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Table of Contents

IBM Stochastic Solutions - Introduction 1
Stochastic Solutions Users Guide 3
Example Problems and Code 18
Stochastic Solutions Reference 47
Bibliography 70

[User's Guide | Download | Bottom of page]

IBM Stochastic Solutions

Introduction

Stochastic programming supports decision making under uncertainty. It is a methodology for bringing uncertain future scenarios into the traditional decision making framework of linear programming. Just as linear programming models the optimal allocation of constrained resources to meet known demands, stochastic programming models the allocation of today's resources to meet tomorrow's unknown demands in such a way that the user can explore the trade offs with respect to expected risks and rewards and make informed decisions.

Users seeking the greater modeling power and flexibility of stochastic programming come up against high hurdles: there is more input data to be managed, the optimization problems are very large, and the solution arrays are larger and more difficult to analyze.

IBM Stochastic Solutions offers new technology to help the user meet the demands of modeling stochastic programs. It has an easy-to-use solver that operates from the command line. It is the first commercial-grade optimization solution to implement the Stochastic Mathematical Programming System (SMPS) input format for multistage stochastic programs. The flexible decomposition solver is robust and fast, and with callable modules, the user has node-by-node access to data and solutions for efficient solution analysis.

The components of IBM Stochastic Solutions are a solver, a suite of callable modules for advanced development, and the User's Guide and Reference containing documentation, problem examples, and sample drivers.

The Stochastic Solution Stand-alone Solver

The stand-alone solver runs from the command line. With multiple switches and command line parameters, the user can solve a stochastic program in Stochastic Mathematical Programming System format with IBM Stochastic Solutions' powerful flexible decomposition solver. The solver can also be deployed to analyze the optimal distribution of the stochastic solution. The Reference Section contains many example problems and applications. Without compiling a single line of code, the user has complete access to all aspects of the most sophisticated modeling environment for stochastic programming!

The Stochastic Solutions Callable Modules

More advanced modeling development is supported by the IBM Stochastic Solutions Callable Modules. These are designed to facilitate the integration of IBM Stochastic Solutions into applications. The independently callable modules are accessed by constructing specialized driver programs. These functions support advanced model generation, control of solver operation through callbacks, and analysis of solution data. Input modules support in-core modeling of stochastic programs, user callbacks monitor solver progress, and data access modules retrieve the solution for use in application processing.

Guide, Reference and Examples

The Guide and Reference is divided into three parts. The User's Guide contains basic information to help users formulate, solve, and analyze stochastic programming problems. The Reference Section contains detailed information about calling sequences, data structures, and messages. The Examples contains example problems and several driver programs.

Readers seeking a fuller introduction to the ideas and techniques of stochastic programming should consult the recently published texts by Birge and Louveaux, and Kall and Wallace .

If you would like to have softcopy of the html user guide on your PC, click here to download the zipped postscript HTML (192 KB)

If you prefer hardcopy documentation, click here to download a postscript (1054KB) or zipped postscript (274KB) version.

Notes:	1. Viewing these postcript files is problematical. An inability to view them satisfactorily does not necessarily mean that they will not print correctly. 2. There are no hypertext links in the postcript files, and so the cross references are undetectable.

[**Top of Page | Previous Page | User's Guide**]

IBM HOME ORDER PRIVACY LