0, 1\} & c \in C &
\end{array}
$$

The constraint (incomp_pair) ensures that each node (incompatible pair) in the graph is intersected at most once. That is, a donor can donate a kidney only once. You can use PROC OPTMODEL to solve this mixed integer linear programming problem as follows:

```
/* solve set packing problem to find maximum weight node-disjoint union
   of short directed cycles */
set CYCLES = setof {<c,i,j> in ID_FROM_TO} c;
set ARCS_c {c in CYCLES} = setof {<(c),i,j> in ID_FROM_TO} <i,j>;
set NODES_c {c in CYCLES} = union {<i,j> in ARCS_c[c]} {i,j};
set NODES = union {c in CYCLES} NODES_c[c];
num cycle_weight {c in CYCLES} = sum {<i,j> in ARCS_c[c]} weight[i,j];

/* UseCycle[c] = 1 if cycle c is used, 0 otherwise */
var UseCycle {CYCLES} binary;

/* declare objective */
```

```
   max TotalWeight
      = sum {c in CYCLES} cycle_weight[c] * UseCycle[c];

   /* each node appears in at most one cycle */
   con node_packing {i in NODES}:
      sum {c in CYCLES: i in NODES_c[c]} UseCycle[c] <= 1;

   /* call solver */
   solve with milp;

   /* output optimal solution */
   create data Solution from [c]={c in CYCLES: UseCycle[c].sol > 0.5}
      cycle_weight;
quit;
%put &_OROPTMODEL_;
```

PROC OPTMODEL solves the problem by using the mixed integer linear programming solver. As shown in Output 15.2.2, it was able to find a total weight (quality level) of 24.85.

Output 15.2.2 Cycles for Kidney Donor Exchange MILP Solver Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 395 variables (0 free, 0 fixed).
NOTE: The problem has 395 binary and 0 integer variables.
NOTE: The problem has 64 linear constraints (64 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 3431 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 122 variables and 30 constraints.
NOTE: The MILP presolver removed 1720 constraint coefficients.
NOTE: The MILP presolver modified 6 constraint coefficients.
NOTE: The presolved problem has 273 variables, 34 constraints, and 1711
      constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 12 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      3     20.7854479   1160.1140129   98.21%       0
             0        1      3     20.7854479     25.4194215   18.23%       0
             0        1      4     21.4335632     25.4194215   15.68%       0
             0        1      4     21.4335632     24.9474075   14.09%       0
             0        1      5     22.3018383     24.9474075   10.60%       0
             0        1      6     24.8508554     24.8508554    0.00%       0
             0        0      6     24.8508554     24.8508554    0.00%       0
NOTE: The MILP solver added 23 cuts with 2672 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 24.850855395.
NOTE: The data set WORK.SOLUTION has 7 observations and 2 variables.
STATUS=OK ALGORITHM=BAC SOLUTION_STATUS=OPTIMAL OBJECTIVE=24.850855395
RELATIVE_GAP=0 ABSOLUTE_GAP=0 PRIMAL_INFEASIBILITY=8.881784E-16
BOUND_INFEASIBILITY=8.881784E-16 INTEGER_INFEASIBILITY=8.881784E-16
BEST_BOUND=24.850855395 NODES=1 SOLUTIONS_FOUND=6 ITERATIONS=129
PRESOLVE_TIME=0.02 SOLUTION_TIME=0.07
```

The data set Solution, shown in Output 15.2.3, now contains the cycles that define the best exchange and their associated weight (quality).

Output 15.2.3 Maximum Quality Solution for Kidney Donor Exchange

c	cycle_weight
29	4.35416
117	4.97483
213	4.34026
274	5.08435
289	1.72530
294	2.42954
388	1.94241

Example 15.3: Linear Assignment Problem for Minimizing Relay Times

A swimming coach needs to assign male and female swimmers to each leg of a medley relay team; each swimmer in the relay uses a different stroke (backstroke, breaststroke, butterfly, or freestyle). The swimmers' best times for each stroke are stored in a SAS data set. The LINEARASSIGNMENT option evaluates the times and matches strokes and swimmers to find the lowest relay time.

The data are stored in matrix format, where the row identifier is the swimmer's name (variable name) and each swimming stroke is a column (variables back, breast, fly, and free). In the following DATA step, the relay times are split into two categories, male (M) and female (F):

```
data RelayTimes;
   input name $ sex $ back breast fly free;
   datalines;
Sue     F 35.1 36.7 28.3 36.1
Karen   F 34.6 32.6 26.9 26.2
Jan     F 31.3 33.9 27.1 31.2
Andrea  F 28.6 34.1 29.1 30.3
Carol   F 32.9 32.2 26.6 24.0
Ellen   F 27.8 32.5 27.8 27.0
Jim     M 26.3 27.6 23.5 22.4
Mike    M 29.0 24.0 27.9 25.4
Sam     M 27.2 33.8 25.2 24.1
Clayton M 27.0 29.2 23.0 21.9
;
```

The following statements solve the linear assignment problem for both male and female relay teams:

```
proc contents data=RelayTimes
   out=stroke_data(rename=(name=stroke) where=(type=1));
run;

proc optmodel;
   set <str> STROKES;
   read data stroke_data into STROKES=[stroke];
   set <str> SWIMMERS;
   str sex {SWIMMERS};
```

```
   num time {SWIMMERS, STROKES};
   read data RelayTimes into SWIMMERS=[name] sex
      {stroke in STROKES} <time[name,stroke]=col(stroke)>;
   set FEMALES = {i in SWIMMERS: sex[i] = 'F'};
   set FNODES = FEMALES union STROKES;
   set MALES = {i in SWIMMERS: sex[i] = 'M'};
   set MNODES = MALES union STROKES;
   set <str,str> PAIRS;

   solve with NETWORK /
      graph_direction = directed
      links           = (weight=time)
      subgraph        = (nodes=FNODES)
      lap
      out             = (assignments=PAIRS)
   ;
   put PAIRS;
   create data LinearAssignF from [name assign]=PAIRS sex[name] cost=time;

   solve with NETWORK /
      graph_direction = directed
      links           = (weight=time)
      subgraph        = (nodes=MNODES)
      lap
      out             = (assignments=PAIRS)
   ;
   put PAIRS;
   create data LinearAssignM from [name assign]=PAIRS sex[name] cost=time;
quit;
```

The progress of the two SOLVE WITH NETWORK calls is shown in Output 15.3.1.

Output 15.3.1 Network Solver Log: Linear Assignment for Swim Times

```
NOTE: The data set WORK.STROKE_DATA has 4 observations and 41 variables.
NOTE: There were 4 observations read from the data set WORK.STROKE_DATA.
NOTE: There were 10 observations read from the data set WORK.RELAYTIMES.
NOTE: The SUBGRAPH= option filtered 16 elements from 'time.'
NOTE: The number of nodes in the input graph is 10.
NOTE: The number of links in the input graph is 24.
NOTE: The network solver is called.
NOTE: Processing the linear assignment problem using 1 threads across 1
      machines.
NOTE: Objective = 111.5.
NOTE: Processing the linear assignment problem used 0.00 (cpu: 0.00) seconds.
{<'Karen','breast'>,<'Jan','fly'>,<'Carol','free'>,<'Ellen','back'>}
NOTE: The data set WORK.LINEARASSIGNF has 4 observations and 4 variables.
NOTE: The SUBGRAPH= option filtered 24 elements from 'time.'
NOTE: The number of nodes in the input graph is 8.
NOTE: The number of links in the input graph is 16.
NOTE: The network solver is called.
NOTE: Processing the linear assignment problem using 1 threads across 1
      machines.
NOTE: Objective = 96.6.
NOTE: Processing the linear assignment problem used 0.00 (cpu: 0.00) seconds.
{<'Jim','fly'>,<'Mike','breast'>,<'Sam','back'>,<'Clayton','free'>}
NOTE: The data set WORK.LINEARASSIGNM has 4 observations and 4 variables.
```

The data sets LinearAssignF and LinearAssignM contain the optimal assignments. Note that in the case of the female data, there are more people (set S) than there are strokes (set T). Therefore, the solver allows for some members of S to remain unassigned.

Output 15.3.2 Optimal Assignments for Best Female Swim Times

name	assign	sex	cost
Karen	breast	F	32.6
Jan	fly	F	27.1
Carol	free	F	24.0
Ellen	back	F	27.8
			111.5

Output 15.3.3 Optimal Assignments for Best Male Swim Times

name	assign	sex	cost
Jim	fly	M	23.5
Mike	breast	M	24.0
Sam	back	M	27.2
Clayton	free	M	21.9
			96.6

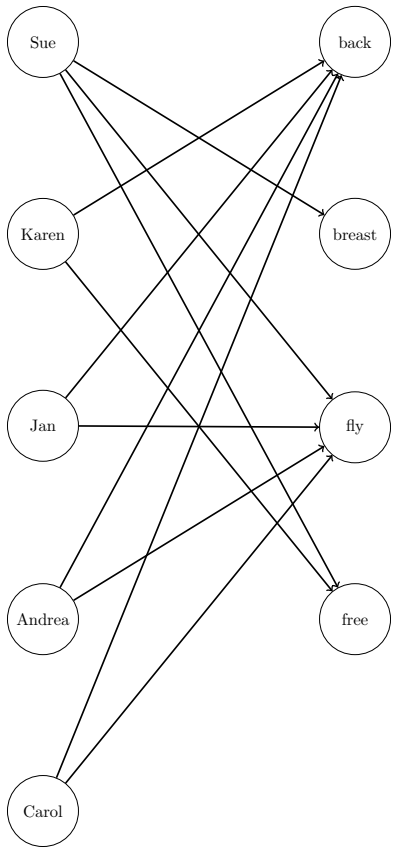
Example 15.4: Linear Assignment Problem, Sparse Format versus Dense Format

This example looks at the problem of assigning swimmers to legs of a medley relay based on their best stroke times. Certain swimmers are not eligible to perform certain strokes, because they do not excel at these strokes. A missing (.) value in the data matrix identifies an ineligible assignment. For example:

```
data RelayTimesMatrix;
   input name $ sex $ back breast fly free;
   datalines;
Sue     F   .  36.7 28.3 36.1
Karen   F 34.6    .    . 26.2
Jan     F 31.3    . 27.1    .
Andrea  F 28.6    . 29.1    .
Carol   F 32.9    . 26.6    .
;
```

The linear assignment problem can also be interpreted as the minimum-weight matching in a bipartite directed graph. The eligible assignments define links between the rows (swimmers) and the columns (strokes), as in Figure 15.117.

Figure 15.117 Bipartite Graph for Linear Assignment Problem



You can represent the same data in RelayTimesMatrix by using a links data set as follows:

```
data RelayTimesLinks;
   input name $ attr $ cost;
   datalines;
Sue     breast 36.7
Sue     fly    28.3
Sue     free   36.1
Karen   back   34.6
Karen   free   26.2
Jan     back   31.3
Jan     fly    27.1
Andrea  back   28.6
Andrea  fly    29.1
Carol   back   32.9
Carol   fly    26.6
;
```

This graph must be bipartite (such that S and T are disjoint). If it is not, the network solver returns an error.

Now, you can use either input format to solve the same problem, as follows:

```
proc contents data=RelayTimesMatrix
   out=stroke_data(rename=(name=stroke) where=(type=1));
run;

proc optmodel;
   set <str> STROKES;
   read data stroke_data into STROKES=[stroke];
   set <str> SWIMMERS;
   str sex {SWIMMERS};
   num time {SWIMMERS, STROKES};
   read data RelayTimesMatrix into SWIMMERS=[name]
      sex
      {stroke in STROKES} <time[name,stroke]=col(stroke)>;
   set SWIMMERS_STROKES =
      {name in SWIMMERS, stroke in STROKES: time[name,stroke] ne .};
   set <str,str> PAIRS;

   solve with NETWORK /
      graph_direction = directed
      links           = (weight=time)
      subgraph        = (links=SWIMMERS_STROKES)
      lap
      out             = (assignments=PAIRS)
   ;

   put PAIRS;
   create data LinearAssignMatrix from [name assign]=PAIRS
      sex[name] cost=time;
quit;

proc sql;
   create table stroke_data as
   select distinct attr as stroke
   from RelayTimesLinks;
```

```
quit;

proc optmodel;
   set <str> STROKES;
   read data stroke_data into STROKES=[stroke];
   set <str> SWIMMERS;
   str sex {SWIMMERS};
   set <str,str> SWIMMERS_STROKES;
   num time {SWIMMERS_STROKES};
   read data RelayTimesLinks into SWIMMERS_STROKES=[name attr] time=cost;
   set <str,str> PAIRS;

   solve with NETWORK /
      graph_direction = directed
      links           = (weight=time)
      lap
      out             = (assignments=PAIRS)
   ;

   put PAIRS;
   create data LinearAssignLinks from [name attr]=PAIRS cost=time;
quit;
```

The data sets LinearAssignMatrix and LinearAssignLinks now contain the optimal assignments, as shown in Output 15.4.1 and Output 15.4.2.

Output 15.4.1 Optimal Assignments for Swim Times (Dense Input)

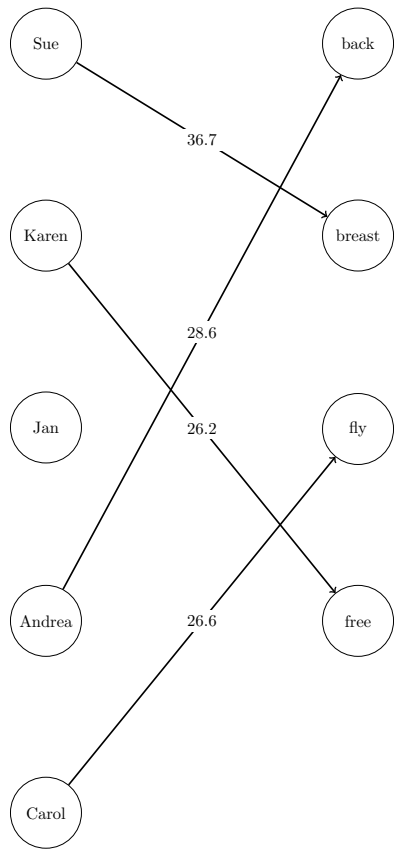
name	assign	sex	cost
Sue	breast	F	36.7
Karen	free	F	26.2
Andrea	back	F	28.6
Carol	fly	F	26.6
			118.1

Output 15.4.2 Optimal Assignments for Swim Times (Sparse Input)

name	attr	cost
Sue	breast	36.7
Karen	free	26.2
Andrea	back	28.6
Carol	fly	26.6
		118.1

The optimal assignments are shown graphically in Figure 15.118.

Figure 15.118 Optimal Assignments for Swim Times

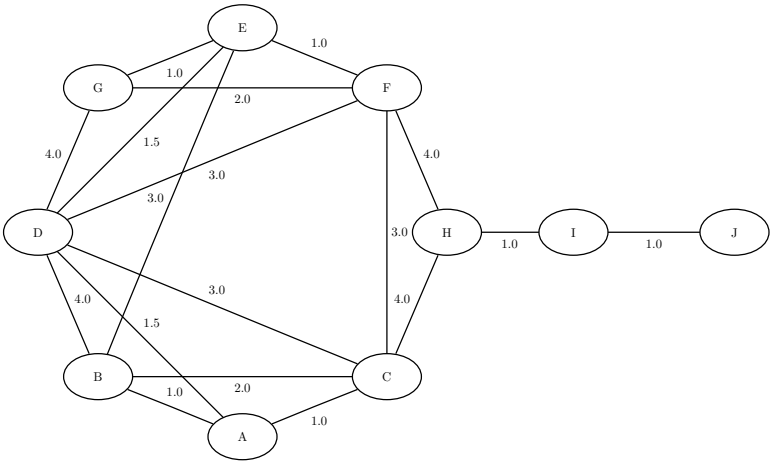


For large problems where a number of links are forbidden, the sparse format can be faster and can save a great deal of memory. Consider an example that uses the dense format with 15,000 columns ($|S| = 15{,}000$) and 4,000 rows ($|T| = 4{,}000$). To store the dense matrix in memory, the network solver needs to allocate approximately $|S| \cdot |T| \cdot 8/1{,}024/1{,}024 = 457$ MB. If the data have mostly ineligible links, then the sparse (graph) format is much more efficient with respect to memory. For example, if the data have only 5% of the eligible links ($15{,}000 \cdot 4{,}000 \cdot 0.05 = 3{,}000{,}000$), then the dense storage would still need 457 MB. The sparse storage for the same example needs approximately $|S| \cdot |T| \cdot 0.05 \cdot 12/1{,}024/1{,}024 = 34$ MB. If the problem is fully dense (all links are eligible), then the dense format is more efficient.

Example 15.5: Minimum Spanning Tree for Computer Network Topology

Consider the problem of designing a small network of computers in an office. In designing the network, the goal is to make sure that each machine in the office can reach every other machine. To accomplish this goal, Ethernet lines must be constructed and run between the machines. The construction costs for each possible link are based approximately on distance and are shown in Figure 15.119. Besides distance, the costs also reflect some restrictions due to physical boundaries. To connect all the machines in the office at minimal cost, you need to find a minimum spanning tree on the network of possible links.

Figure 15.119 Potential Office Computer Network



Define the link data set as follows:

```
data LinkSetInCompNet;
   input from $ to $ weight @@;
   datalines;
A B 1.0  A C 1.0  A D 1.5  B C 2.0  B D 4.0
B E 3.0  C D 3.0  C F 3.0  C H 4.0  D E 1.5
D F 3.0  D G 4.0  E F 1.0  E G 1.0  F G 2.0
F H 4.0  H I 1.0  I J 1.0
;
```

The following statements find a minimum spanning tree:

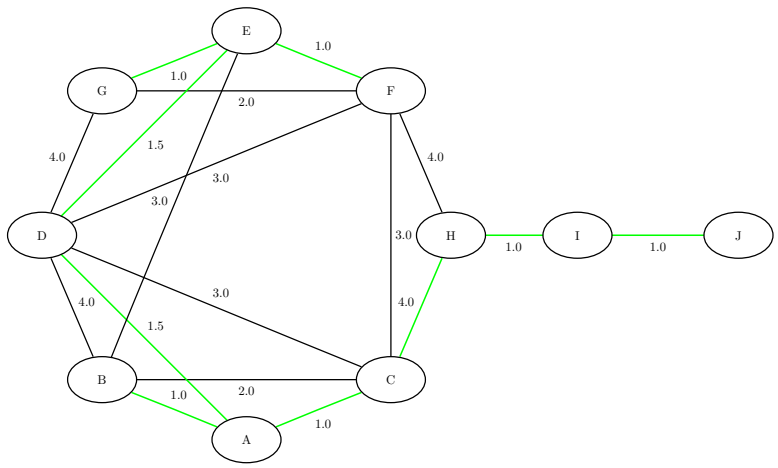
```
proc optmodel;
   set<str,str> LINKS;
   num weight{LINKS};
   read data LinkSetInCompNet into LINKS=[from to] weight;
   set<str,str> FOREST;

   solve with NETWORK /
      links       = (weight=weight)
      minspantree
      out         = (forest=FOREST)
   ;

   put FOREST;
   put (sum {<i,j> in FOREST} weight[i,j]);
   create data MinSpanTree from [from to]=FOREST weight;
quit;
```

Output 15.5.1 shows the resulting data set MinSpanTree, which is displayed graphically in Figure 15.120 with the minimal cost links shown in green.

Figure 15.120 Minimum Spanning Tree for Office Computer Network



Output 15.5.1 Minimum Spanning Tree of a Computer Network Topology

from	to	weight
A	B	1.0
A	C	1.0
E	F	1.0
E	G	1.0
H	I	1.0
I	J	1.0
A	D	1.5
D	E	1.5
C	H	4.0
		13.0

Example 15.6: Transitive Closure for Identification of Circular Dependencies in a Bug Tracking System

Most software bug tracking systems have some notion of *duplicate bugs* in which one bug is declared to be the same as another bug. If bug A is considered a duplicate (DUP) of bug B, then a fix for B would also fix A. You can represent the DUPs in a bug tracking system as a directed graph where you add a link $A \rightarrow B$ if A is a DUP of B.

The bug tracking system needs to check for two situations when users declare a bug to be a DUP. The first situation is called a *circular dependence*. Consider bugs A, B, C, and D in the tracking system. The first user declares that A is a DUP of B and that C is a DUP of D. Then, a second user declares that B is a DUP of C, and a third user declares that D is a DUP of A. You now have a circular dependence, and no primary bug is defined on which the development team should focus. You can easily see this circular dependence in the graph representation, because $A \rightarrow B \rightarrow C \rightarrow D \rightarrow A$. Finding such circular dependencies can be done using cycle detection, which is described in the section "Cycle" on page 826. However, the second situation that needs to be checked is more general. If a user declares that A is a DUP of B and another user declares that B is a DUP of C, this chain of duplicates is already an issue. The bug tracking system needs to provide

one primary bug to which the rest of the bugs are duplicated. The existence of these chains can be identified by calculating the transitive closure of the directed graph that is defined by the DUP links.

Given the original directed graph G (defined by the DUP links) and its transitive closure G^T, any link in G^T that is not in G exists because of some chain that is present in G.

Consider the following data that define some duplicated bugs (called *defects*) in a small sample of the bug tracking system:

```
data DefectLinks;
   input defectId $ linkedDefect $ linkType $ when datetime16.;
   format when datetime16.;
   datalines;
D0096978 S0711218 DUPTO 20OCT10:00:00:00
S0152674 S0153280 DUPTO 30MAY02:00:00:00
S0153280 S0153307 DUPTO 30MAY02:00:00:00
S0153307 S0152674 DUPTO 30MAY02:00:00:00
S0162973 S0162978 DUPTO 29NOV10:16:13:16
S0162978 S0165405 DUPTO 29NOV10:16:13:16
S0325026 S0575748 DUPTO 01JUN10:00:00:00
S0347945 S0346582 DUPTO 03MAR06:00:00:00
S0350596 S0346582 DUPTO 21MAR06:00:00:00
S0539744 S0643230 DUPTO 10MAY10:00:00:00
S0575748 S0643230 DUPTO 15JUN10:00:00:00
S0629984 S0643230 DUPTO 01JUN10:00:00:00
;
```

The following statements calculate cycles in addition to the transitive closure of the graph G that is defined by the duplicated defects in DefectLinks. The output data set Cycles contains any circular dependencies, and the data set TransClosure contains the transitive closure G^T. To identify the chains, you can use PROC SQL to identify the links in G^T that are not in G.

```
proc optmodel;
   set<str,str> LINKS;
   read data DefectLinks into LINKS=[defectId linkedDefect];
   set<num,num,str> CYCLES;
   set<str,str> CLOSURE;

   solve with NETWORK /
      loglevel        = moderate
      graph_direction = directed
      links           = (include=LINKS)
      cycle           = (maxcycles=1)
      out             = (cycles=CYCLES)
   ;

   put CYCLES;
   create data Cycles from [cycle order node]=CYCLES;

   solve with NETWORK /
      loglevel           = moderate
      graph_direction    = directed
      links              = (include=LINKS)
      transitive_closure
```

```
      out                 = (closure=CLOSURE)
   ;

   put CLOSURE;
   create data TransClosure from [defectId linkedDefect]=CLOSURE;
quit;

proc sql;
   create table Chains as
   select defectId, linkedDefect from TransClosure
      except
   select defectId, linkedDefect from DefectLinks;
quit;
```

The progress of the procedure is shown in Output 15.6.1.

Output 15.6.1 Network Solver Log: Transitive Closure for Identification of Circular Dependencies in a Bug Tracking System

```
NOTE: There were 12 observations read from the data set WORK.DEFECTLINKS.
NOTE: The number of nodes in the input graph is 16.
NOTE: The number of links in the input graph is 12.
NOTE: The network solver is called.
NOTE: Processing cycle enumeration using 1 threads across 1 machines.
NOTE: Processing cycle enumeration using the backtrack algorithm.
NOTE: Required number of cycles found.
NOTE: The algorithm found 1 cycles.
NOTE: Processing cycle enumeration used 0.00 (cpu: 0.00) seconds.
{<1,1,'S0152674'>,<1,2,'S0153280'>,<1,3,'S0153307'>,<1,4,'S0152674'>}
NOTE: The data set WORK.CYCLES has 4 observations and 3 variables.
NOTE: The number of nodes in the input graph is 16.
NOTE: The number of links in the input graph is 12.
NOTE: The network solver is called.
NOTE: Processing the transitive closure using 1 threads across 1 machines.
NOTE: Processing the transitive closure used 0.00 (cpu: 0.00) seconds.
{<'D0096978','S0711218'>,<'S0152674','S0152674'>,<'S0152674','S0153280'>,<
'S0152674','S0153307'>,<'S0153280','S0152674'>,<'S0153280','S0153280'>,<
'S0153280','S0153307'>,<'S0153307','S0152674'>,<'S0153307','S0153280'>,<
'S0153307','S0153307'>,<'S0162973','S0162978'>,<'S0162973','S0165405'>,<
'S0162978','S0165405'>,<'S0325026','S0575748'>,<'S0325026','S0643230'>,<
'S0575748','S0643230'>,<'S0347945','S0346582'>,<'S0350596','S0346582'>,<
'S0539744','S0643230'>,<'S0629984','S0643230'>}
NOTE: The data set WORK.TRANSCLOSURE has 20 observations and 2 variables.
NOTE: Table WORK.CHAINS created, with 8 rows and 2 columns.
```

The data set Cycles contains one case of a circular dependence in which the DUPs start and end at S0152674.

Output 15.6.2 Cycle in Bug Tracking System

cycle	order	node
1	1	S0152674
1	2	S0153280
1	3	S0153307
1	4	S0152674

The data set Chains contains the chains in the bug tracking system that come from the links in G^T that are not in G.

Output 15.6.3 Chains in Bug Tracking System

defectId	linkedDefect
S0152674	S0152674
S0152674	S0153307
S0153280	S0152674
S0153280	S0153280
S0153307	S0153280
S0153307	S0153307
S0162973	S0165405
S0325026	S0643230

Example 15.7: Traveling Salesman Tour of US Capital Cities

Consider a cross-country trip where you want to travel the fewest miles to visit all the capital cities in all US states (and the District of Columbia) except Alaska and Hawaii. Finding the optimal route is an instance of the traveling salesman problem, which is described in the section "Traveling Salesman Problem" on page 882.

The following data set provides a list of the capital cities and their latitude and longitude:

```
data Cities;
   input city $20. lat long;
   datalines;
Albany, NY          42.652552778 -73.75732222
Annapolis, MD       38.978611111 -76.49111111
Atlanta, GA         33.749272222 -84.38826111
Augusta, ME         44.307236111 -69.78167778
Austin, TX          30.274722222 -97.74055556
Baton Rouge, LA     30.457072222 -91.18740556
Bismarck, ND        46.820813889 -100.7827417
Boise, ID           43.617697222 -116.1996139
Boston, MA          42.357708333 -71.06356389
Carson City, NV     39.164075    -119.7662917
Charleston, WV      38.336388889 -81.61222222
Cheyenne, WY        41.140277778 -104.8197222
Columbia, SC        34.000433333 -81.03314722
Columbus, OH        39.961388889 -82.99888889
Concord, NH         43.206747222 -71.53812778
Denver, CO          39.739094444 -104.9848972
```

```
Des Moines, IA      41.591177778 -93.60386944
Dover, DE           39.157305556 -75.51972222
Frankfort, KY       38.186777778 -84.87533333
Harrisburg, PA      40.264444444 -76.86666667
Hartford, CT        41.764136111 -72.68277778
Helena, MT          46.5857      -112.0184
Indianapolis, IN    39.768611111 -86.1625
Jackson, MS         32.303888889 -90.18222222
Jefferson City, MO  38.579119444 -92.17299167
Lansing, MI         42.733727778 -84.55558889
Lincoln, NE         40.808088889 -96.69958611
Little Rock, AR     34.746758333 -92.28876111
Madison, WI         43.074444444 -89.38472222
Montgomery, AL      32.377447222 -86.30094167
Montpelier, VT      44.262222222 -72.58083333
Nashville, TN       36.165833333 -86.78416667
Oklahoma City, OK   35.492280556 -97.50337222
Olympia, WA         47.035277778 -122.9063889
Phoenix, AZ         33.448097222 -112.0970944
Pierre, SD          44.367166667 -100.3463528
Providence, RI      41.830833333 -71.415
Raleigh, NC         35.780277778 -78.63916667
Richmond, VA        37.538758333 -77.43359444
Sacramento, CA      38.576572222 -121.4934111
Saint Paul, MN      44.955147222 -93.10223611
Salem, OR           44.938730556 -123.0300972
Salt Lake City, UT  40.777222222 -111.8880556
Santa Fe, NM        35.682280556 -105.9396583
Springfield, IL     39.798516667 -89.65488889
Tallahassee, FL     30.438111111 -84.2816
Topeka, KS          39.048008333 -95.67815556
Trenton, NJ         40.220436111 -74.76990278
Washington, DC      38.889802778 -77.00911389
;
```

From this list, you can generate a links data set, CitiesDist, that contains the distances (in miles) between each pair of cities. The distances are calculated by using the SAS function GEODIST.

```
/* create a list of all the possible pairs of cities */
proc sql;
   create table CitiesDist as
   select
      a.city as city1, a.lat as lat1, a.long as long1,
      b.city as city2, b.lat as lat2, b.long as long2,
      geodist(lat1, long1, lat2, long2, 'DM') as distance
      from Cities as a, Cities as b
      where a.city < b.city;
quit;
```

The following PROC OPTMODEL statements find the optimal tour of all the capital cities:

```
/* find optimal tour by using the network solver */
proc optmodel;
   set<str,str> CAPPAIRS;
   set<str> CAPITALS = union {<i,j> in CAPPAIRS} {i,j};
   num distance{i in CAPITALS, j in CAPITALS: i < j};
   read data CitiesDist into CAPPAIRS=[city1 city2] distance;
   set<str,str> TOUR;
   num order{CAPITALS};

   solve with NETWORK /
      loglevel  = moderate
      links     = (weight=distance)
      tsp
      out       = (order=order tour=TOUR)
   ;

   put (sum{<i,j> in TOUR} distance[i,j]);
   /* create tour-ordered pairs (rather than input-ordered pairs) */
   str CAPbyOrder{1..card(CAPITALS)};
   for {i in CAPITALS} CAPbyOrder[order[i]] = i;
   set TSPEDGES init
      setof{i in 2..card(CAPITALS)} <CAPbyOrder[i-1],CAPbyOrder[i]>
      union {<CAPbyOrder[card(CAPITALS)],CAPbyOrder[1]>};
   num distance2{<i,j> in TSPEDGES} =
      if i < j then distance[i,j] else distance[j,i];
   create data TSPTourNodes from [node] tsp_order=order;
   create data TSPTourLinks from [city1 city2]=TSPEDGES distance=distance2;
quit;
```

The progress of the procedure is shown in Output 15.7.1. The total mileage that is needed to optimally tour the capital cities is 10,635.09 miles.

Output 15.7.1 Network Solver Log: Traveling Salesman Tour of US Capital Cities

```
NOTE: There were 1176 observations read from the data set WORK.CITIESDIST.
NOTE: The number of nodes in the input graph is 49.
NOTE: The number of links in the input graph is 1176.
NOTE: The network solver is called.
NOTE: Processing the traveling salesman problem using 1 threads across 1
      machines.
NOTE: The initial TSP heuristics found a tour with cost 10635.088264 using 0.08
      (cpu: 0.08) seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      1  10635.0882639  10054.2390851    5.78%       0
             0        1      1  10635.0882639  10260.8132168    3.65%       0
             0        1      1  10635.0882639  10281.6424575    3.44%       0
             0        1      1  10635.0882639  10313.3113690    3.12%       0
             0        1      1  10635.0882639  10402.5601933    2.24%       0
             0        1      1  10635.0882639  10416.4037477    2.10%       0
             0        1      1  10635.0882639  10486.4120251    1.42%       0
             0        1      1  10635.0882639  10496.2272412    1.32%       0
             0        1      1  10635.0882639  10547.4389577    0.83%       0
             0        1      1  10635.0882639  10578.8621709    0.53%       0
             0        1      1  10635.0882639  10594.2920698    0.39%       0
             0        1      1  10635.0882639  10600.5194477    0.33%       0
             0        1      1  10635.0882639  10627.5814570    0.07%       0
             0        0      1  10635.0882639  10635.0882639    0.00%       0
NOTE: The MILP solver added 13 cuts with 1570 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 10635.088264.
NOTE: Processing the traveling salesman problem used 0.11 (cpu: 0.09) seconds.
10635.088264
NOTE: The data set WORK.TSPTOURNODES has 49 observations and 2 variables.
NOTE: The data set WORK.TSPTOURLINKS has 49 observations and 3 variables.
```

The following statements produce a graphical display of the solution:

```
/* merge latitude and longitude */
proc sql;
   /* merge in the lat & long for city1 */
   create table TSPTourLinksAnno1 as
   select unique TSPTourLinks.*, cities.lat as lat1, cities.long as long1
      from TSPTourLinks left join cities
      on TSPTourLinks.city1=cities.city;
   /* merge in the lat & long for city2 */
   create table TSPTourLinksAnno2 as
   select unique TSPTourLinksAnno1.*, cities.lat as lat2, cities.long as long2
      from TSPTourLinksAnno1 left join cities
      on TSPTourLinksAnno1.city2=cities.city;
quit;
```

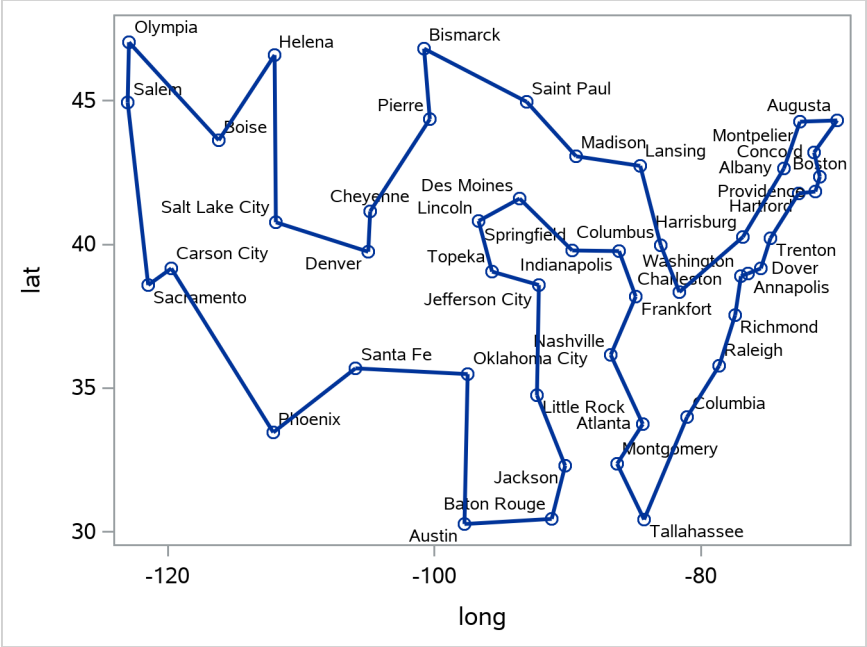
```
data sganno;
   set TSPTourLinksAnno2(rename=(long1=x1 lat1=y1 long2=x2 lat2=y2));
   drawspace = 'datavalue';
   function  = 'line';
run;

data Cities2;
   set Cities;
   label = scan(city,1,',');
run;

proc sgplot data=Cities2 sganno=sganno;
   scatter y=lat x=long / datalabel=label;
   yaxis offsetmax=0.05;
run;
```

The minimal-cost tour of the capital cities is shown in Figure 15.7.2.

Output 15.7.2 Optimal Traveling Salesman Tour of US Capital Cities



The data set TSPTourLinks contains the links in the optimal tour. To display the links in the order in which they are to be visited, you can use the following DATA step:

```
/* create the directed optimal tour */
data TSPTourLinksDirected(drop=next);
   set TSPTourLinks;
   retain next;
   if _N_ ne 1 and city1 ne next then do;
      city2 = city1;
      city1 = next;
   end;
   next = city2;
```

```
run;
```

The data set TSPTourLinksDirected is shown in Figure 15.121.

Figure 15.121 Links in the Optimal Traveling Salesman Tour

city1	city2	distance
Albany, NY	Harrisburg, PA	230.66
Harrisburg, PA	Charleston, WV	286.98
Charleston, WV	Columbus, OH	134.58
Columbus, OH	Lansing, MI	207.73
Lansing, MI	Madison, WI	246.15
Madison, WI	Saint Paul, MN	226.17
Saint Paul, MN	Bismarck, ND	392.00
Bismarck, ND	Pierre, SD	170.77
Pierre, SD	Cheyenne, WY	318.33
Cheyenne, WY	Denver, CO	97.07
Denver, CO	Salt Lake City, UT	371.76
Salt Lake City, UT	Helena, MT	401.06
Helena, MT	Boise, ID	289.44
Boise, ID	Olympia, WA	402.81
Olympia, WA	Salem, OR	144.92
Salem, OR	Sacramento, CA	446.18
Sacramento, CA	Carson City, NV	101.57
Carson City, NV	Phoenix, AZ	581.40
Phoenix, AZ	Santa Fe, NM	383.30
Santa Fe, NM	Oklahoma City, OK	475.13
Oklahoma City, OK	Austin, TX	359.82
Austin, TX	Baton Rouge, LA	391.58
Baton Rouge, LA	Jackson, MS	140.42
Jackson, MS	Little Rock, AR	207.66
Little Rock, AR	Jefferson City, MO	264.34
Jefferson City, MO	Topeka, KS	191.90
Topeka, KS	Lincoln, NE	133.00
Lincoln, NE	Des Moines, IA	170.15
Des Moines, IA	Springfield, IL	241.45
Springfield, IL	Indianapolis, IN	185.89
Indianapolis, IN	Frankfort, KY	129.26
Frankfort, KY	Nashville, TN	174.68
Nashville, TN	Atlanta, GA	215.02
Atlanta, GA	Montgomery, AL	145.79
Montgomery, AL	Tallahassee, FL	179.13
Tallahassee, FL	Columbia, SC	310.53
Columbia, SC	Raleigh, NC	183.13
Raleigh, NC	Richmond, VA	138.52
Richmond, VA	Washington, DC	96.00
Washington, DC	Annapolis, MD	28.57
Annapolis, MD	Dover, DE	53.67
Dover, DE	Trenton, NJ	83.53
Trenton, NJ	Hartford, CT	152.49
Hartford, CT	Providence, RI	65.63
Providence, RI	Boston, MA	40.60
Boston, MA	Concord, NH	63.38
Concord, NH	Augusta, ME	116.18
Augusta, ME	Montpelier, VT	138.86
Montpelier, VT	Albany, NY	125.89
		10,635.09

Example 15.8: Vehicle Routing Problem (CVRPLIB)

A standard set of benchmark instances for the vehicle routing problem (from the Capacitated Vehicle Routing Problem Library, or CVRPLIB) is maintained at http://vrp.galgos.inf.puc-rio.br/index.php/en/. The following data set, NodeSetIn, represents an instance from CVRPLIB that has 22 nodes and eight vehicles (P-n22-k8.vrp), which was originally described in Augerat et al. (1995). The data set lists each node, its coordinates, and its demand.

```
/* the depot node */
%let depot = 1;
/* number of routes to use (max=min) */
%let numRoutes = 8;
/* capacity of each vehicle */
%let capacity = 3000;
/* node, x coordinate, y coordinate, demand */
data NodeSetIn;
```

```
   input node x y demand;
   datalines;
1  145 215    0
2  151 264 1100
3  159 261  700
4  130 254  800
5  128 252 1400
6  163 247 2100
7  146 246  400
8  161 242  800
9  142 239  100
10 163 236  500
11 148 232  600
12 128 231 1200
13 156 217 1300
14 129 214 1300
15 146 208  300
16 164 208  900
17 141 206 2100
18 147 193 1000
19 164 193  900
20 129 189 2500
21 155 185 1800
22 139 182  700
;
```

From this list, you can generate a links data set, LinkSetIn, that contains the rounded Euclidean distances between each pair of locations, as follows:

```
/* create a list of all possible pairs of locations */
proc sql;
   create table LinkSetIn as
   select
      a.node as node1, a.x as x1, a.y as y1,
      b.node as node2, b.x as x2, b.y as y2,
      round(sqrt((a.x-b.x)**2 + (a.y-b.y)**2)) as distance
      from NodeSetIn as a, NodeSetIn as b
      where a.node < b.node;
quit;
```

The following PROC OPTMODEL statements find the optimal routes:

```
/* find optimal routes by using the network solver */
proc optmodel;
   /* inputs */
   set<num,num> LINKS;
   num distance{LINKS};
   read data LinkSetIn into LINKS=[node1 node2] distance;
   set NODES;
   num x{NODES}, y{NODES};
   num demand{NODES};
   read data NodeSetIn into NODES=[node] x y demand;
   set DEPOT=/&depot/;

   /* outputs */
```

```
   set<num,num,num,num> ROUTELINKS;
   num order{NODES};
   num route{NODES};

   solve with network /
      logFreq  = 0
      links    = (weight=distance)
      vrp      = (depot=DEPOT capacity=&capacity demand=demand
                  minRoutes=&numRoutes maxRoutes=&numRoutes)
      out      = (vrplinks=ROUTELINKS route=route order=order)
   ;

   create data RoutesLinks
      from [route route_order node1 node2]=ROUTELINKS distance[node1, node2];
   create data RoutesNodes
      from [node]=NODES demand x y route route_order=order;
quit;
```

The progress of the procedure is shown in Output 15.8.1.

Output 15.8.1 Network Solver Log: P-n22-k8.vrp

```
NOTE: There were 231 observations read from the data set WORK.LINKSETIN.
NOTE: There were 22 observations read from the data set WORK.NODESETIN.
NOTE: The number of nodes in the input graph is 22.
NOTE: The number of links in the input graph is 231.
NOTE: The network solver is called.
NOTE: Processing the vehicle routing problem using 1 threads across 1 machines.
NOTE: The initial VRP heuristics did not find a solution using 0.06 (cpu: 0.05)
      seconds.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Branch and Cut algorithm is used.
NOTE: The MILP solver added 42 cuts with 2623 cut coefficients at the root.
NOTE: Optimal.
NOTE: Objective = 603.
NOTE: Processing the vehicle routing problem used 1.32 (cpu: 0.91) seconds.
NOTE: The data set WORK.ROUTESLINKS has 29 observations and 5 variables.
NOTE: The data set WORK.ROUTESNODES has 22 observations and 6 variables.
```

The output data set RoutesNodes now contains the nodes of the optimal routes. The following statements sort the resulting data and display each route along with the sum of the customer demands serviced by that route, as shown in Figure 15.122:

```
proc sort data=RoutesNodes;
   by route route_order;
run;
proc print data=RoutesNodes;
   by route;
   sum demand;
run;
```

Figure 15.122 Nodes in the Optimal Routes

route=.

Obs	node	demand	x	y	route_order
1	1	0	145	215	1

route=1

Obs	node	demand	x	y	route_order
2	7	400	146	246	2
3	2	1100	151	264	3
4	3	700	159	261	4
5	10	500	163	236	5
route		**2700**			

route=2

Obs	node	demand	x	y	route_order
6	5	1400	128	252	2
7	4	800	130	254	3
8	9	100	142	239	4
9	11	600	148	232	5
route		**2900**			

route=3

Obs	node	demand	x	y	route_order
10	6	2100	163	247	2
11	8	800	161	242	3
route		**2900**			

route=4

Obs	node	demand	x	y	route_order
12	12	1200	128	231	2
13	14	1300	129	214	3
route		**2500**			

route=5

Obs	node	demand	x	y	route_order
14	13	1300	156	217	2
15	18	1000	147	193	3
16	22	700	139	182	4
route		**3000**			

route=6

Obs	node	demand	x	y	route_order
17	15	300	146	208	2
18	21	1800	155	185	3
19	19	900	164	193	4
route		**3000**			

Figure 15.122 *continued*

route=7

Obs	node	demand	x	y	route_order
20	16	900	164	208	2
21	17	2100	141	206	3
route		**3000**			

route=8

Obs	node	demand	x	y	route_order
22	20	2500	129	189	2
		22500			

The output data set RoutesLinks now contains the links of the optimal routes as a sequence of links. The following statements sort the resulting data and display each route along with the sum of the link weights for that route, as shown in Figure 15.123:

```
proc sort data=RoutesLinks;
   by route route_order;
run;
proc print data=RoutesLinks;
   by route;
   sum distance;
run;
```

Figure 15.123 Links in the Optimal Routes

route=1

Obs	route_order	node1	node2	distance
1	1	1	7	31
2	2	2	7	19
3	3	2	3	9
4	4	3	10	25
5	5	1	10	28
route				**112**

route=2

Obs	route_order	node1	node2	distance
6	1	1	5	41
7	2	4	5	3
8	3	4	9	19
9	4	9	11	9
10	5	1	11	17
route				**89**

route=3

Obs	route_order	node1	node2	distance
11	1	1	6	37
12	2	6	8	5
13	3	1	8	31
route				**73**

Figure 15.123 *continued*

route=4

Obs	route_order	node1	node2	distance
14	1	1	12	23
15	2	12	14	17
16	3	1	14	16
route				**56**

route=5

Obs	route_order	node1	node2	distance
17	1	1	13	11
18	2	13	18	26
19	3	18	22	14
20	4	1	22	34
route				**85**

route=6

Obs	route_order	node1	node2	distance
21	1	1	15	7
22	2	15	21	25
23	3	19	21	12
24	4	1	19	29
route				**73**

route=7

Obs	route_order	node1	node2	distance
25	1	1	16	20
26	2	16	17	23
27	3	1	17	10
route				**53**

route=8

Obs	route_order	node1	node2	distance
28	1	1	20	31
29	2	1	20	31
route				**62**
				603

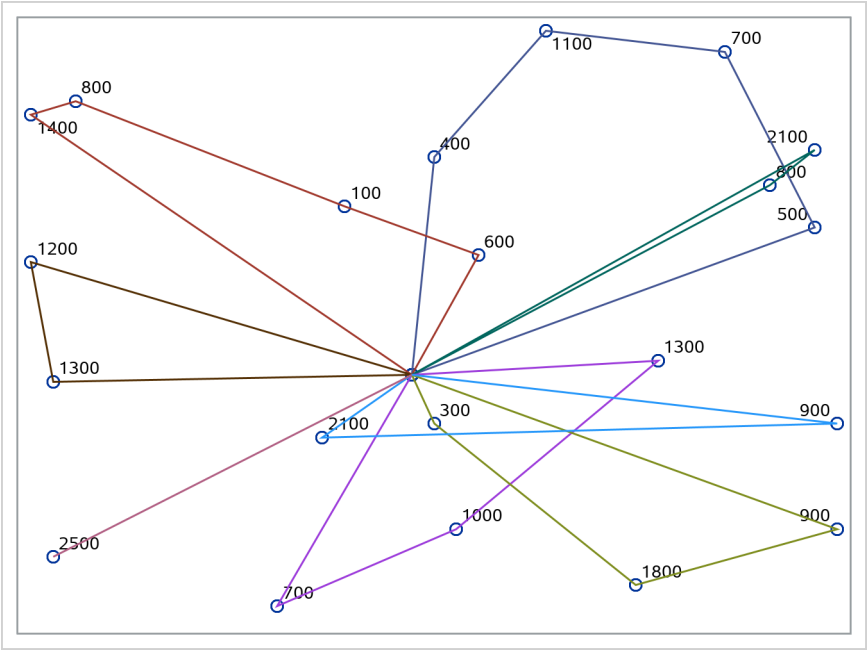
The following statements produce a graphical display of the solution by using PROC SGPLOT:

```
data RoutesNodes(drop=r);
   set RoutesNodes;
   if node=&depot then do;
      demand=.;
      do r = 1 to &numRoutes;
         route_order = 1;
         route       = r;
         output;
         route_order = constant('BIG');
         output;
```

```
      end;
   end;
   else output;
run;
proc sort data=RoutesNodes;
   by route route_order;
run;
proc sgplot data=RoutesNodes noautolegend;
   scatter x=x y=y / datalabel=demand;
   series  x=x y=y / group=route;
   xaxis   display=none;
   yaxis   display=none;
run;
```

The minimal-cost routes are shown in Figure 15.8.2. The node label represents the demand at each customer location.

Output 15.8.2 Optimal Routes



You can also solve the vehicle routing problem directly by using a mixed integer linear programming (MILP) solver. An example of this is shown in "Example 18.8: Vehicle Routing Problem" on page 1105. Using a direct MILP solver gives you more flexibility to handle variants of the standard VRP.

References

Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993). *Network Flows: Theory, Algorithms, and Applications*. Englewood Cliffs, NJ: Prentice-Hall.

Applegate, D. L., Bixby, R. E., Chvátal, V., and Cook, W. J. (2006). *The Traveling Salesman Problem: A Computational Study*. Princeton, NJ: Princeton University Press.

Augerat, P., Belenguer, J. M., Benavent, E., Corberán, A., Naddef, D., and Rinaldi, G. (1995). *Computational Results with a Branch and Cut Code for the Capacitated Vehicle Routing Problem*. Technical Report 949-M, Université Joseph Fourier, Grenoble.

Boykov, Y., and Kolmogorov, V. (2004). "An Experimental Comparison of Min-Cut/Max-Flow Algorithms for Energy Minimization in Vision." *IEEE Transactions on Pattern Analysis and Machine Intelligence* 26:1124–1137. https://doi.org/10.1109/TPAMI.2004.60.

Bron, C., and Kerbosch, J. (1973). "Algorithm 457: Finding All Cliques of an Undirected Graph." *Communications of the ACM* 16:48–50.

Chu, Y. J., and Liu, T. H. (1965). "On the Shortest Arborescence of a Directed Graph." *Scientia Sinica* 14:1396–1400.

CNN (2012). "Record Kidney Transplant Chain." CNN Health. Video. Accessed April 2, 2019. https://www.cnn.com/videos/health/2012/02/20/dnt-kidney-transplant-chain.wls.

Cormen, T. H., Leiserson, C. E., and Rivest, R. L. (1990). *Introduction to Algorithms*. Cambridge, MA, and New York: MIT Press and McGraw-Hill.

Edmonds, J. (1967). "Optimum Branchings." *Journal of Research of the National Bureau of Standards B* 71B:233–240.

Google (2011). "Google Maps." Accessed March 16, 2011. http://maps.google.com.

Harley, E. R. (2003). "Graph Algorithms for Assembling Integrated Genome Maps." Ph.D. diss., University of Toronto.

Johnson, D. B. (1975). "Finding All the Elementary Circuits of a Directed Graph." *SIAM Journal on Computing* 4:77–84.

Jonker, R., and Volgenant, A. (1987). "A Shortest Augmenting Path Algorithm for Dense and Sparse Linear Assignment Problems." *Computing* 38:325–340.

Krebs, V. (2002). "Uncloaking Terrorist Networks." *First Monday* 7. https://firstmonday.org/ojs/index.php/fm/article/view/941/863.

Kruskal, J. B. (1956). "On the Shortest Spanning Subtree of a Graph and the Traveling Salesman Problem." *Proceedings of the American Mathematical Society* 7:48–50.

Kumar, R., and Li, H. (1994). "On Asymmetric TSP: Transformation to Symmetric TSP and Performance Bound." https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=31fb40f6e3b6525bda21d325386da95000260967.

Liu, H., and Wang, J. (2006). "A New Way to Enumerate Cycles in Graph." In *Proceedings of the Advanced International Conference on Telecommunications and International Conference on Internet and Web Applications and Services*, 57–59.

Lysgaard, J., Letchford, A. N., and Eglese, R. W. (2004). "A New Branch-and-Cut Algorithm for the Capacitated Vehicle Routing Problem." *Mathematical Programming* 100:423–445.

Stoer, M., and Wagner, F. (1997). "A Simple Min-Cut Algorithm." *Journal of the Association for Computing Machinery* 44:585–591.

Tarjan, R. E. (1972). "Depth-First Search and Linear Graph Algorithms." *SIAM Journal on Computing* 1:146–160.

Tarjan, R. E. (1977). "Finding Optimum Branchings." *Networks* 7:25–35.

Yen, J. Y. (1971). "Finding the K Shortest Loopless Paths in a Network." *Management Science* 17:712–716.

Chapter 16
The Nonlinear Programming Solver

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Overview: NLP Solver

The sparse nonlinear programming (NLP) solver is a component of the OPTMODEL procedure that can solve optimization problems containing both nonlinear equality and inequality constraints. The general nonlinear optimization problem can be defined as

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & h_i(x) = 0, i \in \mathcal{E} = \{1, 2, \ldots, p\} \\ & g_i(x) \geq 0, i \in \mathcal{I} = \{1, 2, \ldots, q\} \\ & l \leq x \leq u \end{array}$$

where $x \in \mathbb{R}^n$ is the vector of the decision variables; $f : \mathbb{R}^n \mapsto \mathbb{R}$ is the objective function; $h : \mathbb{R}^n \mapsto \mathbb{R}^p$ is the vector of equality constraints—that is, $h = (h_1, \ldots, h_p)$; $g : \mathbb{R}^n \mapsto \mathbb{R}^q$ is the vector of inequality constraints—that is, $g = (g_1, \ldots, g_q)$; and $l, u \in \mathbb{R}^n$ are the vectors of the lower and upper bounds, respectively, on the decision variables.

It is assumed that the functions f, h_i, and g_i are twice continuously differentiable. Any point that satisfies the constraints of the NLP problem is called a *feasible point*, and the set of all those points forms the feasible region of the NLP problem—that is, $\mathcal{F} = \{x \in \mathbb{R}^n : h(x) = 0, g(x) \geq 0, l \leq x \leq u\}$.

The NLP problem can have a unique minimum or many different minima, depending on the type of functions involved. If the objective function is convex, the equality constraint functions are linear, and the inequality constraint functions are concave, then the NLP problem is called a convex program and has a unique minimum. All other types of NLP problems are called nonconvex and can contain more than one minimum, usually called *local minima*. The solution that achieves the lowest objective value of all local minima is called the *global minimum* or *global solution* of the NLP problem. The NLP solver can find the unique minimum of convex programs and a local minimum of a general NLP problem. In addition, the solver is equipped with specific options that enable it to locate the global minimum or a good approximation of it, for those problems that contain many local minima.

The NLP solver implements the following primal-dual methods for finding a local minimum:

- interior point trust-region line-search algorithm
- interior point line-search algorithm, which uses direct linear algebra
- active-set trust-region line-search algorithm

Both of the interior point primal-dual methods use barrier functions to ensure that the algorithm remains feasible with respect to the bound constraints. Interior point methods are extremely useful when the optimization problem contains many inequality constraints and you suspect that most of these constraints will be satisfied as strict inequalities at the optimal solution.

The active-set technique implements an active-set algorithm in which only the inequality constraints that are satisfied as equalities, together with the original equality constraints, are considered. Once that set of constraints is identified, active-set algorithms typically converge faster than interior point algorithms. They converge faster because the size and the complexity of the original optimization problem can be reduced if only a few constraints need to be considered.

All three of these methods can solve small-, medium-, and large-scale optimization problems efficiently and robustly, and they use exact first and second derivatives to calculate search directions. The memory requirements of all algorithms are reduced dramatically because only nonzero elements of matrices are stored. Convergence of all algorithms is achieved in either of the following ways:

- by using a trust-region line-search framework that guides the iterations toward the optimal solution. If a trust-region subproblem fails to provide a suitable step of improvement, a line search is then used to fine-tune the trust-region radius and ensure a sufficient decrease in objective function and constraint violations.
- by simply performing a backtracking line search on a primal-dual merit function.

For optimization problems that contain many local optima, the NLP solver can be run in multistart mode. If the multistart mode is specified, the solver samples the feasible region and generates a number of starting points. Then the local solvers can be called from each of those starting points to converge to different local optima. The local minimum with the smallest objective value is then reported back to the user as the optimal solution.

The NLP solver implements many powerful features that are obtained from recent research in the field of nonlinear optimization algorithms (Akrotirianakis and Rustem 2005; Armand, Gilbert, and Jan-Jégou 2002; Armand and Omheni 2017a, b; Erway, Gill, and Griffin 2007; Forsgren and Gill 1998; Vanderbei 1999; Wächter and Biegler 2006; Yamashita 1998). The term *primal-dual* means that the algorithm iteratively generates better approximations of the decision variables x (usually called *primal* variables) in addition to the dual variables (also referred to as Lagrange multipliers). At every iteration, the algorithm uses a modified Newton's method to solve a system of nonlinear equations. The modifications made to Newton's method are implicitly controlled by the current trust-region radius. The solution of that system provides the direction and the steps along which the next approximation of the local minimum is searched. The active-set algorithm ensures that the primal iterations are always within their bounds—that is, $l \leq x^k \leq u$, for every iteration k. However, the interior approach relaxes this condition by using slack variables, and intermediate iterations might be infeasible.

Finally, for parameter estimation problems such as least squares, maximum likelihood, or Bayesian estimation problems, the NLP solver can calculate the covariance matrix after it successfully obtains parameter estimates.

Getting Started: NLP Solver

The NLP solver implements three techniques that can solve a wide class of optimization problems efficiently and robustly. This section presents three examples that introduce these three techniques. The examples also introduce basic features of the modeling language of PROC OPTMODEL, which is used to define the optimization problem.

The NLP solver can be invoked by the SOLVE statement,

SOLVE WITH NLP <*/ options*> **;**

where *options* specify the technique name, termination criteria, and how to display the results in the iteration log. For a detailed description of the *options*, see the section "NLP Solver Options" on page 951.

A Simple Problem

Consider the following simple example of a nonlinear optimization problem, which consists of a quadratic objective function, a linear equality constraint, and a nonlinear inequality constraint:

$$\begin{array}{ll} \text{minimize} & f(x) = (x_1 + 3x_2 + x_3)^2 + 4(x_1 - x_2)^2 \\ \text{subject to} & x_1 + x_2 + x_3 = 1 \\ & 6x_2 + 4x_3 - x_1^3 - 3 \geq 0 \\ & x_i \geq 0, i = 1, 2, 3 \end{array}$$

The goal of this example is to find a local minimum, starting from the point $x^0 = (0.1, 0.7, 0.2)$. You can use the following call to PROC OPTMODEL to find a local minimum:

```
proc optmodel;
   var x{1..3} >= 0;
   minimize f = (x[1] + 3*x[2] + x[3])**2 + 4*(x[1] - x[2])**2;

   con constr1: sum{i in 1..3}x[i] = 1;
   con constr2: 6*x[2] + 4*x[3] - x[1]**3 - 3 >= 0;

   /* starting point */
   x[1] = 0.1;
   x[2] = 0.7;
   x[3] = 0.2;

   solve with NLP;
   print x;
quit;
```

Because no options have been specified, the default solver is used to solve the problem. The SAS output displays a detailed summary of the problem along with the status of the solver at termination, the total number of iterations that were required, and the value of the objective function at the best feasible solution that was found. The summaries and the returned solution are shown in Figure 16.1.

Figure 16.1 Problem Summary, Solution Summary, and the Returned Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	3
Bounded Above	0
Bounded Below	3
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	2
Linear LE (<=)	0
Linear EQ (=)	1
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	0
Nonlinear GE (>=)	1
Nonlinear Range	0

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	1.000001505
Optimality Error	7.085305E-7
Infeasibility	7.771561E-16
Iterations	11
Presolve Time	0.00
Solution Time	0.02

[1]	x
1	0.00059501
2	0.00000002
3	0.99940497

The SAS log shown in Figure 16.2 displays a brief summary of the problem being solved, followed by the iterations that are generated by the solver.

Figure 16.2 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 1 linear constraints (0 LE, 1 EQ, 0 GE, 0 range).
NOTE: The problem has 3 linear constraint coefficients.
NOTE: The problem has 1 nonlinear constraints (0 LE, 0 EQ, 1 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: Using analytic derivatives for objective.
NOTE: Using analytic derivatives for nonlinear constraints.
NOTE: The NLP solver is called.
NOTE: The Interior Point Direct algorithm is used.
                        Objective                          Optimality
           Iter             Value     Infeasibility             Error
              0        7.20000000                 0        1.01921656
              1        1.48152460   0.0000000004258        0.62856026
              2        1.23918702   0.0000000002687        0.45598668
              3        1.09672021   0.0000000000299        0.02791417
              4        1.01439797   0.0000000000651        0.01425055
              5        1.00694706  5.9410254494E-12        0.00216039
              6        1.00114968  1.4483969579E-12        0.00067005
              7        1.00046496  8.9039886575E-14        0.00015905
              8        1.00007980  6.4503957731E-14        0.00005577
              9        1.00002225  1.1102230246E-15        0.00001023
             10        1.00000742  1.1102230246E-16        0.00000279
             11        1.00000150  7.7715611724E-16   0.0000007085305
NOTE: Optimal.
NOTE: Objective = 1.000001505.
```

A Least Squares Problem

Although the NLP solver does not implement techniques that are specialized for least squares problems, this example illustrates how the NLP solver can use general nonlinear optimization techniques to solve least squares problems.

The Bard function, $f(x)$, (Moré, Garbow, and Hillstrom 1981) is a least squares problem that has $n = 3$ parameters and $m = 15$ functions f_i,

$$f(x) = \frac{1}{2}\sum_{i=1}^{15} f_i^2(x), \quad x = (x_1, x_2, x_3)$$

where the functions are defined as

$$f_i(x) = y_i - \left(x_1 + \frac{u_i}{v_i x_2 + w_i x_3}\right)$$

with $u_i = i$, $v_i = 16 - i$, $w_i = \min(u_i, v_i)$, and

$$y = (0.14, 0.18, 0.22, 0.25, 0.29, 0.32, 0.35, 0.39, 0.37, 0.58, 0.73, 0.96, 1.34, 2.10, 4.39)$$

Starting from $x^0 = (1, 1, 1)$, you can reach the minimum at the point $(0.08, 1.13, 2.34)$, with corresponding objective value $f(x^*) = 4.107\text{E}{-3}$. You can use the following SAS code to formulate and solve this problem:

```
proc optmodel;
   set S = 1..15;
   number u{i in S} = i;
   number v{i in S} = 16 - i;
   number w{i in S} = min(u[i], v[i]);
   number y{S} = [ .14 .18 .22 .25 .29 .32 .35 .39 .37 .58
                   .73 .96 1.34 2.10 4.39 ];
   var x{1..3} init 1;
   min f = 0.5 * sum{i in S} ( y[i] -
             ( x[1] + u[i]/(v[i] * x[2] + w[i] * x[3]) )
           )^2;
   solve with nlp / algorithm=interiorpoint;
   print x;
quit;
```

The output that summarizes the problem characteristics and the solution that the INTERIORPOINT solver obtains are displayed in Figure 16.3.

Figure 16.3 Problem Summary, Solution Summary, and Returned Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	3
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	3
Fixed	0
Number of Constraints	0

Solution Summary	
Solver	NLP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	0.0041074387
Optimality Error	1.1287133E-7
Infeasibility	0
Iterations	12
Presolve Time	0.00
Solution Time	0.00

Figure 16.3 *continued*

[1]	x
1	0.08241
2	1.13303
3	2.34370

The SAS log shown in Figure 16.4 displays a brief summary of the problem being solved, followed by the iterations that are generated by the solver.

Figure 16.4 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (3 free, 0 fixed).
NOTE: The problem has 0 linear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: Using analytic derivatives for objective.
NOTE: The NLP solver is called.
NOTE: The Interior Point algorithm is used.
                        Objective                          Optimality
           Iter             Value     Infeasibility             Error
              0       20.84084793                 0       12.96780938
              1       13.15512458                 0        8.28509025
              2        3.55996018                 0        3.65091384
              3        0.40842764                 0        0.60542870
              4        0.17751290                 0        0.27719412
              5        0.02966229                 0        0.07110366
              6        0.01094468                 0        0.01524637
              7        0.00673822                 0        0.00787377
              8        0.00483931                 0        0.00562081
              9        0.00421528                 0        0.00294758
             10        0.00411181                 0        0.00075047
             11        0.00410745                 0        0.00004204
             12        0.00410744                 0   0.0000001128713
NOTE: Optimal.
NOTE: Objective = 0.0041074387.
```

A Larger Optimization Problem

Consider the following larger optimization problem:

$$
\begin{array}{ll}
\text{minimize} & f(x,y,z) = \sum_{i=1}^{1000} x_i y_i + \frac{1}{2}\sum_{j=1}^{5} z_j^2 \\
\text{subject to} & x_k + y_k + \sum_{j=1}^{5} z_j = 5, \text{ for } k = 1,2,\ldots,1000 \\
& \sum_{i=1}^{1000}(x_i + y_i) + \sum_{j=1}^{5} z_j \geq 6 \\
& -1 \leq x_i \leq 1, i = 1,2,\ldots,1000 \\
& -1 \leq y_i \leq 1, i = 1,2,\ldots,1000 \\
& 0 \leq z_i \leq 2, i = 1,2,\ldots,5
\end{array}
$$

The problem consists of a quadratic objective function, 1,000 linear equality constraints, and a linear inequality constraint. There are also 2,005 variables. The goal is to find a local minimum by using the ACTIVESET technique. This can be accomplished by issuing the following call to PROC OPTMODEL:

```
proc optmodel;
   number n = 1000;
   number b = 5;
   var x{1..n} >= -1 <= 1 init  0.99;
   var y{1..n} >= -1 <= 1 init -0.99;
   var z{1..b} >=  0 <= 2 init  0.5;

   minimize f = sum{i in 1..n} x[i]*y[i] + 0.5*sum{j in 1..b} z[j]^2;
   con cons1{k in 1..n}: x[k] + y[k] + sum{j in 1..b} z[j] = b;
   con cons2: sum{i in 1..n} (x[i] + y[i]) + sum{j in 1..b} z[j] >= b + 1;

   solve with NLP / algorithm=activeset logfreq=2;
quit;
```

The SAS output displays a detailed summary of the problem along with the status of the solver at termination, the total number of iterations required, and the value of the objective function at the local minimum. The summaries are shown in Figure 16.5.

Figure 16.5 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	2005
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2005
Free	0
Fixed	0
Number of Constraints	1001
Linear LE (<=)	0
Linear EQ (=)	1000
Linear GE (>=)	1
Linear Range	0

Solution Summary	
Solver	NLP
Algorithm	Active Set
Objective Function	f
Solution Status	Optimal
Objective Value	-996.4999999
Optimality Error	3.9546176E-7
Infeasibility	8.8359338E-9
Iterations	9
Presolve Time	0.00
Solution Time	0.17

The SAS log shown in Figure 16.6 displays a brief summary of the problem that is being solved, followed by the iterations that are generated by the solver.

Figure 16.6 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 2005 variables (0 free, 0 fixed).
NOTE: The problem has 1001 linear constraints (0 LE, 1000 EQ, 1 GE, 0 range).
NOTE: The problem has 9005 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: Using analytic derivatives for objective.
NOTE: Using 2 threads for nonlinear evaluation.
NOTE: The NLP solver is called.
NOTE: The Active Set algorithm is used.
                        Objective                          Optimality
           Iter             Value     Infeasibility             Error
              0      -979.47500000        3.50000000        0.14142857
              2      -977.52422199   0.0000000088697        0.00010000
              4      -997.42812286        1.00137967        0.17118894
              6      -996.50051939        0.00084508        0.00201631
              8      -996.49999978   0.0000000002513        0.00001305
              9      -996.49999991   0.0000000088359   0.0000003954618
NOTE: Optimal.
NOTE: Objective = -996.4999999.
```

An Optimization Problem with Many Local Minima

Consider the following optimization problem:

$$\begin{aligned} \text{minimize } f(x,y) &= e^{\sin(50x)} + \sin(60e^{y}) + \sin(70\sin(x)) + \sin(\sin(80y)) \\ &\quad - \sin(10(x+y)) + (x^2+y^2)/4 \\ \text{subject to} &\quad -1 \le x \le 1 \\ &\quad -1 \le y \le 1 \end{aligned}$$

The objective function is highly nonlinear and contains many local minima. The NLP solver provides you with the option of searching the feasible region and identifying local minima of better quality. This is achieved by writing the following SAS program:

```
proc optmodel;
  var x >= -1 <= 1;
  var y >= -1 <= 1;
  min f = exp(sin(50*x)) + sin(60*exp(y)) + sin(70*sin(x)) + sin(sin(80*y))
          - sin(10*(x+y)) + (x^2+y^2)/4;
  solve with nlp / multistart=(maxstarts=30) seed=94245;
quit;
```

The MULTISTART=() option is specified, which directs the algorithm to start the local solver from many different starting points. The SAS log is shown in Figure 16.7.

Figure 16.7 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 2 variables (0 free, 0 fixed).
NOTE: The problem has 0 linear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: Using analytic derivatives for objective.
NOTE: The NLP solver is called.
NOTE: The Interior Point Direct algorithm is used.
NOTE: The MULTISTART option is enabled.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Multistart algorithm is executing in single-machine mode.
NOTE: The Multistart algorithm is using up to 12 threads.
NOTE: Random number seed 94245 is used.
                    Best       Local  Optimality    Infeasi-  Local  Local
      Start    Objective   Objective       Error      bility  Iters  Status
          1   -3.0038322  -3.0038322   9.0914E-8           0      5  Optimal
          2   -3.0038322  -2.6355024  9.09111E-8           0      4  Optimal
          3   -3.0038322  -2.2819866  9.09185E-8           0      4  Optimal
          4   -3.0038322  -2.0314902  9.41215E-8           0      5  Optimal
          5   -3.0038322  -1.6540199  9.09401E-8           0      4  Optimal
          6   -3.0038322  -1.2469547  9.09094E-8           0      4  Optimal
          7   -3.0038322  -2.9404574  9.09091E-8           0      5  Optimal
          8   -3.0038322  -2.2288571  9.09548E-8           0      6  Optimal
          9   -3.0038322  -2.7726003  9.09091E-8           0      6  Optimal
         10   -3.0038322  -1.3373711  9.09091E-8           0      5  Optimal
         11   -3.0038322  -2.3883262  9.09091E-8           0      5  Optimal
         12   -3.1440794  -3.1440794  9.09091E-8           0      6  Optimal
         13   -3.1440794   -2.119774  9.09091E-8           0      5  Optimal
         14   -3.1440794  -2.4632393  9.09091E-8           0     13  Optimal
         15   -3.1440794  -1.9014304  9.09214E-8           0      7  Optimal
         16   -3.1440794  -1.1844979  9.09415E-8           0      4  Optimal
         17   -3.1440794  -1.9746745  9.09113E-8           0      8  Optimal
         18   -3.1440794  -1.3289057  9.09099E-8           0      4  Optimal
         19   -3.1440794  -1.4471721  9.09559E-8           0      5  Optimal
         20   -3.1440794  -0.0898021  9.09091E-8           0      6  Optimal
         21   -3.1440794  -1.6414837  9.09091E-8           0      6  Optimal
         22   -3.1440794  -1.0893788  9.09844E-8           0     11  Optimal
         23   -3.1440794  -1.8059789  9.09091E-8           0      6  Optimal
         24   -3.1440794  -1.3833247  9.09185E-8           0      6  Optimal
         25   -3.1440794  -0.7154452  9.10814E-8           0      5  Optimal
         26   -3.1440794  -2.1413722  9.10683E-8           0      9  Optimal
         27   -3.1440794  -1.1249717  9.09137E-8           0      4  Optimal
         28   -3.1440794  -1.8640098  9.10232E-8           0      6  Optimal
         29   -3.1440794  -2.2355863  9.09091E-8           0      7  Optimal
         30   -3.1440794  -0.4829685  9.09095E-8           0      9  Optimal
NOTE: The Multistart algorithm generated 480 sample points.
NOTE: 30 distinct local optima were found.
NOTE: The best objective value found by local solver = -3.14407941.
```

Figure 16.7 *continued*

```
NOTE: The solution found by local solver with objective = -3.14407941 was
      returned.
```

The SAS log presents additional information when the MULTISTART=() option is specified. The first column counts the number of restarts of the local solver. The second column records the best local optimum that has been found so far, and the third through sixth columns record the local optimum to which the solver has converged. The final column records the status of the local solver at every iteration.

The SAS output is shown in Figure 16.8.

Figure 16.8 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2
Free	0
Fixed	0
Number of Constraints	0

Solution Summary	
Solver	Multistart NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	-3.003832209
Number of Starts	30
Number of Sample Points	480
Number of Distinct Optima	30
Random Seed Used	94245
Optimality Error	9.0914049E-8
Infeasibility	0
Presolve Time	0.00
Solution Time	0.01

A Least Squares Estimation Problem for a Regression Model

The following data are used to build a regression model:

```
data samples;
   input x1 x2 y;
   datalines;
 4  8   43.71
62  5  351.29
81 62 2878.91
85 75 3591.59
65 54 2058.71
96 84 4487.87
98 29 1773.52
36 33  767.57
30 91 1637.66
 3 59  215.28
62 57 2067.42
11 48  394.11
66 21  932.84
68 24 1069.21
95 30 1770.78
34 14  368.51
86 81 3902.27
37 49 1115.67
46 80 2136.92
87 72 3537.84
;
```

Suppose you want to compute the parameters in your regression model based on the preceding data, and the model is

$$L(a, b, c) = a * x1 + b * x2 + c * x1 * x2$$

where a, b, c are the parameters that need to be found.

The following PROC OPTMODEL call specifies the least squares problem for the regression model:

```
/* Reqression model with interactive term: y = a*x1 + b*x2 + c*x1*x2 */
proc optmodel;
   set obs;
   num x1{obs}, x2{obs}, y{obs};
   num mycov{i in 1.._nvar_, j in 1..i};
   var a, b, c;
   read data samples into obs=[_n_] x1 x2 y;
   impvar Err{i in obs} = y[i] - (a*x1[i]+b*x2[i]+c*x1[i]*x2[i]);
   min f = sum{i in obs} Err[i]^2;
   solve with nlp/covest=(cov=5 covout=mycov);
   print mycov;
   print a b c;
quit;
```

The solution is displayed in Figure 16.9.

Figure 16.9 Least Squares Problem Estimation Results

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	3
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	3
Fixed	0
Number of Constraints	0

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	7.1862967833
Optimality Error	1.4236901E-8
Infeasibility	0
Iterations	1
Presolve Time	0.00
Solution Time	0.00

mycov			
	1	**2**	**3**
1	0.0000047825		
2	-.0000000996	0.0000032426	
3	-.0000000676	-.0000000442	0.0000000017

a	b	c
3.0113	2.0033	0.4998

Syntax: NLP Solver

The following PROC OPTMODEL statement is available for the NLP solver:

SOLVE WITH NLP < / *options* > **;**

Functional Summary

Table 16.1 summarizes the options that can be used with the SOLVE WITH NLP statement.

Table 16.1 Options for the NLP Solver

Description	Option
Covariance Matrix Options and Suboptions	
Requests that the NLP solver compute a covariance matrix	COVEST=()
Specifies an absolute singularity criterion for matrix inversion	ASINGULAR=
Specifies the type of covariance matrix	COV=
Specifies the name of the output covariance matrix	COVOUT=
Specifies the tolerance for deciding whether a matrix is singular	COVSING=
Specifies a relative singularity criterion for matrix inversion	MSINGULAR=
Specifies a number for calculating the divisor for the covariance matrix when VARDEF=DF	NDF=
Specifies a number for calculating the scale factor for the covariance matrix	NTERMS=
Specifies a scalar factor for computing the covariance matrix	SIGSQ=
Specifies the divisor for calculating the covariance matrix	VARDEF=
Miscellaneous Option	
Specifies the seed to use to generate random numbers	SEED=
Multistart Options	
Directs the local solver to start from multiple initial points	MULTISTART=()
Specifies the maximum range of values that each variable can take during the sampling process	BNDRANGE=
Specifies the tolerance for local optima to be considered distinct	DISTTOL=
Specifies the amount of printing solution progress in multistart mode	LOGLEVEL=
Specifies the time limit in multistart mode	MAXTIME=
Specifies the maximum number of starting points to be used by the multistart algorithm	MAXSTARTS=
Specifies the probability distribution to be used by the multistart algorithm in the sampling process	SAMPLINGMETHOD=
Optimization Option	
Specifies the optimization technique	ALGORITHM=
Output Options	
Specifies the frequency of printing solution progress (local solvers)	LOGFREQ=
Specifies the allowable types of output solution	SOLTYPE=

Table 16.1 *continued*

Description	Option
Feasibility-Seeking Options	
Seeks a feasible solution to an optimization problem by reformulating it via relaxation and penalization	SEEKFEASIBLE=()
Specifies one of the four different formulations	FORMULATION=
Specifies the scale factor for the objective function	OBJSCALE=
Specifies the penalty parameter for the slack variables	PENALTYPARM=
Solver Options	
Specifies the feasibility tolerance	FEASTOL=
Specifies the type of Hessian used by the solver	HESSTYPE=
Enables or disables IIS detection with respect to linear constraints and variable bounds	IIS=
Specifies whether the initial values of the dual variables are to be used by the solver	INITDUAL=
Specifies the number of vector pairs to store when the Hessian is approximated using the limited-memory BFGS option	LMUPDATESIZE=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the number of threads to use to perform linear algebra operations	NLPTHREADS=
Specifies the number of threads to use for threaded processing when the MULTISTART= option is specified	NTHREADS=
Specifies the upper limit on the objective	OBJLIMIT=
Specifies the convergence tolerance	OPTTOL=
Specifies whether the solver is allowed to shift the user-supplied initial point to be interior to the bounds	PRESERVEINIT=
Specifies units of CPU time or real time	TIMETYPE=

NLP Solver Options

This section describes the options that are recognized by the NLP solver. These options can be specified after a forward slash (/) in the SOLVE statement, provided that the NLP solver is explicitly specified using a WITH clause.

Covariance Matrix Options

COVEST=(*suboptions*)

requests that the NLP solver produce a covariance matrix. When this option is applied, the following PROC OPTMODEL options are automatically set: PRESOLVER=NONE and SOLTYPE=0. For more information, see the section "Covariance Matrix" on page 971.

You can specify the following *suboptions*:

ASINGULAR=*asing*

specifies an absolute singularity criterion for measuring the singularity of the Hessian and crossproduct Jacobian and their projected forms, which might have to be inverted to compute the covariance matrix. The value of *asing* can be any number between the machine precision and the largest positive number representable in your operating environment. The default is the square root of the machine precision. For more information, see the section "Covariance Matrix" on page 971.

COV=*number* | *string*

specifies one of six formulas for computing the covariance matrix. The formula that is used depends on the type of objective (MIN or LSQ) that is specified. Table 16.2 describes the valid values for this option and their corresponding formulas, where *nterms* is the value of the NTERMS= option and MIN, LSQ, and other symbols are defined in the section "Covariance Matrix" on page 971.

Table 16.2 Values for COV= Option

number	*string*	**MIN Objective**	**LSQ Objective**
1	M	$(nterms/d)G^{-1}JJ(f)G^{-1}$	$(nterms/d)G^{-1}VG^{-1}$
2	H	$(nterms/d)G^{-1}$	$\sigma^2 G^{-1}$
3	J	$(1/d)W^{-1}$	$\sigma^2 JJ(f)^{-1}$
4	B	$(1/d)G^{-1}WG^{-1}$	$\sigma^2 G^{-1}JJ(f)G^{-1}$
5	E	$(nterms/d)JJ(f)^{-1}$	$(1/d)V^{-1}$
6	U	$(nterms/d)W^{-1}JJ(f)W^{-1}$	$(nterms/d)JJ(f)^{-1}VJJ(f)^{-1}$

For MAX type problems, the covariance matrix is converted to MIN type by using negative Hessian, Jacobian, and function values in the computation. For more information, see the section "Covariance Matrix" on page 971.

By default, COV=2.

COVOUT=*parameter*

specifies the name of the parameter that contains the output covariance matrix. Because a covariance matrix is symmetric, you should declare the covariance matrix as either a lower-triangular matrix or a square matrix with indexes starting from 1. For example:

```
num mycov{i in 1..N, j in 1..i};   /* a  lower triangular matrix */
```

or

```
num mycov{i in 1..N, j in 1..N};   /* a square matrix */
```

where N is the number of variables.

Depending on the type of output covariance matrix, the solver updates either the lower-triangular matrix or the full square matrix. If you declare the covariance matrix as neither a lower-triangular

matrix nor a square matrix, or if the indexes do not start from 1, the NLP solver issues an error message. You can use the CREATE DATA statement to output the results to a SAS data set. For more information, see the section "Covariance Matrix" on page 971.

COVSING=*covsing*

specifies a threshold, *covsing* > 0, that determines whether to consider the eigenvalues of a matrix to be 0. The value of *covsing* can be any number between the machine precision and the largest positive number representable in your operating environment. The default is set internally by the algorithm. For more information, see the section "Covariance Matrix" on page 971.

MSINGULAR=*msing*

specifies a relative singularity criterion *msing* > 0 for measuring the singularity of the Hessian and crossproduct Jacobian and their projected forms. The value of *msing* can be any number between machine precision and the largest positive number representable in your operating environment. The default is 1E–12. For more information, see the section "Covariance Matrix" on page 971.

NDF=*ndf*

specifies a number to be used in calculating the divisor d, which is used in calculating the covariance matrix when VARDEF=DF. The value of *ndf* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. The default is the number of optimization variables in the objective function. For more information, see the section "Covariance Matrix" on page 971.

NTERMS=*nterms*

specifies a number to be used in calculating the scale factor for the covariance matrix, as shown in Table 16.2. The value of *nterms* can be any positive integer up to the largest four-byte signed integer, which is $2^{31} - 1$. The default is the number of nonconstant terms in the objective function. For more information, see the section "Covariance Matrix" on page 971.

SIGSQ=*sq*

specifies a real scalar factor, *sq* > 0, for computing the covariance matrix. The value of *sq* can be any number between the machine precision and the largest positive number representable in your operating environment. For more information, see the section "Covariance Matrix" on page 971.

VARDEF=DF | N

controls how the divisor d is calculated. This divisor is used in calculating the covariance matrix and approximate standard errors. The value of d also depends on the values of the NDF= and NTERMS= options, *ndf* and *nterms*, respectively, as follows:

$$d = \begin{cases} \max(1, \mathit{nterms} - \mathit{ndf}) & \text{for VARDEF=DF} \\ \mathit{nterms} & \text{for VARDEF=N} \end{cases}$$

By default, VARDEF=DF if the SIGSQ= option is not specified; otherwise, by default VARDEF=N. For more information, see the section "Covariance Matrix" on page 971.

Miscellaneous Option

SEED=*N*

specifies a positive integer to be used as the seed for generating random number sequences. You can use this option to replicate results from different runs.

Multistart Options

MULTISTART=(*suboptions***)**

MS=(*suboptions***)**

enables multistart mode. In this mode, the local solver solves the problem from multiple starting points, possibly finding a better local minimum as a result. This option is disabled by default. For more information about multistart mode, see the section "Multistart" on page 970.

You can specify the following *suboptions*:

BNDRANGE=*M*

defines the range from which each variable can take values during the sampling process. This option affects only the sampling process that determines starting points for the local solver. It does not affect the bounds of the original nonlinear optimization problem. More specifically, if the ith variable x_i has lower and upper bounds ℓ_i and u_i, respectively (that is, $\ell_i \le x_i \le u_i$), then an initial point is generated by a sampling process as follows:

For each sample point x, the ith coordinate x_i is generated so that the following bounds hold, where x_i^0 is the default starting point or a specified starting point:

$l_i \le x_i \le u_i$	if l_i and u_i are both finite
$l_i \le x_i \le l_i + M$	if only l_i is finite
$u_i - M \le x_i \le u_i$	if only u_i is finite
$x_i^0 - M/2 \le x_i \le x_i^0 + M/2$	otherwise

The default value is 200 in a shared-memory computing environment and 1,000 in a distributed computing environment.

DISTTOL=ϵ

defines the tolerance by which two optimal points are considered distinct. Optimal points are considered distinct if the Euclidean distance between them is at least ϵ. The default is 1.0E–6.

LOGLEVEL=*number*

PRINTLEVEL=*number*

defines the amount of information that the multistart algorithm displays in the SAS log. Table 16.3 describes the valid values of this suboption.

Table 16.3 Values for LOGLEVEL= Suboption

number	**Description**
0	Turns off all solver-related messages to SAS log
1	Displays multistart summary information when the algorithm terminates
2	Displays multistart iteration log and summary information when the algorithm terminates
3	Displays the same information as LOGLEVEL=2 and might display additional information

By default, LOGLEVEL=2.

MAXTIME=*T*

defines the maximum allowable time *T* (in seconds) for the NLP solver to locate the best local optimum in multistart mode. The value of the TIMETYPE= option determines the type of units that are used. The time that is specified by the MAXTIME= suboption is checked only once after the completion of the local solver. Because the local solver might be called many times, the maximum time that is specified for multistart is recommended to be greater than the maximum time specified for the local solver. If you do not specify this option, the multistart algorithm does not stop based on the amount of time elapsed.

MAXSTARTS=*N*

defines the maximum number of starting points to be used for local optimization. That is, there will be no more than *N* local optimization calls in the multistart algorithm. You can specify *N* to be any nonnegative integer. When $N = 0$, the algorithm uses the default value of this option. In a shared-memory computing environment, the default value is 100. In a distributed computing environment, the default value is usually greater than 100 and proportional to the number of grid nodes.

SAMPLINGMETHOD=*keyword*

defines the probability distribution to be used by the multistart algorithm in the sampling process. The starting points of local optimization are selected from among the generated sample points. The following *keywords* are valid:

NORMAL | **GAUSSIAN** uses a normal distribution to generate sample points.

UNIFORM uses a uniform distribution to generate sample points.

By default, SAMPLINGMETHOD=UNIFORM.

Optimization Options

ALGORITHM=*keyword*

TECHNIQUE=*keyword*

TECH=*keyword*

SOLVER=*keyword*

specifies the optimization technique to be used to solve the problem. The following *keywords* are valid:

INTERIORPOINT uses a primal-dual interior point method. This technique is recommended for both small- and large-scale nonlinear optimization problems. This is the preferred solver if the problem includes a large number of inactive constraints.

IPDIRECT uses a primal-dual interior point augmented Lagrangian method. The use of direct factorizations and other enhancements can reduce both the number of iterations and the CPU time for many problem types. This method is also called the interior point direct algorithm in this chapter.

ACTIVESET uses a primal-dual active-set method. This technique is recommended for both small- and large-scale nonlinear optimization problems. This is the preferred solver if the problem includes only bound constraints or if the optimal active set can be quickly determined by the solver.

CONCURRENT runs the INTERIORPOINT and ACTIVESET techniques in parallel, with one thread using the INTERIORPOINT technique and the other thread using the ACTIVESET technique. The solution is returned by the first method that terminates.

By default, ALGORITHM=IPDIRECT, unless the optimization problem has fixed variables and PRESOLVER=NONE; in the latter case, ALGORITHM=INTERIORPOINT.

Output Options

LOGFREQ=*N*

PRINTFREQ=*N*

specifies how often the iterations are displayed in the SAS log. *N* should be an integer between zero and the largest four-byte, signed integer, which is $2^{31} - 1$. If $N \geq 1$, the solver prints only those iterations that are a multiple of *N*. If $N = 0$, no iteration is displayed in the log. The default value is 1.

SOLTYPE=0 | 1

specifies the type of solution to return:

0 returns a locally optimal solution, provided that the solver locates one.

1 returns the best feasible solution found, provided that its objective value is better than that of the locally optimal solution found.

By default, SOLTYPE=1.

Feasibility-Seeking Options

SEEKFEASIBLE=(*suboptions*)

SEEKFEAS=(*suboptions*)

seeks a feasible solution to an optimization problem by reformulating it via relaxation and penalization. For more information about feasibility-seeking options, see the section "Feasibility-Seeking Reformulation" on page 968.

You can specify the following *suboptions*:

FORMULATION=1 | 2 | 3 | 4

specifies one of the four different formulations. For more information about the four formulations, see the section "Feasibility-Seeking Reformulation" on page 968.

OBJSCALE=ρ

specifies the scale factor ρ for the objective function.

PENALTYPARM=τ

specifies the penalty parameter τ for the slack variables.

When this option is enabled, the iteration log displays the progress of optimization of the reformulated problem.

Solver Options

FEASTOL=ϵ

defines the feasible tolerance. The solver exits if the constraint violation is less than ϵ and the scaled optimality conditions are less than the value of the OPTTOL= option. By default, FEASTOL=1E–6.

HESSTYPE=BFGS | FULL | LBFGS | PRODUCT | SR1

specifies the type of Hessian for the solver to use:

BFGS computes a dense quasi-Newton Broyden-Fletcher-Goldfarb-Shanno (BFGS) Hessian approximation. This option uses the gradient information to build a symmetric, positive-definite approximation of the Hessian matrix. Because this option maintains a dense Hessian approximation, it is recommended for problems that have fewer than 1,000 variables.

FULL uses a full Hessian. In this case, the algorithm can create a better preconditioner to solve the problem in less CPU time.

LBFGS uses a limited-memory quasi-Newton BFGS formula to approximate the Hessian matrix. It stores only a limited number of vectors that represent the approximation implicitly, which makes this option more suitable for large-scale problems. The number of vectors that are used to approximate the Hessian is controlled by the LMUPDATESIZE= option.

PRODUCT uses only Hessian-vector products rather than the full Hessian. When the solver uses only Hessian-vector products to find a search direction, it usually uses much less memory, especially when the problem is large and the Hessian is not sparse. You cannot specify this option when you specify ALGORITHM=IPDIRECT because the IPDIRECT solver needs the full expression of the Hessian matrix.

SR1 uses the gradient information calculated at two points to compute a dense quasi-Newton symmetric rank 1 (SR1) Hessian approximation. Unlike the BFGS approximation, the SR1 update might not guarantee the positive definiteness of the Hessian approximation. Because this option maintains a dense Hessian approximation, it is recommended for problems that have fewer than 1,000 variables.

By default, HESSTYPE=FULL.

IIS=TRUE | FALSE

specifies whether the NLP solver attempts to identify a set of linear constraints and variables that form an irreducible infeasible set (IIS). You can specify the following values:

TRUE enables IIS detection. All other NLP solver options are ignored except the following: FEASTOL=, LOGFREQ=, LOGLEVEL=, MAXITER=, MAXTIME=, and TIMETYPE=.

FALSE disables IIS detection.

By default, IIS=FALSE.

The NLP solver ignores nonlinear constraints, if any, and invokes the LP solver's algorithm to attempt to identify an IIS. If an IIS is found, information about the infeasibilities can be found in the .status suffix values of the constraints and variables. For more information about the IIS= option, see the section "Irreducible Infeasible Set" on page 655 of Chapter 13, "The Linear Programming Solver." Also see Example 16.8 for an example that demonstrates the use of the IIS= option of the NLP solver.

INITDUAL=TRUE | FALSE

specifies whether the initial values of the dual variables are to be used by the solver. You can specify the following values:

TRUE specifies that the current values of dual variables that are stored in the constraint and variable .dual suffixes, if not empty, be used by the solver.

FALSE specifies that the current values of dual variables that are stored in the .dual suffixes, even if not empty, be ignored by the solver.

By default, INITDUAL=FALSE.

You can specify the dual values of the constraints and variables by using the .dual suffix in PROC OPTMODEL. The use of the suffix .dual is demonstrated in Example 16.4. For more information about suffixes in PROC OPTMODEL, see the section "Suffixes" on page 420 in Chapter 9, "The OPTMODEL Procedure."

LMUPDATESIZE=*number*

specifies the number of vector pairs to store when the Hessian matrix is approximated using the limited-memory quasi-Newton Broyden-Fletcher-Goldfarb-Shanno (BFGS) option. This option is used only with HESSTYPE=LBFGS. The valid range for this integer option is between 2 and 100, inclusive. It is recommended that you experiment with different values of the LMUPDATESIZE= option. By default, LMUPDATESIZE=8.

MAXITER=*number*

specifies that the solver take at most *N* major iterations to determine an optimum of the NLP problem. The value of *N* is an integer between zero and the largest four-byte, signed integer, which is $2^{31} - 1$. A major iteration in NLP consists of finding a descent direction and a step size along which the next approximation of the optimum resides. The default is 5,000 iterations.

MAXTIME=*t*

specifies an upper limit of *t* units of time for the optimization process, including problem generation time and solution time. The value of the TIMETYPE= option determines the type of units used. If you do not specify the MAXTIME= option, the solver does not stop based on the amount of time elapsed. The value of *t* can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

NLPTHREADS=*number*

specifies the number of threads that the interior point direct, interior point, active-set, or concurrent algorithm can use to perform linear algebra operations. When the MULTISTART= option is used, the NLPTHREADS= option is ignored. The value of *number* must be an integer between 1 and 256, inclusive. By default, NLPTHREADS=1.

NTHREADS=*number*

specifies the number of threads for the multistart algorithm to use to concurrently start local solves. This option is considered only when the MULTISTART= option is specified. The value of *number* must be an integer between 1 and 256, inclusive. The default is the value of the NTHREADS= option in PROC OPTMODEL.

OBJLIMIT=*M*

specifies an upper limit on the magnitude of the objective value. For a minimization problem, the algorithm terminates when the objective value becomes less than –*M*; for a maximization problem, the algorithm stops when the objective value exceeds *M*. The algorithm stopping implies that either the problem is unbounded or the algorithm diverges. If optimization were allowed to continue, numerical difficulty might be encountered. The default is *M*=1E+20. The minimum acceptable value of *M* is 1E+8. If the specified value of *M* is less than 1E+8, the value is reset to the default value 1E+20.

OPTTOL=ϵ

RELOPTTOL=ϵ

defines the measure by which you can decide whether the current iterate is an acceptable approximation of a local minimum. The value of this option is a positive real number. The NLP solver determines that the current iterate is a local minimum when the norm of the scaled vector of the optimality conditions is less than ϵ and the true constraint violation is less than FEASTOL. The default is ϵ=1E–6.

PRESERVEINIT=*number* | *string*

specifies whether the solver is allowed to shift the user-supplied initial point to be interior to the bounds. Table 16.4 describes the valid values of the PRESERVEINIT= option.

Table 16.4 Values for PRESERVEINIT= Option

number	*string*	**Description**
0	OFF	Shifts the user-supplied initial point to be interior to the bounds
1	ON	Uses the user-supplied initial point without shifting

This option can be used only when calling the INTERIORPOINT algorithm. By default, PRESERVEINIT=OFF.

TIMETYPE=CPU | REAL

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMODEL_ macro variable. Table 16.5 describes the valid values of the TIMETYPE= option.

Table 16.5 Values for TIMETYPE= Option

string	**Description**
CPU	Specifies units of CPU time
REAL	Specifies units of real time

The "Optimization Statistics" table, an output of PROC OPTMODEL if you specify PRINTLEVEL=2 in the PROC OPTMODEL statement, also includes the same time units for Presolver Time and Solver Time. The other times (such as Problem Generation Time) in the "Optimization Statistics" table are also in the same units.

The default value of the TIMETYPE= option is REAL.

Details: NLP Solver

This section presents a brief discussion about the algorithmic details of the NLP solver. First, the notation is defined. Next, an introduction to the fundamental ideas in constrained optimization is presented; the main point of the second section is to present the necessary and sufficient optimality conditions, which play a central role in all optimization algorithms. The section concludes with a general overview of primal-dual interior point and active-set algorithms for nonlinear optimization. A detailed treatment of the preceding topics can be found in Nocedal and Wright (1999), Wright (1997), and Forsgren, Gill, and Wright (2002).

Basic Definitions and Notation

The gradient of a function $f : \mathbb{R}^n \mapsto \mathbb{R}$ is the vector of all the first partial derivatives of f and is denoted by

$$\nabla f(x) = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \ldots, \frac{\partial f}{\partial x_n}\right)^{\mathrm{T}}$$

where the superscript T denotes the transpose of a vector.

The Hessian matrix of f, denoted by $\nabla^2 f(x)$, or simply by $H(x)$, is an $n \times n$ symmetric matrix whose (i, j) element is the second partial derivative of $f(x)$ with respect to x_i and x_j. That is, $H_{i,j}(x) = \frac{\partial^2 f(x)}{\partial x_i \partial x_j}$.

Consider the vector function, $c : \mathbb{R}^n \mapsto \mathbb{R}^{p+q}$, whose first p elements are the equality constraint functions $h_i(x), i = 1, 2, \ldots, p$, and whose last q elements are the inequality constraint functions $g_i(x), i = 1, 2, \ldots, q$. That is,

$$c(x) = (h(x) : g(x))^{\mathrm{T}} = (h_1(x), \ldots, h_p(x) : g_1(x), \ldots, g_q(x))^{\mathrm{T}}$$

The $(p + q) \times n$ matrix whose ith row is the gradient of the ith element of $c(x)$ is called the Jacobian matrix of $c(x)$ (or simply the Jacobian of the NLP problem) and is denoted by $J(x)$. You can also use $J_h(x)$ to denote the $p \times n$ Jacobian matrix of the equality constraints and use $J_g(x)$ to denote the $q \times n$ Jacobian matrix of the inequality constraints.

Constrained Optimization

A function that plays a pivotal role in establishing conditions that characterize a local minimum of an NLP problem is the Lagrangian function $\mathcal{L}(x, y, z)$, which is defined as

$$\mathcal{L}(x, y, z) = f(x) - \sum_{i \in \mathcal{E}} y_i h_i(x) - \sum_{i \in \mathcal{I}} z_i g_i(x)$$

Note that the Lagrangian function can be seen as a linear combination of the objective and constraint functions. The coefficients of the constraints, $y_i, i \in \mathcal{E}$, and $z_i, i \in \mathcal{I}$, are called the Lagrange multipliers or dual variables. At a feasible point $\hat{x}$, an inequality constraint is called active if it is satisfied as an equality—that is, $g_i(\hat{x}) = 0$. The set of active constraints at a feasible point $\hat{x}$ is then defined as the union of the index set of the equality constraints, $\mathcal{E}$, and the indices of those inequality constraints that are active at $\hat{x}$; that is,

$$\mathcal{A}(\hat{x}) = \mathcal{E} \cup \{i \in \mathcal{I} : g_i(\hat{x}) = 0\}$$

An important condition that is assumed to hold in the majority of optimization algorithms is the so-called linear independence constraint qualification (LICQ). The LICQ states that at any feasible point $\hat{x}$, the gradients of all the active constraints are linearly independent. The main purpose of the LICQ is to ensure that the set of constraints is well-defined in a way that there are no redundant constraints or in a way that there are no constraints defined such that their gradients are always equal to zero.

The First-Order Necessary Optimality Conditions

If x^* is a local minimum of the NLP problem and the LICQ holds at x^*, then there are vectors of Lagrange multipliers y^* and z^*, with components $y_i^*, i \in \mathcal{E}$, and $z_i^*, i \in \mathcal{I}$, respectively, such that the following conditions are satisfied:

$$\begin{aligned} \nabla_x \mathcal{L}(x^*, y^*, z^*) &= 0 \\ h_i(x^*) &= 0, \quad i \in \mathcal{E} \\ g_i(x^*) &\geq 0, \quad i \in \mathcal{I} \\ z_i^* &\geq 0, \quad i \in \mathcal{I} \\ z_i^* g_i(x^*) &= 0, \quad i \in \mathcal{I} \end{aligned}$$

where $\nabla_x \mathcal{L}(x^*, y^*, z^*)$ is the gradient of the Lagrangian function with respect to x, defined as

$$\nabla_x \mathcal{L}(x^*, y^*, z^*) = \nabla f(x) - \sum_{i \in \mathcal{E}} y_i \nabla h_i(x) - \sum_{i \in \mathcal{I}} z_i \nabla g_i(x)$$

The preceding conditions are often called the *Karush-Kuhn-Tucker (KKT) conditions*. The last group of equations ($z_i g_i(x) = 0, i \in I$) is called the complementarity condition. Its main aim is to try to force the Lagrange multipliers, z_i^*, of the inactive inequalities (that is, those inequalities with $g_i(x^*) > 0$) to zero.

The KKT conditions describe the way the first derivatives of the objective and constraints are related at a local minimum x^*. However, they are not enough to fully characterize a local minimum. The second-order optimality conditions attempt to fulfill this aim by examining the curvature of the Hessian matrix of the Lagrangian function at a point that satisfies the KKT conditions.

The Second-Order Necessary Optimality Condition

Let x^* be a local minimum of the NLP problem, and let y^* and z^* be the corresponding Lagrange multipliers that satisfy the first-order optimality conditions. Then $d^{\mathrm{T}} \nabla_x^2 \mathcal{L}(x^*, y^*, z^*) d \geq 0$ for all nonzero vectors d that satisfy the following conditions:

1. $\nabla h_i^{\mathrm{T}}(x^*) d = 0, \forall i \in \mathcal{E}$
2. $\nabla g_i^{\mathrm{T}}(x^*) d = 0, \forall i \in \mathcal{A}(x^*) \cap \mathcal{I}$, such that $z_i^* > 0$
3. $\nabla g_i^{\mathrm{T}}(x^*) d \geq 0, \forall i \in \mathcal{A}(x^*) \cap \mathcal{I}$, such that $z_i^* = 0$

The second-order necessary optimality condition states that, at a local minimum, the curvature of the Lagrangian function along the directions that satisfy the preceding conditions must be nonnegative.

Interior Point Algorithm

Primal-dual interior point methods can be classified into two categories: feasible and infeasible. The first category requires that the starting point and all subsequent iterations of the algorithm strictly satisfy all the inequality constraints. The second category relaxes those requirements and allows the iterations to violate some or all of the inequality constraints during the course of the minimization procedure. The NLP solver implements an infeasible algorithm; this section concentrates on that type of algorithm.

To make the notation less cluttered and the fundamentals of interior point methods easier to understand, consider without loss of generality the following simpler NLP problem:

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) \geq 0, i \in \mathcal{I} = \{1, 2, \ldots, q\} \end{array}$$

Note that the equality and bound constraints have been omitted from the preceding problem. Initially, slack variables are added to the inequality constraints, giving rise to the problem

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) - s_i = 0, i \in \mathcal{I} \\ & s \geq 0 \end{array}$$

where $s = (s_1, \ldots, s_q)^{\mathrm{T}}$ is the vector of slack variables, which are required to be nonnegative. Next, all the nonnegativity constraints on the slack variables are eliminated by being incorporated into the objective function, by means of a logarithmic function. This gives rise to the equality-constrained NLP problem

$$\begin{array}{ll} \text{minimize} & B(x, s) = f(x) - \mu \sum_{i \in \mathcal{I}} \ln(s_i) \\ \text{subject to} & g_i(x) - s_i = 0, i \in \mathcal{I} \end{array}$$

where μ is a positive parameter. The nonnegativity constraints on the slack variables are implicitly enforced by the logarithmic functions, since the logarithmic function prohibits s from taking zero or negative values.

Next, the equality constraints can be absorbed by using a quadratic penalty function to obtain the following:

$$\text{minimize} \quad \mathcal{M}(x, s) = f(x) + \frac{1}{2\mu} \|g(x) - s\|_2^2 - \mu \sum_{i \in \mathcal{I}} \ln(s_i)$$

The preceding unconstrained problem is often called the *penalty-barrier subproblem*. Depending on the size of the parameter μ, a local minimum of the barrier problem provides an approximation to the local minimum of the original NLP problem. The smaller the size of μ, the better the approximation becomes. Infeasible primal-dual interior point algorithms repeatedly solve the penalty-barrier problem for different values of μ that progressively go to zero, in order to get as close as possible to a local minimum of the original NLP problem.

An unconstrained minimizer of the penalty-barrier problem must satisfy the equations

$$\begin{array}{rcl} \nabla f(x) - J(x)^{\mathrm{T}} z & = & 0 \\ z - \mu S^{-1} e & = & 0 \end{array}$$

where $z = -(g(x) - s)/\mu$, $J(x)$ is the Jacobian matrix of the vector function $g(x)$, S is the diagonal matrix whose elements are the elements of the vector s (that is, $S = \mathrm{diag}\{s_1, \ldots, s_q\}$), and e is a vector of all ones.

Multiplying the second equation by S and adding the definition of z as a third equation produces the following equivalent nonlinear system:

$$F^{\mu}(x,s,z) = \begin{pmatrix} \nabla f(x) - J(x)^{\mathrm{T}} z \\ Sz - e \\ g(x) - s + \mu z \end{pmatrix} = 0$$

Note that if $\mu = 0$, the preceding conditions represent the optimality conditions of the original optimization problem, after adding slack variables. One of the main aims of the algorithm is to gradually reduce the value of μ to zero, so that it converges to a local optimum of the original NLP problem. The rate by which μ approaches zero affects the overall efficiency of the algorithm. Algorithms that treat z as an additional variable are considered primal-dual, while those that enforce the definition of $z = -(g(x) - s)/\mu$ at each iteration are consider purely primal approaches.

At iteration k, the infeasible primal-dual interior point algorithm approximately solves the preceding system by using Newton's method. The Newton system is

$$\begin{bmatrix} H_{\mathcal{L}}(x^k, z^k) & 0 & -J(x^k)^{\mathrm{T}} \\ 0 & Z_k & S_k \\ J(x^k) & -I & \mu I \end{bmatrix} \begin{bmatrix} \Delta x^k \\ \Delta s^k \\ \Delta z^k \end{bmatrix} = - \begin{bmatrix} \nabla_x f(x^k) - J(x^k)^{\mathrm{T}} z \\ -\mu e + S_k z^k \\ g(x^k) - s^k + \mu z^k \end{bmatrix}$$

where $H_{\mathcal{L}}$ is the Hessian matrix of the Lagrangian function $\mathcal{L}(x,z) = f(x) - z^{\mathrm{T}} g(x)$ of the original NLP problem; that is,

$$H_{\mathcal{L}}(x,z) = \nabla^2 f(x) - \sum_{i \in \mathcal{I}} z_i \nabla^2 g_i(x)$$

The solution $(\Delta x^k, \Delta s^k, \Delta z^k)$ of the Newton system provides a direction to move from the current iteration (x^k, s^k, z^k) to the next,

$$(x^{k+1}, s^{k+1}, z^{k+1}) = (x^k, s^k, z^k) + \alpha(\Delta x^k, \Delta s^k, \Delta z^k)$$

where α is the step length along the Newton direction. The step length is determined through a line-search procedure that ensures sufficient decrease of a merit function based on the augmented Lagrangian function of the barrier problem. The role of the merit function and the line-search procedure is to ensure that the objective and the infeasibility reduce sufficiently at every iteration and that the iterations approach a local minimum of the original NLP problem.

Interior Point Direct Algorithm

This primal-dual algorithm combines interior point techniques for handling the inequality constraints and an augmented Lagrangian method for the equalities. It uses tools that have been developed in recent research papers (Armand and Omheni 2017a, b). For the sake of simplicity, this section uses the slack formulation that is introduced in the previous section,

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) - s_i = 0, i \in \mathcal{I} \\ & s \geq 0 \end{array}$$

where $s = (s_1, \ldots, s_q)^{\mathrm{T}}$ is the vector of slack variables, which are required to be nonnegative. To deal with the nonnegative lower bound on s, the logarithmic term $-\mu \sum_{i \in \mathcal{I}} \ln(s_i)$ is added to the objective function, resulting in the barrier problem,

$$\begin{array}{ll} \text{minimize} & B(x,s) = f(x) - \mu \sum_{i \in \mathcal{I}} \ln(s_i) \\ \text{subject to} & g_i(x) - s_i = 0, i \in \mathcal{I} \end{array}$$

where $\mu > 0$ is the barrier parameter. The nonlinear equality constraints are handled using an augmented Lagrangian term. The resulting unconstrained formulation is

$$\text{minimize} \quad \mathcal{M}(x,s) = f(x) + \lambda^{\top}(g(x) - s) + \tfrac{1}{2\sigma}\|g(x) - s\|^2 - \mu \sum_{i \in \mathcal{I}} \ln(s_i)$$

where $\lambda \in \mathbb{R}^q$ is an estimate of the Lagrange multiplier that is associated with equality constraints and where $\sigma > 0$ is the penalty parameter. The first-order optimality conditions of this unconstrained problem are:

$$\begin{array}{rcl} \nabla f(x) + J(x)^{\mathrm{T}}(\lambda + \frac{1}{\sigma}(g(x) - s)) & = & 0 \\ -\lambda - \frac{1}{\sigma}(g(x) - s) - \mu S^{-1} e & = & 0 \end{array}$$

By introducing the variables $y = \lambda + \frac{1}{\sigma}(g(x) - s)$ and $z = \mu S^{-1} e$, this system of equations can be rewritten in the following form:

$$\begin{array}{rcl} \nabla f(x) + J(x)^{\mathrm{T}} y & = & 0 \\ -y - z & = & 0 \\ g(x) - s & = & \sigma(y - \lambda) \\ SZe & = & \mu e \end{array}$$

These optimality conditions can be interpreted as perturbed optimality conditions for the original slack formulation problem. That is, if $\sigma = 0$ or if $\lambda = y$ and $\mu = 0$, then the preceding conditions reduce to the standard first-order optimality conditions. The algorithm is designed to encourage λ to naturally converge to y; thus, the penalty term σ might then remain bounded, resulting in better conditioning and fewer iterations overall.

The basic idea of the algorithm is to apply Newton's method to the perturbed optimality conditions system while preserving strict feasibility with respect to s and z, driving the barrier term, μ, to 0, and driving the penalty term, σ, to 0 while periodically updating the Lagrange multiplier estimate, λ. These update rules ensure convergence to an optimal solution of the original problem. The algorithm has two types of iterations: *outer* and *inner*. At an outer iteration k, the algorithm computes a search direction by using the Newton equations

$$\begin{bmatrix} \nabla_x^2 \mathcal{L}(x^k, y^k, z^k) & 0 & J(x^k)^{\top} & 0 \\ 0 & 0 & -I & -I \\ J(x^k) & -I & -\sigma I & 0 \\ 0 & Z_k & 0 & S_k \end{bmatrix} \begin{bmatrix} \Delta x^k \\ \Delta s^k \\ \Delta y^k \\ \Delta z^k \end{bmatrix} = - \begin{bmatrix} \nabla f(x^k) + J(x^k)^{\top} y^k \\ -y^k - z^k \\ g(x^k) - s^k + \sigma(\lambda - y^k) \\ S_k Z_k e - \mu e \end{bmatrix}$$

where $\mathcal{L}$ denotes the Lagrangian function,

$$\mathcal{L}(x, y, z) = f(x) + y^{\top}(g(x) - s) - z^{\top} s$$

A solution to the Newton equations is obtained by solving the equivalent reduced symmetric linear system:

$$\begin{bmatrix} \nabla_x^2 \mathcal{L}(x^k, y^k, z^k) & 0 & J(x^k)^{\top} \\ 0 & {S_k}^{-1} Z_k & -I \\ J(x^k) & -I & -\sigma I \end{bmatrix} \begin{bmatrix} \Delta x^k \\ \Delta s^k \\ \Delta y^k \end{bmatrix} = - \begin{bmatrix} \nabla f(x^k) + J(x^k)^{\top} y^k \\ -y^k - \mu {S_k}^{-1} e \\ g(x^k) - s^k + \sigma(\lambda - y^k) \end{bmatrix}$$

The search direction Δz^k is then recovered by the following equation:

$$\Delta z^k = \mu {S_k}^{-1} e - z^k - {S_k}^{-1} Z_k \Delta s^k$$

For nonconvex problems, an inertia-correcting diagonal modification can be used to ensure downhill search directions, resulting in the following modified KKT matrix:

$$\begin{bmatrix} \nabla_x^2 \mathcal{L}(x^k, y^k, z^k) + \theta I & 0 & J(x^k)^\top \\ 0 & {S_k}^{-1} Z_k + \theta I & -I \\ J(x^k) & -I & -\sigma I \end{bmatrix}$$

The regularization parameter, $\theta \geq 0$, is updated to make sure that the KKT matrix has exactly $n + q$ positive, q negative, and no zero eigenvalues. During inner iterations, the inertia control mechanism guarantees that the solution of the linear system is a descent direction for some primal-dual merit function. This mechanism is also applied along outer iterations to avoid convergence to a stationary point that would not be a minimum. The natural regularization that is introduced by σ in the lower right block of the KKT matrix plays an important role whenever degenerate problems are solved for which the constraint Jacobian, $J(x^k)$, is rank deficient.

The resolution of the linear system is followed by the computation of the step sizes α^P and $\alpha^D \in (0, 1]$ by applying the fraction to the boundary rule in order to maintain strict feasibility of the iterates with respect to the bound constraints. The trial new iterate is then defined as

$$(x_+^k, s_+^k, y_+^k) = (x^k, s^k, y^k) + \alpha^P (\Delta x^k, \Delta s^k, \Delta y^k) \quad \text{and} \quad z_+^k = z^k + \alpha^D \Delta z^k$$

Note that this algorithm allows the use of different step sizes for the dual variable z from the variables x, s, and y. If the norm of the perturbed KKT conditions is deemed sufficiently small, then the trial point is accepted as a new iterate; that is,

$$(x^{k+1}, s^{k+1}, y^{k+1}, z^{k+1}) = (x_+^k, s_+^k, y_+^k, z_+^k)$$

Otherwise, a sequence of inner iterations is applied to find a new iterate $(x^{k+1}, s^{k+1}, y^{k+1}, z^{k+1})$ that decreases the perturbed KKT conditions. The inner iterations correspond to a backtracking line-search algorithm that is applied to a primal-dual merit function. Depending on the problem type, the step length might be determined through a filter technique.

Before a new outer iteration is started, the penalty parameter and the estimate of the Lagrange multiplier are updated depending on the reduction of the constraint violation, as in classical augmented Lagrangian. The barrier parameter is decreased as soon as the KKT conditions of the barrier problem are satisfied to some tolerance.

The main differences between the two interior point methods are:

- The IPDIRECT solver uses direct linear algebra to compute the solution of the linear system, whereas the INTERIORPOINT solver uses an iterative approach. Unless your problem is very large and sparse, it is suggested that you try the direct approach first. The direct approach has been empirically demonstrated to improve robustness while reducing CPU time, function evaluations, and iterations.

- To handle challenges such as nonconvexity and singular systems, safeguards and globalization strategies have been added to both the INTERIORPOINT and IPDIRECT solvers to ensure robust convergence on a wide range of challenging optimization problems. However, the IPDIRECT solver has been aggressively streamlined to minimize the negative impact that these safeguard strategies might have on asymptotic convergence rates.

Active-Set Method

Active-set methods differ from interior point methods in that no barrier term is used to ensure that the algorithm remains interior with respect to the inequality constraints. Instead, attempts are made to learn the true active set. For simplicity, use the same initial slack formulation used by the interior point method description,

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & g_i(x) - s_i = 0, i \in \mathcal{I} \\ & s \geq 0 \end{array}$$

where $s = (s_1, \ldots, s_q)^{\mathrm{T}}$ is the vector of slack variables, which are required to be nonnegative. Begin by absorbing the equality constraints as before into a penalty function, but keep the slack bound constraints explicitly:

$$\begin{array}{ll} \text{minimize} & \mathcal{M}(x, s) = f(x) + \dfrac{1}{2\mu}\|g(x) - s\|_2^2 \\ \text{subject to} & s \geq 0 \end{array}$$

where μ is a positive parameter. Given a solution pair $(x(\mu), s(\mu))$ for the preceding problem, you can define the active-set projection matrix P as follows:

$$P_{ij} = \begin{cases} 1 & \text{if } i = j \text{ and } s_i(\mu) = 0 \\ 0 & \text{otherwise.} \end{cases}$$

Then $(x(\mu), s(\mu))$ is also a solution of the equality constraint subproblem:

$$\begin{array}{ll} \text{minimize} & \mathcal{M}(x, s) = f(x) + \dfrac{1}{2\mu}\|g(x) - s\|_2^2 \\ \text{subject to} & Ps = 0. \end{array}$$

The minimizer of the preceding subproblem must be a stationary point of the Lagrangian function

$$\mathcal{L}^{\mu}(x, s, z) = f(x) + \frac{1}{2\mu}\|g(x) - s\|_2^2 - z^T P s$$

which gives the optimality equations

$$\begin{array}{rclcl} \nabla_x \mathcal{L}^{\mu}(x, s, z) & = & \nabla f(x) - J(x)^T y & = & 0 \\ \nabla_s \mathcal{L}^{\mu}(x, s, z) & = & y - P^T z & = & 0 \\ & = & Ps & = & 0 \end{array}$$

where $y = -(g(x) - s)/\mu$. Using the second equation, you can simplify the preceding equations to get the following optimality conditions for the bound-constrained penalty subproblem:

$$\begin{array}{rcl} \nabla f(x) - J(x)^T P^T z & = & 0 \\ P(g(x) - s) + \mu z & = & 0 \\ Ps & = & 0 \end{array}$$

Using the third equation directly, you can reduce the system further to

$$\begin{array}{rcl} \nabla f(x) - J(x)^T P^T z & = & 0 \\ Pg(x) + \mu z & = & 0 \end{array}$$

At iteration k, the primal-dual active-set algorithm approximately solves the preceding system by using Newton's method. The Newton system is

$$\begin{bmatrix} H_{\mathcal{L}}(x^k, z^k) & -J_{\mathcal{A}}^{\mathrm{T}} \\ J_{\mathcal{A}} & \mu I \end{bmatrix} \begin{bmatrix} \Delta x^k \\ \Delta z^k \end{bmatrix} = - \begin{bmatrix} \nabla_x f(x^k) - J_{\mathcal{A}}^{\mathrm{T}} z \\ P g(x^k) + \mu z^k \end{bmatrix}$$

where $J_{\mathcal{A}} = PJ(x^k)$ and $H_{\mathcal{L}}$ denotes the Hessian of the Lagrangian function $f(x) - z^{\mathrm{T}} P g(x)$. The solution $(\Delta x^k, \Delta z^k)$ of the Newton system provides a direction to move from the current iteration (x^k, s^k, z^k) to the next,

$$(x^{k+1}, z^{k+1}) = (x^k, z^k) + \alpha(\Delta x^k, \Delta z^k)$$

where α is the step length along the Newton direction. The corresponding slack variable update s^{k+1} is defined as the solution to the following subproblem whose solution can be computed analytically:

$$\begin{array}{ll} \text{minimize} & \mathcal{M}(x^{k+1}, s) = f(x) + \dfrac{1}{2\mu} \| g(x^{k+1}) - s \|_2^2 \\ \text{subject to} & s \geq 0 \end{array}$$

The step length α is then determined in a similar manner to the preceding interior point approach. At each iteration, the definition of the active-set projection matrix P is updated with respect to the new value of the constraint function $g(x^{k+1})$. For large-scale NLP, the computational bottleneck typically arises in seeking to solve the Newton system. Thus active-set methods can achieve substantial computational savings when the size of $J_{\mathcal{A}}$ is much smaller than $J(x)$; however, convergence can be slow if the active-set estimate changes combinatorially. Further, the active-set algorithm is often the superior algorithm when only bound constraints are present. In practice, both the interior point and active-set approach incorporate more sophisticated merit functions than those described in the preceding sections; however, their description is beyond the scope of this document. See Gill and Robinson (2010) for further reading.

Feasibility-Seeking Reformulation

In constrained nonlinear optimization, finding a feasible solution can be a nontrivial task. In certain cases where nonlinear equality constraints are present, convergence to a feasible solution can be slow. One way to speed up the convergence in those cases is to reformulate the original optimization problem by relaxing the constraints via slack variables. Then L1 penalty terms for the slack variables are added to the original objective function or to a surrogate objective function in order to force the solution to the reformulated problem to be feasible to the original problem. The SEEKFEASIBLE= option enables you to reformulate your problem and solve for a feasible solution.

Suppose the original problem is of the following form:

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & c^l \leq c(x) \leq c^u \\ & x^l \leq x \leq x^u \end{array}$$

where x, x^l, and $x^u \in \mathbb{R}^n$; c^l and $c^u \in \mathbb{R}^m$; f is a function: $\mathbb{R}^n \mapsto \mathbb{R}$; and c is a function: $\mathbb{R}^n \mapsto \mathbb{R}^m$. You can use the FORMULATION= suboption to specify one of the following four different formulations for reformulating the original problem:

- Formulation 1: When FORMULATION=1 is specified, the following form is used to reformulate the original problem by adding slack variables r and s:

$$\begin{array}{ll} \text{minimize} & \rho f(x) + \tau e^T (r + s) \\ \text{subject to} & c^l \le c(x) + r - s \le c^u \\ & x^l \le x \le x^u \\ & r, s \ge 0 \end{array}$$

  where r and $s \in \mathbb{R}^m$.

- Formulation 2: When FORMULATION=2 is specified, the following form is used to reformulate the original problem by adding slack variables r and s:

$$\begin{array}{ll} \text{minimize} & \rho f(x) + \tau e^T (r + s) \\ \text{subject to} & [c_i(x)]_{i \in \mathcal{I}} + r \ge \left[c_i^l\right]_{i \in \mathcal{I}} \\ & [c_i(x)]_{i \in \mathcal{J}} - s \le \left[c_i^u\right]_{i \in \mathcal{J}} \\ & x^l \le x \le x^u \\ & r, s \ge 0 \end{array}$$

  where $\mathcal{I} = \{i = 1, \ldots, m : c_i^l > -\infty\}$ and $\mathcal{J} = \{i = 1, \ldots, m : c_i^u < \infty\}$. Let $p = |\mathcal{I}|$ and $q = |\mathcal{J}|$, and you have $r \in \mathbb{R}^p$ and $s \in \mathbb{R}^q$.

- Formulation 3: Suppose you define $\bar{f}(x)$ as follows:

$$\bar{f}(x) = \frac{1}{2} \| D(x - x^r) \|_2^2$$

  where x^r is the user-supplied initial point and $D = \underset{i=1,\ldots,n}{\text{diag}} \left(\min \left\{ 1, \frac{1}{|x_i^r|} \right\} \right)$. When FORMULATION=3 is specified, the following form is used to reformulate the original problem by replacing the original objective function with $\bar{f}(x)$ and adding slack variables r and s:

$$\begin{array}{ll} \text{minimize} & \rho \bar{f}(x) + \tau e^T (r + s) \\ \text{subject to} & c^l \le c(x) + r - s \le c^u \\ & x^l \le x \le x^u \\ & r, s \ge 0 \end{array}$$

  where r and $s \in \mathbb{R}^m$. Note that the constraints are the same as in Formulation 1.

- Formulation 4: Suppose you define $\bar{f}(x)$ as in Formulation 3. When FORMULATION=4 is specified, the following form is used to reformulate the original problem by replacing the original objective function with $\bar{f}(x)$ and adding slack variables r and s:

$$\begin{array}{ll} \text{minimize} & \rho \bar{f}(x) + \tau e^T (r + s) \\ \text{subject to} & [c_i(x)]_{i \in \mathcal{I}} + r \ge \left[c_i^l\right]_{i \in \mathcal{I}} \\ & [c_i(x)]_{i \in \mathcal{J}} - s \le \left[c_i^u\right]_{i \in \mathcal{J}} \\ & x^l \le x \le x^u \\ & r, s \ge 0 \end{array}$$

  where $\mathcal{I}$, $\mathcal{J}$, r, and s are defined in the same way as in Formulation 2. Note that the constraints are the same as in Formulation 2.

In the preceding four formulations, you can specify the scale factor ρ for the objective function in the OBJSCALE= suboption and the penalty parameter τ for the slack variables in the PENALTYPARM= suboption.

Multistart

Frequently, nonlinear optimization problems contain many local minima because the objective or the constraints are nonconvex functions. The quality of different local minima is measured by the objective value achieved at those points. For example, if x_1^* and x_2^* are two distinct local minima and $f(x_1^*) \leq f(x_2^*)$, then x_1^* is said to be of better quality than x_2^*. The NLP solver provides a mechanism that can locate local minima of better quality by starting the local solver multiple times from different initial points. By doing so, the local solver can converge to different local minima. The local minimum with the lowest objective value is then reported back to the user.

The multistart feature consists of two phases. In the first phase, the entire feasible region is explored by generating sample points from a uniform distribution. The aim of this phase is to place at least one sample point in the region of attraction of every local minimum. Here the region of attraction of a local minimum is defined as the set of feasible points that, when used as starting points, enable a local solver to converge to that local minimum.

During the second phase, a subset of the sample points generated in the first phase is chosen by applying a clustering technique. The goal of the clustering technique is to group the initial sample points around the local minima and allow only a single local optimization to start from each cluster or group. The clustering technique aims to reduce computation time by sparing the work of unnecessarily starting multiple local optimizations within the region of attraction of the same local minimum.

The number of starting points is critical to the time spent by the solver to find a good local minimum. You can specify the maximum number of starting points by using the MAXSTARTS= suboption. If this option is not specified, the solver determines the minimum number of starting points that can provide reasonable evidence that a good local minimum will be found.

Many optimization problems contain variables with infinite upper or lower bounds. These variables can cause the sampling procedure to generate points that are not useful for locating different local minima. The efficiency of the sampling procedure can be increased by reducing the range of these variables by using the BNDRANGE= suboption. This option forces the sampling procedure to generate points that are in a smaller interval, thereby increasing the efficiency of the solver to converge to a local optimum.

The multistart feature currently supports deterministic parallel processing in a shared-memory computing environment and in single-machine mode of a distributed computing environment. To ensure reproducible results, specify a nonzero value for the SEED= option. In a distributed computing environment, the multistart feature is nondeterministic.

Accessing the Starting Point That Leads to the Best Local Optimum

The starting point that leads to the best local optimum can be accessed by using the .msinit suffix in PROC OPTMODEL. In some cases, the knowledge of that starting point might be useful. For example, you can run the local solver again but this time providing as initial point the one that is stored in .msinit. This way the multistart explores a different part of the feasible region and might discover a local optimum of better quality than those found in previous runs. The use of the suffix .msinit is demonstrated in Example 16.6.

For more information about suffixes in PROC OPTMODEL, see "Suffixes" on page 420 in Chapter 9, "The OPTMODEL Procedure."

Covariance Matrix

You must specify the COVEST=() option to compute an approximate covariance matrix for the parameter estimates under asymptotic theory for least squares, maximum likelihood, or Bayesian estimation, with or without corrections for degrees of freedom as specified in the VARDEF= option.

The standard form of this class of the problems is one of following:

- least squares (LSQ): $\min f(x) = s \sum_{i=1}^{m} f_i^2(x)$
- minimum or maximum (MIN/MAX): $\mathrm{opt}\ f(x) = s \sum_{i=1}^{m} f_i(x)$

For example, two groups of six different forms of covariance matrices (and therefore approximate standard errors) can be computed corresponding to the following two situations, where TERMS is an index set.

- LSQ: The objective function consists solely of a positively scaled sum of squared terms, which means that least squares estimates are being computed:

  $$\min f(x) = s \sum_{(i,j)\in \mathrm{TERMS}} f_{ij}^2(x)$$

  where $s > 0$.

- MIN or MAX: The MIN or MAX declaration is specified, and the objective is not in least squares form. Together, these characteristics mean that maximum likelihood or Bayesian estimates are being computed:

  $$\mathrm{opt}\ f(x) = s \sum_{(i,j)\in \mathrm{TERMS}} f_{ij}(x)$$

  where opt is either $\min$ or $\max$ and s is arbitrary.

In the preceding section, TERMS is used to denote an arbitrary index set. For example, if your problem is

$$\min z = 0.5 \sum_{i\in\mathcal{I}} (g_1^2[i] + g_2^2[i])$$

then TERMS = $\{(i, j) : i \in \mathcal{I} \text{ and } j \in \{1, 2\}\}$, where $\mathcal{I}$ is the index set of input data. The following rules apply when you specify your objective function:

- The terms $f_{ij}(x)$ can be either IMPVAR expressions or constant expressions (expressions that do not depend on variables). The i and j values can be partitioned among observation and function indices as needed. Any number of indices can be used, including non-array indices to implicit variables.
- The nonconstant terms are defined by using the IMPVAR declaration. Each nonconstant IMPVAR element can be referenced at most once in the objective.

- The objective consists of a scaled sum of terms (or squared terms for least squares). The scaling, shown as s in the preceding equations, consists of outer multiplication or division by constants of the unscaled sum of terms (or squared terms for least squares). The unary + or − operators can also be used for scaling.
- Least squares objectives require the scaling to be positive ($s > 0$). The individual f_{ij} values are scaled by $\sqrt{2s}$ by PROC OPTMODEL.
- Objectives that are not least squares allow arbitrary scaling. The scale value is distributed to the f_{ij} values.
- The summation of terms (or squared terms for least squares) is constructed with the binary +, SUM, and IF-THEN-ELSE operators (where IF-THEN-ELSE must have a first operand that does not depend on variables). The operands can be terms or a summation of terms (or squared terms for least squares).
- A squared term is specified as **term^2** or **term**2**.
- The default value of the NTERMS= option is determined by counting the nonconstant terms. The constant terms do not contribute to the covariance matrix.

The following PROC OPTMODEL statements demonstrate these rules:

```
var x{VARS};
impvar g{OBS} = ...;  /* expression involves x */
impvar h{OBS} = ...;  /* expression involves x */

/* This objective is okay. */
min z1 = sum{i in OBS} (g[i] + h[i]);

/* This objective is okay. */
min z2 = 0.5*sum{i in OBS} (g[i]^2 + h[i]^2);

/* This objective is okay. It demonstrates multiple levels of scaling. */
min z3 = 3*(sum{i in OBS} (g[i]^2 + h[i]^2))/2;

/* This objective is okay. */
min z4 = (sum{i in OBS} (g[i]^2 + h[i]^2))/2;
```

Note that the following statements are not accepted:

```
/* This objective causes an error because individual scaling is not allowed. */
/* (division applies to inner term)                                          */
min z5 = sum{i in OBS} (g[i]^2 + h[i]^2)/2;

/* This objective causes an error because individual scaling is not allowed. */
min z6 = sum{i in OBS} 0.5*g[i]^2;

/* This objective causes an error because the element g[1] is repeated. */
min z7 = g[1] + sum{i in OBS} g[i];
```

The covariance matrix is always positive semidefinite. For MAX type problems, the covariance matrix is converted to MIN type by using negative Hessian, Jacobian, and function values in the computation. You can use the following options to check for a rank deficiency of the covariance matrix:

- The ASINGULAR= and MSINGULAR= options enable you to set two singularity criteria for the inversion of the matrix A that is needed to compute the covariance matrix, when A is either the Hessian or one of the crossproduct Jacobian matrices. The singularity criterion that is used for the inversion is

  $$|d_{j,j}| \leq \max(\mathit{asing}, \mathit{msing} \times \max(|A_{1,1}|, \ldots, |A_{n,n}|))$$

  where $d_{j,j}$ is the diagonal pivot of the matrix A, and *asing* and *msing* are the specified values of the ASINGULAR= and MSINGULAR= options, respectively.

- If the matrix A is found to be singular, the NLP solver computes a generalized inverse that satisfies Moore-Penrose conditions. The generalized inverse is computed using the computationally expensive but numerically stable eigenvalue decomposition, $A = Z\Lambda Z^T$, where Z is the orthogonal matrix of eigenvectors and Λ is the diagonal matrix of eigenvalues, $\Lambda = \mathrm{diag}(\lambda_1, \ldots, \lambda_n)$. The generalized inverse of A is set to

  $$A^- = Z\Lambda^- Z^T$$

  where the diagonal matrix $\Lambda^- = \mathrm{diag}(\lambda_1^-, \ldots, \lambda_n^-)$ is defined as follows, where *covsing* is the specified value of the COVSING= option:

  $$\lambda_i^- = \begin{cases} 1/\lambda_i & \text{if } |\lambda_i| > \mathit{covsing} \\ 0 & \text{if } |\lambda_i| \leq \mathit{covsing} \end{cases}$$

  If the COVSING= option is not specified, then the default is $\max(\mathit{asing}, \mathit{msing} \times \max(|A_{1,1}|, \ldots, |A_{n,n}|))$, where *asing* and *msing* are the specified values of the ASINGULAR= and MSINGULAR= options, respectively.

For problems of the MIN or LSQ type, the matrices that are used to compute the covariance matrix are

$$G = \nabla^2 f(x)$$

$$J(f) = (\nabla f_1, \ldots, \nabla f_m) = \left(\frac{\partial f_i}{\partial x_j}\right)$$

$$JJ(f) = J(f)^T J(f)$$

$$V = J(f)^T \mathrm{diag}(f_i^2) J(f)$$

$$W = J(f)^T (\mathrm{diag}(f_i))^{-1} J(f)$$

where f_i is defined in the standard form of the covariance matrix problem. Note that when some f_i are 0, $(\mathrm{diag}(f_i))^{-1}$ is computed as a generalized inverse.

For unconstrained minimization, the formulas of the six types of covariance matrices are given in Table 16.2. The value of d in the table depends on the VARDEF= option and the values of the NDF= and NTERMS= options, *ndf* and *nterms*, respectively, as follows:

$$d = \begin{cases} \max(1, \mathit{nterms} - \mathit{ndf}) & \text{for VARDEF=DF} \\ \mathit{nterms} & \text{for VARDEF=N} \end{cases}$$

The value of σ^2 depends on the specification of the SIGSQ= option and on the value of d,

$$\sigma^2 = \begin{cases} \mathit{sq} \times \mathit{nterms}/d & \text{if SIGSQ=}\mathit{sq}\text{ is specified} \\ 2f(x^*)/d & \text{if SIGSQ= is not specified} \end{cases}$$

where $f(x^*)$ is the value of the objective function at the optimal solution x^*.

Because of the analytic definition, in exact arithmetic the covariance matrix is positive semidefinite at the solution. A warning message is issued if numerical computation does not result in a positive semidefinite matrix. This can happen because round-off error is introduced or the incorrect type of covariance matrix for a specified problem is selected.

Iteration Log for the Local Solver

The iteration log for the local solver provides detailed information about progress towards a locally optimal solution. This log appears when multistart mode is disabled.

The following information is displayed in the log:

Iter	indicates the iteration number.
Objective Value	indicates the objective function value.
Infeasibility	indicates the maximum value out of all constraint violations.
Optimality Error	indicates the relative optimality error (see the section "Solver Termination Criterion" on page 975).

Iteration Log for Multistart

When the MULTISTART=() option is specified, the iteration log differs from that of the local solver. More specifically, when a value of 2 is specified for the LOGLEVEL= suboption, the following information is displayed in the log:

Start	indicates the index number of each local optimization run. The following indicator can appear beside this number to provide additional information about the run: * indicates the local optimization started from a user-supplied point.
Best Objective	indicates the value of the objective function at the best local solution found so far.
Local Objective	indicates the value of the objective function obtained at the solution returned by the local solver.
Infeasibility	indicates the infeasibility error at the solution returned by the local solver.
Optimality Error	indicates the optimality error at the solution returned by the local solver.
Local Iters	indicates the number of iterations taken by the local solver.
Local Status	indicates the solution status of the local solver. Several different values can appear in this column: OPTIMAL — indicates that the local solver found a locally optimal solution. BESTFEASIBLE — indicates that the local solver returned the best feasible point found. See the SOLTYPE= option for more information.

INFEASIBLE	indicates that the local solver converged to a point that might be infeasible.
LOCALINFEAS	indicates that the local solver converged to a point of minimal local infeasibility.
UNBOUNDED	indicates that the local solver determined that the problem is unbounded.
ITERLIMIT	indicates that the local solver reached the maximum number of iterations and could not find a locally optimal solution.
TIMELIMIT	indicates that the local solver reached the maximum allowable time and could not find a locally optimal solution.
ABORTED	indicates that the local solver terminated due to a user interrupt.
FUNEVALERR	indicates that the local solver encountered a function evaluation error.
NUMERICERR	indicates that the local solver encountered a numerical error other than a function evaluation error.
INTERNALERR	indicates that the local solver encountered a solver system error.
OUTMEMORY	indicates that the local solver ran out of memory.
FAILED	indicates a general failure of the local solver in the absence of any other error.

Solver Termination Criterion

Because badly scaled problems can lead to slow convergence, the NLP solver dynamically rescales both the objective and constraint functions adaptively as needed. The optimality conditions are always stated with respect to the rescaled NLP. However, because typically you are most interested in the constraint violation of the original NLP, and not the internal scaled variant, you always work with respect to the true constraint violation. Thus, the solver terminates when both of the following conditions are true:

- The norm of the optimality conditions of the scaled NLP is less than the user-defined or default tolerance (OPTTOL= option).
- The norm of the constraint violation of the original NLP is less than the user-defined feasibility tolerance (FEASTOL= option).

More specifically, if

$$F(x,s,z) = (\nabla_x f(x) - J(x)^{\mathrm{T}} z, \quad Sz, \quad g(x) - s)^{\mathrm{T}}$$

is the vector of the optimality conditions of the rescaled NLP problem, then the solver terminates when

$$\| F(x,s,z) \| \leq \mathrm{OPTTOL}(1 + \|(x,s)\|)$$

and the maximum constraint violation is less than FEASTOL.

Solver Termination Messages

Upon termination, the solver produces the following messages in the log:

Optimal
The solver has successfully found a local solution to the optimization problem.

Conditionally optimal solution found
The solver is sufficiently close to a local solution, but it has difficulty in completely satisfying the user-defined optimality tolerance. This can happen when the line search finds very small steps that result in very slight progress of the algorithm. It can also happen when the prespecified tolerance is too strict for the optimization problem at hand.

Maximum number of iterations reached
The solver could not find a local optimum in the prespecified number of iterations.

Maximum specified time reached
The solver could not find a local optimum in the prespecified maximum real time for the optimization process.

Did not converge
The solver could not satisfy the optimality conditions and failed to converge.

Problem might be unbounded
The objective function takes arbitrarily large values, and the optimality conditions fail to be satisfied. This can happen when the problem is unconstrained or when the problem is constrained and the feasible region is not bounded.

Problem might be infeasible
The solver cannot identify a point in the feasible region.

Problem is infeasible
The solver detects that the problem is infeasible.

Out of memory
The problem is so large that the solver requires more memory to solve the problem.

Problem solved by the OPTMODEL presolver
The problem was solved by the OPTMODEL presolver.

Macro Variable _OROPTMODEL_

The OPTMODEL procedure always creates and initializes a SAS macro variable called _OROPTMODEL_, which contains a character string. After each PROC OPTMODEL run, you can examine this macro variable by specifying `%put &_OROPTMODEL_`; and check the execution of the most recently invoked solver from the value of the macro variable. After the NLP solver is called, the various terms of the variable are interpreted as follows:

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	The use of syntax is incorrect.
DATA_ERROR	The input data are inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem in reading or writing of data has occurred.
SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, has occurred.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produced the solution data in the macro variable. This term only appears when STATUS=OK. It can take one of the following values:

IP	The interior point algorithm produced the solution data.
IPDIR	The interior point direct algorithm produced the solution data.
AS	The active-set algorithm produced the solution data.

When running algorithms concurrently (ALGORITHM=CONCURRENT), this term indicates which algorithm was the first to terminate.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The optimality of the solution cannot be proven.
BEST_FEASIBLE	The solution returned is the best feasible solution. This solution status indicates that the algorithm has converged to a local optimum but a feasible (not locally optimal) solution with a better objective value has been found and hence is returned.
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem might be unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.

BAD_PROBLEM_TYPE	The problem type is not supported by the solver.
ITERATION_LIMIT_REACHED	The maximum allowable number of iterations has been reached.
TIME_LIMIT_REACHED	The solver reached its execution time limit.
FAILED	The solver failed to converge, possibly due to numerical issues.

OBJECTIVE
indicates the objective value that is obtained by the solver at termination.

NUMSTARTS
indicates the number of starting points. This term appears only in multistart mode.

SAMPLE_POINTS
indicates the number of points that are evaluated in the sampling phase. This term appears only in multistart mode.

DISTINCT_OPTIMA
indicates the number of distinct local optima that the solver finds. This term appears only in multistart mode.

SEED
indicates the seed value that is used to initialize the solver. This term appears only in multistart mode.

INFEASIBILITY
indicates the level of infeasibility of the constraints at the solution.

OPTIMALITY_ERROR
indicates the norm of the optimality conditions at the solution. See the section "Solver Termination Criterion" on page 975 for details.

ITERATIONS
indicates the number of iterations required to solve the problem.

PRESOLVE_TIME
indicates the real time taken for preprocessing (seconds).

SOLUTION_TIME
indicates the real time taken by the solver to perform iterations for solving the problem (seconds).

NOTE: The time that is reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

Examples: NLP Solver

Example 16.1: Solving Highly Nonlinear Optimization Problems

This example demonstrates the use of the NLP solver to solve the following highly nonlinear optimization problem, which appears in Hock and Schittkowski (1981):

$$
\begin{array}{ll}
\text{minimize} & f(x) = 0.4(x_1/x_7)^{0.67} + 0.4(x_2/x_8)^{0.67} + 10 - x_1 - x_2 \\
\text{subject to} & 1 - 0.0588x_5x_7 - 0.1x_1 \geq 0 \\
& 1 - 0.0588x_6x_8 - 0.1x_1 - 0.1x_2 \geq 0 \\
& 1 - 4x_3/x_5 - 2/(x_3^{0.71}x_5) - 0.0588x_7/x_3^{1.3} \geq 0 \\
& 1 - 4x_4/x_6 - 2/(x_4^{0.71}x_6) - 0.0588x_8/x_4^{1.3} \geq 0 \\
& 0.1 \leq f(x) \leq 4.2 \\
& 0.1 \leq x_i \leq 10, i = 1, 2, \ldots, 8
\end{array}
$$

The initial point used is $x^0 = (6, 3, 0.4, 0.2, 6, 6, 1, 0.5)$. You can call the NLP solver within PROC OPTMODEL to solve the problem by writing the following SAS statements:

```
proc optmodel;
   var x{1..8} >= 0.1 <= 10;

   min f = 0.4*(x[1]/x[7])^0.67 + 0.4*(x[2]/x[8])^0.67 + 10 - x[1] - x[2];

   con c1: 1 - 0.0588*x[5]*x[7] - 0.1*x[1] >= 0;
   con c2: 1 - 0.0588*x[6]*x[8] - 0.1*x[1] - 0.1*x[2] >= 0;
   con c3: 1 - 4*x[3]/x[5] - 2/(x[3]^0.71*x[5]) - 0.0588*x[7]/x[3]^1.3 >= 0;
   con c4: 1 - 4*x[4]/x[6] - 2/(x[4]^0.71*x[6]) - 0.0588*x[8]/x[4]^1.3 >= 0;
   con c5: 0.1 <= f <= 4.2;

   /* starting point */
   x[1] = 6;
   x[2] = 3;
   x[3] = 0.4;
   x[4] = 0.2;
   x[5] = 6;
   x[6] = 6;
   x[7] = 1;
   x[8] = 0.5;

   solve with nlp / algorithm=activeset;
   print x;
 quit;
```

The summaries and the solution are shown in Output 16.1.1.

Output 16.1.1 Summaries and the Returned Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	8
Bounded Above	0
Bounded Below	0
Bounded Below and Above	8
Free	0
Fixed	0
Number of Constraints	5
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	0
Nonlinear GE (>=)	4
Nonlinear Range	1

Solution Summary	
Solver	NLP
Algorithm	Active Set
Objective Function	f
Solution Status	Optimal
Objective Value	3.9511639721
Optimality Error	7.794084E-7
Infeasibility	2.0842698E-7
Iterations	24
Presolve Time	0.00
Solution Time	0.01

[1]	x
1	6.46488
2	2.23292
3	0.66740
4	0.59576
5	5.93272
6	5.52724
7	1.01338
8	0.40067

Example 16.2: Solving Unconstrained and Bound-Constrained Optimization Problems

Although the NLP techniques are suited for solving generally constrained nonlinear optimization problems, these techniques can also be used to solve unconstrained and bound-constrained problems efficiently. This example considers the relatively large nonlinear optimization problems

$$\text{minimize } f(x) = \sum_{i=1}^{n-1}(-4x_i + 3.0) + \sum_{i=1}^{n-1}(x_i^2 + x_n^2)^2$$

and

$$\begin{array}{ll} \text{minimize} & f(x) = \sum_{i=1}^{n-1} \cos(-.5x_{i+1} - x_i^2) \\ \text{subject to} & 1 \le x_i \le 2,\ i = 1, \ldots, n \end{array}$$

with $n = 100{,}000$. These problems are unconstrained and bound-constrained, respectively.

For large-scale problems, the default memory limit might be too small, which can lead to out-of-memory status. To prevent this occurrence, it is recommended that you set a larger memory size. See the section "Memory Limit" on page 18 in Chapter 3, "Shared Concepts," for more information.

To solve the first problem, you can write the following statements:

```
proc optmodel;
   number N=100000;
   var x{1..N} init 1.0;

   minimize f = sum {i in 1..N - 1} (-4 * x[i] + 3.0)  +
                sum {i in 1..N - 1} (x[i]^2 + x[N]^2)^2;

   solve with nlp;
quit;
```

The problem and solution summaries are shown in Output 16.2.1.

Output 16.2.1 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	100000
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	100000
Fixed	0
Number of Constraints	0

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	0
Optimality Error	1.153672E-10
Infeasibility	0
Iterations	6
Presolve Time	0.01
Solution Time	0.47

To solve the second problem, you can write the following statements (here the active-set method is specifically selected):

```
proc optmodel;
   number N=100000;
   var x{1..N} >= 1 <= 2;

   minimize f = sum {i in 1..N - 1} cos(-0.5*x[i+1] - x[i]^2);

   solve with nlp / algorithm=activeset;
quit;
```

The problem and solution summaries are shown in Output 16.2.2.

Output 16.2.2 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	100000
Bounded Above	0
Bounded Below	0
Bounded Below and Above	100000
Free	0
Fixed	0
Number of Constraints	0

Solution Summary	
Solver	NLP
Algorithm	Active Set
Objective Function	f
Solution Status	Optimal
Objective Value	-99999
Optimality Error	2.3197923E-8
Infeasibility	0
Iterations	4
Presolve Time	0.01
Solution Time	1.68

Example 16.3: Solving Equality-Constrained Problems

In real applications, many problems are formulated as nonlinear optimization problems that have only equality constraints. The problems of this type are efficiently handled by the NLP solver. Consider the following equality-constrained problem, taken from Hock and Schittkowski (1981):

$$\begin{array}{ll} \text{minimize} & f(x) = \prod_{i=1}^{5} x_i \\ \text{subject to} & \sum_{i=1}^{5} x_i^2 = 10 \\ & x_2 x_3 - 5 x_4 x_5 = 0 \\ & x_1^3 + x_2^3 = -1 \end{array}$$

An initial point is given at $x^0 = (-2, 1.5, 2, -1, -1)$. You can use the following SAS code to formulate and solve this problem:

```
proc optmodel;
   var x{1..5};

   minimize obj = prod {i in 1..5} x[i];

   con constr1: sum {i in 1..5} x[i]^2 = 10;
   con constr2: x[2] * x[3] - 5 * x[4] * x[5] = 0;
   con constr3: x[1]^3 + x[2]^3 = -1;

   /* starting point */
   x[1] = -2;
   x[2] =  1.5;
   x[3] =  2;
   x[4] = -1;
   x[5] = -1;

   solve with nlp / algorithm=ipdirect;
   print x;
quit;
```

To solve this equality-constrained problem, the interior point direct algorithm (IPDIRECT) is invoked. The problem summary, solution summary, and the optimal solution are shown in Output 16.3.1.

Output 16.3.1 Summaries and the Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	obj
Objective Type	Nonlinear
Number of Variables	5
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	5
Fixed	0
Number of Constraints	3
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	3
Nonlinear GE (>=)	0
Nonlinear Range	0

Output 16.3.1 *continued*

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	obj
Solution Status	Optimal
Objective Value	-2.919700415
Optimality Error	2.6808758E-9
Infeasibility	4.8986188E-9
Iterations	3
Presolve Time	0.00
Solution Time	0.00

[1]	x
1	-1.71714
2	1.59571
3	1.82725
4	-0.76364
5	-0.76364

Example 16.4: Solving NLP Problems with Range Constraints

Some constraints have both lower and upper bounds (that is, $a \le g(x) \le b$). These constraints are called *range constraints*. The NLP solver can handle range constraints in an efficient way. Consider the following NLP problem, taken from Hock and Schittkowski (1981),

$$
\begin{aligned}
\text{minimize} \quad & f(x) = 5.35(x_3)^2 + 0.83x_1x_5 + 37.29x_1 - 40792.141 \\
\text{subject to} \quad & 0 \le a_1 + a_2x_2x_5 + a_3x_1x_4 - a_4x_3x_5 \le 92 \\
& 0 \le a_5 + a_6x_2x_5 + a_7x_1x_2 + a_8x_3^2 - 90 \le 20 \\
& 0 \le a_9 + a_{10}x_3x_5 + a_{11}x_1x_3 + a_{12}x_3x_4 - 20 \le 5 \\
& 78 \le x_1 \le 102 \\
& 33 \le x_2 \le 45 \\
& 27 \le x_i \le 45, \quad i = 3, 4, 5
\end{aligned}
$$

where the values of the parameters $a_i, i = 1, 2, \ldots, 12$, are shown in Table 16.6.

Table 16.6 Data for Example 4

i	a_i	i	a_i	i	a_i
1	85.334407	5	80.51249	9	9.300961
2	0.0056858	6	0.0071317	10	0.0047026
3	0.0006262	7	0.0029955	11	0.0012547
4	0.0022053	8	0.0021813	12	0.0019085

The initial point that is used is $x^0 = (78, 33, 27, 27, 27)$. The initial dual values of the variables and constraints are $(1, 2, 3, 4, 5)$ and $(-100, 5, 30)$, respectively. You can call the NLP solver within PROC OPTMODEL to solve this problem by writing the following statements:

```
proc optmodel;
   number l {1..5} = [78 33 27 27 27];
   number u {1..5} = [102 45 45 45 45];

   number a {1..12} =
      [85.334407 0.0056858 0.0006262 0.0022053
      80.51249 0.0071317 0.0029955 0.0021813
      9.300961 0.0047026 0.0012547 0.0019085];

   var x {j in 1..5} >= l[j] <= u[j] init l[j];

   minimize f = 5.35*x[3]^2 + 0.83*x[1]*x[5] + 37.29*x[1]
                  - 40792.141;

   con constr1:
      0 <= a[1] + a[2]*x[2]*x[5] + a[3]*x[1]*x[4] -
         a[4]*x[3]*x[5] <= 92;
   con constr2:
      0 <= a[5] + a[6]*x[2]*x[5] + a[7]*x[1]*x[2] +
         a[8]*x[3]^2 - 90 <= 20;
   con constr3:
      0 <= a[9] + a[10]*x[3]*x[5] + a[11]*x[1]*x[3] +
         a[12]*x[3]*x[4] - 20 <= 5;

   for {j in 1..5} x[j].dual = j;

   constr1.dual = -100;
   constr2.dual =    5;
   constr3.dual =   30;

   solve with nlp / algorithm=activeset initdual=true;
   print x x.dual;
   print constr1.dual;
   print constr2.dual;
   print constr3.dual;
quit;
```

The summaries and solution are shown in Output 16.4.1. In particular, the final dual values of the variables and constraints are printed.

Output 16.4.1 Summaries and the Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	5
Bounded Above	0
Bounded Below	0
Bounded Below and Above	5
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	0
Nonlinear GE (>=)	0
Nonlinear Range	3

Solution Summary	
Solver	NLP
Algorithm	Active Set
Objective Function	f
Solution Status	Optimal
Objective Value	-30689.176
Optimality Error	3.2880189E-8
Infeasibility	0
Iterations	61
Presolve Time	0.00
Solution Time	0.02

[1]	x	x.DUAL
1	78.000	48.827
2	33.000	84.678
3	29.995	0.000
4	45.000	-26.459
5	36.776	0.000

constr1.DUAL
-404.97

Output 16.4.1 *continued*

constr2.DUAL
0.00048694

constr3.DUAL
807.72

Example 16.5: Solving Large-Scale NLP Problems

The following example is a selected large-scale problem from the CUTEr test set (Gould, Orban, and Toint 2003) that has 20,400 variables, 20,400 lower bounds, and 9,996 linear equality constraints. This problem was selected to provide an idea of the size of problem that the NLP solver is capable of solving. In general, the maximum size of nonlinear optimization problems that can be solved with the NLP solver is controlled less by the number of variables and more by the density of the first and second derivatives of the nonlinear objective and constraint functions.

For large-scale problems, the default memory limit might be too small, which can lead to out-of-memory status. To prevent this occurrence, it is recommended that you set a larger memory size. See the section "Memory Limit" on page 18 in Chapter 3, "Shared Concepts," for more information.

```
proc optmodel;
   num nx = 100;
   num ny = 100;

   var x {1..nx, 0..ny+1} >= 0;
   var y {0..nx+1, 1..ny} >= 0;

   min f = (
         sum {i in 1..nx-1, j in 1..ny-1} (x[i,j] - 1)^2
      + sum {i in 1..nx-1, j in 1..ny-1} (y[i,j] - 1)^2
      + sum {i in 1..nx-1} (x[i,ny] - 1)^2
      + sum {j in 1..ny-1} (y[nx,j] - 1)^2
      ) / 2;

   con con1 {i in 2..nx-1, j in 2..ny-1}:
      (x[i,j] - x[i-1,j]) + (y[i,j] - y[i,j-1]) = 1;
   con con2 {i in 2..nx-1}:
      x[i,0] + (x[i,1] - x[i-1,1]) + y[i,1] = 1;
   con con3 {i in 2..nx-1}:
      x[i,ny+1] + (x[i,ny] - x[i-1,ny]) - y[i,ny-1] = 1;
   con con4 {j in 2..ny-1}:
      y[0,j] + (y[1,j] - y[1,j-1]) + x[1,j] = 1;
   con con5 {j in 2..ny-1}:
      y[nx+1,j] + (y[nx,j] - y[nx,j-1]) - x[nx-1,j] = 1;

   for {i in 1..nx-1} x[i,ny].lb = 1;
   for {j in 1..ny-1} y[nx,j].lb = 1;

   solve with nlp;
quit;
```

The problem and solution summaries are shown in Output 16.5.1.

Output 16.5.1 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	20400
Bounded Above	0
Bounded Below	20400
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	9996
Linear LE (<=)	0
Linear EQ (=)	9996
Linear GE (>=)	0
Linear Range	0

Solution Summary	
Solver	NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	6237011.7791
Optimality Error	5.0754294E-7
Infeasibility	2.842171E-14
Iterations	23
Presolve Time	0.01
Solution Time	0.74

Example 16.6: Solving NLP Problems That Have Several Local Minima

Some NLP problems contain many local minima. By default, the NLP solver converges to a single local minimum. However, the NLP solver can search the feasible region for other local minima. After it completes the search, it returns the point where the objective function achieves its minimum value. (This point might not be a local minimum; see the SOLTYPE= option for more details.) Consider the following example, taken from Hock and Schittkowski (1981):

$$
\begin{array}{ll}
\text{minimize} & f(x) = (x_1 - 1)^2 + (x_1 - x_2)^2 + (x_2 - x_3)^3 + (x_3 - x_4)^4 + (x_4 - x_5)^4 \\
\text{subject to} & x_1 + x_2^2 + x_3^3 = 2 + 3\sqrt{2} \\
& x_2 + x_4 - x_3^2 = -2 + 2\sqrt{2} \\
& x_1 x_5 = 2 \\
& -5 \le x_i \le 5, i = 1, \ldots, 5
\end{array}
$$

The following statements call the NLP solver to search the feasible region for different local minima. The NTHREADS= option in the SOLVE statement requests that the multistart algorithm use up to four threads. The SEED= option is specified for reproducibility, but it is not required in running the multistart algorithm.

```
proc optmodel;
   var x{i in 1..5} >= -5 <= 5 init -2;

   min f=(x[1] - 1)^2 + (x[1] - x[2])^2 + (x[2] - x[3])^3 +
         (x[3] - x[4])^4 + (x[4] - x[5])^4;

   con g1: x[1] + x[2]^2 + x[3]^3 =  2 + 3*sqrt(2);
   con g2: x[2] + x[4]   - x[3]^2 = -2 + 2*sqrt(2);
   con g3: x[1]*x[5] = 2;

   solve with nlp/multistart=(maxstarts=10) seed=1234 nthreads=4;
   print x.msinit x;
quit;
```

The PRINT statement prints the starting point (x.msinit) that led to the best local solution and the best local solution (x) that the NLP solver found in multistart mode. The SAS log is shown in Output 16.6.1.

Output 16.6.1 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 5 variables (0 free, 0 fixed).
NOTE: The problem has 0 linear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 3 nonlinear constraints (0 LE, 3 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: Using analytic derivatives for objective.
NOTE: Using analytic derivatives for nonlinear constraints.
NOTE: The NLP solver is called.
NOTE: The Interior Point Direct algorithm is used.
NOTE: The MULTISTART option is enabled.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Multistart algorithm is executing in single-machine mode.
NOTE: The Multistart algorithm is using up to 4 threads.
NOTE: Random number seed 1234 is used.
                   Best       Local  Optimality    Infeasi-  Local  Local
      Start    Objective   Objective       Error      bility  Iters  Status
          1   0.02931083  0.02931083  9.37369E-7  5.18962E-9     28  Optimal
          2   0.02931083  607.035515  4.76175E-7  1.1642E-12     28  Optimal
          3 * 0.02931083  607.035515  4.76156E-7   2.558E-13     12  Optimal
          4   0.02931083  52.9025797  5.01512E-7   9.333E-11     10  Optimal
          5   0.02931083  0.02931083  9.40456E-7  8.18281E-8     42  Optimal
          6   0.02931083  27.8719052  7.65419E-7  1.0303E-13      7  Optimal
          7   0.02931083  27.8719052  7.65418E-7  8.8818E-14      7  Optimal
          8   0.02931083  64.8739923  4.62578E-7  2.29006E-8     10  Optimal
          9   0.02931083  0.02931083  9.36835E-7  7.92016E-9     17  Optimal
         10   0.02931083  0.02931083  9.36209E-7  6.4694E-10     15  Optimal
NOTE: The Multistart algorithm generated 800 sample points.
NOTE: 5 distinct local optima were found.
NOTE: The best objective value found by local solver = 0.0293108307.
NOTE: The solution found by local solver with objective = 0.0293108307 was
      returned.
```

The first column in the log indicates the index of the current starting point. An additional indicator (*) can appear after the index to provide more information about the optimization run that started from the current point. For more information, see the section "Iteration Log for Multistart" on page 974. The second column records the best objective that has been found so far. Columns 3 to 6 report the objective value, optimality error, infeasibility, and number of iterations that the local solver returned when it was started from the current starting point. Finally, the last column records the status of the local solver—namely, whether it was able to converge to a local optimum from the current starting point.

The summaries and solution are shown in Output 16.6.2. Note that the best local solution was found by starting the local solver from a point at x.msinit.

Output 16.6.2 Summaries and the Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	5
Bounded Above	0
Bounded Below	0
Bounded Below and Above	5
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	3
Nonlinear GE (>=)	0
Nonlinear Range	0

Solution Summary	
Solver	Multistart NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	0.0293108307
Number of Starts	10
Number of Sample Points	800
Number of Distinct Optima	5
Random Seed Used	1234
Optimality Error	9.3620894E-7
Infeasibility	6.469356E-10
Presolve Time	0.00
Solution Time	0.02

[1]	x.MSINIT	x
1	-0.23856	1.1166
2	2.93912	1.2204
3	1.08486	1.5378
4	-1.11094	1.9728
5	1.80540	1.7911

Alternatively, the following SAS statements show how you can solve this problem in a distributed computing environment. After you create a CAS session named mysess, you specify the SESSREF="MYSESS" option to run the OPTMODEL procedure on CAS. For more information about creating a CAS session, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts." Note that the NTHREADS= option in PROC OPTMODEL is used to specify the number of threads to use on each CAS node.

```
proc optmodel sessref="mysess" nthreads=16;
   var x{i in 1..5} >= -5 <= 5 init -2;

   min f=(x[1] - 1)^2 + (x[1] - x[2])^2 + (x[2] - x[3])^3 +
         (x[3] - x[4])^4 + (x[4] - x[5])^4;

   con g1: x[1] + x[2]^2 + x[3]^3 =  2 + 3*sqrt(2);
   con g2: x[2] + x[4]   - x[3]^2 = -2 + 2*sqrt(2);
   con g3: x[1]*x[5] = 2;

   solve with nlp/multistart=(maxstarts=200) seed=12345;
   print x;
quit;
```

The SAS log is displayed in Output 16.6.3. It shows that 120 worker nodes with 16 threads on each node are used in distributed mode.

Output 16.6.3 Progress of the Algorithm as Shown in the Log

```
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 5 variables (0 free, 0 fixed).
NOTE: The problem has 0 linear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 3 nonlinear constraints (0 LE, 3 EQ, 0 GE, 0 range).
NOTE: The OPTMODEL presolver removed 0 variables, 0 linear constraints, and 0
      nonlinear constraints.
NOTE: The SOLVE statement is executing in the distributed computing environment
      with 120 worker nodes.
NOTE: Using analytic derivatives for objective.
NOTE: Using analytic derivatives for nonlinear constraints.
NOTE: The NLP solver is called.
NOTE: The Interior Point Direct algorithm is used.
NOTE: The MULTISTART option is enabled.
NOTE: The nondeterministic parallel mode is enabled.
NOTE: The Multistart algorithm is executing in the distributed computing
      environment with 120 worker nodes.
NOTE: The Multistart algorithm is using up to 16 threads.
NOTE: Random number seed 12345 is used.
WARNING: The solution of the current run may not be reproducible even if you
         specify SEED=12345 in a subsequent SOLVE statement.
                    Best       Local  Optimality    Infeasi-  Local  Local
      Start    Objective   Objective       Error      bility  Iters  Status
          1   52.9025797  52.9025797  5.01576E-7  1.3956E-10     11  Optimal
          2   52.9025797  52.9025797  5.01648E-7  1.8517E-10     14  Optimal
          3   52.9025797  52.9025797  5.01626E-7  1.6408E-10     14  Optimal
          4   52.9025797  607.035515   4.7619E-7   2.256E-12     23  Optimal
          5   52.9025797  607.035515  4.76175E-7  1.1036E-12     14  Optimal
              << skipped lines >>
        194   0.02931083  52.9025797  5.01707E-7  2.2285E-10     38  Optimal
        195   0.02931083  607.035515  4.76179E-7  1.3753E-12     21  Optimal
        196   0.02931083  0.02931083  9.36136E-7  1.00689E-9     24  Optimal
        197   0.02931083  52.9025797  5.01494E-7  8.9499E-11     12  Optimal
        198   0.02931083  607.035515  4.76181E-7  1.5814E-12     41  Optimal
        199   0.02931083  607.035515  4.76183E-7   1.688E-12     31  Optimal
        200   0.02931083  52.9025797  5.02824E-7  9.1894E-10     12  Optimal
NOTE: The Multistart algorithm generated 192000 sample points.
NOTE: 172 distinct local optima were found.
NOTE: The best objective value found by local solver = 0.0293108307.
NOTE: The solution found by local solver with objective = 0.0293108307 was
      returned.
```

Output 16.6.4 shows the summaries and solution.

Output 16.6.4 Summaries and the Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Nonlinear
Number of Variables	5
Bounded Above	0
Bounded Below	0
Bounded Below and Above	5
Free	0
Fixed	0
Number of Constraints	3
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Nonlinear LE (<=)	0
Nonlinear EQ (=)	3
Nonlinear GE (>=)	0
Nonlinear Range	0

Solution Summary	
Solver	Multistart NLP
Algorithm	Interior Point Direct
Objective Function	f
Solution Status	Optimal
Objective Value	0.0293108307
Number of Starts	200
Number of Sample Points	192000
Number of Distinct Optima	172
Random Seed Used	12345
Optimality Error	1.7535577E-8
Infeasibility	5.110579E-12
Presolve Time	0.00
Solution Time	0.06

[1]	x
1	1.1166
2	1.2204
3	1.5378
4	1.9728
5	1.7911

Example 16.7: Maximum Likelihood Weibull Estimation

The following data are taken from Lawless (1982, p. 193) and represent the number of days that it took rats that were painted with a carcinogen to develop carcinoma. The last two observations are censored data from a group of 19 rats.

```
data pike;
   input days cens @@;
   datalines;
143  0  164  0  188  0  188  0
190  0  192  0  206  0  209  0
213  0  216  0  220  0  227  0
230  0  234  0  246  0  265  0
304  0  216  1  244  1
;
```

Suppose you want to compute the maximum likelihood estimates of the scale parameter σ (α in Lawless), the shape parameter c (β in Lawless), and the location parameter θ (μ in Lawless). The observed likelihood function of the three-parameter Weibull transformation (Lawless 1982, p. 191) is

$$L(\theta,\sigma,c) = \frac{c^m}{\sigma^m}\prod_{i\in D}\left(\frac{t_i-\theta}{\sigma}\right)^{c-1}\prod_{i=1}^{n}\exp\left(-\left(\frac{t_i-\theta}{\sigma}\right)^c\right)$$

where n is the number of individuals involved in the experiment, D is the set of individuals whose lifetimes are observed, $m = |D|$, and t_i is defined by the data set. Then the log-likelihood function is

$$l(\theta,\sigma,c) = m\log c - mc\log\sigma + (c-1)\sum_{i\in D}\log(t_i-\theta) - \sum_{i=1}^{n}\left(\frac{t_i-\theta}{\sigma}\right)^c$$

For $c < 1$, the logarithmic terms become infinite as $\theta \uparrow \min_{i\in D}(t_i)$. That is, $l(\theta,\sigma,c)$ is unbounded. Thus our interest is restricted to c values greater than or equal to 1. Further, for the logarithmic terms to be defined, it is required that $\sigma > 0$ and $\theta < \min_{i\in D}(t_i)$.

The following PROC OPTMODEL call specifies the maximization of the log-likelihood function for the three-parameter Weibull estimation:

```
proc optmodel;
   set OBS;
   num days {OBS};
   num cens {OBS};
   read data pike into OBS=[_N_] days cens;
   var sig   >= 1.0e-6 init 10;
   var c     >= 1.0e-6 init 10;
   var theta >= 0 <= min {i in OBS: cens[i] = 0} days[i] init 10;

   impvar fi {i in OBS} =
      (if cens[i] = 0 then
```

```
        log(c) - c * log(sig) + (c - 1) * log(days[i] - theta)
      )
    - ((days[i] - theta) / sig)^c;
   max logf = sum {i in OBS} fi[i];

   set VARS = 1.._NVAR_;
   num mycov {i in VARS, j in 1..i};
   solve with NLP / algorithm=interiorpoint covest=(cov=2 covout=mycov);
   print sig c theta;
   print mycov;
   create data covdata from [i j]={i in VARS, j in 1..i}
   var_i=_VAR_[i].name var_j=_VAR_[j].name mycov;
   num std_error {i in VARS} = sqrt(mycov[i,i]);
   num t_stat    {i in VARS} = _VAR_[i].sol / std_error[i];
   num p_value   {i in VARS} = 2 * (1 - cdf('T', t_stat[i], card(OBS)));
   print _VAR_.name _VAR_ std_error t_stat p_value;
quit;
```

The solution is displayed in Output 16.7.1. The solution that the NLP solver obtains closely matches the local maximum $\theta^* = 122$, $\sigma^* = 108.4$, and $c^* = 2.712$ that are given in Lawless (1982, p. 193). Note that the result from the NLP solver is platform-dependent and might not match this result.

Output 16.7.1 Three-Parameter Weibull Estimation Results

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	logf
Objective Type	Nonlinear
Number of Variables	3
Bounded Above	0
Bounded Below	2
Bounded Below and Above	1
Free	0
Fixed	0
Number of Constraints	0

Output 16.7.1 *continued*

Solution Summary	
Solver	NLP
Algorithm	Interior Point
Objective Function	logf
Solution Status	Optimal
Objective Value	-87.32424712
Optimality Error	5E-7
Infeasibility	0
Iterations	27
Presolve Time	0.00
Solution Time	0.20

sig	c	theta
108.38	2.7115	122.03

mycov			
	1	**2**	**3**
1	1259.9447		
2	35.5368	1.3311	
3	-1056.9633	-31.6623	977.5953

[1]	_VAR_.NAME	_VAR_	std_error	t_stat	p_value
1	sig	108.3826	35.4957	3.0534	0.00653936
2	c	2.7115	1.1537	2.3501	0.02972289
3	theta	122.0261	31.2665	3.9028	0.00095673

Example 16.8: Finding an Irreducible Infeasible Set

This example demonstrates the use of the IIS= option to locate an irreducible infeasible set. Suppose you have the following nonlinear programming problem:

$$
\begin{array}{lrcccccccl}
\text{minimize} & & x_1^4 & + & x_2^4 & + & x_3^4 & & & \\
\text{subject to} & & x_1 & + & x_2 & & & \geq & 10 & \text{(c1)} \\
 & & x_1 & & & + & x_3 & \leq & 4 & \text{(c2)} \\
 & 4 \leq & & & x_2 & + & x_3 & \leq & 5 & \text{(c3)} \\
 & & x_1^2 & & & + & x_3 & \leq & 5 & \text{(c4)} \\
 & & & & & x_1, & x_2 & \geq & 0 & \\
 & & & & 0 & \leq & x_3 & \leq & 3 &
\end{array}
$$

It is easy to verify that the following three linear constraints and one variable bound form an IIS for this problem:

$$
\begin{array}{rcccccl}
x_1 & + & x_2 & & \geq & 10 & \text{(c1)} \\
x_1 & & & + \; x_3 & \leq & 4 & \text{(c2)} \\
 & & x_2 & + \; x_3 & \leq & 5 & \text{(c3)} \\
 & & & x_3 & \geq & 0 &
\end{array}
$$

You can formulate the problem and call the NLP solver by using the following statements:

```
proc optmodel;
   /* declare variables */
   var x{1..3} >= 0;

   /* upper bound on variable x[3] */
   x[3].ub = 3;

   /* objective function */
   min f = x[1]^4 + x[2]^4 + x[3]^4;

   /* constraints */
   con c1: x[1] + x[2] >= 10;
   con c2: x[1] + x[3] <= 4;
   con c3: 4 <= x[2] + x[3] <= 5;
   con c4: x[1]^2 + x[3] <= 5;

   solve with nlp / iis = true;

   print x.status;
   print c1.status c2.status c3.status;

   expand / IIS;
quit;
```

The SAS log output is shown in Output 16.8.1. Note that the PROC OPTMODEL presolver is disabled because the IIS= option is enabled. Also, a warning message is displayed to alert the user that the nonlinear constraints are ignored for the purpose of detecting an IIS.

Output 16.8.1 Finding an IIS: Original Problem

```
NOTE: The OPTMODEL presolver is disabled when the IIS= option is enabled.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 linear constraints (1 LE, 0 EQ, 1 GE, 1 range).
NOTE: The problem has 6 linear constraint coefficients.
NOTE: The problem has 1 nonlinear constraints (1 LE, 0 EQ, 0 GE, 0 range).
WARNING: The nonlinear constraints are ignored because the IIS= option is
         enabled.
NOTE: The NLP solver is called.
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                           Objective
      Phase Iteration        Value         Time
       P 1          1    6.000000E+00         0
       P 1          3    9.998343E-01         0
NOTE: Applying the IIS sensitivity filter.
NOTE: The sensitivity filter removed 1 constraints and 3 variable bounds.
NOTE: Applying the IIS deletion filter.
NOTE: Processing constraints.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: Processing variable bounds.
      Processed     Removed      Time
              0           0         0
              1           0         0
              2           0         0
              3           0         0
NOTE: The deletion filter removed 0 constraints and 0 variable bounds.
NOTE: The IIS= option found this problem to be infeasible.
NOTE: The IIS= option found an irreducible infeasible set with 1 variables and
      3 constraints.
NOTE: The IIS solve time is 0.00 seconds.
```

There are two ways to display the rows and columns that are included in the IIS. One way is to use the PRINT statement to print the value of the .status suffix for each variable and constraint. The more straightforward approach is to use the EXPAND statement with the IIS option.

The “Solution Summary” table and the output of both approaches appear in Output 16.8.2.

Output 16.8.2 Solution Summary and PRINT Statement Output

The OPTMODEL Procedure

Solution Summary	
Solver	NLP
Algorithm	IIS
Objective Function	f
Solution Status	Infeasible
Iterations	10
Iterations2	0
Presolve Time	0.00
Solution Time	0.01

[1]	x.STATUS
1	
2	
3	I_L

c1.STATUS	c2.STATUS	c3.STATUS
I_L	I_U	I_U

```
The OPTMODEL Procedure

Var x[3] >= 0 <= 3
Constraint c1: x[1] + x[2] >= 10
Constraint c2: x[1] + x[3] <= 4
Constraint c3: 4 <= x[2] + x[3] <= 5
```

The "Solution Summary" table shows that the problem is infeasible. As you can see, the lower bound of variable x_3, the lower bound of constraint c1, and the upper bounds of constraints c2 and c3 form an IIS.

Making any of the components in the preceding IIS nonbinding removes the infeasibility from the IIS. Because there could be multiple IISs, you would want to remove the infeasibility from the preceding IIS and call the NLP solver with the IIS= option enabled again to see whether there is any other IIS. The following statements show how to modify the original PROC OPTMODEL statements to set the upper bound of constraint c3 to infinity, represented by CONSTANT('BIG'), and invoke the NLP IIS detection:

```
/* relax upper bound on constraint c3 */
c3.ub = constant('BIG');

solve with nlp / iis = true;

print x.status;
print c1.status c2.status c3.status;
```

The SAS log output for the modified problem is shown in Output 16.8.3.

Output 16.8.3 Finding an IIS: Modified Problem

```
NOTE: The OPTMODEL presolver is disabled when the IIS= option is enabled.
NOTE: Problem generation will use 12 threads.
NOTE: The problem has 3 variables (0 free, 0 fixed).
NOTE: The problem has 3 linear constraints (1 LE, 0 EQ, 2 GE, 0 range).
NOTE: The problem has 6 linear constraint coefficients.
NOTE: The problem has 1 nonlinear constraints (1 LE, 0 EQ, 0 GE, 0 range).
WARNING: The nonlinear constraints are ignored because the IIS= option is
         enabled.
NOTE: The NLP solver is called.
NOTE: The LP solver is called.
NOTE: The IIS= option is enabled.
                           Objective
      Phase Iteration        Value         Time
       P 1          1    1.400000E+01         0
       P 1          2    0.000000E+00         0
NOTE: The IIS= option found this problem to be feasible.
NOTE: The IIS solve time is 0.00 seconds.
```

The "Solution Summary" table and the output of the PRINT statements appear in Output 16.8.4. As you can see, both the variable status and constraint status tables are empty. There is no other IIS, and the problem becomes feasible.

Output 16.8.4 Solution Summary and PRINT Statement Output

The OPTMODEL Procedure

Solution Summary	
Solver	NLP
Algorithm	IIS
Objective Function	f
Solution Status	Feasible
Iterations	2
Iterations2	0
Presolve Time	0.00
Solution Time	0.00

[1]	x.STATUS
1	
2	
3	

c1.STATUS	c2.STATUS	c3.STATUS

References

Akrotirianakis, I., and Rustem, B. (2005). "Globally Convergent Interior-Point Algorithm for Nonlinear Programming." *Journal of Optimization Theory and Applications* 125:497–521.

Armand, P., Gilbert, J. C., and Jan-Jégou, S. (2002). "A BFGS-IP Algorithm for Solving Strongly Convex Optimization Problems with Feasibility Enforced by an Exact Penalty Approach." *Mathematical Programming* 92:393–424.

Armand, P., and Omheni, R. (2017a). "A Globally and Quadratically Convergent Primal-Dual Augmented Lagrangian Algorithm for Equality Constrained Optimization." *Optimization Methods and Software* 32:1–21.

Armand, P., and Omheni, R. (2017b). "A Mixed Logarithmic Barrier-Augmented Lagrangian Method for Nonlinear Optimization." *Journal of Optimization Theory and Applications* 173:523–547.

Erway, J., Gill, P. E., and Griffin, J. D. (2007). "Iterative Solution of Augmented Systems Arising in Interior Point Methods." *SIAM Journal on Optimization* 18:666–690.

Forsgren, A., and Gill, P. E. (1998). "Primal-Dual Interior Methods for Nonconvex Nonlinear Programming." *SIAM Journal on Optimization* 8:1132–1152.

Forsgren, A., Gill, P. E., and Wright, M. H. (2002). "Interior Methods for Nonlinear Optimization." *SIAM Review* 44:525–597.

Gill, P. E., and Robinson, D. P. (2010). "A Primal-Dual Augmented Lagrangian." *Computational Optimization and Applications* 47:1–25.

Gould, N. I. M., Orban, D., and Toint, P. L. (2003). "CUTEr and SifDec: A Constrained and Unconstrained Testing Environment, Revised." *ACM Transactions on Mathematical Software* 29:373–394.

Hock, W., and Schittkowski, K. (1981). *Test Examples for Nonlinear Programming Codes.* Vol. 187 of Lecture Notes in Economics and Mathematical Systems. Berlin: Springer-Verlag.

Lawless, J. F. (1982). *Statistical Methods and Methods for Lifetime Data*. New York: John Wiley & Sons.

Moré, J. J., Garbow, B. S., and Hillstrom, K. E. (1981). "Testing Unconstrained Optimization Software." *ACM Transactions on Mathematical Software* 7:17–41.

Nocedal, J., and Wright, S. J. (1999). *Numerical Optimization*. New York: Springer-Verlag.

Vanderbei, R. J. (1999). "LOQO: An Interior Point Code for Quadratic Programming." *Optimization Methods and Software* 11:451–484.

Wächter, A., and Biegler, L. T. (2006). "On the Implementation of an Interior-Point Filter Line-Search Algorithm for Large-Scale Nonlinear Programming." *Mathematical Programming* 106:25–57.

Wright, S. J. (1997). *Primal-Dual Interior-Point Methods*. Philadelphia: SIAM.

Yamashita, H. (1998). "A Globally Convergent Primal-Dual Interior Point Method for Constrained Optimization." *Optimization Methods and Software* 10:443–469.

Chapter 17
The Quadratic Programming Solver

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Overview: QP Solver

The OPTMODEL procedure provides a framework for specifying and solving quadratic programs.

Mathematically, a quadratic programming (QP) problem can be stated as follows:

$$\begin{aligned} \min \quad & \tfrac{1}{2}\,\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} \quad & \mathbf{A}\mathbf{x}\ \{\geq, =, \leq\}\ \mathbf{b} \\ & \mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{aligned}$$

where

$\mathbf{Q}$	$\in$	$\mathbb{R}^{n\times n}$	is the quadratic (also known as Hessian) matrix
$\mathbf{A}$	$\in$	$\mathbb{R}^{m\times n}$	is the constraints matrix
$\mathbf{x}$	$\in$	$\mathbb{R}^{n}$	is the vector of decision variables
$\mathbf{c}$	$\in$	$\mathbb{R}^{n}$	is the vector of linear objective function coefficients
$\mathbf{b}$	$\in$	$\mathbb{R}^{m}$	is the vector of constraints right-hand sides (RHS)
$\mathbf{l}$	$\in$	$\mathbb{R}^{n}$	is the vector of lower bounds on the decision variables
$\mathbf{u}$	$\in$	$\mathbb{R}^{n}$	is the vector of upper bounds on the decision variables

The quadratic matrix $\mathbf{Q}$ is assumed to be symmetric; that is,

$$q_{ij} = q_{ji}, \quad \forall i, j = 1, \ldots, n$$

Indeed, it is easy to show that even if $\mathbf{Q} \neq \mathbf{Q}^{\mathrm{T}}$, the simple modification

$$\tilde{\mathbf{Q}} = \frac{1}{2}(\mathbf{Q} + \mathbf{Q}^{\mathrm{T}})$$

produces an equivalent formulation $\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \equiv \mathbf{x}^{\mathrm{T}}\tilde{\mathbf{Q}}\mathbf{x}$; hence symmetry is assumed. When you specify a quadratic matrix, it suffices to list only lower triangular coefficients.

In addition to being symmetric, $\mathbf{Q}$ is also required to be positive semidefinite for minimization type of models:

$$\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \geq 0, \quad \forall \mathbf{x} \in \mathbb{R}^{n}$$

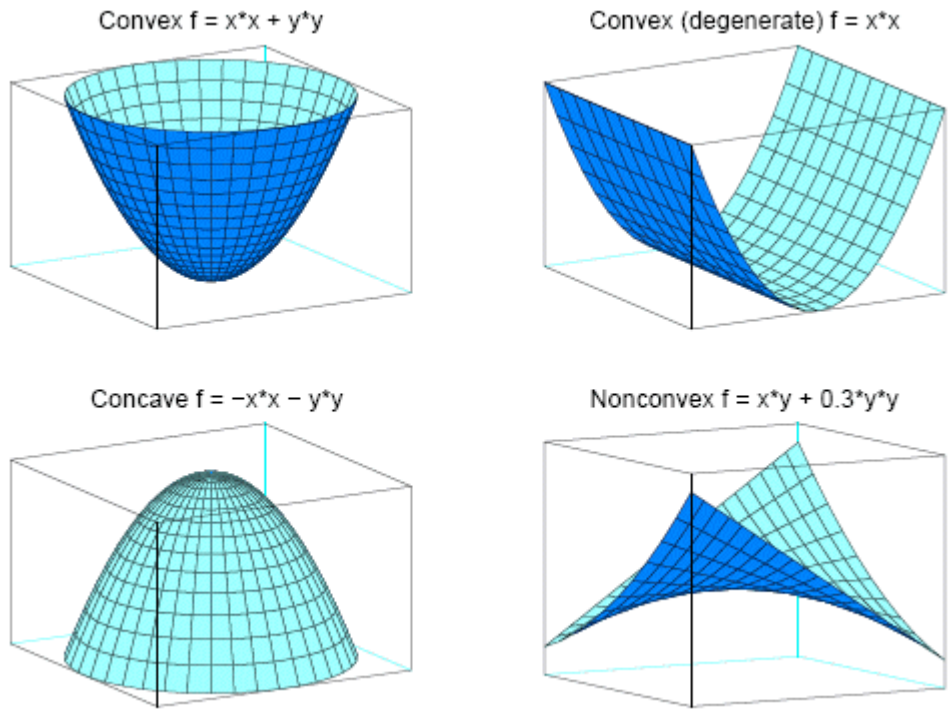
$\mathbf{Q}$ is required to be negative semidefinite for maximization type of models. Convexity can come as a result of a matrix-matrix multiplication

$$\mathbf{Q} = \mathbf{L}\mathbf{L}^{\mathrm{T}}$$

or as a consequence of physical laws, and so on. See Figure 17.1 for examples of convex, concave, and nonconvex objective functions.

The order of constraints is insignificant. Some or all components of $\mathbf{l}$ or $\mathbf{u}$ (lower and upper bounds, respectively) can be omitted.

Figure 17.1 Examples of Convex, Concave, and Nonconvex Objective Functions



Getting Started: QP Solver

Consider a small illustrative example. Suppose you want to minimize a two-variable quadratic function $f(x_1, x_2)$ on the nonnegative quadrant, subject to two constraints:

$$\begin{array}{rrcrcrcrcr} \min & 2x_1 & + & 3x_2 & + & x_1^2 & + & 10x_2^2 & + & 2.5x_1x_2 \\ \text{subject to} & x_1 & - & x_2 & \leq & 1 & & & & \\ & x_1 & + & 2x_2 & \geq & 100 & & & & \\ & x_1 & & & \geq & 0 & & & & \\ & & & x_2 & \geq & 0 & & & & \end{array}$$

To use the OPTMODEL procedure, it is not necessary to fit this problem into the general QP formulation mentioned in the section "Overview: QP Solver" on page 1005 and to compute the corresponding parameters. However, since these parameters are closely related to the data set that is used by the OPTQP procedure and has a quadratic programming system (QPS) format, you can compute these parameters as follows. The linear objective function coefficients, vector of right-hand sides, and lower and upper bounds are identified immediately as

$$\mathbf{c} = \begin{bmatrix} 2 \\ 3 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 1 \\ 100 \end{bmatrix}, \quad \mathbf{l} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} +\infty \\ +\infty \end{bmatrix}$$

Carefully construct the quadratic matrix $\mathbf{Q}$. Observe that you can use symmetry to separate the main-diagonal and off-diagonal elements:

$$\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} \equiv \frac{1}{2}\sum_{i,j=1}^{n} x_i\, q_{ij}\, x_j = \frac{1}{2}\sum_{i=1}^{n} q_{ii}\, x_i^2 + \sum_{i>j} x_i\, q_{ij}\, x_j$$

The first expression

$$\frac{1}{2}\sum_{i=1}^{n} q_{ii}\, x_i^2$$

sums the main-diagonal elements. Thus, in this case you have

$$q_{11} = 2, \quad q_{22} = 20$$

Notice that the main-diagonal values are doubled in order to accommodate the 1/2 factor. Now the second term

$$\sum_{i>j} x_i\, q_{ij}\, x_j$$

sums the off-diagonal elements in the strict lower triangular part of the matrix. The only off-diagonal $(x_i\, x_j,\ i \neq j)$ term in the objective function is $2.5\, x_1\, x_2$, so you have

$$q_{21} = 2.5$$

Notice that you do not need to specify the upper triangular part of the quadratic matrix.

Finally, the matrix of constraints is as follows:

$$\mathbf{A} = \begin{bmatrix} 1 & -1 \\ 1 & 2 \end{bmatrix}$$

The following OPTMODEL program formulates the preceding problem in a manner that is very close to the mathematical specification of the given problem:

```
/* getting started */
proc optmodel;
   var x1 >= 0; /* declare nonnegative variable x1 */
   var x2 >= 0; /* declare nonnegative variable x2 */

   /* objective: quadratic function f(x1, x2) */
   minimize f =
       /* the linear objective function coefficients */
       2 * x1 + 3 * x2 +

       /* quadratic <x, Qx> */
       x1 * x1 + 2.5 * x1 * x2 + 10 * x2 * x2;

   /* subject to the following constraints */
   con r1: x1 - x2 <= 1;
   con r2: x1 + 2 * x2 >= 100;
```

```
   /* specify iterative interior point algorithm (QP)
    * in the SOLVE statement */
   solve with qp;

   /* print the optimal solution */
   print x1 x2;
   save qps qpsdata;
quit;
```

The "with qp" clause in the SOLVE statement invokes the QP solver to solve the problem. The output is shown in Figure 17.2.

Figure 17.2 Summaries and Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	2
Bounded Above	0
Bounded Below	2
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	2
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	4
Hessian Diagonal Elements	2
Hessian Elements Below Diagonal	1

Figure 17.2 *continued*

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	15018.000046
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	7.8497851E-9
Complementarity	0
Iterations	4
Presolve Time	0.00
Solution Time	0.04

x1	x2
34	33

In this example, the SAVE QPS statement is used to save the QP problem in the QPS-format data set qpsdata, shown in Figure 17.3. The data set is consistent with the parameters of general quadratic programming previously computed. Also, the data set can be used as input to the OPTQP procedure.

Figure 17.3 QPS-Format Data Set

Obs	FIELD1	FIELD2	FIELD3	FIELD4	FIELD5	FIELD6
1	NAME		qpsdata	.		.
2	ROWS			.		.
3	N	f		.		.
4	L	r1		.		.
5	G	r2		.		.
6	COLUMNS			.		.
7		x1	f	2.0	r1	1
8		x1	r2	1.0		.
9		x2	f	3.0	r1	-1
10		x2	r2	2.0		.
11	RHS			.		.
12		.RHS.	r1	1.0		.
13		.RHS.	r2	100.0		.
14	QSECTION			.		.
15		x1	x1	2.0		.
16		x1	x2	2.5		.
17		x2	x2	20.0		.
18	ENDATA			.		.

Syntax: QP Solver

The following statement is available in the OPTMODEL procedure:

SOLVE WITH QP < / *options* > **;**

Functional Summary

Table 17.1 summarizes the list of options available for the SOLVE WITH QP statement, classified by function.

Table 17.1 Options for the QP Solver

Description	Option
Solver Options	
Enables or disables IIS detection	IIS=
Control Options	
Specifies the stopping criterion based on duality gap	DUALITYGAP=
Specifies the dual feasibility tolerance	DUALTOL=
Specifies how often to print the solution progress	LOGFREQ=
Specifies the detail of solution progress to print in log	LOGLEVEL=
Specifies the maximum number of iterations	MAXITER=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the maximum number of threads	NTHREADS=
Specifies the type of presolve	PRESOLVER=
Specifies the primal feasibility tolerance	PRIMALTOL=
Specifies units of CPU time or real time	TIMETYPE=

QP Solver Options

This section describes the options recognized by the QP solver. These options can be specified after a forward slash (/) in the SOLVE statement, provided that the QP solver is explicitly specified using a WITH clause.

The QP solver does not provide an intermediate solution if the solver terminates before reaching optimality.

DUALITYGAP=δ

specifies the desired relative duality gap, $\delta \in [1E{-}9, 1E{-}4]$. This is the relative difference between the primal and dual objective function values and is the primary solution quality parameter. For more information, see the section "Interior Point Algorithm: Overview" on page 1014. The default value is 1E–6.

DUALTOL=β

OPTTOL=β

specifies the maximum relative dual constraints violation, $\beta \in [1E–9, 1E–4]$. For more information, see the section "Interior Point Algorithm: Overview" on page 1014. The default value is 1E–6.

IIS=FALSE | TRUE

specifies whether to attempt to identify a set of constraints and variables that form an irreducible infeasible set (IIS). You can specify the following values:

FALSE disables IIS detection.

TRUE enables IIS detection.

If an IIS is found, you can find information about the infeasibilities in the .status values of the constraints and variables. For more information about this option, see the section "Irreducible Infeasible Set" on page 1019. For more information about the .status suffix, see the section "Suffixes" on page 420. By default, IIS=FALSE.

LOGFREQ=*k*

PRINTFREQ=*k*

prints the solution progress to the iteration log after every k iterations, where k is an integer between 0 and the largest four-byte signed integer, which is $2^{31} - 1$. The value $k = 0$ suppresses printing of the progress of the solution. By default, LOGFREQ=1.

LOGLEVEL=NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that the QP solver displays in the SAS log, from a solver summary to details at each iteration. You can specify the following values:

NONE turns off all solver-related messages in the SAS log.

BASIC displays a solver summary after stopping.

MODERATE prints a solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

AGGRESSIVE prints a detailed solver summary and an iteration log by using the value that you specify in the LOGFREQ= option.

By default, LOGLEVEL=MODERATE.

MAXITER=*k*

specifies the maximum number of iterations, where k can be any integer between 1 and the largest four-byte signed integer, which is $2^{31} - 1$. If you do not specify this option, the procedure does not stop based on the number of iterations performed.

MAXTIME=*t*

specifies an upper limit of t units of time for the optimization process, including problem generation time and solution time. The value of the TIMETYPE= option determines the type of units used. If you do not specify the MAXTIME= option, the solver does not stop based on the amount of time elapsed. The value of t can be any positive number; the default value is the positive number that has the largest absolute value that can be represented in your operating environment.

NTHREADS=*k*

specifies the number of threads that the QP solver can use, where *k* can be any integer between 1 and 256, inclusive. The default is the value of the OPTMODEL NTHREADS= option.

Specifying *k* as a number greater than the actual number of available cores might result in reduced performance. Specifying a high value for *k* does not guarantee shorter solution time; the actual change in solution time depends on the computing hardware and the scalability of the underlying algorithms in the QP solver. In some circumstances, the QP solver might use fewer than *k* threads because the solver's internal algorithms have determined that a smaller number is preferable.

PRESOLVER=AUTOMATIC | **NONE** | **BASIC** | **MODERATE** | **AGGRESSIVE**

specifies the presolve level. You can specify the following values:

AUTOMATIC	applies the presolver by using the default setting.
NONE	disables the presolver.
BASIC	applies the basic presolver.
MODERATE	applies the moderate presolver.
AGGRESSIVE	applies the aggressive presolver.

By default, PRESOLVER=AUTOMATIC.

PRIMALTOL=α

FEASTOL=α

specifies the maximum relative bound and primal constraints violation, $\alpha \in$ [1E–9, 1E–4]. For more information, see the section "Interior Point Algorithm: Overview" on page 1014. The default value is 1E–6.

TIMETYPE=CPU | **REAL**

specifies the units of time used by the MAXTIME= option and reported by the PRESOLVE_TIME and SOLUTION_TIME terms in the _OROPTMODEL_ macro variable. You can specify the following values:

CPU	specifies that units are in CPU time.
REAL	specifies that units are in real time.

The "Optimization Statistics" table, an output of the OPTMODEL procedure if you specify PRINTLEVEL=2 in the PROC OPTMODEL statement, also includes the same time units for Presolver Time, Solver Time, and other times (such as Problem Generation Time).

By default, TIMETYPE=REAL.

Details: QP Solver

Interior Point Algorithm: Overview

The QP solver implements an infeasible primal-dual predictor-corrector interior point algorithm. To illustrate the algorithm and the concepts of duality and dual infeasibility, consider the following QP formulation (the primal):

$$\begin{array}{rl} \min & \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} + \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & \mathbf{A}\mathbf{x} \geq \mathbf{b} \\ & \mathbf{x} \geq \mathbf{0} \end{array}$$

The corresponding dual formulation is

$$\begin{array}{rrcrcrcl} \max & -\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Q}\mathbf{x} & + & \mathbf{b}^{\mathrm{T}}\mathbf{y} & & & & \\ \text{subject to} & -\mathbf{Q}\mathbf{x} & + & \mathbf{A}^{\mathrm{T}}\mathbf{y} & + & \mathbf{w} & = & \mathbf{c} \\ & & & & & \mathbf{y} & \geq & \mathbf{0} \\ & & & & & \mathbf{w} & \geq & \mathbf{0} \end{array}$$

where $\mathbf{y} \in \mathbb{R}^m$ refers to the vector of dual variables and $\mathbf{w} \in \mathbb{R}^n$ refers to the vector of dual slack variables.

The dual makes an important contribution to the certificate of optimality for the primal. The primal and dual constraints combined with complementarity conditions define the first-order optimality conditions, also known as KKT (Karush-Kuhn-Tucker) conditions, which can be stated as follows where $\mathbf{e} \equiv (1, \ldots, 1)^{\mathrm{T}}$ of appropriate dimension and $\mathbf{s} \in \mathbb{R}^m$ is the vector of primal *slack* variables:

$$\begin{array}{rcll} \mathbf{A}\mathbf{x} - \mathbf{s} & = & \mathbf{b} & \text{(primal feasibility)} \\ -\mathbf{Q}\mathbf{x} + \mathbf{A}^{\mathrm{T}}\mathbf{y} + \mathbf{w} & = & \mathbf{c} & \text{(dual feasibility)} \\ \mathbf{W}\mathbf{X}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{S}\mathbf{Y}\mathbf{e} & = & \mathbf{0} & \text{(complementarity)} \\ \mathbf{x},\ \mathbf{y},\ \mathbf{w},\ \mathbf{s} & \geq & \mathbf{0} & \end{array}$$

NOTE: Slack variables (the *s* vector) are automatically introduced by the solver when necessary; it is therefore recommended that you not introduce any slack variables explicitly. This enables the solver to handle slack variables much more efficiently.

The letters $\mathbf{X}$, $\mathbf{Y}$, $\mathbf{W}$, and $\mathbf{S}$ denote matrices with corresponding x, y, w, and s on the main diagonal and zero elsewhere, as in the following example:

$$\mathbf{X} \equiv \begin{bmatrix} x_1 & 0 & \cdots & 0 \\ 0 & x_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & x_n \end{bmatrix}$$

If $(\mathbf{x}^*, \mathbf{y}^*, \mathbf{w}^*, \mathbf{s}^*)$ is a solution of the previously defined system of equations that represent the KKT conditions, then $\mathbf{x}^*$ is also an optimal solution to the original QP model.

At each iteration the interior point algorithm solves a large, sparse system of linear equations,

$$\begin{bmatrix} \mathbf{Y}^{-1}\mathbf{S} & \mathbf{A} \\ \mathbf{A}^{\mathrm{T}} & -\mathbf{Q} - \mathbf{X}^{-1}\mathbf{W} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{y} \\ \Delta\mathbf{x} \end{bmatrix} = \begin{bmatrix} \Xi \\ \Theta \end{bmatrix}$$

where $\Delta\mathbf{x}$ and $\Delta\mathbf{y}$ denote the vector of *search directions* in the primal and dual spaces, respectively, and Θ and Ξ constitute the vector of the right-hand sides.

The preceding system is known as the reduced KKT system. The QP solver uses a preconditioned quasi-minimum residual algorithm to solve this system of equations efficiently.

An important feature of the interior point algorithm is that it takes full advantage of the sparsity in the constraint and quadratic matrices, thereby enabling it to efficiently solve large-scale quadratic programs.

The interior point algorithm works simultaneously in the primal and dual spaces. It attains optimality when both primal and dual feasibility are achieved and when complementarity conditions hold. Therefore, it is of interest to observe the following four measures where $\|v\|_2$ is the Euclidean norm of the vector v:

- relative primal infeasibility measure α:

$$\alpha = \frac{\|\mathbf{Ax} - \mathbf{b} - \mathbf{s}\|_2}{\|\mathbf{b}\|_2 + 1}$$

- relative dual infeasibility measure β:

$$\beta = \frac{\|\mathbf{Qx} + \mathbf{c} - \mathbf{A}^{\mathrm{T}}\mathbf{y} - \mathbf{w}\|_2}{\|\mathbf{c}\|_2 + 1}$$

- relative duality gap δ:

$$\delta = \frac{|\mathbf{x}^{\mathrm{T}}\mathbf{Qx} + \mathbf{c}^{\mathrm{T}}\mathbf{x} - \mathbf{b}^{\mathrm{T}}\mathbf{y}|}{|\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{Qx} + \mathbf{c}^{\mathrm{T}}\mathbf{x}| + 1}$$

- absolute complementarity γ:

$$\gamma = \sum_{i=1}^{n} x_i w_i + \sum_{i=1}^{m} y_i s_i$$

These measures are displayed in the iteration log.

Iteration Log

The following information is displayed in the iteration log:

Iter	indicates the iteration number.
Complement	indicates the (absolute) complementarity.
Duality Gap	indicates the (relative) duality gap.
Primal Infeas	indicates the (relative) primal infeasibility measure.
Bound Infeas	indicates the (relative) bound infeasibility measure.
Dual Infeas	indicates the (relative) dual infeasibility measure.
Time	indicates the time elapsed (in seconds).

If the sequence of solutions converges to an optimal solution of the problem, you should see all columns in the iteration log converge to zero or very close to zero. Nonconvergence can be the result of insufficient iterations being performed to reach optimality. In this case, you might need to increase the value that you specify in the MAXITER= or MAXTIME= option. If the complementarity or the duality gap does not converge, the problem might be infeasible or unbounded. If the infeasibility columns do not converge, the problem might be infeasible.

Linear Least Squares Objectives

The QP solver can recognize a linear least squares objective when it has a standard form. You can use a least squares problem formulation to estimate parameters for a model from an overdetermined system of linear equations. (See Example 17.1 for more details about the least squares problem.) The QP solver can process least squares objectives that are in standard form more efficiently than the expanded quadratic objectives.

The standard form of a least squares objective is a sum of positively weighted squared linear functions $f_i(x)$ that represent the modeling error at each equation i in the system:

$$\min \sum_i s_i f_i^2(x) + c$$

where $s_i > 0$. The standard form allows an arbitrary constant value c. Equivalently, the objective can be maximized:

$$\max \sum_i s_i f_i^2(x) + c$$

where $s_i < 0$. Note that the standard form cannot contain linear terms or products of different variable or implicit variable (IMPVAR) locations.

The error function at equation i in the system is

$$f_i(x) = \sum_j a_{ij} x_j - b_i$$

The a_{ij} represent the linear equation coefficients, and b_i represents the expected value (also known as the response). The optimization variables x_j are the desired parameter values. The a_{ij} values are the elements of the least squares matrix $\mathbb{A}$, which has a row for each equation and a column for each x_j.

In the OPTMODEL procedure, you can specify the squared linear functions as **`term^2`** or **`term**2`**, where the **`term`** expression represents a linear function. If the function is a simple variable or linear IMPVAR *identifier expression*, then you can express the squared linear function as **`id*id`**, where both identifiers refer to the same location.

The following OPTMODEL program solves a simple least squares problem by using the standard form:

```
proc optmodel;
   var x{1..2};
   min f = 4*(x[1]-1)^2 + x[2]*x[2];
   con c: x[1]+x[2] >= 2;
   solve;
   print x;
quit;
```

The output is shown in Output 17.4. The ODS ProblemSummary table indicates that the objective has the standard least squares form. The ODS output displays information about the least squares matrix instead of the Hessian of the objective.

Figure 17.4 Simple Least Squares Problem

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Linear Least Squares
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	2
Least Squares Matrix Rows	2

Figure 17.4 *continued*

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	0.8000001884
Primal Infeasibility	0
Dual Infeasibility	3.223279E-10
Bound Infeasibility	0
Duality Gap	4.5833192E-8
Complementarity	0
Iterations	5
Presolve Time	0.00
Solution Time	0.01

[1]	x
1	1.2
2	0.8

Problem Statistics

Optimizers can encounter difficulty when solving poorly formulated models. Information about data magnitude provides a simple gauge to determine how well a model is formulated. For example, a model whose constraint matrix contains one very large entry (on the order of 10^9) can cause difficulty when the remaining entries are single-digit numbers. The PRINTLEVEL=2 option in the OPTMODEL procedure causes the ODS table ProblemStatistics to be generated when the QP solver is called. This table provides basic data magnitude information that enables you to improve the formulation of your models.

The example output in Figure 17.5 demonstrates the contents of the ODS table ProblemStatistics.

Figure 17.5 ODS Table ProblemStatistics

The OPTMODEL Procedure

Problem Statistics	
Number of Constraint Matrix Nonzeros	4
Maximum Constraint Matrix Coefficient	2
Minimum Constraint Matrix Coefficient	1
Average Constraint Matrix Coefficient	1.25
Number of Linear Objective Nonzeros	2
Maximum Linear Objective Coefficient	3
Minimum Linear Objective Coefficient	2
Average Linear Objective Coefficient	2.5
Number of Nonzeros Below Diagonal in the Hessian	1
Number of Diagonal Nonzeros in the Hessian	2
Maximum Hessian Coefficient	20
Minimum Hessian Coefficient	2
Average Hessian Coefficient	6.75
Number of RHS Nonzeros	2
Maximum RHS	100
Minimum RHS	1
Average RHS	50.5
Maximum Number of Nonzeros per Column	2
Minimum Number of Nonzeros per Column	2
Average Number of Nonzeros per Column	2
Maximum Number of Nonzeros per Row	2
Minimum Number of Nonzeros per Row	2
Average Number of Nonzeros per Row	2

Irreducible Infeasible Set

For a quadratic programming problem, an irreducible infeasible set (IIS) is an infeasible subset of constraints and variable bounds that becomes feasible if any single constraint or variable bound is removed. It is possible to have more than one IIS in an infeasible QP. Identifying an IIS can help isolate the structural infeasibility in a QP. The IIS=TRUE option directs the QP solver to search for an IIS in a specified QP.

Whether a quadratic programming problem is feasible or infeasible is determined by its constraints and variable bounds, which have nothing to do with its objective function. When you specify the IIS=TRUE option, the QP solver treats this problem as a linear programming problem by ignoring its objective function. Then finding IIS is the same as what the LP solver does with the IIS=TRUE option. For more information about the irreducible infeasible set, see the section "Irreducible Infeasible Set" on page 655 in Chapter 13, "The Linear Programming Solver."

Macro Variable _OROPTMODEL_

The OPTMODEL procedure always creates and initializes a SAS macro called _OROPTMODEL_. This variable contains a character string. After each PROC OROPTMODEL run, you can examine this macro by specifying `%put &_OROPTMODEL_;` and check the execution of the most recently invoked solver from the value of the macro variable. The various terms of the variable after the QP solver is called are interpreted as follows.

STATUS

indicates the solver status at termination. It can take one of the following values:

OK	The solver terminated normally.
SYNTAX_ERROR	Incorrect syntax was used.
DATA_ERROR	The input data were inconsistent.
OUT_OF_MEMORY	Insufficient memory was allocated to the procedure.
IO_ERROR	A problem occurred in reading or writing data.
SEMANTIC_ERROR	An evaluation error, such as an invalid operand type, occurred.
ERROR	The status cannot be classified into any of the preceding categories.

ALGORITHM

indicates the algorithm that produced the solution data in the macro variable. This term appears only when STATUS=OK. It can take the following value:

IP	The interior point algorithm produced the solution data.
IIS	The IIS functionality produced the solution data.

SOLUTION_STATUS

indicates the solution status at termination. It can take one of the following values:

OPTIMAL	The solution is optimal.
CONDITIONAL_OPTIMAL	The solution is optimal, but some infeasibilities (primal, dual or bound) exceed tolerances because of scaling or preprocessing.
FEASIBLE	The problem is feasible (IIS).
INFEASIBLE	The problem is infeasible.
UNBOUNDED	The problem is unbounded.
INFEASIBLE_OR_UNBOUNDED	The problem is infeasible or unbounded.
NONCONVEX	The quadratic matrix is nonconvex (minimization).
NONCONCAVE	The quadratic matrix is nonconcave (maximization).
BAD_PROBLEM_TYPE	The problem type is unsupported by the solver.
ITERATION_LIMIT_REACHED	The maximum allowable number of iterations was reached.

TIME_LIMIT_REACHED	The solver reached its execution time limit.
FUNCTION_CALL_LIMIT_REACHED	The solver reached its limit on function evaluations.
INTERRUPTED	The solver was interrupted externally.
FAILED	The solver failed to converge, possibly because of numerical issues.

OBJECTIVE
indicates the objective value obtained by the solver at termination.

PRIMAL_INFEASIBILITY
indicates the (relative) infeasibility of the primal constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 1014.

DUAL_INFEASIBILITY
indicates the (relative) infeasibility of the dual constraints at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 1014.

BOUND_INFEASIBILITY
indicates the (relative) violation by the solution of the lower or upper bounds (or both). For more information, see the section "Interior Point Algorithm: Overview" on page 1014.

DUALITY_GAP
indicates the (relative) duality gap. For more information, see the section "Interior Point Algorithm: Overview" on page 1014.

COMPLEMENTARITY
indicates the (absolute) complementarity at the solution. For more information, see the section "Interior Point Algorithm: Overview" on page 1014.

ITERATIONS
indicates the number of iterations required to solve the problem.

PRESOLVE_TIME
indicates the time (in seconds) taken for preprocessing.

SOLUTION_TIME
indicates the time (in seconds) taken to solve the problem, including preprocessing time.

NOTE: The time that is reported in PRESOLVE_TIME and SOLUTION_TIME is either CPU time or real time. The type is determined by the TIMETYPE= option.

Examples: QP Solver

This section presents examples that illustrate the use of the OPTMODEL procedure to solve quadratic programming problems. Example 17.1 illustrates how to model a linear least squares problem and solve it by using PROC OPTMODEL. Example 17.2 and Example 17.3 show in detail how to model the portfolio optimization and selection problems.

Example 17.1: Linear Least Squares Problem

The linear least squares problem arises in the context of determining a solution to an overdetermined set of linear equations. In practice, these equations could arise in data fitting and estimation problems. An overdetermined system of linear equations can be defined as

$$\mathbf{Ax} = \mathbf{b}$$

where $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{x} \in \mathbb{R}^n$, $\mathbf{b} \in \mathbb{R}^m$, and $m > n$. Since this system usually does not have a solution, you need to be satisfied with some sort of approximate solution. The most widely used approximation is the least squares solution, which minimizes $\|\mathbf{Ax} - \mathbf{b}\|_2^2$.

This problem is called a least squares problem for the following reason. Let $\mathbf{A}$, $\mathbf{x}$, and $\mathbf{b}$ be defined as previously. Let $k_i(x)$ be the kth component of the vector $\mathbf{Ax} - \mathbf{b}$:

$$k_i(x) = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n - b_i, \; i = 1, 2, \ldots, m$$

By definition of the Euclidean norm, the objective function can be expressed as follows:

$$\|\mathbf{Ax} - \mathbf{b}\|_2^2 = \sum_{i=1}^{m} k_i(x)^2$$

Therefore, the function you minimize is the sum of squares of m terms $k_i(x)$; hence the term least squares. The following example is an illustration of the *linear* least squares problem; that is, each of the terms k_i is a linear function of x .

Consider the following least squares problem defined by

$$\mathbf{A} = \begin{bmatrix} 4 & 0 \\ -1 & 1 \\ 3 & 2 \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

This translates to the following set of linear equations:

$$4x_1 = 1, \quad -x_1 + x_2 = 0, \quad 3x_1 + 2x_2 = 1$$

The corresponding least squares problem is:

$$\text{minimize} \quad (4x_1 - 1)^2 + (-x_1 + x_2)^2 + (3x_1 + 2x_2 - 1)^2$$

The preceding objective function can be expanded to:

$$\text{minimize} \quad 26x_1^2 + 5x_2^2 + 10x_1x_2 - 14x_1 - 4x_2 + 2$$

In addition, you impose the following constraint so that the equation $3x_1 + 2x_2 = 1$ is satisfied within a tolerance of 0.1:

$$0.9 \leq 3x_1 + 2x_2 \leq 1.1$$

You can use the following SAS statements to solve the least squares problem:

```
/* example 1: linear least squares problem */
proc optmodel;
   /* declare free (no explicit bounds) variables x[1] and x[2] */
   var x {1..2};

   /* objective function: minimize the sum of squares */
   minimize f = 26*x[1]^2 + 5*x[2]^2 + 10*x[1]*x[2] - 14*x[1] - 4*x[2] + 2;

   /* subject to the following constraint */
   con R: 0.9 <= 3*x[1] + 2*x[2] <= 1.1;

   /* call the QP solver */
   solve;

   /* print the optimal solution */
   print x;
quit;
```

The output is shown in Output 17.1.1.

Output 17.1.1 Summaries and Optimal Solution

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	2
Bounded Above	0
Bounded Below	0
Bounded Below and Above	0
Free	2
Fixed	0
Number of Constraints	1
Linear LE (<=)	0
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	1
Constraint Coefficients	2
Hessian Diagonal Elements	2
Hessian Elements Below Diagonal	1

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	0.0095238095
Primal Infeasibility	0
Dual Infeasibility	6.290213E-8
Bound Infeasibility	0
Duality Gap	9.4234001E-8
Complementarity	0
Iterations	5
Presolve Time	0.00
Solution Time	0.01

[1]	x
1	0.2381
2	0.1619

Example 17.2: Portfolio Optimization

Consider a portfolio optimization example. The two competing goals of investment are (1) long-term growth of capital and (2) low risk. A good portfolio grows steadily without wild fluctuations in value. The Markowitz model is an optimization model for balancing the return and risk of a portfolio. The decision variables are the amounts invested in each asset. The objective is to minimize the variance of the portfolio's total return, subject to the constraints that (1) the expected growth of the portfolio reaches at least some target level and (2) you do not invest more capital than you have.

Let $x_1, \ldots, x_n$ be the amount invested in each asset, $\mathcal{B}$ be the amount of capital you have, $\mathbf{R}$ be the random vector of asset returns over some period, and $\mathbf{r}$ be the expected value of $\mathbf{R}$. Let G be the minimum growth you hope to obtain, and $\mathcal{C}$ be the covariance matrix of $\mathbf{R}$. The objective function is $\mathrm{Var}\left(\sum_{i=1}^{n} x_i R_i\right)$, which can be equivalently denoted as $\mathbf{x}^{\mathrm{T}}\mathcal{C}\mathbf{x}$.

Assume, for example, $n = 4$. Let $\mathcal{B} = 10{,}000$, $G = 1{,}000$, $\mathbf{r} = [0.05, -0.2, 0.15, 0.30]$, and

$$\mathcal{C} = \begin{bmatrix} 0.08 & -0.05 & -0.05 & -0.05 \\ -0.05 & 0.16 & -0.02 & -0.02 \\ -0.05 & -0.02 & 0.35 & 0.06 \\ -0.05 & -0.02 & 0.06 & 0.35 \end{bmatrix}$$

The QP formulation can be written as:

$$\begin{aligned} \min \quad & 0.08x_1^2 - 0.1x_1x_2 - 0.1x_1x_3 - 0.1x_1x_4 + 0.16x_2^2 \\ & -0.04x_2x_3 - 0.04x_2x_4 + 0.35x_3^2 + 0.12x_3x_4 + 0.35x_4^2 \end{aligned}$$

$$\begin{array}{lrcl} \text{subject to} & & & \\ \text{(budget)} & x_1 + x_2 + x_3 + x_4 & \leq & 10000 \\ \text{(growth)} & 0.05x_1 - 0.2x_2 + 0.15x_3 + 0.30x_4 & \geq & 1000 \\ & x_1,\ x_2,\ x_3,\ x_4 & \geq & 0 \end{array}$$

Use the following SAS statements to solve the problem:

```
/* example 2: portfolio optimization */
proc optmodel;
   /* let x1, x2, x3, x4 be the amount invested in each asset */
   var x{1..4} >= 0;

   num coeff{1..4, 1..4} = [0.08 -.05 -.05 -.05
                            -.05 0.16 -.02 -.02
                            -.05 -.02 0.35 0.06
                            -.05 -.02 0.06 0.35];
   num r{1..4}=[0.05 -.20 0.15 0.30];

   /* minimize the variance of the portfolio's total return */
   minimize f = sum{i in 1..4, j in 1..4}coeff[i,j]*x[i]*x[j];

   /* subject to the following constraints */
   con BUDGET: sum{i in 1..4}x[i] <= 10000;
   con GROWTH: sum{i in 1..4}r[i]*x[i] >= 1000;
```

```
solve with qp;

/* print the optimal solution */
print x;
```

The summaries and the optimal solution are shown in Output 17.2.1.

Output 17.2.1 Portfolio Optimization

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	4
Bounded Above	0
Bounded Below	4
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	2
Linear LE (<=)	1
Linear EQ (=)	0
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	8
Hessian Diagonal Elements	4
Hessian Elements Below Diagonal	6

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	2232313.4432
Primal Infeasibility	0
Dual Infeasibility	2.0178577E-9
Bound Infeasibility	0
Duality Gap	1.080341E-12
Complementarity	0
Iterations	9
Presolve Time	0.00
Solution Time	0.01

Output 17.2.1 *continued*

[1]	x
1	3452.9
2	0.0
3	1068.8
4	2223.5

Thus, the minimum variance portfolio that earns an expected return of at least 10% is $x_1 = 3{,}452.9$, $x_2 = 0$, $x_3 = 1{,}068.8$, $x_4 = 2{,}223.5$. Asset 2 gets nothing because its expected return is -20% and its covariance with the other assets is not sufficiently negative for it to bring any diversification benefits. What if you drop the nonnegativity assumption?

Financially, that means you are allowed to short-sell—that is, sell low-mean-return assets and use the proceeds to invest in high-mean-return assets. In other words, you put a negative portfolio weight in low-mean assets and "more than 100%" in high-mean assets.

To solve the portfolio optimization problem with the short-sale option, continue to submit the following SAS statements:

```
    /* example 2: portfolio optimization with short-sale option */
    /* dropping nonnegativity assumption */
    for {i in 1..4} x[i].lb=-x[i].ub;

    solve with qp;

    /* print the optimal solution */
    print x;
quit;
```

You can see in the optimal solution displayed in Output 17.2.2 that the decision variable x_2, denoting Asset 2, is equal to $-1{,}563.61$, which means short sale of that asset.

Output 17.2.2 Portfolio Optimization with Short-Sale Option

The OPTMODEL Procedure

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	1907122.2254
Primal Infeasibility	4.998392E-14
Dual Infeasibility	4.4944805E-8
Bound Infeasibility	0
Duality Gap	3.886238E-11
Complementarity	0
Iterations	5
Presolve Time	0.00
Solution Time	0.01

[1]	x
1	1684.35
2	-1563.61
3	682.51
4	1668.95

Example 17.3: Portfolio Selection with Transactions

Consider a portfolio selection problem with a slight modification. You are now required to take into account the current position and transaction costs associated with buying and selling assets. The objective is to find the minimum variance portfolio. In order to understand the scenario better, consider the following data.

You are given three assets. The current holding of the three assets is denoted by the vector $\mathbf{c}$ = [200, 300, 500], the amount of asset bought and sold is denoted by b_i and s_i, respectively, and the net investment in each asset is denoted by x_i and is defined by the following relation:

$$x_i - b_i + s_i = c_i, \quad i = 1, 2, 3$$

Suppose that you pay a transaction fee of 0.01 every time you buy or sell. Let the covariance matrix $\mathcal{C}$ be defined as

$$\mathcal{C} = \begin{bmatrix} 0.027489 & -0.00874 & -0.00015 \\ -0.00874 & 0.109449 & -0.00012 \\ -0.00015 & -0.00012 & 0.000766 \end{bmatrix}$$

Assume that you hope to obtain at least 12% growth. Let $\mathbf{r}$ = [1.109048, 1.169048, 1.074286] be the vector of expected return on the three assets, and let $\mathcal{B}$=1000 be the available funds. Mathematically, this problem can be written in the following manner:

$$\begin{aligned} \min \quad & 0.027489x_1^2 - 0.01748x_1x_2 - 0.0003x_1x_3 + 0.109449x_2^2 \\ & -0.00024x_2x_3 + 0.000766x_3^2 \end{aligned}$$

$$
\begin{array}{rrcll}
\text{subject to} & & & & \\
\text{(return)} & \sum_{i=1}^{3} r_i x_i & \geq & 1.12\mathcal{B} & \\
\text{(budget)} & \sum_{i=1}^{3} x_i + \sum_{i=1}^{3} 0.01(b_i + s_i) & = & \mathcal{B} & \\
\text{(balance)} & x_i - b_i + s_i & = & c_i, & i = 1, 2, 3 \\
 & x_i,\, b_i,\, s_i & \geq & 0, & i = 1, 2, 3
\end{array}
$$

The problem can be solved by the following SAS statements:

```
/* example 3: portfolio selection with transactions */
proc optmodel;
   /* let x1, x2, x3 be the amount invested in each asset */
   var x{1..3} >= 0;
   /* let b1, b2, b3 be the amount of asset bought */
   var b{1..3} >= 0;
   /* let s1, s2, s3 be the amount of asset sold */
   var s{1..3} >= 0;

   /* current holdings */
   num c{1..3}=[ 200 300 500];
   /* covariance matrix */
   num coeff{1..3, 1..3} = [0.027489  -.008740  -.000150
                            -.008740  0.109449  -.000120
                            -.000150  -.000120  0.000766];
   /* returns */
   num r{1..3}=[1.109048 1.169048 1.074286];

   /* minimize the variance of the portfolio's total return */
   minimize f = sum{i in 1..3, j in 1..3}coeff[i,j]*x[i]*x[j];

   /* subject to the following constraints */
   con BUDGET: sum{i in 1..3}(x[i]+.01*b[i]+.01*s[i]) <= 1000;
   con RETURN: sum{i in 1..3}r[i]*x[i] >= 1120;
   con BALANC{i in 1..3}: x[i]-b[i]+s[i]=c[i];

   solve with qp;

   /* print the optimal solution */
   print x b s;
quit;
```

The output is displayed in Output 17.3.1.

Output 17.3.1 Portfolio Selection with Transactions

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Minimization
Objective Function	f
Objective Type	Quadratic
Number of Variables	9
Bounded Above	0
Bounded Below	9
Bounded Below and Above	0
Free	0
Fixed	0
Number of Constraints	5
Linear LE (<=)	1
Linear EQ (=)	3
Linear GE (>=)	1
Linear Range	0
Constraint Coefficients	21
Hessian Diagonal Elements	3
Hessian Elements Below Diagonal	3

Solution Summary	
Solver	QP
Algorithm	Interior Point
Objective Function	f
Solution Status	Optimal
Objective Value	19560.725756
Primal Infeasibility	5.474143E-11
Dual Infeasibility	0
Bound Infeasibility	0
Duality Gap	7.794437E-10
Complementarity	0
Iterations	10
Presolve Time	0.00
Solution Time	0.01

[1]	x	b	s
1	397.58	197.58	0.00
2	406.12	106.12	0.00
3	190.17	0.00	309.83

References

Freund, R. W. (1991). "On Polynomial Preconditioning and Asymptotic Convergence Factors for Indefinite Hermitian Matrices." *Linear Algebra and Its Applications* 154–156:259–288.

Freund, R. W., and Jarre, F. (1997). "A QMR-Based Interior Point Algorithm for Solving Linear Programs." *Mathematical Programming* 76:183–210.

Freund, R. W., and Nachtigal, N. M. (1996). "QMRPACK: A Package of QMR Algorithms." *ACM Transactions on Mathematical Software* 22:46–77.

Vanderbei, R. J. (1999). "LOQO: An Interior Point Code for Quadratic Programming." *Optimization Methods and Software* 11:451–484.

Wright, S. J. (1997). *Primal-Dual Interior-Point Methods*. Philadelphia: SIAM.

Chapter 18
The Decomposition Algorithm

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Overview: Decomposition Algorithm

The decomposition algorithm (DECOMP) provides an alternative method of solving linear programs (LPs) and mixed integer linear programs (MILPs) by exploiting the ability to efficiently solve a relaxation of the original problem. The algorithm is available as an option in the OPTMODEL, OPTLP, and OPTMILP procedures and is based on the methodology described in Galati (2009).

A standard linear or mixed integer linear program has the formulation

$$
\begin{array}{llllll}
\text{minimize} & \mathbf{c}^\top\mathbf{x} & + & \mathbf{f}^\top\mathbf{y} & & \\
\text{subject to} & \mathbf{D}\mathbf{x} & + & \mathbf{B}\mathbf{y} & \{\geq, =, \leq\} \;\; \mathbf{d} & \text{(master)} \\
 & \mathbf{A}\mathbf{x} & & & \{\geq, =, \leq\} \;\; \mathbf{b} & \text{(subproblem)} \\
 & \underline{\mathbf{x}} \leq \mathbf{x} \leq \overline{\mathbf{x}} & & & & \\
 & & & \underline{\mathbf{y}} \leq \mathbf{y} \leq \overline{\mathbf{y}} & & \\
 & x_i \in \mathbb{Z} & & & i \in \mathcal{S}_x & \\
 & & & y_i \in \mathbb{Z} & i \in \mathcal{S}_y &
\end{array}
$$

where

$\mathbf{x} \in \mathbb{R}^n$	is the vector of structural variables
$\mathbf{y} \in \mathbb{R}^s$	is the vector of master-only structural variables
$\mathbf{c} \in \mathbb{R}^n$	is the vector of objective function coefficients that are associated with variables $\mathbf{x}$
$\mathbf{f} \in \mathbb{R}^s$	is the vector of objective function coefficients that are associated with variables $\mathbf{y}$
$\mathbf{D} \in \mathbb{R}^{t\times n}$	is the matrix of master constraint coefficients that are associated with variables $\mathbf{x}$
$\mathbf{B} \in \mathbb{R}^{t\times s}$	is the matrix of master constraint coefficients that are associated with variables $\mathbf{y}$
$\mathbf{A} \in \mathbb{R}^{m\times n}$	is the matrix of subproblem constraint coefficients
$\mathbf{d} \in \mathbb{R}^t$	is the vector of master constraints' right-hand sides
$\mathbf{b} \in \mathbb{R}^m$	is the vector of subproblem constraints' right-hand sides
$\underline{\mathbf{x}} \in \mathbb{R}^n$	is the vector of lower bounds on variables $\mathbf{x}$
$\overline{\mathbf{x}} \in \mathbb{R}^n$	is the vector of upper bounds on variables $\mathbf{x}$
$\underline{\mathbf{y}} \in \mathbb{R}^s$	is the vector of lower bounds on variables $\mathbf{y}$
$\overline{\mathbf{y}} \in \mathbb{R}^s$	is the vector of upper bounds on variables $\mathbf{y}$
$\mathcal{S}_x$	is a subset of the set $\{1, \ldots, n\}$ of indices on variables $\mathbf{x}$
$\mathcal{S}_y$	is a subset of the set $\{1, \ldots, s\}$ of indices on variables $\mathbf{y}$

You can form a relaxation of the preceding mathematical program by removing the master constraints, which are defined by the matrices $\mathbf{D}$ and $\mathbf{B}$. The resulting constraint system, defined by the matrix $\mathbf{A}$, forms the subproblem, which can often be solved much more efficiently than the entire original problem. This is one of the key motivators for using the decomposition algorithm.

The decomposition algorithm works by finding convex combinations of extreme points of the subproblem polyhedron that satisfy the constraints defined in the master. For MILP subproblems, the strength of the relaxation is another important motivator for using this method. If the subproblem polyhedron defines feasible solutions that are close to the original feasible space, the chance of success for the algorithm increases.

The region that defines the subproblem space is often separable. That is, the formulation of the preceding mathematical program can be written in *block-angular* form as

$$
\begin{array}{lllllllllll}
\text{minimize} & \mathbf{c}^1\mathbf{x}^1 & + & \mathbf{c}^2\mathbf{x}^2 & + & \cdots & + & \mathbf{c}^\kappa\mathbf{x}^\kappa & + & \mathbf{f}^\top y & \\
\text{subject to} & \mathbf{D}^1\mathbf{x}^1 & + & \mathbf{D}^2\mathbf{x}^2 & + & \cdots & + & \mathbf{D}^\kappa\mathbf{x}^\kappa & + & \mathbf{B}\mathbf{y} & \{\geq,=,\leq\} \quad \mathbf{d} \\
 & \mathbf{A}^1\mathbf{x}^1 & & & & & & & & & \{\geq,=,\leq\} \quad \mathbf{b}^1 \\
 & & & \mathbf{A}^2\mathbf{x}^2 & & & & & & & \{\geq,=,\leq\} \quad \mathbf{b}^2 \\
 & & & & & \ddots & & & & & \{\geq,=,\leq\} \quad \vdots \\
 & & & & & & & \mathbf{A}^\kappa\mathbf{x}^\kappa & & & \{\geq,=,\leq\} \quad \mathbf{b}^\kappa \\
 & & & & & \underline{\mathbf{x}} \leq \mathbf{x} \leq \overline{\mathbf{x}} & & & & & \\
 & & & & & & & & & \underline{\mathbf{y}} \leq \mathbf{y} \leq \overline{\mathbf{y}} & \\
 & & & & & x_i \in \mathbb{Z} & & & & & i \in \mathcal{S}_x \\
 & & & & & & & & & y_i \in \mathbb{Z} & i \in \mathcal{S}_y
\end{array}
$$

where $K = \{1, \ldots, \kappa\}$ defines a partition of the constraints (and variables) into independent subproblems (blocks) such that $\mathbf{A} = [\mathbf{A}^1 \ldots \mathbf{A}^\kappa]$, $\mathbf{D} = [\mathbf{D}^1 \ldots \mathbf{D}^\kappa]$, $\mathbf{c} = [\mathbf{c}^1 \ldots \mathbf{c}^\kappa]$, $\mathbf{b} = [\mathbf{b}^1 \ldots \mathbf{b}^\kappa]$, $\underline{\mathbf{x}} = [\underline{\mathbf{x}}^1 \ldots \underline{\mathbf{x}}^\kappa]$, $\overline{\mathbf{x}} = [\overline{\mathbf{x}}^1 \ldots \overline{\mathbf{x}}^\kappa]$, and $\mathbf{x} = [\mathbf{x}^1 \ldots \mathbf{x}^\kappa]$. This type of structure is relatively common in modeling mathematical programs. For example, consider a model that defines a workplace that has separate departmental restrictions (defined as the subproblem constraints), which are coupled together by a company-wide budget across departments (defined as the master constraint). By relaxing the budget (master) constraint, the decomposition algorithm can take advantage of the fact that the decoupled subproblems are separable, and it can process them in parallel. A special case of block-angular form, called *block-diagonal* form, occurs when the set of master constraints is empty. In this special case, the subproblem matrices define the entire original problem.

An important indicator of a problem that is well suited for decomposition is the amount by which the subproblems cover the original problem with respect to both variables and constraints in the original presolved model. This value, which is expressed as a percentage of the original model, is known as the *coverage*. For LPs, the decomposition algorithm usually performs better than standard approaches only if the subproblems cover a significant amount of the original problem. For MILPs, the correlation between performance and coverage is more difficult to determine, because the strength of the subproblem with respect to integrality is not always proportional to the size of the system. Regardless, it is unlikely that the decomposition algorithm will outperform more standard methods (such as branch-and-cut) in problems that have small coverage.

The primary input and output for the decomposition algorithm are identical to those that are needed and produced by the OPTLP, OPTMILP, and OPTMODEL procedures. For more information, see the following sections:

- "Data Input and Output" on page 134 in Chapter 5, "The OPTLP Procedure"
- "Data Input and Output" on page 200 in Chapter 6, "The OPTMILP Procedure"
- "Details: LP Solver" on page 645 in Chapter 13, "The Linear Programming Solver"
- "Details: MILP Solver" on page 722 in Chapter 14, "The Mixed Integer Linear Programming Solver"

The only additional input that can be provided for the decomposition algorithm is an explicit definition of the partition of the subproblem constraints. The following section gives a simple example of providing this input for both PROC OPTMILP and PROC OPTMODEL.

Getting Started: Decomposition Algorithm

This example illustrates how you can use the decomposition algorithm to solve a simple mixed integer linear program. Suppose you want to solve the following problem:

$$
\begin{array}{lrcrcrcrcrcrcll}
\text{maximize} & x_{11} & + & 2x_{21} & + & x_{31} & & & + & x_{22} & + & x_{32} & & & \\
\text{subject to} & x_{11} & & & & & + & x_{12} & & & & & \geq & 1 & \text{(m)} \\
 & 5x_{11} & + & 7x_{21} & + & 4x_{31} & & & & & & & \leq & 11 & \text{(s1)} \\
 & & & & & & & x_{12} & + & 2x_{22} & + & x_{32} & \leq & 2 & \text{(s2)} \\
 & & & & & & & & & & & x_{ij} & \in & \{0,1\} & i \in \{1,2,3\},\ j \in \{1,2\}
\end{array}
$$

It is obvious from the structure of the problem that if constraint m is removed, then the remaining constraints s1 and s2 decompose into two independent subproblems. The next two sections describe how to solve this MILP by using the decomposition algorithm in the OPTMODEL procedure and OPTMILP procedure, respectively.

Solving a MILP with DECOMP and PROC OPTMODEL

The following statements use the OPTMODEL procedure and the decomposition algorithm to solve the MILP:

```
proc optmodel sessref="mysess";
   var x{i in 1..3, j in 1..2} binary;

   max f =    x[1,1] + 2*x[2,1] +   x[3,1]
                     +   x[2,2] +   x[3,2];

   con m :    x[1,1] +   x[1,2]            >=  1;
   con s1:  5*x[1,1] + 7*x[2,1] + 4*x[3,1] <= 11;
   con s2:    x[1,2] + 2*x[2,2] +   x[3,2] <=  2;

   s1.block = 0;
   s2.block = 1;

   solve with milp / presolver=none decomp=(logfreq=1);
   print x;
quit;
```

Here, the PRESOLVER=NONE option is used, because otherwise the presolver solves this small instance without invoking any solver. The solution summary and optimal solution are displayed in Figure 18.1.

Figure 18.1 Solution Summary and Optimal Solution

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	f
Solution Status	Optimal
Objective Value	4
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	4
Nodes	1
Solutions Found	2
Iterations	2
Presolve Time	0.00
Solution Time	0.02

	x	
	1	**2**
1	0	1
2	1	0
3	1	1

The iteration log, which displays the problem statistics, the progress of the solution, and the optimal objective value, is shown in Figure 18.2.

Figure 18.2 Log

```
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 6 binary and 0 integer variables.
NOTE: The problem has 3 linear constraints (2 LE, 0 EQ, 1 GE, 0 range).
NOTE: The problem has 8 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 2 threads.
NOTE: The problem has a decomposable structure with 2 blocks. The largest block covers 33.33%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 6 (100%) variables and 2 (66.67%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
         .       4.0000       3.0000       3.0000   25.00%   25.00%    0    0
         1       4.0000       3.0000       3.0000   25.00%   25.00%    0    0
         2       4.0000       4.0000       4.0000    0.00%    0.00%    0    0
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1      2       4.0000       4.0000    0.00%      0      0
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 0.02 seconds.
NOTE: Optimal.
NOTE: Objective = 4.
```

Solving a MILP with DECOMP and PROC OPTMILP

Alternatively, to solve the MILP with the OPTMILP procedure, create a corresponding data table that uses the mathematical programming system (MPS) format as follows:

```
data mpsdata;
   input field1 $ field2 $ field3 $ field4 field5 $ field6;
   datalines;
NAME     .        mpsdata  .        .        .
ROWS     .        .        .        .        .
MAX      f        .        .        .        .
G        m        .        .        .        .
```

```
L       s1       .        .        .        .
L       s2       .        .        .        .
COLUMNS .        .        .        .        .
.       .MRK0000 'MARKER' .        'INTORG' .
.       x[1,1]   f        1        m        1
.       x[1,1]   s1       5        .        .
.       x[2,1]   f        2        s1       7
.       x[3,1]   f        1        s1       4
.       x[1,2]   m        1        s2       1
.       x[2,2]   f        1        s2       2
.       x[3,2]   f        1        s2       1
.       .MRK0001 'MARKER' .        'INTEND' .
RHS     .        .        .        .        .
.       .RHS.    m        1        .        .
.       .RHS.    s1       11       .        .
.       .RHS.    s2       2        .        .
BOUNDS  .        .        .        .        .
UP      .BOUNDS. x[1,1]   1        .        .
UP      .BOUNDS. x[2,1]   1        .        .
UP      .BOUNDS. x[3,1]   1        .        .
UP      .BOUNDS. x[1,2]   1        .        .
UP      .BOUNDS. x[2,2]   1        .        .
UP      .BOUNDS. x[3,2]   1        .        .
ENDATA  .        .        .        .        .
;
data mycas.mpsdata;
   set mpsdata;
   _id_ = _n_;
;
```

Next, use the following data table to define the subproblem blocks:

```
data mycas.blocks;
   input _row_ $ _block_;
   datalines;
s1 0
s2 1
;
```

Now, you can use the following PROC OPTMILP statements to solve this MILP:

```
proc optmilp
   data       = mycas.mpsdata
   presolver  = none;
   decomp
      logfreq = 1
      blocks  = mycas.blocks;
run;
```

Syntax: Decomposition Algorithm

You can specify the decomposition algorithm either by using options in a SOLVE statement in the OPTMODEL procedure or by using statements in the OPTLP and OPTMILP procedures. Except for the fact that you use SOLVE statement options in PROC OPTMODEL or you use statements in PROC OPTLP and PROC OPTMILP, the syntax is identical.

You can specify the following decomposition algorithm options in the SOLVE statement in the OPTMODEL procedure:

```
SOLVE WITH LP / <options>
                <DECOMP<=(decomp-options)>>
                <DECOMPMASTER=(<master-options>)>
                <DECOMPSUBPROB=(<subprob-options>)> ;

SOLVE WITH MILP / <options>
                  <DECOMP<=(decomp-options)>>
                  <DECOMPMASTER=(<master-options>)>
                  <DECOMPMASTERIP=(<masterip-options>)>
                  <DECOMPSUBPROB=(<subprob-options>)> ;
```

You can specify the following statements in the OPTLP procedure:

```
PROC OPTLP <options> ;
   DECOMP <decomp-options> ;
   DECOMPMASTER <master-options> ;
   DECOMPSUBPROB <subprob-options> ;
```

You can specify the following statements in the OPTMILP procedure:

```
PROC OPTMILP <options> ;
   DECOMP <decomp-options> ;
   DECOMPMASTER <master-options> ;
   DECOMPMASTERIP <masterip-options> ;
   DECOMPSUBPROB <subprob-options> ;
```

Decomposition Algorithm Options in the PROC OPTLP Statement or the SOLVE WITH LP Statement in PROC OPTMODEL

To solve a linear program, you can specify the decomposition algorithm in a SOLVE WITH LP statement in the OPTMODEL procedure or in a PROC OPTLP statement in the OPTLP procedure. To control the overall decomposition algorithm, you can specify one or more of the LP solver options shown in Table 18.1. (As the table indicates, you can specify some options only in the PROC OPTLP statement.)

The options in Table 18.1 control the overall process flow for solving a linear program; they are equivalent to the options that are used in PROC OPTLP and PROC OPTMODEL with standard methods. These options are called main solver options in this chapter. They are described in detail in the section "Syntax: LP Solver" on page 637 in Chapter 13, "The Linear Programming Solver," and the section "Syntax: OPTLP Procedure" on page 125 in Chapter 5, "The OPTLP Procedure." The DUALIZE= option has a different default when you use the decomposition algorithm, as shown in Table 18.1.

Table 18.1 LP Options in the PROC OPTLP Statement or SOLVE WITH LP Statement

Description	*option*	Different Default
Data Table Options (OPTLP procedure only)		
Specifies the input data table	DATA=	
Specifies the dual solution output data table	DUALOUT=	
Specifies whether the model is a maximization or minimization problem	OBJSENSE=	
Specifies the primal solution output data table	PRIMALOUT=	
Presolve Options		
Controls the dualization of the problem	DUALIZE=	OFF
Controls the folding of the problem	FOLD=	AUTOMATIC
Specifies the type of presolve	PRESOLVER=	
Control Options		
Specifies the feasibility tolerance	FEASTOL=	
Specifies how frequently to print the solution progress	LOGFREQ=	
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=	
Specifies the maximum number of iterations	MAXITER=	
Specifies the time limit for the optimization process	MAXTIME=	
Specifies the optimality tolerance	OPTTOL=	
Enables or disables printing summary (OPTLP procedure only)	PRINTLEVEL=	
Specifies whether time units are CPU time or real time	TIMETYPE=	
Algorithm Options		
Enables or disables scaling of the problem	SCALE=	

Decomposition Algorithm Options in the PROC OPTMILP Statement or the SOLVE WITH MILP Statement in PROC OPTMODEL

To solve a mixed integer linear program, you can specify the decomposition algorithm in a SOLVE WITH MILP statement in the OPTMODEL procedure or in a PROC OPTMILP statement in the OPTMILP procedure. To control the overall decomposition algorithm, you can specify one or more of the MILP solver options shown in Table 18.2. (As the table indicates, you can specify some options only in the PROC OPTMILP statement.)

The options in Table 18.2 control the overall process flow for solving a mixed integer linear program; they are equivalent to the options that are used in the OPTMILP and OPTMODEL procedures with standard methods. These options are called main solver options in this chapter. They are described in detail in the section "Syntax: MILP Solver" on page 708 and the section "Syntax: OPTMILP Procedure" on page 185.

Table 18.2 MILP Options in the PROC OPTMILP Statement or SOLVE WITH MILP Statement

Description	*option*
Data Table Options (OPTMILP procedure only)	
Specifies the input data table	DATA=
Specifies the constraint activities output data table	DUALOUT=
Specifies whether the model is a maximization or minimization problem	OBJSENSE=
Specifies the primal solution input data table (warm start)	PRIMALIN=
Specifies the primal solution output data table	PRIMALOUT=
Presolve Option	
Specifies the type of presolve	PRESOLVER=
Control Options	
Specifies the stopping criterion based on an absolute objective gap	ABSOBJGAP=
Specifies the cutoff value for node removal	CUTOFF=
Emphasizes feasibility or optimality	EMPHASIS=
Specifies the maximum violation of variables and constraints	FEASTOL=
Specifies the maximum difference allowed between an integer variable's value and an integer	INTTOL=
Specifies how frequently to print the node log	LOGFREQ=
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=
Specifies the maximum number of nodes to process	MAXNODES=
Specifies the maximum number of solutions to find	MAXSOLS=
Specifies the time limit for the optimization process	MAXTIME=
Specifies the overall capacity for the number of active threads (per machine)	NTHREADS=
Specifies the tolerance to use in determining the optimality of nodes in the branch-and-bound tree	OPTTOL=
Uses the input primal solution (warm start) (OPTMODEL procedure only)	PRIMALIN
Enables or disables printing summary (OPTMILP procedure only)	PRINTLEVEL=
Specifies the probing level	PROBE=
Specifies the stopping criterion based on a relative objective gap	RELOBJGAP=
Specifies the scale of the problem matrix	SCALE=
Specifies the initial seed for the random number generator	SEED=
Specifies the stopping criterion based on a target objective value	TARGET=
Specifies whether time units are CPU time or real time	TIMETYPE=
Control Options (OPTMODEL procedure only)	
Specifies the maximum number of solutions to return from the pool	MAXPOOLSOLS=
Heuristics Option	
Specifies the primal heuristics level	HEURISTICS=
Search Options	
Specifies the restarting strategy	RESTARTS=
Specifies the number of iterations to perform on each variable for strong branching	STRONGITER=
Specifies the number of candidates for strong branching	STRONGLEN=
Specifies the level of symmetry detection	SYMMETRY=
Specifies the rule for selecting the branching variable	VARSEL=

Table 18.2 *continued*

Description	*option*
Cut Options	
Specifies the cut level for all cuts	ALLCUTS=
Specifies the clique cut level	CUTCLIQUE=
Specifies the flow cover cut level	CUTFLOWCOVER=
Specifies the flow path cut level	CUTFLOWPATH=
Specifies the Gomory cut level	CUTGOMORY=
Specifies the generalized upper bound (GUB) cover cut level	CUTGUB=
Specifies the implied bounds cut level	CUTIMPLIED=
Specifies the knapsack cover cut level	CUTKNAPSACK=
Specifies the lift-and-project cut level	CUTLAP=
Specifies the mixed lifted 0-1 cut level	CUTMILIFTED=
Specifies the mixed integer rounding (MIR) cut level	CUTMIR=
Specifies the multicommodity network flow cut level	CUTMULTICOMMODITY=
Specifies the row multiplier factor for cuts	CUTSFACTOR=
Specifies the overall cut aggressiveness	CUTSTRATEGY=
Specifies the zero-half cut level	CUTZEROHALF=

The HYBRID= option in the DECOMP statement indicates the processing mode for the root node of the branch-and-bound search tree. When HYBRID=TRUE, the root node is first processed using standard MILP techniques, as described in the section "Details: MILP Solver" on page 722. When HYBRID=FALSE, the root processing is done solely by the decomposition algorithm, and the following direct MILP options are ignored: CUTOFF=, EMPHASIS=, RESTARTS=, SEED=, TARGET=, and all the cut options.

The following search options, listed in Table 18.2, have a different interpretation or a different set of options from what is described in the MILP solver sections:

LOGFREQ=*number*

PRINTFREQ=*number*

specifies how often to print information in the node log, where *number* can be any 32-bit integer greater than or equal to 0. If *number* is 0, then the node log is disabled. If *number* is positive, then an entry is made every *number* seconds. An entry is also made in the node log each time the solver finds a better integer solution or improved bound. By default, LOGFREQ=10.

STRONGITER=*number* | **AUTOMATIC**

specifies the number of pricing iterations that are performed for each variable in the candidate list when you use the strong branching variable selection strategy. The value of *number* can be any positive 32-bit integer. If you specify the keyword AUTOMATIC, the MILP solver uses the default value, which is calculated automatically.

VARSEL=AUTOMATIC | MAXINFEAS | PSEUDO | RYANFOSTER | STRONG

specifies the rule for selecting the branching variable. You can specify the following values:

AUTOMATIC uses automatic branching variable selection.

MAXINFEAS selects the variable in the original compact formulation with maximum infeasibility.

PSEUDO selects the variable in the original compact formulation that maximizes the weighted up and down pseudocosts.

RYANFOSTER when appropriate, uses a specialized branching rule known as *Ryan-Foster branching*.

STRONG selects the variable in the original compact formulation that maximizes the estimated improvement in the objective value based on strong branching.

By default, VARSEL=AUTOMATIC. For more information about variable selection, see the sections "Variable Selection" on page 206 and "Special Case: Identical Blocks and Ryan-Foster Branching" on page 1058.

DECOMP Statement

DECOMP < *decomp-options* > **;**

DECOMPOSITION < *decomp-options* > **;**

The DECOMP statement controls the overall decomposition algorithm.

Table 18.3 summarizes the *decomp-options* available in the DECOMP statement. These options control the overall decomposition algorithm process flow during the solution of an LP or a MILP. (As the table indicates, you can specify the data table options only in the OPTLP or OPTMILP procedure, and you can specify some control options only for a MILP.)

Table 18.3 Options in the DECOMP Statement

Description	*decomp-option*
Data Table Options (OPTLP and OPTMILP procedures only)	
Specifies the blocks input data table	BLOCKS=
Control Options	
Specifies the stopping criterion based on an absolute objective gap	ABSOBJGAP=
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=
Specifies the maximum number of blocks to allow	MAXBLOCKS=
Specifies the block-specification method	METHOD=
Specifies the number of blocks to search for in the automated detection methods	NBLOCKS=
Specifies the range for the number of blocks to search for in the automated detection methods	NBLOCKSRANGE=
Specifies the number of block threads to use in the decomposition algorithm	NTHREADS=
Specifies the stopping criterion based on a relative objective gap	RELOBJGAP=
Control Options (MILP only)	
Specifies whether to process the root node by using standard MILP techniques	HYBRID=
Specifies how frequently to print the continuous iteration log	LOGFREQ=
Specifies the maximum number of outer iterations for the decomposition algorithm	MAXITER=

You can specify the following *decomp-options*:

ABSOBJGAP=*number*

ABSOLUTEOBJECTIVEGAP=*number*

specifies a stopping criterion for the continuous bound of the decomposition. When the absolute difference between the master objective and the best dual bound falls below *number*, the decomposition algorithm stops adding columns. The value of *number* can be any nonnegative number. The default value is the value of the OPTTOL= main solver option.

BLOCKS=*CAS-libref.data-table*

specifies (for OPTLP and OPTMILP procedures only) the input data table that contains block definitions to use in the decomposition algorithm if METHOD=USER. For more information, see the section "The BLOCKS= Data Table in PROC OPTMILP and PROC OPTLP" on page 1056. To specify blocks in PROC OPTMODEL, use the **.block** constraint suffix instead (see the section "The **.block** Constraint Suffix in PROC OPTMODEL" on page 1056). *CAS-libref.data-table* is a two-level name, where *CAS-libref* refers to the caslib and session identifier, and *data-table* specifies the name of the input data table. For more information about this two-level name, see the section "Using CAS Sessions and CAS Engine Librefs" on page 15 in Chapter 3, "Shared Concepts."

HYBRID=FALSE | TRUE

specifies whether to first process the root node by using standard MILP techniques, as described in the section "Details: MILP Solver" on page 722. You can specify the following values:

FALSE disables root processing by using standard MILP techniques.

TRUE enables root processing by using standard MILP techniques.

By default, HYBRID=TRUE if METHOD=AUTO or METHOD=COMMUNITY, and HYBRID=FALSE otherwise.

LOGFREQ=*number*

specifies (for MILP problems only) how often to print information in the continuous iteration log. The value of *number* can be any nonnegative 32-bit integer. The default value of *number* is 10. If *number* is 0, then the iteration log is disabled. If *number* is positive, then an entry is made in the log at the first iteration, at the last iteration, and at intervals that are dictated by the value of *number*. An entry is also made each time a better integer solution or improved bound is found.

LOGLEVEL=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

controls the amount of information that the decomposition algorithm displays in the SAS log.

You can specify the following values for an LP:

AUTOMATIC prints the continuous iteration log at the interval dictated by the LOGFREQ= main solver option.

NONE turns off printing of all the decomposition algorithm messages to the SAS log.

BASIC prints the continuous iteration log at the interval dictated by the LOGFREQ= main solver option.

MODERATE prints the continuous iteration log and summary information for each iteration at the interval dictated by the LOGFREQ= main solver option.

AGGRESSIVE prints the continuous iteration log and detailed information for each iteration at the interval dictated by the LOGFREQ= main solver option.

You can specify the following values for a MILP:

AUTOMATIC prints the continuous iteration log for the root node at the interval dictated by the LOGFREQ= option in the DECOMP statement. Prints the branch-and-bound node log at the interval dictated by the LOGFREQ= main solver option.

NONE turns off printing of all the decomposition algorithm messages to the SAS log.

BASIC prints the continuous iteration log for each branch-and-bound node at the interval dictated by the LOGFREQ= option in the DECOMP statement.

MODERATE prints the continuous iteration log and summary information for each iteration of each branch-and-bound node at the interval dictated by the LOGFREQ= option in the DECOMP statement.

AGGRESSIVE prints the continuous iteration log and detailed information for each iteration of each branch-and-bound node at the interval dictated by the LOGFREQ= option in the DECOMP statement.

By default, LOGLEVEL=AUTOMATIC for both LPs and MILPs.

MAXBLOCKS=*number*
specifies the maximum number of blocks to allow. If the defined number of blocks exceeds *number*, the algorithm creates superblocks by using a very simple round-robin scheme. The value of *number* can be any positive 32-bit integer. The default is the largest number that can be represented by a 32-bit integer.

MAXITER=*number*
specifies (for MILP problems only) the maximum number of outer iterations for the decomposition algorithm. The value of *number* can be any positive 32-bit integer. The default is the largest number that can be represented by a 32-bit integer.

METHOD=AUTO | COMMUNITY | CONCOMP | NETWORK | SET | USER
specifies the block-specification method. You can specify the following values:

AUTO attempts to find a block-angular structure in the constraint matrix by using matrix-stretching techniques similar to those described in Grcar (1990) and Aykanat, Pinar, and Çatalyürek (2004). The NBLOCKS= and NBLOCKSRANGE= options specify the range of the number of blocks into which the algorithm attempts to decompose the constraint matrix. If the algorithm fails to find a decomposition, the MILP solver is called directly.

COMMUNITY attempts to find a block-angular structure in the constraint matrix by using community detection algorithms similar to those described in Khaniyev, Elhedhli, and Erenay (2018). You can use the matrix-stretching techniques from METHOD=AUTO in conjunction with the community detection algorithms by specifying the NBLOCKS= or NBLOCKSRANGE= option (or both). If the algorithm fails to find a decomposition, the MILP solver is called directly.

CONCOMP attempts to find a block-diagonal (not block-angular) structure in the constraint matrix. Unless your problem separates into completely independent problems with no linking constraints, this method finds only one block and hence is equivalent to calling the MILP solver directly.

NETWORK attempts to find an embedded network similar to what is described in the section "The Network Simplex Algorithm" on page 646. The weakly connected components of this network are used as the blocks.

SET attempts to find a set partitioning or set covering structure in the constraint matrix and defines this as the master (linking) constraints. The weakly connected components of the remaining constraints are used as the blocks.

USER uses a user-defined method to specify which rows belong to which blocks (subproblems). In PROC OPTMODEL, use the `.block` constraint suffix. In PROC OPTLP and PROC OPTMILP, use the BLOCKS= data table instead.

By default, METHOD=USER if blocks are defined, and an automated method which first runs METHOD=AUTO and then runs METHOD=COMMUNITY, otherwise.

NBLOCKS=*n*

NUMBLOCKS=*n*

specifies the number of blocks to search for when using automated detection methods, where *n* can be any positive number less than or equal to the number of rows in the presolved model. If the NUMBLOCKSRANGE=*r* option is specified, then the value of *n* specifies the starting point and *n*+*r* specifies the ending point for the search. If the algorithm fails to find a decomposition that contains at least two blocks, then the standard MILP solver is called directly. By default, NBLOCKS=2 when METHOD=AUTO; when METHOD=COMMUNITY, NBLOCKS=0 by default.

NBLOCKSRANGE=*r*

NUMBLOCKSRANGE=*r*

specifies the range for the number of blocks to search for when using automated detection methods, where *r* can be any positive number less than or equal to the number of rows in the presolved model. If the NUMBLOCKS=*n* option is specified, then the value of *n* specifies the starting point and *n*+*r* specifies the ending point for the search. By default, NBLOCKSRANGE=20 when METHOD=AUTO; when METHOD=COMMUNITY, NBLOCKSRANGE=0 by default.

NTHREADS=*number*

NUMTHREADS=*number*

specifies the number of block threads to use in the decomposition algorithm. The value of the NTHREADS= option in the main solver statement serves as the overall capacity for the number of active threads that can run at one time. By default, the number of block threads is $t = \min(p, d, b)$, where p is the value of the NTHREADS= option in the main solver statement, d is the value of the NTHREADS= option in the DECOMP statement, and b is the number of blocks that the decomposition algorithm sets or finds.

RELOBJGAP=*number*

specifies the relative objective gap as a stopping criterion. The relative objective gap is based on the master objective (MasterObjective) and the best dual bound (BestBound); it is equal to

$$|\text{MasterObjective} - \text{BestBound}| / (1\text{E–}10 + |\text{BestBound}|)$$

When this value becomes smaller than the specified gap size *number*, the decomposition algorithm stops adding columns. The value of *number* can be any nonnegative number. For LP, the default value is 0; for MILP, the default value is 1E–4.

DECOMPMASTER Statement

DECOMPMASTER < *master-options* > **;**

DECOMPOSITIONMASTER < *master-options* > **;**

MASTER < *master-options* > **;**

The DECOMPMASTER statement controls the master problem.

Table 18.4 summarizes the options available in the DECOMPMASTER statement. These options control the master LP solver in the decomposition algorithm during the solution of an LP or a MILP. (As the table indicates, you can specify the PRINTLEVEL= option only in the OPTLP procedure.) For descriptions of these options, see the section "LP Solver Options" on page 638 in Chapter 13, "The Linear Programming Solver," and the section "PROC OPTLP Statement" on page 126 in Chapter 5, "The OPTLP Procedure." Some options have different defaults when you use the decomposition algorithm, as indicated in Table 18.4.

Table 18.4 Options in the DECOMPMASTER Statement

Description	*master-option*	Different Default
Algorithm Option		
Specifies the master algorithm	ALGORITHM=	PS†
Presolve Option		
Controls the dualization of the problem	DUALIZE=	OFF
Controls the folding of the problem	FOLD=	AUTOMATIC
Specifies, for the first master solve only, the type of presolve	INITPRESOLVER=	
Specifies the type of presolve	PRESOLVER=	NONE†
Control Options		
Specifies the feasibility tolerance	FEASTOL=	1E–7
Specifies how frequently to print the solution progress	LOGFREQ=	
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=	NONE
Specifies the time limit for the optimization process	MAXTIME=	
Specifies the number of threads to use in the master solver	NTHREADS=	
Specifies the optimality tolerance	OPTTOL=	1E–7
Enables or disables printing summary (OPTLP procedure only)	PRINTLEVEL=	
Specifies whether time units are CPU time or real time	TIMETYPE=	
Specifies the type of initial basis	BASIS=	WARMSTART†
Specifies the type of pricing strategy	PRICETYPE=	
Specifies the queue size for determining the entering variable	QUEUESIZE=	
Enables or disables scaling of the problem	SCALE=	
Specifies the initial seed for the random number generator	SEED=	
Interior Point Algorithm Options		
Enables or disables interior crossover	CROSSOVER=	
Specifies the stopping criterion based on a duality gap	DUALITYGAP=	

† The reason for the different defaults (ALGORITHM=PS, PRESOLVER=NONE, and BASIS=WARMSTART) is that primal feasibility of the master problem is preserved when columns are added, so a warm start from the previous optimal basis tends to be

more efficient than solving the master from scratch at each iteration.

The following options, listed in Table 18.4, are specific to the DECOMPMASTER statement and are not described in the LP solver sections:

INITPRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
INITPRESOL=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
specifies, for the first master solve only, the presolve level. You can specify the following values:

AUTOMATIC	applies the default level of presolve processing.
NONE	disables the presolver.
BASIC	performs minimal presolve processing.
MODERATE	applies a higher level of presolve processing.
AGGRESSIVE	applies the highest level of presolve processing.

By default, INITPRESOLVER=AUTOMATIC.

NTHREADS=*number*
NUMTHREADS=*number*
specifies the number of threads to use in the master solver (if the selected solver method supports multithreading). The value of the NTHREADS= option in the main solver statement serves as the overall capacity for the number of active threads that can run at one time. By default, the number of master threads is the value of the NTHREADS= option in the main solver statement.

DECOMPMASTERIP Statement

DECOMPMASTERIP < *masterip-options* > **;**

DECOMPOSITIONMASTERIP < *masterip-options* > **;**

MASTERIP < *masterip-options* > **;**

For mixed integer linear programming problems, the DECOMPMASTERIP statement controls the (restricted) master problem, which is solved as a MILP with the current set of columns in an effort to obtain an integer feasible solution.

Table 18.5 summarizes the options available in the DECOMPMASTERIP statement. These options control the MILP solver that is used to solve the integer version of the master problem. For descriptions of these options, see the section "MILP Solver Options" on page 710 in Chapter 14, "The Mixed Integer Linear Programming Solver," and the section "PROC OPTMILP Statement" on page 187 in Chapter 6, "The OPTMILP Procedure." Some options have different defaults when you use the decomposition algorithm, as shown in Table 18.5.

Table 18.5 Options in the DECOMPMASTERIP Statement

Description	*masterip-option*	Different Default
Presolve Option		
Specifies the type of presolve	PRESOLVER=	
Control Options		
Specifies the stopping criterion based on an absolute objective gap	ABSOBJGAP=	
Specifies the cutoff value for node removal	CUTOFF=	
Emphasizes feasibility or optimality	EMPHASIS=	
Specifies the maximum violation on variables and constraints	FEASTOL=	1E–7
Specifies the maximum difference allowed between an integer variable's value and an integer	INTTOL=	
Specifies how frequently to print the node log	LOGFREQ=	
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=	NONE
Specifies the maximum number of nodes to process	MAXNODES=†	
Specifies the maximum number of solutions to find	MAXSOLS=	
Specifies the time limit for the optimization process	MAXTIME=	
Specifies the number of threads to use in the master integer solver	NTHREADS=	
Specifies the tolerance to use in determining the optimality of nodes in the branch-and-bound tree	OPTTOL=	1E–7
Specifies whether to use the previous best primal solution as a warm start	PRIMALIN=	
Specifies the probing level	PROBE=	
Specifies the stopping criterion based on a relative objective gap	RELOBJGAP=	0.01
Specifies the scale of the problem matrix	SCALE=	
Specifies the initial seed for the random number generator	SEED=	
Specifies the stopping criterion based on a target objective value	TARGET=	
Specifies whether time units are CPU time or real time	TIMETYPE=	
Heuristics Option		
Specifies the primal heuristics level	HEURISTICS=	
Search Options		
Specifies the level of conflict search	CONFLICTSEARCH=	
Specifies the node selection strategy	NODESEL=	
Specifies the restarting strategy	RESTARTS=	
Specifies the number of iterations to perform on each variable for strong branching strategy	STRONGITER=	
Specifies the number of candidates for strong branching	STRONGLEN=	
Specifies the level of symmetry detection	SYMMETRY=	
Specifies the rule for selecting branching variable	VARSEL=	
Cut Options		
Specifies the cut level for all cuts	ALLCUTS=	
Specifies the clique cut level	CUTCLIQUE=	
Specifies the flow cover cut level	CUTFLOWCOVER=	
Specifies the flow path cut level	CUTFLOWPATH=	
Specifies the Gomory cut level	CUTGOMORY=	
Specifies the generalized upper bound (GUB) cover cut level	CUTGUB=	

Table 18.5 *continued*

Description	*masterip-option*	Different Default
Specifies the implied bounds cut level	CUTIMPLIED=	
Specifies the knapsack cover cut level	CUTKNAPSACK=	
Specifies the lift-and-project cut level	CUTLAP=	
Specifies the mixed lifted 0-1 cut level	CUTMILIFTED=	
Specifies the mixed integer rounding (MIR) cut level	CUTMIR=	
Specifies the multicommodity network flow cut level	CUTMULTICOMMODITY=	
Specifies the row multiplier factor for cuts	CUTSFACTOR=	
Specifies the overall cut aggressiveness	CUTSTRATEGY=	
Specifies the zero-half cut level	CUTZEROHALF=	

† MAXNODES=100000 in the root node, and MAXNODES=10000 in nodes that are not the root.

The following options are listed in Table 18.5 but are not described in the MILP solver sections. These options are specific to the DECOMPMASTERIP statement.

NTHREADS=*number*

NUMTHREADS=*number*

specifies the number of threads to use in the master integer solver (if the selected solver method supports multithreading). The value of the NTHREADS= option in the main solver statement serves as the overall capacity for the number of active threads that can run at one time. By default, the number of master integer threads is the value of the NTHREADS= option in the main solver statement.

PRIMALIN=FALSE | TRUE

PIN=FALSE | TRUE

specifies whether the MILP solver is to use the previous best solution's variables values as a starting solution (warm start). If the MILP solver finds that the input solution is feasible, then the input solution provides an incumbent solution and a bound for the branch-and-bound algorithm. If the solution is not feasible, the MILP solver tries to repair it. When it is difficult to find a good integer feasible solution for a problem, a warm start can reduce solution time significantly. You can specify the following values:

FALSE ignores the previous solution.

TRUE starts from the previous solution.

By default, PRIMALIN=TRUE.

DECOMPSUBPROB Statement

DECOMPSUBPROB < *subprob-options* > **;**

DECOMPOSITIONSUBPROB < *subprob-options* > **;**

SUBPROB < *subprob-options* > **;**

The DECOMPSUBPROB statement controls the subproblem.

Table 18.6 summarizes the options available for the decomposition algorithm in the DECOMPSUBPROB statement when the chosen subproblem algorithm is an LP algorithm. (As the table indicates, you can specify the PRINTLEVEL= option only in the OPTLP procedure.) For descriptions of these options, see the section "LP Solver Options" on page 638 in Chapter 13, "The Linear Programming Solver," and the section "PROC OPTLP Statement" on page 126 in Chapter 5, "The OPTLP Procedure." Some options have different defaults when you use the decomposition algorithm, as shown in Table 18.6.

Table 18.6 Options in the DECOMPSUBPROB Statement Used with an LP Algorithm

Description	*subprob-option*	Different Default
Algorithm Option		
Specifies the subproblem algorithm	ALGORITHM=	†
Presolve Option		
Controls the dualization of the problem	DUALIZE=	OFF
Controls the folding of the problem	FOLD=	AUTOMATIC
Specifies, for the first subproblem solve only, the type of presolve	INITPRESOLVER=	
Specifies the type of presolve	PRESOLVER=	NONE†
Control Options		
Specifies the feasibility tolerance	FEASTOL=	1E–7
Specifies how frequently to print the solution progress	LOGFREQ=	
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=	NONE
Specifies the time limit for the optimization process	MAXTIME=	
Specifies the number of threads to use in the subproblem solver	NTHREADS=	
Specifies the optimality tolerance	OPTTOL=	1E–7
Enables or disables printing summary (OPTLP procedure only)	PRINTLEVEL=	
Specifies the initial seed for the random number generator	SEED=	
Specifies whether time units are CPU time or real time	TIMETYPE=	
Simplex Algorithm Options		
Specifies the type of initial basis	BASIS=	WARMSTART†
Specifies the type of pricing strategy	PRICETYPE=	
Specifies the queue size for determining entering variable	QUEUESIZE=	
Enables or disables scaling of the problem	SCALE=	
Interior Point Algorithm Options		
Enables or disables interior crossover	CROSSOVER=	
Specifies the stopping criterion based on a duality gap	DUALITYGAP=	

† When you specify METHOD=USER, METHOD=AUTO or METHOD=COMMUNITY in the DECOMP statement, ALGORITHM=PS, PRESOLVER=NONE, and BASIS=WARMSTART by default. The reason for these defaults is that primal feasibility of the subproblem is preserved when the objective is changed, so a warm start from the previous optimal basis tends to be more efficient than solving the subproblem from scratch at each iteration. When METHOD=NETWORK, ALGORITHM=NETWORKPURE by default because each subproblem is a pure network, causing the specialized pure network solver to usually be the most efficient choice. When METHOD=CONCOMP, ALGORITHM=DS by default because dual simplex generally has the best performance on linear programs and, in this case, one outer iteration is sufficient (that is, warm starts are not required).

Table 18.7 summarizes the options available in the DECOMPSUBPROB statement when the chosen subproblem algorithm is a MILP algorithm. When the subproblem consists of multiple blocks (a block-diagonal structure), these settings apply to all subproblems. For descriptions of these options, see the section "MILP Solver Options" on page 710 in Chapter 14, "The Mixed Integer Linear Programming Solver," and the section "PROC OPTMILP Statement" on page 187 in Chapter 6, "The OPTMILP Procedure."

Table 18.7 Options in the DECOMPSUBPROB Statement Used with a MILP Algorithm

Description	*subprob-option*	**Different Default**
Algorithm Option		
Specifies the subproblem algorithm	ALGORITHM=	
Presolve Option		
Specifies, for the first subproblem solve only, the type of presolve	INITPRESOLVER=	
Specifies the type of presolve	PRESOLVER=	
Control Options		
Specifies the stopping criterion based on an absolute objective gap	ABSOBJGAP=	
Emphasizes feasibility or optimality	EMPHASIS=	
Specifies the maximum violation on variables and constraints	FEASTOL=	1E–7
Specifies the maximum difference allowed between an integer variable's value and an integer	INTTOL=	
Specifies how frequently to print the node log	LOGFREQ=	
Specifies the level of detail of solution progress to print in the log	LOGLEVEL=	
Specifies the maximum number of nodes to process	MAXNODES=	
Specifies the maximum number of solutions to find	MAXSOLS=	
Specifies the time limit for the optimization process	MAXTIME=	
Specifies the number of threads to use in the subproblem solver	NTHREADS=	
Specifies the tolerance to use in determining the optimality of nodes in the branch-and-bound tree	OPTTOL=	1E–7
Specifies whether to use the previous best primal solution as a warm start	PRIMALIN=	
Specifies the probing level	PROBE=	
Specifies the stopping criterion based on a relative objective gap	RELOBJGAP=	
Specifies the scale of the problem matrix	SCALE=	
Specifies the initial seed for the random number generator	SEED=	
Specifies the stopping criterion based on a target objective value	TARGET=	
Specifies whether time units are CPU time or real time	TIMETYPE=	
Heuristics Option		
Specifies the primal heuristics level	HEURISTICS=	

Table 18.7 *continued*

Description	*subprob-option*	Different Default
Search Options		
Specifies the level of conflict search	CONFLICTSEARCH=	
Specifies the node selection strategy	NODESEL=	
Specifies the restarting strategy	RESTARTS=	
Specifies the number of iterations to perform for strong branching	STRONGITER=	
Specifies the number of candidates for strong branching	STRONGLEN=	
Specifies the level of symmetry detection	SYMMETRY=	
Specifies the rule for selecting branching variable	VARSEL=	
Cut Options		
Specifies the cut level for all cuts	ALLCUTS=	
Specifies the clique cut level	CUTCLIQUE=	
Specifies the flow cover cut level	CUTFLOWCOVER=	
Specifies the flow path cut level	CUTFLOWPATH=	
Specifies the Gomory cut level	CUTGOMORY=	
Specifies the generalized upper bound (GUB) cover cut level	CUTGUB=	
Specifies the implied bounds cut level	CUTIMPLIED=	
Specifies the knapsack cover cut level	CUTKNAPSACK=	
Specifies the lift-and-project cut level	CUTLAP=	
Specifies the mixed lifted 0-1 cut level	CUTMILIFTED=	
Specifies the mixed integer rounding (MIR) cut level	CUTMIR=	
Specifies the multicommodity network flow cut level	CUTMULTICOMMODITY=	
Specifies the row multiplier factor for cuts	CUTSFACTOR=	
Specifies the overall cut aggressiveness	CUTSTRATEGY=	
Specifies the zero-half cut level	CUTZEROHALF=	

The following options, listed in Table 18.6 and Table 18.7, are specific to the DECOMPSUBPROB statement and are not described in the LP or MILP solver sections:

ALGORITHM=*string*

SOLVER=*string*

SOL=*string*

specifies the algorithm to use for the subproblem solves. You can specify the following values (the valid abbreviated value for each *string* follows the vertical bar):

PRIMAL | PS uses the primal simplex algorithm.

DUAL | DS uses the dual simplex algorithm.

NETWORK | NS uses the network simplex algorithm.

NETWORKPURE | NSPURE uses the network simplex algorithm for pure networks.

INTERIORPOINT | IP uses the interior point algorithm.

MILP uses the mixed integer linear solver.

By default, ALGORITHM=NETWORKPURE if METHOD=NETWORK, ALGORITHM=MILP for mixed integer linear programming subproblems, and ALGORITHM=PS for linear programming subproblems.

INITPRESOLVER=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE
INITPRESOL=AUTOMATIC | NONE | BASIC | MODERATE | AGGRESSIVE

specifies, for the first subproblem solve only, the presolve level. You can specify the following values:

AUTOMATIC applies the default level of presolve processing.

NONE disables the presolver.

BASIC performs minimal presolve processing.

MODERATE applies a higher level of presolve processing.

AGGRESSIVE applies the highest level of presolve processing.

By default, INITPRESOLVER=AUTOMATIC.

NTHREADS=*number*
NUMTHREADS=*number*

specifies the number of threads to use in the subproblem solver (if the selected solver method supports multithreading). The value of the NTHREADS= option in the main solver statement serves as the overall capacity for the number of active threads that can run at one time. By default, the number of subproblem threads is $t = \max(1, \lfloor p/n \rfloor)$, where p is the value of the NTHREADS= option in the main solver statement; $n = \min(p, \lceil d/m \rceil)$, which is the number of blocks being processed simultaneously; d is the number of block threads; and m is the number of compute nodes (which can be more than one, when you run the decomposition algorithm in distributed mode).

PRIMALIN=FALSE | TRUE
PIN=FALSE | TRUE

specifies (for MILP problems only) whether the MILP solver is to use the values of the previous best solution's variables as a starting solution (warm start). If the MILP solver finds that the input solution is feasible, then the input solution provides an incumbent solution and a bound for the branch-and-bound algorithm. If the solution is not feasible, the MILP solver tries to repair it. When it is difficult to find a good integer feasible solution for a problem, a warm start can reduce solution time significantly. You can specify the following values:

FALSE ignores the previous solution.

TRUE starts from the previous solution.

By default, PRIMALIN=TRUE.

Details: Decomposition Algorithm

Data Input

This subsection describes the format for describing the partition of the constraint system that defines the subproblem blocks. In the OPTLP and OPTMILP procedures, partitioning is done by using a data table specified in the BLOCKS= data option in the DECOMP statement. In PROC OPTMODEL, partitioning is done by using the **.block** suffix on constraints.

The blocks must be disjoint with respect to variables. If two blocks contain a nonzero coefficient for the same variable, the decomposition algorithm produces an error that contains information about where the blocks overlap.

The BLOCKS= Data Table in PROC OPTMILP and PROC OPTLP

The BLOCKS= data table has two required variables:

ROW
specifies the constraint (row) names of the problem. The values should be a subset of the row names in the DATA= data table for the current problem.

BLOCK
specifies the numeric block identifier for each constraint in the problem. A missing observation or missing value indicates a master (linking) constraint that does not appear in any block. Listing the linking constraints is optional. The block identifiers must start from 0 and be consecutive.

See the section "Solving a MILP with DECOMP and PROC OPTMILP" on page 1038 for an example of using this BLOCKS= data table with PROC OPTMILP.

The .block Constraint Suffix in PROC OPTMODEL

The **.block** constraint suffix specifies the numeric block identifier for each constraint in the problem. The block identifiers do not need to start from 0, nor do they need to be consecutive. Master (linking) constraints can be identified by using a missing value. Listing the linking constraints is optional.

See the section "Solving a MILP with DECOMP and PROC OPTMODEL" on page 1036 for an example of using the **.block** constraint suffix with PROC OPTMODEL.

Decomposition Algorithm

The decomposition algorithm for LPs is based on the original Dantzig-Wolfe method (Dantzig and Wolfe 1960). Embedding this method in the context of a branch-and-bound algorithm for MILPs is described in Barnhart et al. (1998) and is often referred to as *branch-and-price*. The design of a framework that allows for building a generic branch-and-price solver that requires only the original (compact) formulation and the constraint partition was first proposed independently by Ralphs and Galati (2006) and Vanderbeck and Savelsbergh (2006). This method is also commonly referred to as *column generation*, although the algorithm implemented here is only one specific variant of this wider class of algorithms.

The algorithm setup starts by forming various components that are used iteratively during the solver process. These components include the master problem (controlled by options in the DECOMPMASTER statement), one subproblem for each block (controlled by options in the DECOMPSUBPROB statement) and, for MILPs, the integer version of the master problem (controlled by options in the DECOMPMASTERIP statement).

The master problem is a linear program that is defined over a potentially large number of variables that represent the weights of a convex combination. The points in the convex combination satisfy the constraints that are defined in the subproblem. The master constraints of the original problem are enforced in this reformulated space. In this sense, the decomposition algorithm takes the intersection of two polyhedra: one defined by original master constraints and one defined by the subproblem constraints. Since the set of variables needed to define the intersection of the polyhedra can be large, the algorithm works on a restricted subset and generates only those variables (columns) that have good potential with respect to feasibility and optimality. This generation is done by using the dual information that is obtained by solving the master problem to *price out* new variables. These new variables are generated by solving the subproblems over the appropriate cost vector (the reduced cost in the original space). This generation is similar to the revised simplex method, except that the variable space is exponentially large and therefore is generated implicitly by solving an optimization problem. This idea of generating variables as needed is the reason why this method is often referred to as *column generation*.

Similar to the two-phase simplex algorithm, the algorithm first introduces slack variables and solves a phase I problem to find a feasible solution. After the algorithm finds a feasible solution, it switches to a phase II problem to search for an optimal solution. The process of solving the master to generate pricing information and then solving one or more subproblems to generate candidate variables is repeated until there are no longer any improving variables and the method has converged.

For MILPs, this process is then used as a bounding method in a branch-and-bound algorithm, as described in the section "Branch-and-Bound Algorithm" on page 204. The strength of the subproblem polyhedron is one of the key reasons why decomposition can often solve problems that the standard branch-and-cut algorithm cannot solve in a reasonable amount of time. Since the points used in the convex combination are solutions (extreme points) of the subproblem (typically a MILP itself), then the bounds obtained can often be much stronger than the bounds obtained from standard branch-and-bound methods that are based on the LP relaxation. The subproblem polyhedron intersected with the continuous master polyhedron can provide a very good approximation of the true convex hull of the original integer program.

For more information about the algorithm process flow and the framework design, see Galati (2009).

Parallel Processing

At each iteration of the decomposition method, the subproblem is solved to minimize the reduced cost that is derived from the dual information that solving the master problem provides. As discussed in the section "Overview: Decomposition Algorithm" on page 1034, the subproblem often has a block-angular structure that enables the solver to process each block independently.

When solving MILPs, you can run the decomposition algorithm in either single-machine or distributed mode. If the DISTRIBUTED= option in the main solver statement is set to TRUE (and your configured CAS session has two or more workers), then the computation is executed in distributed mode (using multiple machines simultaneously). The decomposition algorithm supports only the deterministic mode (DETERMINISTIC=TRUE in the main solver statement). The default mode of operation is single-machine mode.

You can control the number of threads that are used (by each machine) by specifying the NTHREADS= option in the main solver statement. In distributed mode, if the allowable number of active CPUs differs among machines, the decomposition algorithm will use the minimum number allowed as the limit applied to the NTHREADS= option in the main solver statement. In addition, you can use the NTHREADS= option in each subcomponent statement to specify the number of threads to use for that solver. This is discussed in detail in the following sections:

- NTHREADS= option in the DECOMP statement on page 1047
- NTHREADS= option in the DECOMPMASTER statement on page 1049
- NTHREADS= option in the DECOMPMASTERIP statement on page 1051
- NTHREADS= option in the DECOMPSUBPROB statement on page 1055

Because of communication costs, increasing the number of machines does not guarantee faster execution, especially when you have subproblems that are unbalanced with respect to computational cost. For all the documentation examples, unless otherwise noted, the CAS session is configured for four worker nodes, each having 32 cores. For general information about CAS sessions, see *SAS Cloud Analytic Services: Fundamentals*.

Special Case: Identical Blocks and Ryan-Foster Branching

In the special case of a set partitioning master problem and identical blocks, the underlying algorithm is automatically adjusted to reduce symmetry and improve overall performance. Identical blocks are subproblems (see the section "Overview: Decomposition Algorithm" on page 1034) that have equivalent feasible regions (and optima) when they are projected. Algebraically, this means that

$$
\begin{array}{ccccccc}
\mathbf{A}^1 & = & \mathbf{A}^2 & = & \cdots & = & \mathbf{A}^\kappa \\
\mathbf{D}^1 & = & \mathbf{D}^2 & = & \cdots & = & \mathbf{D}^\kappa \\
\mathbf{c}^1 & = & \mathbf{c}^2 & = & \cdots & = & \mathbf{c}^\kappa \\
\mathbf{b}^1 & = & \mathbf{b}^2 & = & \cdots & = & \mathbf{b}^\kappa \\
\overline{\mathbf{x}}^1 & = & \overline{\mathbf{x}}^2 & = & \ldots & = & \overline{\mathbf{x}}^\kappa \\
\underline{\mathbf{x}}^1 & = & \underline{\mathbf{x}}^2 & = & \ldots & = & \underline{\mathbf{x}}^\kappa
\end{array}
$$

A *set partitioning* problem is a specific type of integer programming model in which each constraint represents choosing exactly one member of a set. These constraints are often referred to as *assignment constraints*. The linear relaxation of a set partitioning problem enables an algorithm to choose fractional parts of several members of some set such that they sum to 1. Algebraically, this means $\mathbf{Ax} = \mathbf{1}$, where all the coefficients in $\mathbf{A}$ are 0 or 1.

The performance of algorithms that use a branch-and-bound method can suffer when the formulation contains substructures that are symmetric. In this context, *symmetric* means that an assignment of solutions can be arbitrarily permuted for some component without affecting the optimality of that solution. For example, if

$$x_{11} = 1 \quad x_{12} = 0 \quad x_{21} = 0 \quad x_{22} = 1$$

and

$$x_{11} = 0 \quad x_{12} = 1 \quad x_{21} = 1 \quad x_{22} = 0$$

are both optimal, then these solutions, x_{ij}, are considered symmetric on index j. That is, you can interchange $j = 1$ and $j = 2$ without affecting the optimality of the solution. The presence of identical blocks in a mathematical program is an obvious case in which symmetry can hurt performance. In order to overcome this handicap, the decomposition algorithm aggregates the identical blocks into one block when it forms the Dantzig-Wolfe master problem. If the Dantzig-Wolfe master problem is a set partitioning model, the algorithm uses a specialized branching rule known as *Ryan-Foster branching*. If the original master model (after aggregation) is equivalent to the identity matrix, this guarantees that the Dantzig-Wolfe master problem is of the appropriate form. For more information about the aggregate formulation and Ryan-Foster branching, see Barnhart et al. (1998).

Suppose you want to solve the following problem:

$$\begin{array}{lrcrcrcrcrcrcll}
\text{maximize} & x_{11} & + & 2x_{21} & + & x_{31} & + & x_{12} & + & 2x_{22} & + & x_{32} & & & \\
\text{subject to} & x_{11} & & & & & + & x_{12} & & & & & = & 1 & \text{(m1)} \\
 & & & x_{21} & & & & & + & x_{22} & & & = & 1 & \text{(m2)} \\
 & 5x_{11} & + & 7x_{21} & + & 4x_{31} & & & & & & & \leq & 11 & \text{(s1)} \\
 & & & & & & & 5x_{12} & + & 7x_{22} & + & 4x_{32} & \leq & 11 & \text{(s2)} \\
 & & & & & & & & & & & x_{ij} & \in & \{0,1\} & i \in \{1,2,3\}, \\
 & & & & & & & & & & & & & & j \in \{1,2\}
\end{array}$$

If constraints m1 and m2 are removed, then the remaining constraints s1 and s2 decompose into two independent and identical subproblems. In addition, constraints m1 and m2 form a set partitioning master problem.

The following statements use the OPTMODEL procedure and the decomposition algorithm to solve the preceding problem:

```
proc optmodel sessref="mysess";
   var x{i in 1..3, j in 1..2} binary;

   max f =    x[1,1] + 2*x[2,1] +   x[3,1] +
              x[1,2] + 2*x[2,2] +   x[3,2];

   con m1:    x[1,1] +   x[1,2]             =  1;
   con m2:    x[2,1] +   x[2,2]             =  1;
   con s1:  5*x[1,1] + 7*x[2,1] + 4*x[3,1] <= 11;
```

```
   con s2:  5*x[1,2] + 7*x[2,2] + 4*x[3,2] <= 11;

   s1.block = 0;
   s2.block = 1;

   solve with milp / presolver=none decomp=(logfreq=1);
   print x;
quit;
```

Here, the PRESOLVER=NONE option is used again, because otherwise the presolver solves this small instance without invoking any solver. The solution summary and optimal solution are displayed in Figure 18.3.

Figure 18.3 Solution Summary and Optimal Solution

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	f
Solution Status	Optimal
Objective Value	5
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	5
Nodes	1
Solutions Found	1
Iterations	2
Presolve Time	0.00
Solution Time	0.02

	x	
	1	**2**
1	1	0
2	0	1
3	1	1

The iteration log, which displays the problem statistics, the progress of the solution, and the optimal objective value, is shown in Figure 18.4.

Figure 18.4 Log

```
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 6 variables (0 free, 0 fixed).
NOTE: The problem has 6 binary and 0 integer variables.
NOTE: The problem has 4 linear constraints (2 LE, 2 EQ, 0 GE, 0 range).
NOTE: The problem has 10 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value NONE is applied.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: All blocks are identical and the master model is set partitioning.
NOTE: The Decomposition algorithm is using an aggregate formulation and Ryan-Foster branching.
NOTE: The number of block threads has been reduced to 1 threads.
NOTE: The problem has a decomposable structure with 2 blocks. The largest block covers 25% of
      the constraints in the problem.
NOTE: The decomposition subproblems cover 6 (100%) variables and 2 (50%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
         .        6.0000       5.0000       5.0000   16.67%   16.67%    0    0
         1        6.0000       5.0000       5.0000   16.67%   16.67%    0    0
         2        5.0000       5.0000       5.0000    0.00%    0.00%    0    0
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1      1       5.0000       5.0000    0.00%      0      0
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 0.02 seconds.
NOTE: Optimal.
NOTE: Objective = 5.
```

The decomposition solver recognizes that the original master model is of the appropriate form and that each block is identical. It formulates the aggregate master and uses Ryan-Foster branching to solve the model.

In the presence of identical blocks, under certain circumstances, the aggregate formulation can also be used with a set covering master formulation. A *set covering* problem is an integer programming model in which each constraint represents choosing at least one member of a set. Algebraically, this means $\mathbf{Ax} \geq \mathbf{1}$, where all the coefficients in $\mathbf{A}$ are 0 or 1. Aggregate formulation and Ryan-Foster branching can be used if there exists an optimal solution, $\mathbf{x}^*$, that is binding at equality ($\mathbf{Ax}^* = \mathbf{1}$). If you can guarantee such a condition, you can greatly improve performance by explicitly using VARSEL=RYANFOSTER as a MILP main solver option. The decomposition algorithm usually performs better when it uses a set covering formulation as opposed to a set partitioning formulation, because it is usually easier to find integer feasible solutions. If the models are equivalent, using the set covering formulation is recommended. For two examples, see Example 18.6, which shows the bin packing problem, and Example 18.8, which shows the vehicle routing problem.

Similarly, a *set packing* problem is an integer programming model in which each constraint represents choosing at most one member of a set. Algebraically, this means $\mathbf{Ax} \leq \mathbf{1}$, where all the coefficients in $\mathbf{A}$ are 0 or 1. Aggregate formulation and Ryan-Foster branching can be used if there exists an optimal solution, $\mathbf{x}^*$, that is binding at equality ($\mathbf{Ax}^* = \mathbf{1}$). In this case, using VARSEL=RYANFOSTER can improve performance. Alternatively, you can transform any set packing model into a set partitioning model by introducing a zero-cost slack variable for each packing constraint. See Example 18.11, which shows an application that optimizes a kidney donor exchange.

The decomposition algorithm automatically searches for identical blocks and the appropriate set partitioning master formulation. If it finds this structure, the algorithm automatically generates the aggregate formulation and uses Ryan-Foster branching. The aggregate model needs to process only one block at each subproblem iteration. Therefore, parallel processing (in which multiple blocks are processed simultaneously), as described in the section "Parallel Processing" on page 1058, cannot improve performance. For this reason, when the decomposition algorithm runs in distributed mode, it does not create the aggregate formulation, nor does it use Ryan-Foster branching, even if the blocks are found to be identical.

Log for the Decomposition Algorithm

The following subsections describe what to expect in the SAS log when you run the decomposition algorithm.

Setup Information in the SAS Log

In the setup phase of the algorithm, information about the method you choose and the structure of the model is written to the SAS log. One of the most important pieces of information displayed in the log is the number of disjoint blocks and the coverage of those blocks with respect to both variables and constraints in the original presolved model. As explained in the section "Overview: Decomposition Algorithm" on page 1034, the decomposition algorithm usually performs better than standard approaches only if the subproblems cover a significant amount of the original problem. However, this is not always a straightforward indicator for MILPs, because the strength of the subproblem with respect to integrality is not always proportional to the size of the system.

After the structural information is written to the log, the algorithm begins and the iteration log is displayed.

Iteration Log for LPs

When the decomposition algorithm solves LPs, the iteration log shows the progress of convergence in finding the appropriate set of columns in the reformulated space.

The following information is written to the iteration log:

Iter	indicates the iteration number.
Best Bound	indicates the best dual bound found so far.
Master Objective	indicates the current amount of infeasibility in phase I and the primal objective value of the current solution in phase II.
Gap	indicates the relative difference between the master objective and the best known dual bound. This indicates how close the algorithm is to convergence. If the relative gap is greater than 1000%, then the absolute gap is written.

CPU Time	indicates the CPU time elapsed (in seconds).
Real Time	indicates the real time elapsed (in seconds).

Entries are made in the log at a frequency that is specified in the LOGFREQ= option. If LOGFREQ=0, then the iteration log is disabled. If the LOGFREQ= value is positive, then an entry is made in the log at the first iteration, at the last iteration, and at intervals that are specified by the LOGFREQ= value. An entry is also made each time an improved bound is found.

The behavior of objective values in the iteration log depends on both the current phase and on which solver you choose. In phase I, the master formulation has an artificial objective value that decreases to 0 when a feasible solution is found. In phase II, the decomposition algorithm maintains a primal feasible solution, so a minimization problem has decreasing objective values in the iteration log.

When you specify LOGLEVEL=MODERATE or LOGLEVEL=AGGRESSIVE in the DECOMP statement, information about the subproblem solves is written before each iteration line.

Iteration Log for MILPs

When the decomposition algorithm solves MILPs, the iteration log shows the progress of convergence in finding the appropriate set of columns in the reformulated space, in addition to the global convergence of the branch-and-bound algorithm for finding an optimal integer solution.

You can control the amount of information at each node by using the LOGLEVEL= option in the DECOMP statement. By default, the continuous iteration log for the root node is written at the interval specified in the LOGFREQ= option in the DECOMP statement. Then the branch-and-bound node log is written at the interval specified in the LOGFREQ= main solver option.

When the algorithm solves MILPs, the continuous iteration log is similar to the iteration log described in the section "Iteration Log for LPs" on page 1062 except that information about integer feasible solutions is also displayed. The following information is printed in the continuous iteration log when the algorithm solves MILPs:

Iter	indicates the iteration number.
Best Bound	indicates the best dual bound found so far.
Master Objective	indicates the current amount of infeasibility in phase I and the primal objective value of the current solution in phase II.
Best Integer	indicates the objective value of the best integer feasible solution found so far.
LP Gap	indicates the relative difference between the master objective and the best known dual bound. This indicates how close the algorithm for this particular node is to convergence. If the relative gap is greater than 1000%, then the absolute gap is displayed.
IP Gap	indicates the relative difference between the best integer and the best known dual bound. This indicates how close the branch-and-bound algorithm is to convergence. If the relative gap is greater than 1000%, then the absolute gap is displayed.
CPU Time	indicates the CPU time elapsed (in seconds).
Real Time	indicates the real time elapsed (in seconds).

After the root node is complete, the algorithm then moves into the branch-and-bound phase. By default, it displays the branch-and-bound node log and suppresses the continuous iteration log.

The following information is printed in the branch-and-bound node log when the algorithm solves MILPs:

Node	indicates the sequence number of the current node in the search tree.
Active	indicates the current number of active nodes in the branch-and-bound tree.
Sols	indicates the number of feasible solutions found so far.
Best Integer	indicates the objective value of the best integer feasible solution found so far.
Best Bound	indicates the best dual bound found so far.
Gap	indicates the relative difference between the best integer and the best known dual bound. This indicates how close the branch-and-bound algorithm is to convergence. If the relative gap is greater than 1000%, then the absolute gap is displayed.
CPU Time	indicates the CPU time elapsed (in seconds).
Real Time	indicates the real time elapsed (in seconds).

If the LOGLEVEL= option in the DECOMP statement is set to BASIC, MODERATE or AGGRESSIVE, then the continuous iteration log is displayed for each branch-and-bound node at the interval specified in the LOGFREQ= option in the DECOMP statement.

Additional information can be displayed to the log by specifying the LOGLEVEL= option in each of the algorithmic component statements (DECOMPMASTER, DECOMPMASTERIP, and DECOMPSUBPROB). By default, the individual component log levels are all disabled.

Examples: Decomposition Algorithm

Example 18.1: Multicommodity Flow Problem and METHOD=NETWORK

This example demonstrates how to use the decomposition algorithm to find a minimum-cost multicommodity flow (MMCF) in a directed network. This type of problem was motivation for the development of the original Dantzig-Wolfe decomposition method (Dantzig and Wolfe 1960).

Let $G = (N, A)$ be a directed graph, and let K be a set of commodities. For each link $(i, j) \in A$ and each commodity k, associate a cost per unit of flow, designated by c_{ij}^k. The demand (or supply) at each node $i \in N$ for commodity k is designated as b_i^k, where $b_i^k \geq 0$ denotes a supply node and $b_i^k < 0$ denotes a demand node. Define decision variables x_{ij}^k that denote the amount of commodity k sent from node i and node j. The amount of total flow, across all commodities, that can be sent across each link is bounded above by u_{ij}.

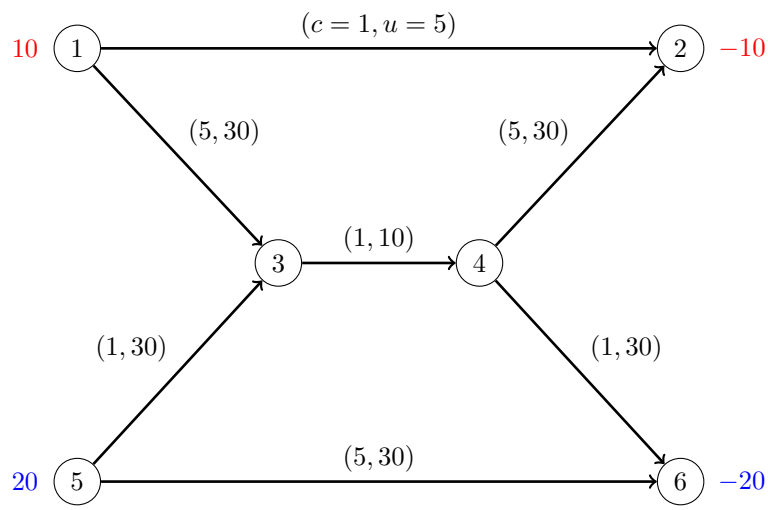
The problem can be modeled as a linear programming problem as follows:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{(i,j)\in A}\sum_{k\in K} c_{ij}^k x_{ij}^k & & \\
\text{subject to} & \displaystyle\sum_{k\in K} x_{ij}^k \le u_{ij} & (i,j)\in A & \text{(Capacity)} \\
& \displaystyle\sum_{(i,j)\in A} x_{ij}^k - \sum_{(j,i)\in A} x_{ji}^k = b_i^k & i\in N,\ k\in K & \text{(Balance)} \\
& x_{ij}^k \ge 0 & (i,j)\in A,\ k\in K &
\end{array}
$$

In this formulation, the Capacity constraints limit the total flow across all commodities on each arc. The Balance constraints ensure that the flow of commodities leaving each supply node and entering each demand node are balanced.

Consider the directed graph in Figure 18.5 which appears in Ahuja, Magnanti, and Orlin (1993).

Figure 18.5 Example Network with Two Commodities



The goal in this example is to minimize the total cost of sending two commodities across the network while satisfying all supplies and demands and respecting arc capacities. If there were no arc capacities linking the two commodities, you could solve a separate minimum-cost network flow problem for each commodity one at a time.

The following data set arc_comm_data provides the cost c_{ij}^k of sending a unit of commodity k along arc (i,j):

```
data arc_comm_data;
   input k i j cost;
   datalines;
1 1 2 1
1 1 3 5
1 5 3 1
1 5 6 5
1 3 4 1
```

```
1 4 2 5
1 4 6 1
2 1 2 1
2 1 3 5
2 5 3 1
2 5 6 5
2 3 4 1
2 4 2 5
2 4 6 1
;
```

Next, the data set arc_data provides the capacity u_{ij} for each arc:

```
data arc_data;
   input i j capacity;
   datalines;
1 2  5
1 3 30
5 3 30
5 6 30
3 4 10
4 2 30
4 6 30
;

data supply_data;
   input k i supply;
   datalines;
1 1  10
1 2 -10
2 5  20
2 6 -20
;
```

The following PROC OPTMODEL statements find the minimum-cost multicommodity flow:

```
proc optmodel sessref="mysess";
   set <num,num,num> ARC_COMM;
   num cost {ARC_COMM};
   read data arc_comm_data into ARC_COMM=[i j k] cost;

   set ARCS = setof {<i,j,k> in ARC_COMM} <i,j>;
   set COMMODITIES = setof {<i,j,k> in ARC_COMM} k;
   set NODES = union {<i,j> in ARCS} {i,j};

   num arcCapacity {ARCS};
   read data arc_data into [i j] arcCapacity=capacity;

   num supply {NODES, COMMODITIES} init 0;
   read data supply_data into [i k] supply;

   var Flow {<i,j,k> in ARC_COMM} >= 0;
   min TotalCost =
      sum {<i,j,k> in ARC_COMM} cost[i,j,k] * Flow[i,j,k];
   con Balance {i in NODES, k in COMMODITIES}:
```

```
      sum {<(i),j,(k)> in ARC_COMM} Flow[i,j,k]
       - sum {<j,(i),(k)> in ARC_COMM} Flow[j,i,k] = supply[i,k];
   con Capacity {<i,j> in ARCS}:
      sum {<(i),(j),k> in ARC_COMM} Flow[i,j,k] <= arcCapacity[i,j];
```

Because each Balance constraint involves variables for only one commodity, a decomposition by commodity is a natural choice. In both the OPTLP and OPTMILP procedures, the block identifiers must be consecutive integers starting from 0. In PROC OPTMODEL, the block identifiers only need to be numeric. The following **FOR** loop populates the **.block** constraint suffix with block identifier *k* for commodity *k*:

```
   for{i in NODES, k in COMMODITIES}
      Balance[i,k].block = k;
```

The **.block** constraint suffix for the linking Capacity constraints is left missing, so these constraints become part of the master problem.

The following SOLVE statement uses the DECOMP option to invoke the decomposition algorithm:

```
   solve with LP / presolver=none decomp subprob=(algorithm=nspure);
   print Flow;
quit;
```

Here, the PRESOLVER=NONE option is used, because otherwise the presolver solves this small instance without invoking any solver. Because each subproblem is a pure network flow problem, you can use the ALGORITHM=NSPURE option in the SUBPROB= option to request that a network simplex algorithm for pure networks be used instead of the default algorithm, which for linear programming subproblems is primal simplex.

It turns out for this example that if you specify METHOD=NETWORK (instead of the default METHOD=USER) in the DECOMP option, the network extractor finds the same blocks, one per commodity. To invoke the METHOD=NETWORK option, simply change the SOLVE statement as follows:

```
solve with LP / presolver=none decomp=(method=network);
```

In this case, the default subproblem solver is NSPURE.

The optimal solution and solution summary are displayed in Output 18.1.1.

Output 18.1.1 Solution Summary and Optimal Solution

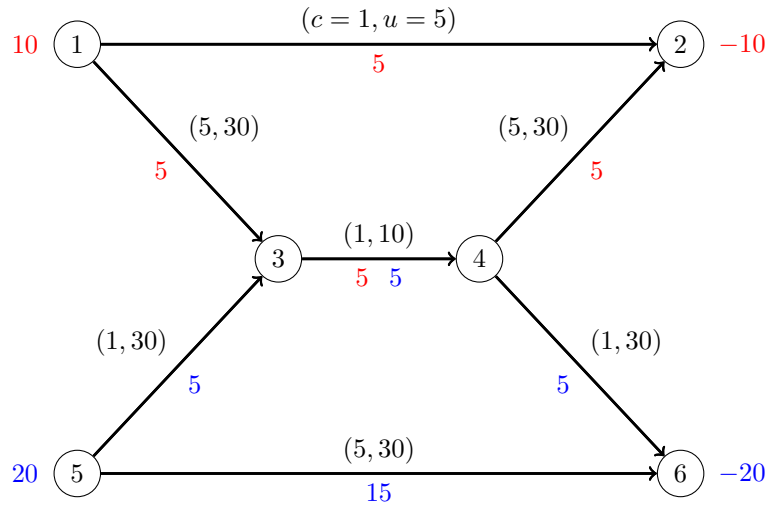
The OPTMODEL Procedure

Solution Summary	
Solver	LP
Algorithm	Decomposition
Objective Function	TotalCost
Solution Status	Optimal
Objective Value	150
Primal Infeasibility	0
Dual Infeasibility	0
Bound Infeasibility	0
Iterations	4
Presolve Time	0.00
Solution Time	0.01

[1]	[2]	[3]	Flow
1	**2**	**1**	5
1	**2**	**2**	0
1	**3**	**1**	5
1	**3**	**2**	0
3	**4**	**1**	5
3	**4**	**2**	5
4	**2**	**1**	5
4	**2**	**2**	0
4	**6**	**1**	0
4	**6**	**2**	5
5	**3**	**1**	0
5	**3**	**2**	5
5	**6**	**1**	0
5	**6**	**2**	15

The optimal solution is shown on the network in Figure 18.6.

Figure 18.6 Optimal Flow on Network with Two Commodities



The iteration log, which contains the problem statistics, the progress of the solution, and the optimal objective value, is shown in Output 18.1.2.

Output 18.1.2 Log

```
NOTE: There were 14 observations read from the data set WORK.ARC_COMM_DATA.
NOTE: There were 7 observations read from the data set WORK.ARC_DATA.
NOTE: There were 4 observations read from the data set WORK.SUPPLY_DATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 14 variables (0 free, 0 fixed).
NOTE: The problem has 19 linear constraints (7 LE, 12 EQ, 0 GE, 0 range).
NOTE: The problem has 42 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The LP presolver value NONE is applied.
NOTE: The LP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 2 threads.
NOTE: The problem has a decomposable structure with 2 blocks. The largest block covers 31.58%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 14 (100%) variables and 12 (63.16%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
       Iter          Best        Master       Gap       CPU      Real
                    Bound     Objective                Time      Time
NOTE: Starting phase 1.
          1        0.0000        1.0000  1.00e+00       0.0       0.0
          2        0.0000        0.0000     0.00%       0.0       0.0
          3        0.0000        0.0000     0.00%       0.0       0.0
NOTE: Starting phase 2.
          4      150.0000      150.0000     0.00%       0.0       0.0
NOTE: The Decomposition algorithm used 2 threads.
NOTE: The Decomposition algorithm time is 0.01 seconds.
NOTE: Optimal.
NOTE: Objective = 150.
```

Example 18.2: Generalized Assignment Problem

The generalized assignment problem (GAP) is that of finding a maximum profit assignment from n tasks to m machines such that each task is assigned to precisely one machine subject to capacity restrictions on the machines. With each possible assignment, associate a binary variable x_{ij}, which, if set to 1, indicates that machine i is assigned to task j. For ease of notation, define two index sets $M = \{1, \ldots, m\}$ and

$N = \{1, \ldots, n\}$. A GAP can be formulated as a MILP as follows:

$$
\begin{array}{llll}
\text{maximize} & \displaystyle\sum_{i \in M} \sum_{j \in N} p_{ij} x_{ij} & & \\
\text{subject to} & \displaystyle\sum_{i \in M} x_{ij} = 1 & j \in N & \text{(Assignment)} \\
& \displaystyle\sum_{j \in N} w_{ij} x_{ij} \leq b_i & i \in M & \text{(Knapsack)} \\
& x_{ij} \in \{0, 1\} & i \in M,\ j \in N &
\end{array}
$$

In this formulation, the Assignment constraints ensure that each task is assigned to exactly one machine. Knapsack constraints ensure that for each machine, the capacity restrictions are met.

Consider the following example taken from Koch et al. (2011) with $n = 24$ tasks to be assigned to $m = 8$ machines. The data set profit_data provides the profit for assigning a particular task to a particular machine:

```
%let NumTasks    = 24;
%let NumMachines = 8;

data profit_data;
   input p1-p&NumTasks;
   datalines;
25 23 20 16 19 22 20 16 15 22 15 21 20 23 20 22 19 25 25 24 21 17 23 17
16 19 22 22 19 23 17 24 15 24 18 19 20 24 25 25 19 24 18 21 16 25 15 20
20 18 23 23 23 17 19 16 24 24 17 23 19 22 23 25 23 18 19 24 20 17 23 23
16 16 15 23 15 15 25 22 17 20 19 16 17 17 20 17 17 18 16 18 15 25 22 17
17 23 21 20 24 22 25 17 22 20 16 22 21 23 24 15 22 25 18 19 19 17 22 23
24 21 23 17 21 19 19 17 18 24 15 15 17 18 15 24 19 21 23 24 17 20 16 21
18 21 22 23 22 15 18 15 21 22 15 23 21 25 25 23 20 16 25 17 15 15 18 16
19 24 18 17 21 18 24 25 18 23 21 15 24 23 18 18 23 23 16 20 20 19 25 21
;
```

The data set weight_data provides the amount of resources used by a particular task when assigned to a particular machine:

```
data weight_data;
   input w1-w&NumTasks;
   datalines;
 8 18 22  5 11 11 22 11 17 22 11 20 13 13  7 22 15 22 24  8  8 24 18  8
24 14 11 15 24  8 10 15 19 25  6 13 10 25 19 24 13 12  5 18 10 24  8  5
22 22 21 22 13 16 21  5 25 13 12  9 24  6 22 24 11 21 11 14 12 10 20  6
13  8 19 12 19 18 10 21  5  9 11  9 22  8 12 13  9 25 19 24 22  6 19 14
25 16 13  5 11  8  7  8 25 20 24 20 11  6 10 10  6 22 10 10 13 21  5 19
19 19  5 11 22 24 18 11  6 13 24 24 22  6 22  5 14  6 16 11  6  8 18 10
24 10  9 10  6 15  7 13 20  8  7  9 24  9 21  9 11 19 10  5 23 20  5 21
 6  9  9  5 12 10 16 15 19 18 20 18 16 21 11 12 22 16 21 25  7 14 16 10
;
```

Finally, the data set capacity_data provides the resource capacity for each machine:

```
data capacity_data;
   input b @@;
   datalines;
36 35 38 34 32 34 31 34
;
```

The following PROC OPTMODEL statements read in the data and define the necessary sets and parameters:

```
proc optmodel sessref="mysess";
   /* declare index sets */
   set TASKS    = 1..&NumTasks;
   set MACHINES = 1..&NumMachines;

   /* declare parameters */
   num profit   {MACHINES, TASKS};
   num weight   {MACHINES, TASKS};
   num capacity {MACHINES};

   /* read data sets to populate data */
   read data profit_data   into [i=_n_] {j in TASKS} <profit[i,j]=col('p'||j)>;
   read data weight_data   into [i=_n_] {j in TASKS} <weight[i,j]=col('w'||j)>;
   read data capacity_data into [_n_] capacity=b;
```

The following statements declare the optimization model:

```
   /* declare decision variables */
   var Assign {MACHINES, TASKS} binary;

   /* declare objective */
   max TotalProfit =
      sum {i in MACHINES, j in TASKS} profit[i,j] * Assign[i,j];

   /* declare constraints */
   con Assignment {j in TASKS}:
      sum {i in MACHINES} Assign[i,j] = 1;

   con Knapsack {i in MACHINES}:
      sum {j in TASKS} weight[i,j] * Assign[i,j] <= capacity[i];
```

The following statements use two different decompositions to solve the problem. The first decomposition defines each Assignment constraint as a block and uses the pure network simplex solver for the subproblem. The second decomposition defines each Knapsack constraint as a block and uses the MILP solver for the subproblem.

```
   /* each Assignment constraint defines a block */
   for{j in TASKS}
      Assignment[j].block = j;

   solve with milp / logfreq=1000
      decomp
      decompsubprob=(algorithm=nspure);

   /* each Knapsack constraint defines a block */
   for{j in TASKS}
```

```
      Assignment[j].block = .;
   for{i in MACHINES}
      Knapsack[i].block = i;

   solve with milp / decomp;
quit;
```

The solution summaries are displayed in Output 18.2.1.

Output 18.2.1 Solution Summaries

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalProfit
Solution Status	Optimal
Objective Value	563
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	563
Nodes	69
Solutions Found	4
Iterations	560
Presolve Time	0.00
Solution Time	0.59

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalProfit
Solution Status	Optimal
Objective Value	563
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	3.996803E-15
Bound Infeasibility	3.996803E-15
Integer Infeasibility	3.996803E-15
Best Bound	563
Nodes	3
Solutions Found	6
Iterations	65
Presolve Time	0.00
Solution Time	0.16

The iteration log for both decompositions is shown in Output 18.2.2. This example is interesting because it shows the trade-off between the strength of the relaxation and the difficulty of its resolution. In the first decomposition, the subproblems are totally unimodular and can be solved trivially. Consequently, each iteration of the decomposition algorithm is very fast. However, the bound obtained is as weak as the bound found in direct methods (the LP bound). The weaker bound leads to the need to enumerate more nodes overall. Alternatively, in the second decomposition, the subproblem is the knapsack problem, which is solved using MILP. In this case, the bound is much tighter and the problem solves in very few nodes. The trade-off, of course, is that each iteration takes longer because solving the knapsack problem is not trivial. Another interesting aspect of this problem is that the subproblem coverage in the second decomposition is much smaller than that of the first decomposition. However, when dealing with MILP, it is not always the size of the coverage that determines the overall effectiveness of a particular choice of decomposition.

Output 18.2.2 Log

```
NOTE: There were 8 observations read from the data set WORK.PROFIT_DATA.
NOTE: There were 8 observations read from the data set WORK.WEIGHT_DATA.
NOTE: There were 8 observations read from the data set WORK.CAPACITY_DATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 192 variables (0 free, 0 fixed).
NOTE: The problem has 192 binary and 0 integer variables.
NOTE: The problem has 32 linear constraints (8 LE, 24 EQ, 0 GE, 0 range).
NOTE: The problem has 384 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 5 constraint coefficients.
NOTE: The presolved problem has 192 variables, 32 constraints, and 384 constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 24 threads.
WARNING: The subproblem solver chosen is an LP solver but at least one block has integer
         variables.
NOTE: The problem has a decomposable structure with 24 blocks. The largest block covers 3.125%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 192 (100%) variables and 24 (75%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
         .     574.0000     558.7419     554.0000    2.66%    3.48%    0    0
         5     570.2597     568.0252     563.0000    0.39%    1.27%    0    0
         6     568.6281     568.6281     563.0000    0.00%    0.99%    0    0
NOTE: Starting branch and bound.
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1      4     563.0000     568.6281    0.99%      0      0
           68       0      4     563.0000     563.0000    0.00%      0      0
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 0.59 seconds.
NOTE: Optimal.
NOTE: Objective = 563.
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
```

Output 18.2.2 *continued*

```
NOTE: The MILP presolver modified 5 constraint coefficients.
NOTE: The presolved problem has 192 variables, 32 constraints, and 384 constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 8 threads.
NOTE: The problem has a decomposable structure with 8 blocks. The largest block covers 3.125%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 192 (100%) variables and 8 (25%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
         .     820.0000     548.0000     548.0000   33.17%   33.17%    0    0
         1     820.0000     548.0000     548.0000   33.17%   33.17%    0    0
         4     669.0000     548.0000     548.0000   18.09%   18.09%    0    0
         5     645.0000     548.0000     548.0000   15.04%   15.04%    0    0
         6     629.2500     548.0000     548.0000   12.91%   12.91%    0    0
         7     613.4643     548.0000     548.0000   10.67%   10.67%    0    0
         9     613.4643     563.0000     563.0000    8.23%    8.23%    0    0
         .     613.4643     563.0000     563.0000    8.23%    8.23%    0    0
        10     601.0000     563.0000     563.0000    6.32%    6.32%    0    0
        11     586.5000     563.0000     563.0000    4.01%    4.01%    0    0
        12     585.8652     563.0000     563.0000    3.90%    3.90%    0    0
        13     576.6667     563.0000     563.0000    2.37%    2.37%    0    0
        14     575.3333     563.0000     563.0000    2.14%    2.14%    0    0
        15     568.5000     563.0000     563.0000    0.97%    0.97%    0    0
        16     567.5000     563.0000     563.0000    0.79%    0.79%    0    0
         .     567.5000     564.0000     563.0000    0.62%    0.79%    0    0
        20     567.5000     564.0000     563.0000    0.62%    0.79%    0    0
        21     564.2500     564.0000     563.0000    0.04%    0.22%    0    0
        23     564.0000     564.0000     563.0000    0.00%    0.18%    0    0
NOTE: Starting branch and bound.
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                  Integer        Bound             Time   Time
            0       1      5     563.0000     564.0000    0.18%      0      0
            2       0      6     563.0000     563.0000    0.00%      0      0
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 0.16 seconds.
NOTE: Optimal.
NOTE: Objective = 563.
```

Example 18.3: Block-Diagonal Structure and METHOD=CONCOMP

This example demonstrates how you can use the METHOD=CONCOMP option in the DECOMP statement to run the decomposition algorithm.

Consider a mixed integer linear program that is defined by the MPS data table mycas.mpsdata. In this case, the structure of the model is unknown and only the MPS data table is provided to you.

The following PROC OPTMILP statements solve the problem by using standard methods. The DATA= option assumes that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
proc optmilp
   nthreads = 4
   data     = mycas.mpsdata;
run;
```

The solution summary is shown in Output 18.3.1.

Output 18.3.1 Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	R0001298
Solution Status	Optimal
Objective Value	120
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	6.833871E-14
Bound Infeasibility	3.036909E-14
Integer Infeasibility	1.998401E-14
Best Bound	120
Nodes	287
Solutions Found	4
Iterations	41238
Presolve Time	0.01
Solution Time	1.00

The iteration log, which contains the problem statistics and the progress of the solution, is shown in Output 18.3.2.

Output 18.3.2 Log

```
NOTE: The problem MPSDATA has 388 variables (36 binary, 0 integer, 1 free, 0 fixed).
NOTE: The problem has 1297 constraints (630 LE, 37 EQ, 630 GE, 0 range).
NOTE: The problem has 4204 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 37 variables and 37 constraints.
NOTE: The MILP presolver removed 424 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 351 variables, 1260 constraints, and 3780 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 4 threads.
NOTE: The problem has a decomposable structure with 4 blocks. The largest block covers 25.08%
      of the constraints in the problem. The DECOMP option with METHOD=CONCOMP is recommended
      for solving problems with this structure.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      3    161.0000000              0    161.0       0
             0        1      3    161.0000000     91.4479396   76.06%       0
             0        1      3    161.0000000    111.7932692   44.02%       0
NOTE: The MILP presolver is applied again.
             0        1      4    128.0000000    111.7932692   14.50%       0
             0        1      5    127.0000000    111.7932692   13.60%       0
             0        1      5    127.0000000    112.1093044   13.28%       0
NOTE: The MILP solver added 1 cuts with 5 cut coefficients at the root.
            10        8      6    126.0000000    112.8931466   11.61%       0
            44       36      7    124.0000000    113.2187120    9.52%       0
            61       47      8    120.0000000    113.2769146    5.94%       0
           168       60      9    120.0000000    116.1478841    3.32%       0
           286        0      9    120.0000000    120.0000000    0.00%       0
NOTE: Optimal.
NOTE: Objective = 120.
NOTE: The Cloud Analytic Services server processed the request in 1.071249 seconds.
```

A note in the log suggests that you can use the decomposition algorithm because of the structure of the problem. The following PROC OPTMILP statements use the METHOD=CONCOMP option in the DECOMP statement. The DATA= option assumes that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
proc optmilp
   nthreads    = 4
   data        = mycas.mpsdata;
   decomp
      loglevel = moderate
      method   = concomp;
run;
```

The solution summary is displayed in Output 18.3.3.

Output 18.3.3 Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	R0001298
Solution Status	Optimal
Objective Value	120
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	120
Nodes	1
Solutions Found	4
Iterations	1
Presolve Time	0.00
Solution Time	0.35

The iteration log, which contains the problem statistics and the progress of the solution, is shown in Output 18.3.4. When you specify NTHREADS=4 in the PROC OPTMILP statement, the blocks are processed simultaneously on four threads.

Output 18.3.4 Log

```
NOTE: The problem MPSDATA has 388 variables (36 binary, 0 integer, 1 free, 0 fixed).
NOTE: The problem has 1297 constraints (630 LE, 37 EQ, 630 GE, 0 range).
NOTE: The problem has 4204 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 37 variables and 37 constraints.
NOTE: The MILP presolver removed 424 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 351 variables, 1260 constraints, and 3780 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in the distributed computing environment in
      single-machine mode.
NOTE: The DECOMP method value CONCOMP is applied.
NOTE: The decomposition identification used 0.00 (cpu: 0.00) seconds.
NOTE: The problem has a decomposable structure with 4 blocks. The largest block covers 25.08%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 351 (100%) variables and 1260 (100%) constraints.
NOTE: Block 1 has 88 (25.07%) variables and 316 (25.08%) constraints.
NOTE: Block 2 has 88 (25.07%) variables and 316 (25.08%) constraints.
NOTE: Block 3 has 88 (25.07%) variables and 316 (25.08%) constraints.
NOTE: Block 4 has 87 (24.79%) variables and 312 (24.76%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 4 threads.
NOTE: ---------------------------------------------------------------
NOTE: Starting to process node 0.
NOTE: ---------------------------------------------------------------
NOTE: Using a starting solution with objective value 161 to provide initial columns.
NOTE: Using a starting solution with objective value 231 to provide initial columns.
NOTE: Using a starting solution with objective value 231 to provide initial columns.
NOTE: The initial column pool using the starting solution contains 8 columns.
NOTE: The subproblem solver for 4 blocks at iteration 0 is starting.
NOTE: The subproblem solver for 4 blocks used 0.32 (cpu: 0.98, max: 0.32) seconds.
NOTE: The initial column pool after generating initial variables contains 12 columns.
      Iter         Best       Master         Best       LP       IP  CPU Real
                  Bound    Objective      Integer      Gap      Gap Time Time
NOTE: The master solver at iteration 1 is starting.
NOTE: The master solver used 0.00 (cpu: 0.00) seconds and 6 iterations.
         1     120.0000     120.0000     120.0000    0.00%    0.00%    1    0
NOTE: The number of active nodes is 1.
NOTE: The objective value of the best integer feasible solution is 120.0000 and the best bound
      is 120.0000.
NOTE: The Decomposition algorithm used 4 threads.
NOTE: The Decomposition algorithm time is 0.35 seconds.
NOTE: Optimal.
NOTE: Objective = 120.
NOTE: The Cloud Analytic Services server processed the request in 0.425122 seconds.
```

In this case, the solver finds that after the presolve, the constraint matrix decomposes into block-diagonal form. That is, all the constraints are covered by subproblem blocks, leaving the set of master constraints empty. Because there are no coupling constraints, the problem decomposes into four completely independent problems. If you specify LOGLEVEL=MODERATE in the DECOMP statement, the log displays the size of each block. The blocks in this case are nicely balanced, allowing parallel execution to be efficient.

Example 18.4: Block-Angular Structure in Single-Machine Mode

This example demonstrates how you can use the default automated method to run the decomposition algorithm in single-machine mode.

As in Example 18.3, consider a mixed integer linear program that is defined by the MPS data table mycas.mpsdata. In this case, the structure of the model is unknown and only the MPS data table is provided to you.

The following PROC OPTMILP statements attempt to solve the problem by using standard methods and a 120-second time limit. The DATA= option assumes that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
proc optmilp
   nthreads = 4
   maxtime  = 120
   data     = mycas.mpsdata;
run;
```

The solution summary is shown in Output 18.4.1.

Output 18.4.1 Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	Total_Profit
Solution Status	Time Limit Reached
Objective Value	6151.1464478
Relative Gap	0.1273212537
Absolute Gap	897.43411372
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	7048.5805615
Nodes	1
Solutions Found	4
Iterations	136229
Presolve Time	0.31
Solution Time	120.04

The iteration log, which contains the problem statistics and the progress of the solution, is shown in Output 18.4.2.

Output 18.4.2 Log

```
NOTE: The problem MPSDATA has 52638 variables (16038 binary, 0 integer, 0 free, 0 fixed).
NOTE: The problem has 3949 constraints (3339 LE, 0 EQ, 610 GE, 0 range).
NOTE: The problem has 148866 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 734 constraints.
NOTE: The MILP presolver removed 17616 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 52638 variables, 3215 constraints, and 131250 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 4 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      4   6151.1464478   8590.4503506   28.40%       0
             0        1      4   6151.1464478   7342.1209241   16.22%       0
NOTE: The MILP solver's symmetry detection found 51226 orbits. The largest orbit contains 2
      variables.
             0        1      4   6151.1464478   7325.2309546   16.03%       2
             0        1      4   6151.1464478   7285.8744051   15.57%       5
             0        1      4   6151.1464478   7250.0626934   15.16%      10
             0        1      4   6151.1464478   7211.9468745   14.71%      16
             0        1      4   6151.1464478   7165.1727513   14.15%      24
             0        1      4   6151.1464478   7132.7240482   13.76%      34
             0        1      4   6151.1464478   7098.5096889   13.35%      43
             0        1      4   6151.1464478   7077.7938690   13.09%      52
             0        1      4   6151.1464478   7068.0194895   12.97%      60
             0        1      4   6151.1464478   7061.7399382   12.89%      68
             0        1      4   6151.1464478   7057.5031192   12.84%      77
             0        1      4   6151.1464478   7054.3557230   12.80%      86
             0        1      4   6151.1464478   7051.9114255   12.77%      94
             0        1      4   6151.1464478   7050.0045715   12.75%     102
             0        1      4   6151.1464478   7048.5805615   12.73%     110
             0        1      4   6151.1464478   7048.5805615   12.73%     119
NOTE: The MILP solver added 17137 cuts with 472498 cut coefficients at the root.
NOTE: Real time limit reached.
NOTE: Objective of the best integer solution found = 6151.1464478.
NOTE: The Cloud Analytic Services server processed the request in 120.338183 seconds.
```

Standard MILP techniques struggle to solve the problem within the specified time limit. The default decomposition method attempts to find a block-angular structure by using the matrix-stretching techniques that are described in Grcar (1990) and Aykanat, Pinar, and Çatalyürek (2004) and techniques that are based on community detection and described in Khaniyev, Elhedhli, and Erenay (2018).

```
proc optmilp
   nthreads  = 4
   data      = mycas.mpsdata;
   decomp
      hybrid = false;
run;
```

The solution summary is displayed in Output 18.4.3.

Output 18.4.3 Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	Total_Profit
Solution Status	Optimal within Relative Gap
Objective Value	6972.3309347
Relative Gap	1.3964946E-8
Absolute Gap	0.0000973682
Primal Infeasibility	1.931788E-14
Bound Infeasibility	7.882583E-15
Integer Infeasibility	6.77236E-15
Best Bound	6972.331032
Nodes	1
Solutions Found	8
Iterations	6
Presolve Time	0.30
Solution Time	40.92

The iteration log, which contains the problem statistics and the progress of the solution, is shown in Output 18.4.4.

Output 18.4.4 Log

```
NOTE: The problem MPSDATA has 52638 variables (16038 binary, 0 integer, 0 free, 0 fixed).
NOTE: The problem has 3949 constraints (3339 LE, 0 EQ, 610 GE, 0 range).
NOTE: The problem has 148866 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 734 constraints.
NOTE: The MILP presolver removed 17616 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 52638 variables, 3215 constraints, and 131250 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in the distributed computing environment in
      single-machine mode.
NOTE: The DECOMP method value DEFAULT is applied.
NOTE: The decomposition identification used 0.16 (cpu: 0.19) seconds.
NOTE: The problem has a decomposable structure with 610 blocks. The largest block covers
      0.2488% of the constraints in the problem.
NOTE: The decomposition subproblems cover 52638 (100%) variables and 3207 (99.75%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 4 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                  Bound    Objective      Integer      Gap      Gap Time Time
         .    7964.0286    6472.3607    6470.8744   18.73%   18.75%   14    9
         2    7273.9736    6472.3607    6470.8744   11.02%   11.04%   26   14
         3    7147.9543    6867.4012    6470.8744    3.92%    9.47%   42   22
         4    6986.0610    6960.3223    6470.8744    0.37%    7.37%   64   32
         5    6986.0610    6967.8235    6967.8235    0.26%    0.26%   76   37
         6    6972.3310    6972.3309    6972.3309    0.00%    0.00%   85   40
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound             Time   Time
            0       1      8    6972.3309    6972.3310    0.00%     85     40
NOTE: The Decomposition algorithm used 4 threads.
NOTE: The Decomposition algorithm time is 40.92 seconds.
NOTE: Optimal within relative gap.
NOTE: Objective = 6972.3309347.
NOTE: The Cloud Analytic Services server processed the request in 41.203789 seconds.
```

As stated in the log, the algorithm successfully finds a decomposition that contains 610 blocks and has more than 99% subproblem coverage.

Example 18.5: Block-Angular Structure in Distributed Mode

This example demonstrates how you can use the default automated method to run the decomposition algorithm in distributed mode.

Consider again the mixed integer linear program that is defined by the MPS data table mycas.mpsdata. The following PROC OPTMILP statements run the decomposition algorithm in distributed mode. The DATA= option assumes that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
proc optmilp
   distributed = true
   nthreads    = 4
   data        = mycas.mpsdata;
   decomp
      hybrid   = false;
run;
```

The solution summary is displayed in Output 18.5.1.

Output 18.5.1 Solution Summary

The OPTMILP Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	Total_Profit
Solution Status	Optimal within Relative Gap
Objective Value	6972.3309347
Relative Gap	1.3964946E-8
Absolute Gap	0.0000973682
Primal Infeasibility	1.931788E-14
Bound Infeasibility	7.882583E-15
Integer Infeasibility	6.77236E-15
Best Bound	6972.331032
Nodes	1
Solutions Found	8
Iterations	6
Presolve Time	0.29
Solution Time	22.80

The iteration log, which contains the problem statistics and the progress of the solution, is shown in Output 18.5.2. When you specify DISTRIBUTED=TRUE and NTHREADS=4 in the OPTMILP statement, the blocks are processed using all the machines in your configured session (four machines in this case). Each machine uses four threads.

Output 18.5.2 Log

```
NOTE: The problem MPSDATA has 52638 variables (16038 binary, 0 integer, 0 free, 0 fixed).
NOTE: The problem has 3949 constraints (3339 LE, 0 EQ, 610 GE, 0 range).
NOTE: The problem has 148866 constraint coefficients.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 734 constraints.
NOTE: The MILP presolver removed 17616 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 52638 variables, 3215 constraints, and 131250 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in the distributed computing environment with 4
      worker nodes.
NOTE: The DECOMP method value DEFAULT is applied.
NOTE: The decomposition identification used 0.16 (cpu: 0.19) seconds.
NOTE: The problem has a decomposable structure with 610 blocks. The largest block covers
      0.2488% of the constraints in the problem.
NOTE: The decomposition subproblems cover 52638 (100%) variables and 3207 (99.75%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 4 threads.
      Iter         Best       Master         Best       LP       IP Real
                  Bound    Objective      Integer      Gap      Gap Time
         .    7964.0286    6472.3607    6470.8744   18.73%   18.75%    6
         2    7273.9736    6472.3607    6470.8744   11.02%   11.04%    9
         3    7147.9543    6867.4012    6470.8744    3.92%    9.47%   13
         4    6986.0610    6960.3223    6470.8744    0.37%    7.37%   17
         5    6986.0610    6967.8235    6967.8235    0.26%    0.26%   20
         6    6972.3310    6972.3309    6972.3309    0.00%    0.00%   22
         Node  Active   Sols         Best         Best      Gap   Real
                                   Integer        Bound            Time
            0       1      8    6972.3309    6972.3310    0.00%     22
NOTE: The Decomposition algorithm used 4 threads.
NOTE: The Decomposition algorithm time is 22.80 seconds.
NOTE: Optimal within relative gap.
NOTE: Objective = 6972.3309347.
NOTE: The Cloud Analytic Services server processed the request in 23.167277 seconds.
```

In this case, the automated method successfully finds a decomposition that contains 610 blocks and has more than 99% subproblem coverage, as in Example 18.4.

Example 18.6: Bin Packing Problem

The bin packing problem (BPP) finds the minimum number of capacitated bins that are needed to store a set of products of varying size. Define a set P of products, their sizes s_p, and a set $B = \{1, \ldots, |P|\}$ of candidate bins, each having capacity C. Let x_{pb} be a binary variable that, if set to 1, indicates that product p is assigned to bin b. In addition, let y_b be a binary variable that, if set to 1, indicates that bin b is used.

A BPP can be formulated as a MILP as follows:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{b \in B} y_b & & \\
\text{subject to} & \displaystyle\sum_{b \in B} x_{pb} = 1 & p \in P & \text{(Assignment)} \\
& \displaystyle\sum_{p \in P} s_p x_{pb} \le C y_b & b \in B & \text{(Capacity)} \\
& x_{pb} \in \{0, 1\} & p \in P,\ b \in B & \\
& y_b \in \{0, 1\} & b \in B &
\end{array}
$$

In this formulation, the Assignment constraints ensure that each product is assigned to exactly one bin. The Capacity constraints ensure that the capacity restrictions are met for each bin. In addition, these constraints enforce the condition that if any product is assigned to bin b, then y_b must be positive.

In this formulation, the bin identifier is arbitrary. For example, in any solution, the assignments to bin 1 can be swapped with the assignments to bin 2 without affecting feasibility or the objective value. Consider a decomposition by bin, where the Assignment constraints form the master problem and the Capacity constraints form identical subproblems. As described in the section "Special Case: Identical Blocks and Ryan-Foster Branching" on page 1058, this is a situation in which an aggregate formulation and Ryan-Foster branching can greatly improve performance by reducing symmetry.

Consider a series of University of North Carolina basketball games that are recorded on a DVR. The following data set, dvr, provides the name of each game in the column opponent and the size of that game in gigabytes (GB) as it resides on the DVR in the column size:

```
/* game, size (in GBs) */
data dvr;
   input opponent $ size;
   datalines;
Clemson  1.36
Clemson2 1.97
Duke     2.76
Duke2    2.52
FSU      2.56
FSU2     2.34
GT       1.49
GT2      1.12
IN       1.45
KY       1.42
Loyola   1.42
MD       1.33
MD2      2.71
```

```
Miami    1.22
NCSU     2.52
NCSU2    2.54
UConn    1.25
VA       2.33
VA2      2.48
VT       1.41
Vermont  1.28
WM       1.25
WM2      1.23
Wake     1.61
;
```

The goal is to use the fewest DVDs on which to store the games for safekeeping. Each DVD can hold 4.38GB recorded data. The problem can be formulated as a bin packing problem and solved by using PROC OPTMODEL and the decomposition algorithm. The following PROC OPTMODEL statements read in the data, declare the optimization model, and use the decomposition algorithm to solve it:

```
proc optmodel sessref="mysess";
   /* read the product and size data */
   set <str> PRODUCTS;
   num size {PRODUCTS};
   read data dvr into PRODUCTS=[opponent] size;

   /* 4.38 GBs per DVD */
   num binsize = 4.38;

   /* the number of products is a trivial upper bound on the
      number of bins needed */
   num upperbound init card(PRODUCTS);
   set BINS = 1..upperbound;

   /* Assign[p,b] = 1, if product p is assigned to bin b */
   var Assign {PRODUCTS, BINS} binary;
   /* UseBin[b] = 1, if bin b is used */
   var UseBin {BINS} binary;

   /* minimize number of bins used */
   min Objective = sum {b in BINS} UseBin[b];

   /* assign each product to exactly one bin */
   con Assignment {p in PRODUCTS}:
      sum {b in BINS} Assign[p,b] = 1;

   /* Capacity constraint on each bin (and definition of UseBin) */
   con Capacity {b in BINS}:
      sum {p in PRODUCTS} size[p] * Assign[p,b] <= binsize * UseBin[b];

   /* decompose by bin (subproblem is a knapsack problem) */
   for {b in BINS} Capacity[b].block = b;

   /* solve using decomp (aggregate formulation) */
   solve with milp / decomp;
```

The following PROC OPTMODEL statements create a sequential numbering of the bins and then output to the data set dvd the optimal assignments of games to bins:

```
   /* create a map from arbitrary bin number to sequential bin number */
   num binId init 1;
   num binMap {BINS};
   for {b in BINS: UseBin[b].sol > 0.5} do;
      binMap[b] = binId;
      binId     = binId + 1;
   end;

   /* create map of product to bin from solution */
   num bin {PRODUCTS};
   for {p in PRODUCTS} do;
      for {b in BINS: Assign[p,b].sol > 0.5} do;
         bin[p] = binMap[b];
         leave;
      end;
   end;

   /* create solution data */
   create data dvd from [product] bin size;
quit;
```

The solution summary is displayed in Output 18.6.1.

Output 18.6.1 Solution Summary

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	Objective
Solution Status	Optimal
Objective Value	11
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	8.881784E-16
Bound Infeasibility	0
Integer Infeasibility	8.881784E-16
Best Bound	11
Nodes	1
Solutions Found	4
Iterations	2
Presolve Time	0.01
Solution Time	0.05

The iteration log is displayed in Output 18.6.2.

Output 18.6.2 Log

```
NOTE: There were 24 observations read from the data set WORK.DVR.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 600 variables (0 free, 0 fixed).
NOTE: The problem has 600 binary and 0 integer variables.
NOTE: The problem has 48 linear constraints (24 LE, 24 EQ, 0 GE, 0 range).
NOTE: The problem has 1176 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 0 variables and 0 constraints.
NOTE: The MILP presolver removed 0 constraint coefficients.
NOTE: The MILP presolver modified 384 constraint coefficients.
NOTE: The presolved problem has 600 variables, 48 constraints, and 1176 constraint coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: All blocks are identical and the master model is set partitioning.
NOTE: The Decomposition algorithm is using an aggregate formulation and Ryan-Foster branching.
NOTE: The number of block threads has been reduced to 1 threads.
NOTE: The problem has a decomposable structure with 24 blocks. The largest block covers 2.083%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 600 (100%) variables and 24 (50%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                  Bound    Objective      Integer      Gap      Gap Time Time
NOTE: The continuous bound was improved to 11 due to objective granularity.
         2      11.0000      11.0000      11.0000    0.00%    0.00%    0    0
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1      4      11.0000      11.0000    0.00%      0      0
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 0.05 seconds.
NOTE: Optimal.
NOTE: Objective = 11.
NOTE: The data set WORK.DVD has 24 observations and 3 variables.
```

The following call to PROC SORT sorts the assignments by bin:

```
proc sort data=dvd;
   by bin;
run;
```

The optimal assignments from the output data set dvd are displayed in Figure 18.7.

Figure 18.7 Optimal Assignment of Games to DVDs

bin=1

product	size
VA	2.33
WM2	1.23
bin	**3.56**

bin=2

product	size
VA2	2.48
Vermont	1.28
bin	**3.76**

bin=3

product	size
KY	1.42
MD	1.33
WM	1.25
bin	**4.00**

bin=4

product	size
Loyola	1.42
NCSU2	2.54
bin	**3.96**

bin=5

product	size
Miami	1.22
NCSU	2.52
bin	**3.74**

bin=6

product	size
IN	1.45
MD2	2.71
bin	**4.16**

Figure 18.7 *continued*

bin=7

product	size
Clemson	1.36
GT	1.49
VT	1.41
bin	**4.26**

bin=8

product	size
Clemson2	1.97
FSU2	2.34
bin	**4.31**

bin=9

product	size
FSU	2.56
UConn	1.25
bin	**3.81**

bin=10

product	size
Duke2	2.52
Wake	1.61
bin	**4.13**

bin=11

product	size
Duke	2.76
GT2	1.12
bin	**3.88**
	43.57

In this example, the objective function ensures that there exists an optimal solution that never assigns a product to more than one bin. Therefore, you could instead model the Assignment constraint as an inequality rather than an equality. In this case, the best performance would come from forcing the use of an aggregate formulation and Ryan-Foster branching by specifying the option VARSEL=RYANFOSTER. An example of doing this is shown in Example 18.8.

Example 18.7: Resource Allocation Problem

This example describes a model for selecting tasks to be run on a shared resource (Gamrath 2010). Consider a set I of tasks and a resource capacity C. Each item $i \in I$ has a profit p_i, a resource utilization level w_i, a starting period s_i, and an ending period e_i. The time horizon that is considered is from the earliest starting time to the latest ending time of all tasks. With each task, associate a binary variable x_i, which, if set to 1, indicates that the task is running from its start time until just before its end time. A task consumes capacity if it is running. The goal is to select which tasks to run in order to maximize profit while not exceeding the shared resource capacity. Let $S = \{s_i \mid i \in I\}$ define the set of start times for all tasks, and let $L_s = \{i \in I \mid s_i \leq s < e_i\}$ define the set of tasks that are running at each start time $s \in S$. You can model the problem as a mixed integer linear programming problem as follows:

$$
\begin{array}{llll}
\text{maximize} & \displaystyle\sum_{i \in I} p_i x_i & & \\
\text{subject to} & \displaystyle\sum_{i \in L_s} w_i x_i \leq C & s \in S & \text{(CapacityCon)} \\
& x_i \in \{0, 1\} & i \in I &
\end{array}
$$

In this formulation, the CapacityCon constraints ensure that the running tasks do not exceed the resource capacity. To illustrate, consider the following five-task example with data: $p_i = (6, 8, 5, 9, 8)$, $w_i = (8, 5, 3, 4, 3)$, $s_i = (1, 3, 5, 7, 8)$, $e_i = (5, 8, 9, 17, 10)$, and $C = 10$. The formulation leads to a constraint matrix that has a *staircase structure* that is determined by tasks coming online and offline:

$$
\begin{array}{lccccccccccl}
\text{maximize} & 6x_1 & + & 8x_2 & + & 5x_3 & + & 9x_4 & + & 8x_5 & & \\
\text{subject to} & 8x_1 & & & & & & & & & \leq & 10 \\
& 8x_1 & + & 5x_2 & & & & & & & \leq & 10 \\
& & & 5x_2 & + & 3x_3 & & & & & \leq & 10 \\
& & & 5x_2 & + & 3x_3 & + & 4x_4 & & & \leq & 10 \\
& & & & & 3x_3 & + & 4x_4 & + & 3x_5 & \leq & 10 \\
& & & & & & & & & x_i & \in & \{0, 1\} \quad i \in I
\end{array}
$$

Lagrangian Decomposition

This formulation clearly has no decomposable structure. However, you can use a common modeling technique known as *Lagrangian decomposition* to bring the model into block-angular form. Lagrangian decomposition works by first partitioning the constraints into blocks. Then, each original variable is split into multiple copies of itself, one copy for each block in which the variable has a nonzero coefficient in the constraint matrix. Constraints are added to enforce the equality of each copy of the original variable. Then, you can write the original constraints in block-angular form by using the duplicate variables.

To apply Lagrangian decomposition to the resource allocation problem, define a set B of blocks and let S_b define the set of start times for a given block b, such that $S = \cup_{b \in B} S_b$. Given this partition of start times, let B_i define the set of blocks in which task $i \in I$ is scheduled to be running. Now, for each task $i \in I$, define duplicate variables x_i^b for each $b \in B_i$. Let m_i define the minimum block index for each class of variable

that represents task i. You can now model the problem in block-angular form as follows:

$$
\begin{array}{llll}
\text{maximize} & \displaystyle\sum_{i \in I} p_i x_i^{m_i} & & \\
\text{subject to} & x_i^b = x_i^{m_i} & i \in I,\ b \in B_i \setminus \{m_i\} & \text{(LinkDupVarsCon)} \\
& \displaystyle\sum_{i \in L_s} w_i x_i^b \le C & b \in B,\ s \in S_b & \text{(CapacityCon)} \\
& x_i^b \in \{0,1\} & i \in I,\ b \in B_i &
\end{array}
$$

In this formulation, the LinkDupVarsCon constraints ensure that the duplicate variables are equal to the original variables. Now, the five-task example has been transformed from a staircase structure to a block-angular structure:

$$
\begin{array}{lrcrcrcrcrcrcrcl}
\text{maximize} & 6x_1^1 & + & 8x_2^1 & & & + & 5x_3^2 & + & 9x_4^2 & & & & & + & 8x_5^3 & \\
\text{subject to} & & & x_2^1 & - & x_2^2 & & & & & & & & & & & = 0 \\
& & & & & & & x_3^2 & & & - & x_3^3 & & & & & = 0 \\
& & & & & & & & & x_4^2 & & & - & x_4^3 & & & = 0 \\
& 8x_1^1 & & & & & & & & & & & & & & & \le 10 \\
& 8x_1^1 & + & 5x_2^1 & & & & & & & & & & & & & \le 10 \\
& & & & & 5x_2^2 & + & 3x_3^2 & & & & & & & & & \le 10 \\
& & & & & 5x_2^2 & + & 3x_3^2 & + & 4x_4^2 & & & & & & & \le 10 \\
& & & & & & & & & & & 3x_3^3 & + & 4x_4^3 & + & 3x_5^3 & \le 10 \\
& & & & & & & & & & & & & & & x_i^b & \in \{0,1\}\ i \in I, b \in B_i
\end{array}
$$

To see how to apply Lagrangian decomposition in PROC OPTMODEL, consider the data set TaskData from Caprara, Furini, and Malaguti (2010), which consists of $|I| = 2{,}916$ tasks:

```
data TaskData;
   input profit weight start end;
   datalines;
99 92 1 9
56 30 1 3
39 73 1 20
86 76 1 9
...
24 94 768 769
95 40 768 769
66 17 768 769
18 48 768 769
97 23 768 769
;
```

Using the MILP Solver Directly in PROC OPTMODEL

The following PROC OPTMODEL statements read in the data and solve the original staircase formulation by calling the MILP solver directly:

```
%macro SetupData(task_data=, capacity=);
   set TASKS;
   num capacity=&capacity;
   num profit{TASKS}, weight{TASKS}, start{TASKS}, end{TASKS};

   read data &task_data into TASKS=[_n_] profit weight start end;
   /* the set of start times */

   set STARTS = setof{i in TASKS} start[i];
   /* the set of tasks i that are active at a given start time s */
   set TASKS_START{s in STARTS}
      = {i in TASKS: start[i] <= s < end[i]};
%mend SetupData;

%macro ResourceAllocation_Direct(task_data=, capacity=);
   proc optmodel sessref="mysess";
      %SetupData(task_data=&task_data,capacity=&capacity);

      /* select task i to come online from period [start to end) */
      var x{TASKS} binary;

      /* maximize the total profit of running tasks */
      max TotalProfit = sum{i in TASKS} profit[i] * x[i];

      /* enforce that the shared resource capacity is not exceeded */
      con CapacityCon{s in STARTS}:
         sum{i in TASKS_START[s]} weight[i] * x[i] <= capacity;

      solve with milp / maxtime=200 logfreq=10000;
   quit;
%mend ResourceAllocation_Direct;

%ResourceAllocation_Direct(task_data=TaskData, capacity=100);
```

The problem summary and solution summary are displayed in Output 18.7.1.

Output 18.7.1 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	TotalProfit
Objective Type	Linear
Number of Variables	2916
Bounded Above	0
Bounded Below	0
Bounded Below and Above	2916
Free	0
Fixed	0
Binary	2916
Integer	0
Number of Constraints	768
Linear LE (<=)	768
Linear EQ (=)	0
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	23236

Solution Summary	
Solver	MILP
Algorithm	Branch and Cut
Objective Function	TotalProfit
Solution Status	Optimal within Relative Gap
Objective Value	40982
Relative Gap	0.0000697953
Absolute Gap	2.8605523603
Primal Infeasibility	0
Bound Infeasibility	0
Integer Infeasibility	0
Best Bound	40984.860552
Nodes	9302
Solutions Found	20
Iterations	365372
Presolve Time	0.15
Solution Time	11.23

The iteration log, which contains the problem statistics, the progress of the solution, and the best integer feasible solution found, is shown in Output 18.7.2.

Output 18.7.2 Log

```
NOTE: There were 2916 observations read from the data set WORK.TASKDATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 2916 variables (0 free, 0 fixed).
NOTE: The problem has 2916 binary and 0 integer variables.
NOTE: The problem has 768 linear constraints (768 LE, 0 EQ, 0 GE, 0 range).
NOTE: The problem has 23236 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The remaining solution time after problem generation and solver initialization is 199.56
      seconds.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 1020 variables and 125 constraints.
NOTE: The MILP presolver removed 12536 constraint coefficients.
NOTE: The MILP presolver modified 986 constraint coefficients.
NOTE: The presolved problem has 1896 variables, 643 constraints, and 10700 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The parallel Branch and Cut algorithm is used.
NOTE: The Branch and Cut algorithm is using up to 80 threads.
          Node   Active   Sols    BestInteger      BestBound      Gap    Time
             0        1      4  33729.0000000         109193   69.11%       0
             0        1      4  33729.0000000  45862.9249030   26.46%       0
             0        1      8  39443.0000000  45862.9249030   14.00%       0
             0        1      8  39443.0000000  43002.5181567    8.28%       0
             0        1      8  39443.0000000  42163.7514284    6.45%       0
             0        1      8  39443.0000000  41811.4280754    5.66%       0
             0        1      8  39443.0000000  41578.4594690    5.14%       0
             0        1      8  39443.0000000  41437.1696709    4.81%       0
             0        1     11  40413.0000000  41437.1696709    2.47%       0
             0        1     11  40413.0000000  41363.7126678    2.30%       0
             0        1     11  40413.0000000  41291.3284842    2.13%       0
             0        1     11  40413.0000000  41252.7749685    2.04%       1
             0        1     11  40413.0000000  41218.3353630    1.95%       1
             0        1     11  40413.0000000  41196.4508661    1.90%       1
             0        1     11  40413.0000000  41168.9188236    1.84%       1
             0        1     11  40413.0000000  41159.9400626    1.81%       1
             0        1     11  40413.0000000  41143.8310665    1.78%       1
             0        1     11  40413.0000000  41137.2851685    1.76%       1
             0        1     11  40413.0000000  41126.2757359    1.73%       1
             0        1     11  40413.0000000  41119.0002779    1.72%       1
             0        1     11  40413.0000000  41109.6102986    1.69%       2
             0        1     11  40413.0000000  41103.7917940    1.68%       2
             0        1     11  40413.0000000  41099.4658087    1.67%       2
NOTE: The MILP solver added 770 cuts with 10886 cut coefficients at the root.
            67       54     14  40732.0000000  41095.7096578    0.89%       2
           541      484     17  40911.0000000  41092.0112570    0.44%       3
NOTE: The Decomposition algorithm is used.
```

Output 18.7.2 *continued*

```
NOTE: The Decomposition algorithm time is 0.21 seconds.
          1377      595     19  40973.0000000  41046.3032726    0.18%       3
          7025     1728     21  40977.0000000  41004.3168656    0.07%      10
          7780     1333     22  40978.0000000  41001.3781360    0.06%      10
          7826     1311     23  40980.0000000  41001.3781360    0.05%      10
          8437      692     24  40981.0000000  40991.7008083    0.03%      11
          8496      644     25  40982.0000000  40991.6614103    0.02%      11
          9301        9     25  40982.0000000  40984.8605524    0.01%      11
NOTE: Optimal within relative gap.
NOTE: Objective = 40982.
```

Using the Decomposition Algorithm in PROC OPTMODEL

To transform this data into block-angular form, first sort the task data to help reduce the number of duplicate variables that are needed in the reformulation as follows:

```
proc sort data=TaskData;
   by start end;
run;
```

Then, create the partition of constraints into blocks of size **block_size** as follows:

```
%macro ResourceAllocation_Decomp(task_data=, capacity=, block_size=);
   proc optmodel sessref="mysess";
      %SetupData(task_data=&task_data,capacity=&capacity);
      /* partition into blocks of size blocks_size */
      num block_size = &block_size;
      num num_blocks = ceil( card(TASKS) / block_size );
      set BLOCKS     = 1..num_blocks;

      /* the set of starts s for which task i is active */
      set STARTS_TASK{i in TASKS} = {s in STARTS: start[i] <= s < end[i]};

      /* partition the start times into blocks of size block_size */
      set STARTS_BLOCK{BLOCKS} init {};
      num block_id    init 1;
      num block_count init 0;
      for{s in STARTS} do;
         STARTS_BLOCK[block_id] = STARTS_BLOCK[block_id] union {s};
         block_count = block_count + 1;
         if(mod(block_count, block_size) = 0) then
             block_id = block_id + 1;
      end;
```

Then, use the following PROC OPTMODEL statements to define the block-angular formulation and solve the problem by using the decomposition algorithm, the PRESOLVER=BASIC option, and **block_size=20**. Because this reformulation is equivalent to the original staircase formulation, disabling some of the advanced presolver techniques ensures that the model maintains block-angularity.

```
      /* blocks in which task i is online */
      set BLOCKS_TASK{i in TASKS} =
         {b in BLOCKS: card(STARTS_BLOCK[b] inter STARTS_TASK[i]) > 0};

      /* minimum block id in which task i is online */
      num min_block{i in TASKS} = min{b in BLOCKS_TASK[i]} b;

      /* select task i to come online from period [start to end)
         in each block */
      var x{i in TASKS, b in BLOCKS_TASK[i]} binary;

      /* maximize the total profit of running tasks */
      max TotalProfit = sum{i in TASKS} profit[i] * x[i,min_block[i]];

      /* enforce that task selection is consistent across blocks */
      con LinkDupVarsCon{i in TASKS, b in BLOCKS_TASK[i] diff {min_block[i]}}:
         x[i,b] = x[i,min_block[i]];

      /* enforce that the shared resource capacity is not exceeded */
      con CapacityCon{b in BLOCKS, s in STARTS_BLOCK[b]}:
         sum{i in TASKS_START[s]} weight[i] * x[i,b] <= capacity;

      /* define blocks for decomposition algorithm */
      for{b in BLOCKS, s in STARTS_BLOCK[b]} CapacityCon[b,s].block = b;

      solve with milp / presolver=basic decomp;
   quit;
%mend ResourceAllocation_Decomp;

%ResourceAllocation_Decomp(task_data=TaskData, capacity=100, block_size=20);
```

The problem summary and solution summary are displayed in Output 18.7.3. Compared to the original formulation, the numbers of variables and constraints are increased by the number of duplicate variables.

Output 18.7.3 Problem Summary and Solution Summary

The OPTMODEL Procedure

Problem Summary	
Objective Sense	Maximization
Objective Function	TotalProfit
Objective Type	Linear
Number of Variables	3924
Bounded Above	0
Bounded Below	0
Bounded Below and Above	3924
Free	0
Fixed	0
Binary	3924
Integer	0
Number of Constraints	1776
Linear LE (<=)	768
Linear EQ (=)	1008
Linear GE (>=)	0
Linear Range	0
Constraint Coefficients	25252

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalProfit
Solution Status	Optimal within Relative Gap
Objective Value	40982
Relative Gap	0.000073215
Absolute Gap	3.0007160137
Primal Infeasibility	2.220446E-16
Bound Infeasibility	1.110223E-15
Integer Infeasibility	1.110223E-15
Best Bound	40985.000716
Nodes	13
Solutions Found	79
Iterations	381
Presolve Time	0.02
Solution Time	123.52

The iteration log, which contains the problem statistics, the progress of the solution, and the optimal objective value, is shown in Output 18.7.4.

Output 18.7.4 Log

```
NOTE: There were 2916 observations read from the data set WORK.TASKDATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 3924 variables (0 free, 0 fixed).
NOTE: The problem has 3924 binary and 0 integer variables.
NOTE: The problem has 1776 linear constraints (768 LE, 1008 EQ, 0 GE, 0 range).
NOTE: The problem has 25252 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value BASIC is applied.
NOTE: The MILP presolver removed 4 variables and 0 constraints.
NOTE: The MILP presolver removed 23 constraint coefficients.
NOTE: The MILP presolver modified 7297 constraint coefficients.
NOTE: The presolved problem has 3920 variables, 1776 constraints, and 25229 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 39 threads.
NOTE: The problem has a decomposable structure with 39 blocks. The largest block covers 1.126%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 3920 (100%) variables and 768 (43.24%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
```

Iter	Best Bound	Master Objective	Best Integer	LP Gap	IP Gap	CPU Time	Real Time
.	44109.0000	37658.0000	37658.0000	14.63%	14.63%	1	0
5	44109.0000	37693.0000	37693.0000	14.55%	14.55%	4	1
7	44109.0000	37746.0000	37746.0000	14.43%	14.43%	5	1
.	44109.0000	37905.0000	37905.0000	14.07%	14.07%	5	2
10	44109.0000	37905.0000	37905.0000	14.07%	14.07%	6	2
11	44109.0000	38193.0000	38193.0000	13.41%	13.41%	7	2
13	44109.0000	38421.0000	38421.0000	12.90%	12.90%	8	3
16	44109.0000	38696.0000	38696.0000	12.27%	12.27%	10	3
18	44109.0000	38790.0000	38790.0000	12.06%	12.06%	11	4
20	44109.0000	38790.0000	39408.0000	12.06%	10.66%	13	4
24	44109.0000	39866.0000	39866.0000	9.62%	9.62%	17	6
27	44109.0000	39898.0000	39898.0000	9.55%	9.55%	22	7
30	44109.0000	39975.5000	39974.0000	9.37%	9.37%	28	8
36	44109.0000	40317.0000	40317.0000	8.60%	8.60%	38	11
.	44109.0000	40557.0000	40557.0000	8.05%	8.05%	43	12
40	44109.0000	40557.0000	40557.0000	8.05%	8.05%	46	13
42	43152.6464	40616.7500	40613.0000	5.88%	5.89%	49	13
43	42661.2466	40616.7500	40613.0000	4.79%	4.80%	52	14
46	42661.2466	40747.2500	40732.0000	4.49%	4.52%	61	16
47	42661.2466	40794.2500	40779.0000	4.38%	4.41%	63	17
49	42661.2466	40810.2500	40795.0000	4.34%	4.37%	68	18

Output 18.7.4 *continued*

```
        50   42661.2466   40810.2500   40795.0000    4.34%    4.37%   70   18
        52   42661.2466   40905.2500   40890.0000    4.12%    4.15%   73   19
        54   42661.2466   40926.2500   40911.0000    4.07%    4.10%   75   19
        60   42661.2466   40926.2500   40911.0000    4.07%    4.10%   85   22
        62   41356.9862   40942.2500   40927.0000    1.00%    1.04%   88   23
        63   41210.2880   40942.2500   40927.0000    0.65%    0.69%   90   23
        69   41210.2880   40972.5833   40957.0000    0.58%    0.61%   97   25
        70   41210.2880   40980.5833   40965.0000    0.56%    0.60%   97   25
         .   41210.2880   40980.5833   40965.0000    0.56%    0.60%  101   27
        80   41210.2880   40980.5833   40965.0000    0.56%    0.60%  101   27
        81   41048.0834   40980.5833   40965.0000    0.16%    0.20%  103   28
        82   41047.5836   40987.5833   40972.0000    0.15%    0.18%  105   28
        83   41001.0834   40987.5833   40972.0000    0.03%    0.07%  106   29
        89   41001.0834   40997.5833   40982.0000    0.01%    0.05%  108   30
        90   41001.0834   40997.5833   40982.0000    0.01%    0.05%  108   30
        92   40997.5835   40997.5833   40982.0000    0.00%    0.04%  109   30
NOTE: Starting branch and bound.
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound             Time   Time
            0       1     79   40982.0000   40997.5835    0.04%    109     30
            1       3     79   40982.0000   40997.5835    0.04%    275     73
            3       3     79   40982.0000   40991.5841    0.02%    329     89
            5       5     79   40982.0000   40991.3335    0.02%    370     99
            9       3     79   40982.0000   40987.3334    0.01%    442    119
           12       0     79   40982.0000   40985.0007    0.01%    458    123
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 123.52 seconds.
NOTE: Optimal within relative gap.
NOTE: Objective = 40982.
```

The Trade-Off between Coverage and Subproblem Difficulty

The reformulation of this resource allocation problem provides a nice example of the potential trade-offs in modeling a problem for use with the decomposition algorithm. As seen in Example 18.2, the strength of the bound is an important factor in the overall performance of the algorithm, but it is not always correlated to the magnitude of the subproblem coverage. In the current example, the block size determines the number of blocks. Moreover, it determines the number of linking variables that are needed in the reformulation. At one extreme, if the block size is set to be $|S|$, then the number of blocks is 1, and the number of copies of original variables is 0. Using one block would be equivalent to the original staircase formulation and would not yield a model conducive to decomposition. As the number of blocks is increased, the number of linking variables increases (the size of the master problem), the strength of the decomposition bound decreases, and the difficulty of solving the subproblems decreases. In addition, as the number of blocks and their relative difficulty change, the efficient utilization of your machine's parallel architecture can be affected.

The previous section used a block size of 20. The following statement calls the decomposition algorithm and uses a block size of 80:

```
%ResourceAllocation_Decomp(task_data=TaskData, capacity=100, block_size=80);
```

The solution summary is displayed in Output 18.7.5.

Output 18.7.5 Solution Summary

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalProfit
Solution Status	Optimal
Objective Value	40982
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	8.881784E-16
Bound Infeasibility	0
Integer Infeasibility	8.881784E-16
Best Bound	40982
Nodes	1
Solutions Found	56
Iterations	58
Presolve Time	0.02
Solution Time	55.24

The iteration log, which contains the problem statistics, the progress of the solution, and the optimal objective value, is shown in Output 18.7.6.

This version of the model provides a stronger initial bound and solves to optimality in the root node.

Output 18.7.6 Log

```
NOTE: There were 2916 observations read from the data set WORK.TASKDATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 3151 variables (0 free, 0 fixed).
NOTE: The problem has 3151 binary and 0 integer variables.
NOTE: The problem has 1003 linear constraints (768 LE, 235 EQ, 0 GE, 0 range).
NOTE: The problem has 23706 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value BASIC is applied.
NOTE: The MILP presolver removed 5 variables and 0 constraints.
NOTE: The MILP presolver removed 29 constraint coefficients.
NOTE: The MILP presolver modified 7295 constraint coefficients.
NOTE: The presolved problem has 3146 variables, 1003 constraints, and 23677 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The number of block threads has been reduced to 10 threads.
NOTE: The problem has a decomposable structure with 10 blocks. The largest block covers 7.976%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 3146 (100%) variables and 768 (76.57%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
```

Iter	Best Bound	Master Objective	Best Integer	LP Gap	IP Gap	CPU Time	Real Time
.	41762.0025	37436.0000	37436.0000	10.36%	10.36%	7	1
9	41762.0025	38314.0000	38314.0000	8.26%	8.26%	23	6
10	41762.0025	38314.0000	38418.0000	8.26%	8.01%	23	6
12	41762.0025	38513.0000	38513.0000	7.78%	7.78%	27	7
17	41762.0025	39548.0000	39548.0000	5.30%	5.30%	37	9
19	41762.0025	39965.0000	39965.0000	4.30%	4.30%	43	11
.	41762.0025	39965.0000	39965.0000	4.30%	4.30%	43	11
20	41762.0025	39965.0000	39965.0000	4.30%	4.30%	50	12
22	41762.0025	40068.0000	40068.0000	4.06%	4.06%	57	14
26	41762.0025	40818.0000	40818.0000	2.26%	2.26%	78	18
29	41762.0025	40859.0000	40859.0000	2.16%	2.16%	93	22
30	41762.0025	40859.0000	40859.0000	2.16%	2.16%	100	23
36	41762.0025	40914.0000	40914.0000	2.03%	2.03%	136	31
39	41762.0025	40930.0000	40930.0000	1.99%	1.99%	156	36
.	41762.0025	40930.0000	40930.0000	1.99%	1.99%	156	36
40	41762.0025	40930.0000	40930.0000	1.99%	1.99%	160	37
41	41284.0001	40930.0000	40930.0000	0.86%	0.86%	167	39
42	41190.5006	40930.0000	40930.0000	0.63%	0.63%	174	41
43	41164.0006	40930.0000	40930.0000	0.57%	0.57%	182	42
46	41164.0006	40953.0000	40953.0000	0.51%	0.51%	191	45
48	41164.0006	40955.0000	40955.0000	0.51%	0.51%	194	47

Output 18.7.6 *continued*

```
        50   41164.0006   40955.0000   40955.0000    0.51%    0.51%  198   48
        52   41164.0006   40982.0000   40982.0000    0.44%    0.44%  202   49
        57   41000.0008   40982.0000   40982.0000    0.04%    0.04%  211   53
        58   40982.0003   40982.0000   40982.0000    0.00%    0.00%  214   55
NOTE: The continuous bound was improved to 40982 due to objective granularity.
        58   40982.0000   40982.0000   40982.0000    0.00%    0.00%  214   55
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1     56   40982.0000   40982.0000    0.00%    214     55
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 55.24 seconds.
NOTE: Optimal.
NOTE: Objective = 40982.
```

Example 18.8: Vehicle Routing Problem

NOTE: This example shows how to use the MILP solver to solve the VRP. For an example of how to use a specialized algorithm to solve the VRP, see the "Examples" section in Chapter 15, "The Network Solver."

The vehicle routing problem (VRP) finds a minimum-cost routing of a fixed number of vehicles to service the demands of a set of customers. Define a set $C = \{2, \ldots, |C| + 1\}$ of customers, and a demand, d_c, for each customer c. Let $N = C \cup \{1\}$ be the set of nodes, including the vehicle depot, which is designated as node $i = 1$. Let $A = N \times N$ be the set of arcs, V be the set of vehicles (each of which has capacity L), and c_{ij} be the travel time from node i to node j.

Let y_{ik} be a binary variable that, if set to 1, indicates that node i is visited by vehicle k. Let z_{ijk} be a binary variable that, if set to 1, indicates that arc (i, j) is traversed by vehicle k, and let x_{ijk} be a continuous variable that denotes the amount of product (flow) on arc (i, j) that is carried by vehicle k.

A VRP can be formulated as a MILP as follows:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{(i,j)\in A}\sum_{k\in V} c_{ij} z_{ijk} & & \\
\text{subject to} & \displaystyle\sum_{k\in V} y_{ik} \geq 1 & i \in C & \text{(Assignment)} \\
& \displaystyle\sum_{(i,j)\in A} z_{ijk} = y_{ik} & i \in N,\ k \in V & \text{(LeaveNode)} \\
& \displaystyle\sum_{(j,i)\in A} z_{jik} = y_{ik} & i \in N,\ k \in V & \text{(EnterNode)} \\
& \displaystyle\sum_{(j,i)\in A} x_{jik} - \sum_{(i,j)\in A} x_{ijk} = d_i y_{ik} & i \in C,\ k \in V & \text{(FlowBalance)} \\
& x_{ijk} \leq L z_{ijk} & (i,j) \in A,\ k \in V & \text{(VehicleCapacity)} \\
& y_{1k} = 1 & k \in V & \text{(Depot)} \\
& x_{ijk} \geq 0 & (i,j) \in A,\ k \in V & \\
& y_{ik} \in \{0,1\} & i \in N,\ k \in V & \\
& z_{ijk} \in \{0,1\} & (i,j) \in A,\ k \in V &
\end{array}
$$

In this formulation, the Assignment constraints ensure that each customer is serviced by at least one vehicle. The objective function ensures that there exists an optimal solution that never assigns a customer to more than one vehicle. The LeaveNode and EnterNode constraints enforce the condition that if node i is visited by vehicle k, then vehicle k must use exactly one arc that enters node i and one arc that leaves node i. Conversely, if node i is not visited by vehicle k, then no arcs that enter or leave node i can be used by vehicle k. The FlowBalance constraints define flow conservation at each node for each vehicle. That is, if a node i is visited by vehicle k, then the amount of product from vehicle k that enters and leaves that node must equal the demand at that node. Conversely, if node i is not visited by vehicle k, then the amount of product from vehicle k that enters and leaves that node must be 0. The VehicleCapacity constraints enforce the condition that the amount of product in each vehicle must always be less than or equal to the vehicle capacity L. Finally, the Depot constraints enforce the condition that each vehicle must start and end at the depot node.

In this formulation, the vehicle identifier is arbitrary. Consider a decomposition by vehicle, where the Assignment constraints form the master problem and all other constraints form identical routing subproblems. As described in the section "Special Case: Identical Blocks and Ryan-Foster Branching" on page 1058, this is a situation in which an aggregate formulation can greatly improve performance by reducing symmetry. Because you know that there exists an optimal solution that satisfies the master Assignment constraints at equality, you can force the use of Ryan-Foster branching by specifying the option VARSEL=RYANFOSTER.

VRPLIB, located at `http://www.coin-or.org/SYMPHONY/branchandcut/VRP/data/index.htm`, is a set of benchmark instances of the VRP. The following data set, vrpdata, represents an instance from VRPLIB that has 22 nodes and eight vehicles (P-n22-k8.vrp), which was originally described in Augerat et al. (1995). The data set lists each node, its coordinates, and its demand.

```
/* number of vehicles available */
%let num_vehicles = 8;
/* capacity of each vehicle */
%let capacity = 3000;
/* node, x coordinate, y coordinate, demand */
data vrpdata;
```

```
   input node x y demand;
   datalines;
1  145 215    0
2  151 264 1100
3  159 261  700
4  130 254  800
5  128 252 1400
6  163 247 2100
7  146 246  400
8  161 242  800
9  142 239  100
10 163 236  500
11 148 232  600
12 128 231 1200
13 156 217 1300
14 129 214 1300
15 146 208  300
16 164 208  900
17 141 206 2100
18 147 193 1000
19 164 193  900
20 129 189 2500
21 155 185 1800
22 139 182  700
;
```

The following PROC OPTMODEL statements read in the data, declare the optimization model, and use the decomposition algorithm to solve it:

```
proc optmodel sessref="mysess";
   /* read the node location and demand data */
   set NODES;
   num x {NODES};
   num y {NODES};
   num demand {NODES};
   num capacity = &capacity;
   num num_vehicles = &num_vehicles;
   read data vrpdata into NODES=[node] x y demand;
   set ARCS = {i in NODES, j in NODES: i ne j};
   set VEHICLES = 1..num_vehicles;

   /* define the depot as node 1 */
   num depot = 1;

   /* define the arc cost as the rounded Euclidean distance */
   num cost {<i,j> in ARCS} = round(sqrt((x[i]-x[j])^2 + (y[i]-y[j])^2));

   /* Flow[i,j,k] is the amount of demand carried on arc (i,j) by vehicle k */
   var Flow {ARCS, VEHICLES} >= 0 <= capacity;
   /* UseNode[i,k] = 1, if and only if node i is serviced by vehicle k */
   var UseNode {NODES, VEHICLES} binary;
   /* UseArc[i,j,k] = 1, if and only if arc (i,j) is traversed by vehicle k */
   var UseArc {ARCS, VEHICLES} binary;
```

```
/* minimize the total distance traversed */
min TotalCost = sum {<i,j> in ARCS, k in VEHICLES} cost[i,j] * UseArc[i,j,k];

/* each non-depot node must be serviced by at least one vehicle */
con Assignment {i in NODES diff {depot}}:
   sum {k in VEHICLES} UseNode[i,k] >= 1;

/* each vehicle must start at the depot node */
for{k in VEHICLES} fix UseNode[depot,k] = 1;

/* some vehicle k traverses an arc that leaves node i
   if and only if UseNode[i,k] = 1 */
con LeaveNode {i in NODES, k in VEHICLES}:
   sum {<(i),j> in ARCS} UseArc[i,j,k] = UseNode[i,k];

/* some vehicle k traverses an arc that enters node i
   if and only if UseNode[i,k] = 1 */
con EnterNode {i in NODES, k in VEHICLES}:
   sum {<j,(i)> in ARCS} UseArc[j,i,k] = UseNode[i,k];

/* the amount of demand supplied by vehicle k to node i must equal demand
   if UseNode[i,k] = 1; otherwise, it must equal 0 */
con FlowBalance {i in NODES diff {depot}, k in VEHICLES}:
    sum {<j,(i)> in ARCS} Flow[j,i,k] - sum {<(i),j> in ARCS} Flow[i,j,k]
    = demand[i] * UseNode[i,k];

/* if UseArc[i,j,k] = 1, then the flow on arc (i,j) must be at most capacity
   if UseArc[i,j,k] = 0, then no flow is allowed on arc (i,j) */
con VehicleCapacity {<i,j> in ARCS, k in VEHICLES}:
   Flow[i,j,k] <= Flow[i,j,k].ub * UseArc[i,j,k];

/* decomp by vehicle */
for {i in NODES, k in VEHICLES} do;
   LeaveNode[i,k].block = k;
   EnterNode[i,k].block = k;
end;
for {i in NODES diff {depot}, k in VEHICLES} FlowBalance[i,k].block = k;
for {<i,j> in ARCS, k in VEHICLES} VehicleCapacity[i,j,k].block = k;

/* solve using decomp (aggregate formulation) */
solve with MILP / varsel=ryanfoster decomp=(logfreq=20);
```

The following PROC OPTMODEL statement creates plot data for the optimal routing:

```
/* create solution data set */
create data solution_data from [i j k]=
   {<i,j> in ARCS, k in VEHICLES: UseArc[i,j,k].sol > 0.5}
   x1=x[i] y1=y[i] x2=x[j] y2=y[j]
   function='line' drawspace='datavalue';
quit;
```

The solution summary is displayed in Output 18.8.1.

Output 18.8.1 Solution Summary

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalCost
Solution Status	Optimal
Objective Value	603
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	2.50111E-12
Bound Infeasibility	1.776357E-15
Integer Infeasibility	1.776357E-15
Best Bound	603
Nodes	1
Solutions Found	7
Iterations	77
Presolve Time	0.06
Solution Time	122.10

The iteration log is displayed in Output 18.8.2.

Output 18.8.2 Log

```
NOTE: There were 22 observations read from the data set WORK.VRPDATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 7568 variables (0 free, 8 fixed).
NOTE: The problem has 3872 binary and 0 integer variables.
NOTE: The problem has 4237 linear constraints (3696 LE, 520 EQ, 21 GE, 0 range).
NOTE: The problem has 22528 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 8 variables and 0 constraints.
NOTE: The MILP presolver removed 16 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 7560 variables, 4237 constraints, and 22512 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: All blocks are identical and the master model is set covering.
WARNING: The master model is not a set partitioning and VARSEL=RYANFOSTER. The objective
         function must ensure that there exists at least one optimal solution that fulfills all
         of the master constraints at equality.
NOTE: The Decomposition algorithm is using an aggregate formulation and Ryan-Foster branching.
NOTE: The number of block threads has been reduced to 1 threads.
NOTE: The problem has a decomposable structure with 8 blocks. The largest block covers 12.44%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 7560 (100%) variables and 4216 (99.5%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
NOTE: Starting phase 1.
         1       0.0000      20.0000            . 2.00e+01        .    1    1
        20       0.0000       1.0000            . 1.00e+00        .    5    4
        31       0.0000       0.0000            .    0.00%        .   11    9
        32       0.0000       0.0000            .    0.00%        .   11    9
NOTE: Starting phase 2.
         .     112.0000    1016.0000    1016.0000  807.14%  807.14%   11    9
         .     112.0000     705.0000     705.0000  529.46%  529.46%   20   15
        40     112.0000     705.0000     705.0000  529.46%  529.46%   20   15
        47     329.0000     705.0000     705.0000  114.29%  114.29%   40   28
        57     329.0000     619.5000     649.0000   88.30%   97.26%   79   52
        59     344.9093     619.5000     649.0000   79.61%   88.17%   87   57
        60     443.3000     610.5000     649.0000   37.72%   46.40%   97   63
        61     498.5000     610.5000     649.0000   22.47%   30.19%  107   69
        65     526.5000     610.5000     649.0000   15.95%   23.27%  123   79
        66     526.5000     608.0000     615.0000   15.48%   16.81%  131   84
```

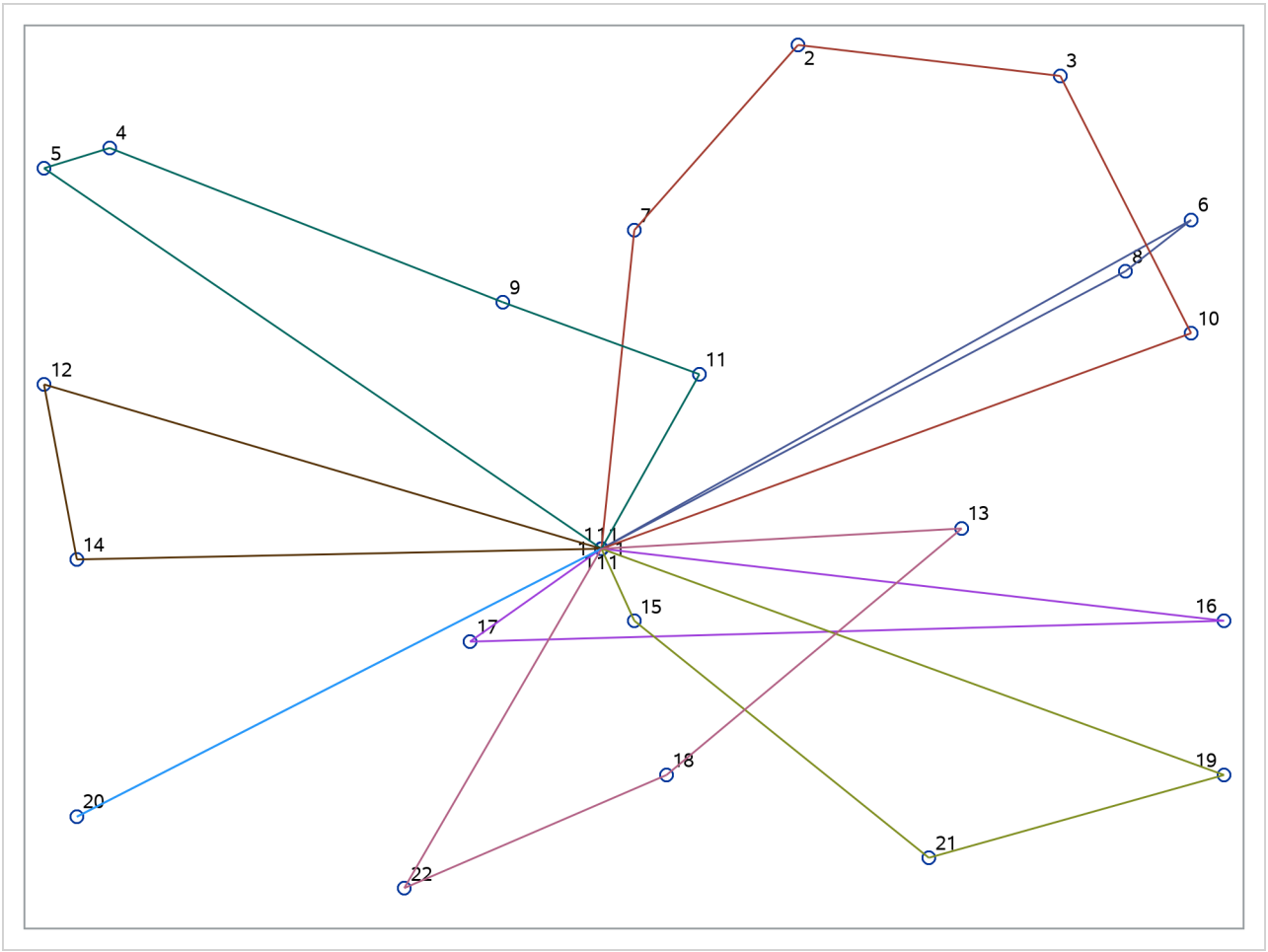
Output 18.8.2 *continued*

```
        68     565.0000     605.0000     605.0000    7.08%    7.08%  141   89
        70     589.0000     605.0000     605.0000    2.72%    2.72%  155   96
        74     589.0000     604.0000     604.0000    2.55%    2.55%  171  105
        75     596.0000     604.0000     604.0000    1.34%    1.34%  180  109
        76     600.3333     603.0000     603.0000    0.44%    0.44%  193  116
        77     603.0000     603.0000     603.0000    0.00%    0.00%  204  122
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                   Integer        Bound            Time   Time
            0       1      7     603.0000     603.0000    0.00%    204    122
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 122.10 seconds.
NOTE: Optimal.
NOTE: Objective = 603.
NOTE: The data set WORK.SOLUTION_DATA has 29 observations and 9 variables.
```

The following call to PROC SGPLOT generates a plot of the optimal routing. The plot is displayed in Figure 18.8.3.

```
proc sgplot data=solution_data noautolegend;
   scatter x=x1 y=y1 / datalabel=i;
   vector x=x2 y=y2 / xorigin=x1 yorigin=y1 group=k noarrowheads;
   xaxis display=none;
   yaxis display=none;
run;
```

Output 18.8.3 Optimal Routing



Example 18.9: ATM Cash Management in Single-Machine Mode

This example describes an optimization model that is used in the management of cash flow for a bank's automated teller machine (ATM) network. The goal of the model is to determine a replenishment schedule for the bank to use in allocating cash inventory at its branches when servicing a preassigned subset of ATMs. Given a history of withdrawals per day for each ATM, the bank can use SAS forecasting tools to predict the expected cash need. The modeling of this prediction depends on various seasonal factors, including the days of the week, weeks of the month, holidays, typical salary disbursement days, location of the ATMs, and other demographic data. The prediction is a parametric mixture of models whose parameters depend on each ATM.

The optimization model performs a polynomial regression that minimizes the error (measured by the L_1 norm) between the predicted and actual withdrawals. The parameter settings in the regression determine the replenishment policy. The amount of cash that is allocated to each day is subject to a budget constraint. In addition, a constraint for each ATM limits the number of days that a *cash-out* (a situation in which the cash flow is less than the predicted withdrawal) can occur. The goal is to determine a policy for cash distribution that balances the predicted inventory levels while satisfying the budget and cash-out constraints. By keeping too much cash on hand for ATM fulfillment, the bank loses an investment opportunity. Moreover, regulatory

agencies in many countries enforce a minimum cash reserve ratio at branch banks; according to regulatory policy, the cash in ATMs or in transit does not contribute toward this threshold.

Mixed Integer Nonlinear Programming Formulation

The most natural formulation for this model is in the form of a mixed integer nonlinear program (MINLP). Let A denote the set of ATMs and D denote the set of days that are used in the training data. The predictive model fit is defined by the following data for each ATM a on each day d: $c_{ad}, c^x_{ad}, c^y_{ad}, c^z_{ad}$, and c^u_{ad}. The model-fitting parameters define the variables (x_a, y_a, u_a) for each ATM that, when applied to the predictive model, estimate the necessary cash flow per day per ATM. In addition, define a surrogate variable f_{ad} for each ATM on each day that defines the cash inventory (replenished from the branch) minus withdrawals. The variable f_{ad} also represents the error in the regression model. Let B_d define the budget per day, K_a define the limit on cash-outs per ATM, and w_{ad} define the historical withdrawals at a particular ATM on a particular day. Then the following MINLP models this problem:

$$
\begin{array}{llll}
\text{minimize} & \displaystyle\sum_{a\in A}\sum_{d\in D} |f_{ad}| & & \\
\text{subject to} & c^x_{ad}x_a + c^y_{ad}y_a + & & \\
& c^z_{ad}x_a y_a + c^u_{ad}u_a + c_{ad} - w_{ad} = f_{ad} & a \in A,\ d \in D & \text{(CashFlowDefCon)} \\
& \displaystyle\sum_{a\in A}(f_{ad} + w_{ad}) \le B_d & d \in D & \text{(BudgetCon)} \\
& |\{d \in D \mid f_{ad} < 0\}| \le K_a & a \in A & \text{(CashOutLimitCon)} \\
& x_a, y_a \in [0,1] & a \in A & \\
& u_a \ge 0 & a \in A & \\
& f_{ad} \ge -w_{ad} & a \in A,\ d \in D &
\end{array}
$$

The CashFlowDefCon constraint defines the surrogate variable f_{ad}, which gives the estimated net cash flow. The BudgetCon and CashOutLimitCon constraints ensure that the solution satisfies the budget and cash-out constraints, respectively.

To express this model in a more standard form, you can first use some standard model reformulations to linearize the absolute value and the CashOutLimitCon constraint.

Linearization of Absolute Value

A well-known reformulation for linearizing the absolute value of a variable is to introduce one variable for each side of the absolute value. The following systems are equivalent:

$$
\begin{array}{lll}
\text{minimize} & |y| & \\
\text{subject to} & Ay & \le\ b
\end{array}
\qquad \text{is equivalent to} \qquad
\begin{array}{lll}
\text{minimize} & y^+ + y^- & \\
\text{subject to} & A(y^+ - y^-) & \le\ b \\
& y^+, y^- & \ge\ 0
\end{array}
$$

Let f_{ad}^{+} and f_{ad}^{-} represent the positive and negative parts, respectively, of the net cash flow f_{ad}. Then you can rewrite the model, removing the absolute value, as the following:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{a \in A} \sum_{d \in D} \left(f_{ad}^{+} + f_{ad}^{-}\right) \\
\text{subject to} \quad & c_{ad}^{x} x_a + c_{ad}^{y} y_a + \\
& c_{ad}^{z} x_a y_a + c_{ad}^{u} u_a + c_{ad} - w_{ad} = f_{ad}^{+} - f_{ad}^{-} && a \in A,\ d \in D \\
& \sum_{a \in A} \left(f_{ad}^{+} - f_{ad}^{-} + w_{ad}\right) \le B_d && d \in D \\
& |\{d \in D \mid (f_{ad}^{+} - f_{ad}^{-}) < 0\}| \le K_a && a \in A \\
& x_a, y_a \in [0, 1] && a \in A \\
& u_a \ge 0 && a \in A \\
& f_{ad}^{+} \ge 0 && a \in A,\ d \in D \\
& f_{ad}^{-} \in [0, w_{ad}] && a \in A,\ d \in D
\end{aligned}
$$

Modeling the Cash-Out Constraints

To count the number of times a cash-out occurs, you need to introduce a binary variable to keep track of when this event occurs. Let v_{ad} be an indicator variable that takes the value 1 when the net cash flow is negative. You can model the implication $f_{ad}^{-} > 0 \Rightarrow v_{ad} = 1$, or its contrapositive $v_{ad} = 0 \Rightarrow f_{ad}^{-} \le 0$, by adding the constraint

$$f_{ad}^{-} \le w_{ad} v_{ad} \quad a \in A,\ d \in D$$

Now you can model the cash-out constraint by counting the number of days that the net-cash flow is negative for each ATM, as follows:

$$\sum_{d \in D} v_{ad} \le K_a \quad a \in A$$

The MINLP model can now be written as follows:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{a \in A} \sum_{d \in D} \left(f_{ad}^{+} + f_{ad}^{-}\right) \\
\text{subject to} \quad & c_{ad}^{x} x_a + c_{ad}^{y} y_a + \\
& c_{ad}^{z} x_a y_a + c_{ad}^{u} u_a + c_{ad} - w_{ad} = f_{ad}^{+} - f_{ad}^{-} && a \in A,\ d \in D \\
& \sum_{a \in A} \left(f_{ad}^{+} - f_{ad}^{-} + w_{ad}\right) \le B_d && d \in D \\
& f_{ad}^{-} \le w_{ad} v_{ad} && a \in A,\ d \in D \\
& \sum_{d \in D} v_{ad} \le K_a && a \in A \\
& x_a, y_a \in [0, 1] && a \in A \\
& u_a \ge 0 && a \in A \\
& f_{ad}^{+} \ge 0 && a \in A,\ d \in D \\
& f_{ad}^{-} \in [0, w_{ad}] && a \in A,\ d \in D \\
& v_{ad} \in \{0, 1\} && a \in A,\ d \in D
\end{aligned}
$$

This MINLP is difficult to solve, in part because the prediction function is not convex. Another approach is to use mixed integer linear programming (MILP) to formulate an approximation of the problem, as described in the next section.

Mixed Integer Linear Programming Approximation

Because the predictive model is a forecast, finding the optimal parameters that are based on nondeterministic data is not of primary importance. Rather, you want to provide as good a solution as possible in a reasonable amount of time. So using MILP to approximate the MINLP is perfectly acceptable. In the original problem you have products of two continuous variables that are both bounded by 0 (lower bound) and 1 (upper bound). This arrangement enables you to create an approximate linear model by using a few standard modeling reformulations.

Discretization of Continuous Variables

The first step is to discretize one of the continuous variables x_a. The goal is to transform the product $x_a y_a$ of a continuous variable and another continuous variable instead to the product of a continuous variable and a binary variable. This transformation enables you to linearize the product form.

You must assume some level of approximation by defining a binary variable (from some discrete set) for each possible setting of the continuous variable For example, if you let $n = 10$, then you allow x to be chosen from the set $\{0.0, 0.1, 0.2, 0.3, \ldots, 1.0\}$. Let $T = \{0, 1, 2, \ldots, n\}$ represent the possible steps and $c_t = t/n$. Then you apply the following transformation to variable x_a:

$$\sum_{t \in T} c_t x_{at} = x_a$$

$$\sum_{t \in T} x_{at} = 1$$

$$x_{at} \in \{0, 1\} \quad t \in T$$

The MINLP model can now be approximated as the following:

$$
\begin{array}{lrll}
\text{minimize} & \displaystyle\sum_{a\in A}\sum_{d\in D}\left(f_{ad}^{+}+f_{ad}^{-}\right) & & \\
\text{subject to} & c_{ad}^{x}\displaystyle\sum_{t\in T}c_t x_{at}+c_{ad}^{y}y_a+ & & \\
& c_{ad}^{z}\displaystyle\sum_{t\in T}c_t x_{at}y_a+c_{ad}^{u}u_a+c_{ad}-w_{ad}=f_{ad}^{+}-f_{ad}^{-} & & a\in A,\ d\in D \\
& \displaystyle\sum_{t\in T}x_{at}=1 & & a\in A \\
& \displaystyle\sum_{a\in A}\left(f_{ad}^{+}-f_{ad}^{-}+w_{ad}\right)\le B_d & & d\in D \\
& f_{ad}^{-}\le w_{ad}v_{ad} & & a\in A,\ d\in D \\
& \displaystyle\sum_{d\in D}v_{ad}\le K_a & & a\in A \\
& y_a\in[0,1] & & a\in A \\
& u_a\ge 0 & & a\in A \\
& f_{ad}^{+}\ge 0 & & a\in A,\ d\in D \\
& f_{ad}^{-}\in[0,w_{ad}] & & a\in A,\ d\in D \\
& v_{ad}\in\{0,1\} & & a\in A,\ d\in D \\
& x_{at}\in\{0,1\} & & a\in A,\ t\in T
\end{array}
$$

Linearization of Products

You still need to linearize the product terms $x_{at}y_a$ in the cash flow constraint. Because these terms are products of a bounded continuous variable and a binary variable, you can linearize them by introducing for each product another variable, z_{at}, which serves as a surrogate. In general, you know the following relationship between the original variables and their surrogates:

$$
\begin{array}{lcll}
z_t & = & x_t y & t\in T \\
\sum_{t\in T}x_t & = & 1 & \\
x_t & \in & \{0,1\} & t\in T \\
y & \in & [0,1] &
\end{array}
\quad\text{is equivalent to}\quad
\begin{array}{lcll}
z_t & \ge & 0 & t\in T \\
z_t & \le & x_t & t\in T \\
\sum_{t\in T}x_t & = & 1 & \\
\sum_{t\in T}z_t & = & y & \\
x_t & \in & \{0,1\} & t\in T \\
y & \in & [0,1] &
\end{array}
$$

Using this relationship to replace each product form, you now can write the problem as an approximate MILP as follows:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{a \in A} \sum_{d \in D} \left(f_{ad}^{+} + f_{ad}^{-} \right) \\
\text{subject to} \quad & c_{ad}^{x} \sum_{t \in T} c_t x_{at} + c_{ad}^{y} y_a + \\
& c_{ad}^{z} \sum_{t \in T} c_t z_{at} + c_{ad}^{u} u_a + c_{ad} - w_{ad} = f_{ad}^{+} - f_{ad}^{-} && a \in A,\ d \in D \\
& \sum_{t \in T} x_{at} = 1 && a \in A \\
& \sum_{a \in A} \left(f_{ad}^{+} - f_{ad}^{-} + w_{ad} \right) \le B_d && d \in D \qquad \text{(BudgetCon)} \\
& f_{ad}^{-} \le w_{ad} v_{ad} && a \in A,\ d \in D \\
& \sum_{d \in D} v_{ad} \le K_a && a \in A \\
& z_{at} \le x_{at} && a \in A,\ t \in T \\
& \sum_{t \in T} z_{at} = y_a && a \in A \\
& z_{at} \ge 0 && a \in A,\ t \in T \\
& y_a \in [0, 1] && a \in A \\
& u_a \ge 0 && a \in A \\
& f_{ad}^{+} \ge 0 && a \in A,\ d \in D \\
& f_{ad}^{-} \in [0, w_{ad}] && a \in A,\ d \in D \\
& v_{ad} \in \{0, 1\} && a \in A,\ d \in D \\
& x_{at} \in \{0, 1\} && a \in A,\ t \in T
\end{aligned}
$$

PROC OPTMODEL Code

Because it is difficult to solve the MINLP model directly, the approximate MILP formulation is attractive. Unfortunately, the approximate MILP is much larger than the associated MINLP. Direct methods for solving this MILP do not work well. However, the problem is nicely suited for the decomposition algorithm.

When you examine the structure of the MILP model, you see clearly that the constraints can be easily decomposed by ATM. In fact, the only set of constraints that involve decision variables across ATMs is the BudgetCon constraint. That is, if you relax the budget constraint, you are left with independent blocks of constraints, one for each ATM.

To show how this is done in PROC OPTMODEL, consider the following data sets, which describe an example that tracks 20 ATMs over a period of 100 days. This particular example was submitted to MIPLIB 2010, which is a collection of difficult MILPs in the public domain (Koch et al. 2011).

The first data set, budget_data, provides the cash budget on each particular day:

```
data budget_data;
   input d $ budget;
   datalines;
DATE0      70079
DATE1      66418
DATE10     52656
DATE11     50439
DATE12     58688
DATE13     45002
DATE14     52369
...
;
```

The second data set, cashout_data, provides the limit on the number of cash-outs that are allowed at each ATM:

```
data cashout_data;
   input a $ cashOutLimit;
   datalines;
ATM0            31
ATM1            24
ATM2            41
ATM3            43
ATM4            29
ATM5            24
ATM6            52
ATM7            44
ATM8            35
ATM9            48
ATM10           31
ATM11           47
ATM12           26
ATM13           34
ATM14           29
ATM15           32
ATM16           33
ATM17           32
ATM18           43
ATM19           28
;
```

The final data set, polyfit_data, provides the polynomial fit coefficients for each ATM on each date. It also provides the historical cash withdrawals.

```
data polyfit_data;
   input a $ d $ cx cy cz cu c withdrawal;
   datalines;
ATM0     DATE0       2822     1984    -1984    1045    1373        780
ATM0     DATE1       1337     2530    -2530    1510     174       2351
ATM0     DATE2       2685      -67       67     145    2820       2288
ATM0     DATE3       -595    -3135     3135     581    3319       1357
...
ATM19    DATE96      -734     3392    -3392     162    1648        914
ATM19    DATE97     -1062      969     -969     444    1746       2264
```

```
ATM19    DATE98      7676     2308    -2308      59    1388        972
ATM19    DATE99      3062     1308    -1308    1080     654        698
;
```

The following PROC OPTMODEL statements read in the data and define the necessary sets and parameters:

```
proc optmodel sessref="mysess";
   set<str> DATES;
   set<str> ATMS;

   /* cash budget per date */
   num budget{DATES};

   /* maximum number of cash-outs allowed at each atm */
   num cashOutLimit{ATMS};

   /* historical withdrawal amount per atm each date */
   num withdrawal{ATMS, DATES};

   /* polynomial fit coefficients for predicted cash flow needed */
   num c {ATMS, DATES};
   num cx{ATMS, DATES};
   num cy{ATMS, DATES};
   num cz{ATMS, DATES};
   num cu{ATMS, DATES};

   /* number of points used in approximation of continuous range */
   num nSteps = 10;
   set STEPS = {0..nSteps};

   read data budget_data into DATES=[d] budget;
   read data cashout_data into ATMS=[a] cashOutLimit;
   read data polyfit_data into [a d] cx cy cz cu c withdrawal;
```

The following statements declare the variables:

```
   var x{ATMS,STEPS}                binary;
   var v{ATMS,DATES}                binary;
   var z{ATMS,STEPS}                >= 0 <= 1;
   var y{ATMS}                      >= 0 <= 1;
   var u{ATMS}                      >= 0;
   var fPlus{ATMS,DATES}            >= 0;
   var fMinus{a in ATMS, d in DATES} >= 0 <= withdrawal[a,d];
```

The following statements declare the objective and the constraints:

```
   min CashFlowDiff =
      sum{a in ATMS, d in DATES} (fPlus[a,d] + fMinus[a,d]);

   con BudgetCon{d in DATES}:
      sum{a in ATMS} (fPlus[a,d] - fMinus[a,d] + withdrawal[a,d])
          <= budget[d];

   con CashFlowDefCon{a in ATMS, d in DATES}:
      cx[a,d] * sum{t in STEPS} (t/nSteps) * x[a,t] +
```

```
      cy[a,d] * y[a]                                  +
      cz[a,d] * sum{t in STEPS} (t/nSteps) * z[a,t] +
      cu[a,d] * u[a]                                  +
      c[a,d] - withdrawal[a,d] = fPlus[a,d] - fMinus[a,d];

   con PickOneStepCon{a in ATMS}:
      sum{t in STEPS} x[a,t] = 1;

   con CashOutLinkCon{a in ATMS, d in DATES}:
      fMinus[a,d] <= withdrawal[a,d] * v[a,d];

   con CashOutLimitCon{a in ATMS}:
      sum{d in DATES} v[a,d] <= cashOutLimit[a];

   con Linear1Con{a in ATMS, t in STEPS}:
      z[a,t] <= x[a,t];

   con Linear2Con{a in ATMS}:
      sum{t in STEPS} z[a,t] = y[a];
```

The following statements define the block decomposition by ATM. The **.block** suffix expects numeric indices, whereas the **set<str> ATMS** statement declares a set of strings. You can create a mapping from the string identifier to a numeric identifier as follows:

```
/* create numeric block index */
num blockIndex {ATMS};
num index init 0;
for{a in ATMS} do;
   blockIndex[a] = index;
   index = index + 1;
end;
```

Then, each constraint can be added to its associated ATM block as follows:

```
/* define blocks for each ATM */
for{a in ATMS} do;
   PickOneStepCon[a].block  = blockIndex[a];
   CashOutLimitCon[a].block = blockIndex[a];
   Linear2Con[a].block      = blockIndex[a];
   for{d in DATES} do;
      CashFlowDefCon[a,d].block = blockIndex[a];
      CashOutLinkCon[a,d].block = blockIndex[a];
   end;
   for{t in STEPS}
      Linear1Con[a,t].block = blockIndex[a];
end;
```

The budget constraint links all the ATMs, and it remains in the master problem. Finally, the following statements use the decomposition algorithm to solve the problem to within 1% of proven optimality:

```
/* solve with the decomposition algorithm */
solve with milp / nthreads=4 relobjgap=0.01 decomp;
```

The solution summary is displayed in Output 18.9.1.

Output 18.9.1 Solution Summary Table

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	CashFlowDiff
Solution Status	Optimal within Relative Gap
Objective Value	2465646.9893
Relative Gap	0.0091889398
Absolute Gap	22450.386528
Primal Infeasibility	3.410605E-13
Bound Infeasibility	2.220446E-16
Integer Infeasibility	2.220446E-16
Best Bound	2443196.6028
Nodes	1
Solutions Found	6
Iterations	11
Presolve Time	0.42
Solution Time	28.27

The iteration log, which contains the problem statistics, the progress of the solution, and the optimal objective value, is shown in Output 18.9.2.

Output 18.9.2 Log

```
NOTE: There were 100 observations read from the data set WORK.BUDGET_DATA.
NOTE: There were 20 observations read from the data set WORK.CASHOUT_DATA.
NOTE: There were 2000 observations read from the data set WORK.POLYFIT_DATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 6480 variables (0 free, 0 fixed).
NOTE: The problem has 2220 binary and 0 integer variables.
NOTE: The problem has 4380 linear constraints (2340 LE, 2040 EQ, 0 GE, 0 range).
NOTE: The problem has 58878 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 562 variables and 390 constraints.
NOTE: The MILP presolver removed 14325 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 5918 variables, 3990 constraints, and 44553 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value USER is applied.
NOTE: The problem has a decomposable structure with 20 blocks. The largest block covers 5.138%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 5918 (100%) variables and 3890 (97.49%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 4 threads.
      Iter         Best       Master         Best       LP       IP  CPU Real
                   Bound    Objective      Integer      Gap      Gap Time Time
NOTE: Starting phase 1.
         1       0.0000       1.1767            . 1.18e+00        .   31   11
         2       0.0000       0.0000            .    0.00%        .   31   11
         3       0.0000       0.0000            .    0.00%        .   31   11
NOTE: Starting phase 2.
         .   2.4432e+06   2.6116e+06   2.6381e+06    6.89%    7.98%   34   14
         8   2.4432e+06   2.4895e+06   2.4947e+06    1.90%    2.11%   68   27
        10   2.4432e+06   2.4656e+06   2.4656e+06    0.91%    0.92%   69   28
NOTE: The Decomposition algorithm stopped on the integer RELOBJGAP= option.
        11   2.4432e+06   2.4656e+06   2.4656e+06    0.91%    0.92%   69   28
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                  Integer        Bound            Time   Time
            0       1      6   2.4656e+06   2.4432e+06    0.92%     69     28
NOTE: The Decomposition algorithm used 4 threads.
NOTE: The Decomposition algorithm time is 28.27 seconds.
NOTE: Optimal within relative gap.
NOTE: Objective = 2465646.9893.
```

Example 18.10: ATM Cash Management in Distributed Mode

This section illustrates how you can use PROC OPTMODEL and the decomposition algorithm in distributed mode. The problem is the same as the one described in Example 18.9 for managing the cash flow of a bank's network of automated teller machines (ATMs). The only difference between single-machine and distributed mode is that the DISTRIBUTED= option is set to TRUE in the main solver statement. In this example, the CAS session is configured for 20 worker nodes, each having 32 cores.

The following statement changes the operating mode to distributed mode:

```
/* solve with the decomposition algorithm (in distributed mode) */
solve with milp / distributed=true nthreads=4 relobjgap=0.01 decomp;
```

When you specify DISTRIBUTED=TRUE and NTHREADS=4, each machine in your configured session processes the subproblems by using up to four threads simultaneously (per machine).

The solution summary is displayed in Output 18.10.1.

Output 18.10.1 Solution Summary Table

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	CashFlowDiff
Solution Status	Optimal within Relative Gap
Objective Value	2464019.7445
Relative Gap	0.0085175834
Absolute Gap	20810.240723
Primal Infeasibility	3.128937E-13
Bound Infeasibility	3.699887E-9
Integer Infeasibility	2.220774E-16
Best Bound	2443209.5037
Nodes	1
Solutions Found	9
Iterations	11
Presolve Time	0.43
Solution Time	15.03

The iteration log, which contains the problem statistics, the progress of the solution, and the optimal objective value, is shown in Output 18.10.2.

Output 18.10.2 Log

```
NOTE: There were 100 observations read from the data set WORK.BUDGET_DATA.
NOTE: There were 20 observations read from the data set WORK.CASHOUT_DATA.
NOTE: There were 2000 observations read from the data set WORK.POLYFIT_DATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 6480 variables (0 free, 0 fixed).
NOTE: The problem has 2220 binary and 0 integer variables.
NOTE: The problem has 4380 linear constraints (2340 LE, 2040 EQ, 0 GE, 0 range).
NOTE: The problem has 58878 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment with 20 worker
      nodes.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value AUTOMATIC is applied.
NOTE: The MILP presolver removed 562 variables and 390 constraints.
NOTE: The MILP presolver removed 14325 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 5918 variables, 3990 constraints, and 44553 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in the distributed computing environment with 20
      worker nodes.
NOTE: The DECOMP method value USER is applied.
NOTE: The problem has a decomposable structure with 20 blocks. The largest block covers 5.138%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 5918 (100%) variables and 3890 (97.49%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 4 threads.
      Iter         Best       Master         Best       LP       IP Real
                  Bound    Objective      Integer      Gap      Gap Time
NOTE: Starting phase 1.
         1       0.0000       1.1767            . 1.18e+00        .    4
         2       0.0000       0.0000            .    0.00%        .    4
         3       0.0000       0.0000            .    0.00%        .    4
NOTE: Starting phase 2.
         .   2.4432e+06   2.5578e+06   2.5887e+06    4.69%    5.95%    7
         8   2.4432e+06   2.4767e+06   2.4774e+06    1.37%    1.40%   13
        10   2.4432e+06   2.4640e+06   2.4640e+06    0.85%    0.85%   15
NOTE: The Decomposition algorithm stopped on the integer RELOBJGAP= option.
        11   2.4432e+06   2.4640e+06   2.4640e+06    0.85%    0.85%   15
         Node  Active   Sols         Best         Best      Gap   Real
                                  Integer        Bound            Time
            0       1      9   2.4640e+06   2.4432e+06    0.85%     15
NOTE: The Decomposition algorithm used 4 threads.
NOTE: The Decomposition algorithm time is 15.03 seconds.
NOTE: Optimal within relative gap.
NOTE: Objective = 2464019.7445.
```

Notice how this iteration log differs from the iteration log for single-machine mode in Example 18.9. In this case, the path is slightly altered because each block solve uses four threads (parallel branch-and-cut) to solve the subproblems as opposed to one thread (sequential branch-and-cut) when running in single-machine mode. The calculation of the default value for the NTHREADS= option in the DECOMPSUBPROB statement is described on page 1055.

Example 18.11: Kidney Donor Exchange and METHOD=SET

This example looks at an application of integer programming to help create a kidney donor exchange. Suppose someone needs a kidney transplant and a family member is willing to be a donor. If the donor and recipient are incompatible (because of blood type, tissue mismatch, and so on), the transplant cannot happen. Now suppose two donor-recipient pairs, i and j, are in this situation, but donor i is compatible with recipient j and donor j is compatible with recipient i. Then two transplants can take place in a two-way swap, shown in Figure 18.8. More generally, an n-way swap can be performed involving n donors and n recipients (CNN 2012).

Figure 18.8 Kidney Donor Exchange Two-Way Swap

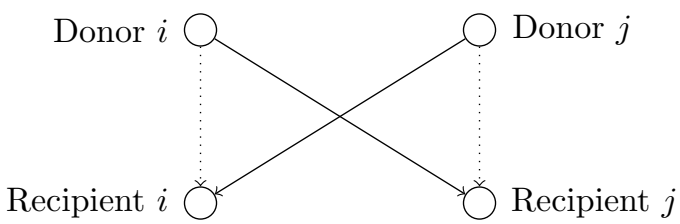
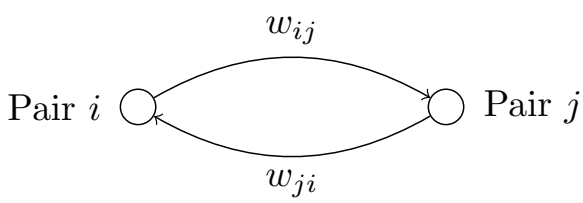


Figure 18.9 Kidney Donor Exchange Network



To model this problem, define a directed graph as follows. Each node is an incompatible donor-recipient pair. Link (i, j) exists if the donor from node i is compatible with the recipient from node j, as shown in Figure 18.9. Let N define the set of nodes and A define the set of arcs. The link weight, w_{ij}, is a measure of the quality of the match. By introducing dummy links whose weight is 0, you can also include altruistic donors who have no recipients or recipients who have no donors. The idea is to find a maximum-weight node-disjoint union of directed cycles. You want the union to be node-disjoint so that no kidney is donated more than once, and you want cycles so that the donor from node i donates a kidney if and only if the recipient from node i receives a kidney.

Without any other constraints, the problem could be solved as a linear assignment problem. But doing so would allow arbitrarily long cycles in the solution. For practical considerations (such as travel) and to mitigate risk, each cycle must have no more than L links. The kidney exchange problem is to find a maximum-weight node-disjoint union of short directed cycles.

Define an index set $M = \{1, \ldots, |N|/2\}$ of candidate disjoint unions of short cycles (called *matchings*). Let x_{ijm} be a binary variable that, if set to 1, indicates that arc (i, j) is in a matching m. Let y_{im} be a binary variable that, if set to 1, indicates that node i is covered by matching m. In addition, let s_i be a binary slack variable that, if set to 1, indicates that node i is not covered by any matching.

The kidney donor exchange can be formulated as a MILP as follows:

$$
\begin{array}{llll}
\text{maximize} & \displaystyle\sum_{(i,j)\in A}\sum_{m\in M} w_{ij}x_{ijm} & & \\
\text{subject to} & \displaystyle\sum_{m\in M} y_{im} + s_i = 1 & i \in N & \text{(Packing)} \\
& \displaystyle\sum_{(i,j)\in A} x_{ijm} = y_{im} & i \in N,\ m \in M & \text{(Donate)} \\
& \displaystyle\sum_{(i,j)\in A} x_{ijm} = y_{jm} & j \in N,\ m \in M & \text{(Receive)} \\
& \displaystyle\sum_{(i,j)\in A} x_{ijm} \le L & m \in M & \text{(Cardinality)} \\
& x_{ijm} \in \{0,1\} & (i,j) \in A,\ m \in M & \\
& y_{im} \in \{0,1\} & i \in N,\ m \in M & \\
& s_i \in \{0,1\} & i \in N &
\end{array}
$$

In this formulation, the Packing constraints ensure that each node is covered by at most one matching. The Donate and Receive constraints enforce the condition that if node i is covered by matching m, then the matching m must use exactly one arc that leaves node i (Donate) and one arc that enters node i (Receive). Conversely, if node i is not covered by matching m, then no arcs that enter or leave node i can be used by matching m. The Cardinality constraints enforce the condition that the number of arcs in matching m must not exceed L.

In this formulation, the matching identifier is arbitrary. Because it is not necessary to cover each incompatible donor-recipient pair (node), the Packing constraints can be modeled by using set partitioning constraints and the slack variable s. Consider a decomposition by matching, in which the Packing constraints form the master problem and all other constraints form identical matching subproblems. As described in the section "Special Case: Identical Blocks and Ryan-Foster Branching" on page 1058, this is a situation in which an aggregate formulation and Ryan-Foster branching can greatly improve performance by reducing symmetry.

The following DATA step sets up the problem by first creating a random graph on n nodes with link probability p and Uniform(0,1) weight:

```
/* create random graph on n nodes with arc probability p
   and uniform(0,1) weight */
%let n = 100;
%let p = 0.02;
data ArcData;
   call streaminit(1);
   do i = 0 to &n - 1;
      do j = 0 to &n - 1;
         if i eq j then continue;
         else if rand('UNIFORM') < &p then do;
            weight = rand('UNIFORM');
```

```
            output;
         end;
      end;
   end;
run;
```

In this case, you can specify METHOD=SET and let the decomposition algorithm automatically detect the set partitioning master constraints (Packing) and each independent matching subproblem. The following PROC OPTMODEL statements read in the data, declare the optimization model, and use the decomposition algorithm to solve it:

```
%let max_length = 10;
proc optmodel sessref="mysess";
   set <num,num> ARCS;
   num weight {ARCS};
   read data ArcData into ARCS=[i j] weight;
   print weight;
   set NODES = union {<i,j> in ARCS} {i,j};
   set MATCHINGS = 1..card(NODES)/2;

   /* UseNode[i,m] = 1 if node i is used in matching m, 0 otherwise */
   var UseNode {NODES, MATCHINGS} binary;

   /* UseArc[i,j,m] = 1 if arc (i,j) is used in matching m, 0 otherwise */
   var UseArc {ARCS, MATCHINGS} binary;

   /* maximize total weight of arcs used */
   max TotalWeight
      = sum {<i,j> in ARCS, m in MATCHINGS} weight[i,j] * UseArc[i,j,m];

   /* each node appears in at most one matching */
   /* rewrite as set partitioning (so decomp uses identical blocks)
      sum{} x <= 1 => sum{} x + s = 1, s >= 0 with no associated cost */
   var Slack {NODES} binary;
   con Packing {i in NODES}:
      sum {m in MATCHINGS} UseNode[i,m] + Slack[i] = 1;

   /* at most one recipient for each donor */
   con Donate {i in NODES, m in MATCHINGS}:
      sum {<(i),j> in ARCS} UseArc[i,j,m] = UseNode[i,m];

   /* at most one donor for each recipient */
   con Receive {j in NODES, m in MATCHINGS}:
      sum {<i,(j)> in ARCS} UseArc[i,j,m] = UseNode[j,m];

   /* exclude long matchings */
   con Cardinality {m in MATCHINGS}:
      sum {<i,j> in ARCS} UseArc[i,j,m] <= &max_length;

   /* automatically decompose using METHOD=SET */
   solve with milp / presolver=basic decomp=(method=set);

   /* save solution to a data set */
   create data Solution from
```

```
        [m i j]={m in MATCHINGS, <i,j> in ARCS: UseArc[i,j,m].sol > 0.5}
        weight[i,j];
quit;
```

In this case, the PRESOLVER=BASIC option ensures that the model maintains its specified symmetry, enabling the algorithm to use the aggregate formulation and Ryan-Foster branching. The solution summary is displayed in Output 18.11.1.

Output 18.11.1 Solution Summary

The OPTMODEL Procedure

Solution Summary	
Solver	MILP
Algorithm	Decomposition
Objective Function	TotalWeight
Solution Status	Optimal
Objective Value	24.850855395
Relative Gap	0
Absolute Gap	0
Primal Infeasibility	1.110223E-15
Bound Infeasibility	8.881784E-16
Integer Infeasibility	8.881784E-16
Best Bound	24.850855395
Nodes	11
Solutions Found	17
Iterations	110
Presolve Time	0.01
Solution Time	33.90

The iteration log is displayed in Output 18.11.2.

Output 18.11.2 Log

```
NOTE: There were 208 observations read from the data set WORK.ARCDATA.
NOTE: Problem generation will use 8 threads.
NOTE: The problem has 15092 variables (0 free, 0 fixed).
NOTE: The problem has 15092 binary and 0 integer variables.
NOTE: The problem has 9751 linear constraints (49 LE, 9702 EQ, 0 GE, 0 range).
NOTE: The problem has 45080 linear constraint coefficients.
NOTE: The problem has 0 nonlinear constraints (0 LE, 0 EQ, 0 GE, 0 range).
NOTE: The SOLVE statement is executing in the distributed computing environment in
      single-machine mode.
NOTE: The initial MILP heuristics are applied.
NOTE: The MILP presolver value BASIC is applied.
NOTE: The MILP presolver removed 5081 variables and 3366 constraints.
NOTE: The MILP presolver removed 15175 constraint coefficients.
NOTE: The MILP presolver modified 0 constraint coefficients.
NOTE: The presolved problem has 10011 variables, 6385 constraints, and 29905 constraint
      coefficients.
NOTE: The MILP solver is called.
NOTE: The Decomposition algorithm is used.
NOTE: The Decomposition algorithm is executing in single-machine mode.
NOTE: The DECOMP method value SET is applied.
NOTE: All blocks are identical and the master model is set partitioning.
NOTE: The Decomposition algorithm is using an aggregate formulation and Ryan-Foster branching.
NOTE: The number of block threads has been reduced to 1 threads.
NOTE: The problem has a decomposable structure with 49 blocks. The largest block covers 2.02%
      of the constraints in the problem.
NOTE: The decomposition subproblems cover 9947 (99.36%) variables and 6321 (99%) constraints.
NOTE: The deterministic parallel mode is enabled.
NOTE: The Decomposition algorithm is using up to 80 threads.
```

Iter	Best Bound	Master Objective	Best Integer	LP Gap	IP Gap	CPU Time	Real Time
.	350.7353	11.5201	11.5201	96.72%	96.72%	1	1
3	339.7809	11.5201	11.5201	96.61%	96.61%	1	1
4	333.3981	11.5201	11.5201	96.54%	96.54%	1	1
5	314.4588	15.7076	15.7076	95.00%	95.00%	1	1
6	314.4588	17.1869	17.1869	94.53%	94.53%	1	1
8	306.9517	17.1869	17.1869	94.40%	94.40%	2	2
9	301.1787	19.8897	17.1869	93.40%	94.29%	3	3
.	301.1787	19.8897	17.1869	93.40%	94.29%	3	3
10	296.4397	19.8897	17.1869	93.29%	94.20%	3	3
11	233.2433	19.8897	17.1869	91.47%	92.63%	4	3
12	205.8663	21.2404	17.1869	89.68%	91.65%	4	3
15	196.2609	22.9988	17.1869	88.28%	91.24%	4	3
17	173.1685	23.2887	21.0803	86.55%	87.83%	4	3
19	139.1889	24.3948	21.0803	82.47%	84.85%	4	4
.	139.1889	24.5468	22.6821	82.36%	83.70%	4	4
20	139.1889	24.5468	22.6821	82.36%	83.70%	4	4
23	126.9471	24.6079	22.6821	80.62%	82.13%	5	4
24	125.2742	24.6642	22.6821	80.31%	81.89%	5	5
26	72.9270	24.8011	22.6821	65.99%	68.90%	5	5

Output 18.11.2 *continued*

```
        30      72.9270      25.2129      22.6821   65.43%   68.90%    6    6
        31      50.7784      25.2129      22.6821   50.35%   55.33%    7    6
        32      47.9590      25.2129      22.6821   47.43%   52.71%    7    6
        34      47.9590      25.2857      23.1920   47.28%   51.64%    7    6
        36      45.2516      25.3484      23.1920   43.98%   48.75%    8    7
        38      35.8558      25.3867      23.1920   29.20%   35.32%    8    7
        39      32.3748      25.3867      23.1920   21.58%   28.36%    9    7
         .      32.3748      25.3911      23.4272   21.57%   27.64%    9    8
        40      29.4267      25.3911      23.4272   13.71%   20.39%    9    8
        41      28.9902      25.4132      23.4272   12.34%   19.19%    9    8
        42      27.5972      25.4173      23.4272    7.90%   15.11%    9    8
        43      26.2637      25.4173      23.4272    3.22%   10.80%   10    8
        45      25.4194      25.4194      23.4272    0.00%    7.84%   10    9
         .      25.4194      25.4194      24.3243    0.00%    4.31%   10    9
NOTE: Starting branch and bound.
         Node  Active   Sols         Best         Best      Gap    CPU   Real
                                  Integer        Bound             Time   Time
            0       1     13      24.3243      25.4194    4.31%     10      9
            1       3     14      24.5652      25.4194    3.36%     15     13
            7       7     15      24.5652      25.0268    1.84%     27     23
           10       0     17      24.8509      24.8509    0.00%     39     33
NOTE: The Decomposition algorithm used 80 threads.
NOTE: The Decomposition algorithm time is 33.90 seconds.
NOTE: Optimal.
NOTE: Objective = 24.850855395.
NOTE: The data set WORK.SOLUTION has 47 observations and 4 variables.
```

The solution is a set of arcs that define a union of short directed cycles (matchings). The following call to PROC OPTNETWORK extracts the corresponding cycles from the list of arcs and outputs them to the data table mycas.Cycles. The DATA step assumes that your CAS engine libref is named mycas, but you can substitute any appropriately defined CAS engine libref.

```
data mycas.Solution;
   set Solution;
run;
proc optnetwork
   direction = directed
   links     = mycas.Solution;
   linksVar
      from   = i
      to     = j;
   cycle
      maxCycles = all
      out       = mycas.Cycles;
run;
```

For more information about PROC OPTNETWORK, see *SAS Optimization: The OPTNETWORK Procedure*. Alternatively, you can extract the cycles by using the SOLVE WITH NETWORK statement in PROC OPTMODEL (see Chapter 15, "The Network Solver"). The optimal donor exchanges from the output data

table mycas.Cycles are displayed in Figure 18.10.

Figure 18.10 Optimal Donor Exchanges

cycle=1

order	node
1	0
2	99
3	33
4	29
5	20
6	24
7	97
8	31
9	46
10	0

cycle=2

order	node
1	2
2	18
3	90
4	26
5	84
6	53
7	62
8	2

cycle=3

order	node
1	3
2	56
3	5
4	83
5	45
6	63
7	14
8	64
9	69
10	92
11	3

Figure 18.10 *continued*

cycle=4

order	node
1	6
2	96
3	27
4	93
5	23
6	51
7	87
8	78
9	43
10	41
11	6

cycle=5

order	node
1	21
2	85
3	82
4	73
5	21

cycle=6

order	node
1	37
2	39
3	89
4	77
5	37

cycle=7

order	node
1	38
2	79
3	71
4	38

References

Ahuja, R. K., Magnanti, T. L., and Orlin, J. B. (1993). *Network Flows: Theory, Algorithms, and Applications*. Englewood Cliffs, NJ: Prentice-Hall.

Augerat, P., Belenguer, J. M., Benavent, E., Corberán, A., Naddef, D., and Rinaldi, G. (1995). *Computational Results with a Branch and Cut Code for the Capacitated Vehicle Routing Problem*. Technical Report 949-M, Université Joseph Fourier, Grenoble.

Aykanat, C., Pinar, A., and Çatalyürek, Ü. V. (2004). "Permuting Sparse Rectangular Matrices into Block-Diagonal Form." *SIAM Journal on Scientific Computing* 25:1860–1879.

Barnhart, C., Johnson, E. L., Nemhauser, G. L., Savelsbergh, M. W. P., and Vance, P. H. (1998). "Branch-and-Price: Column Generation for Solving Huge Integer Programs." *Operations Research* 46:316–329.

Caprara, A., Furini, F., and Malaguti, E. (2010). *Exact Algorithms for the Temporal Knapsack Problem*. Technical Report OR-10-7, Department of Electronics, Computer Science, and Systems, University of Bologna.

CNN (2012). "Record Kidney Transplant Chain." CNN Health. Video. Accessed April 2, 2019. https://www.cnn.com/videos/health/2012/02/20/dnt-kidney-transplant-chain.wls.

Dantzig, G. B., and Wolfe, P. (1960). "Decomposition Principle for Linear Programs." *Operations Research* 8:101–111. https://www.jstor.org/stable/167547.

Galati, M. V. (2009). "Decomposition in Integer Linear Programming." Ph.D. diss., Lehigh University.

Gamrath, G. (2010). "Generic Branch-Cut-and-Price." Diploma thesis, Technische Universität Berlin.

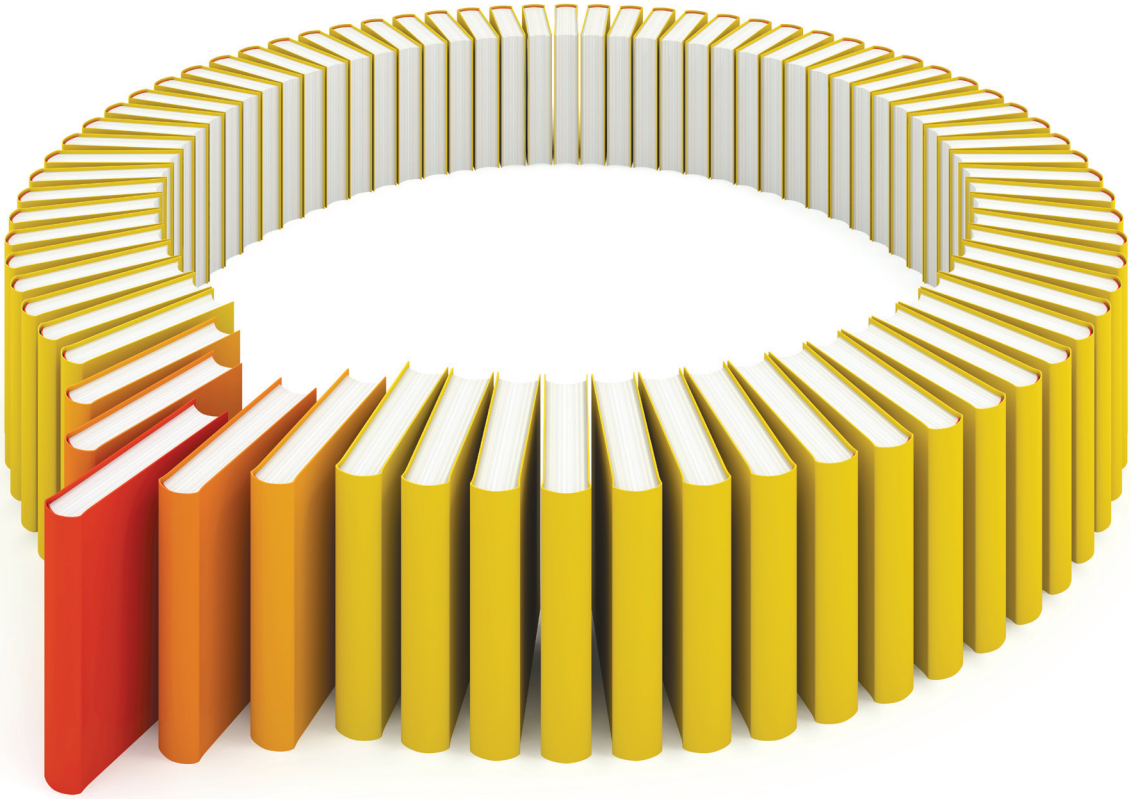
Grcar, J. F. (1990). *Matrix Stretching for Linear Equations*. Technical Report SAND90-8723, Sandia National Laboratories.

Khaniyev, T., Elhedhli, S., and Erenay, F. S. (2018). "Structure Detection in Mixed-Integer Programs." *INFORMS Journal on Computing* 30:570–587.

Koch, T., Achterberg, T., Andersen, E., Bastert, O., Berthold, T., Bixby, R. E., Danna, E., et al. (2011). "MIPLIB 2010: Mixed Integer Programming Library Version 5." *Mathematical Programming Computation* 3:103–163. https://link.springer.com/article/10.1007/s12532-011-0025-9.

Ralphs, T. K., and Galati, M. V. (2006). "Decomposition and Dynamic Cut Generation in Integer Linear Programming." *Mathematical Programming* 106:261–285. http://dx.doi.org/10.1007/S10107-005-0606-3.

Vanderbeck, F., and Savelsbergh, M. W. P. (2006). "A Generic View of Dantzig-Wolfe Decomposition in Mixed Integer Programming." *Operations Research Letters* 34:296–306. http://dx.doi.org/10.1016/j.orl.2005.05.009.



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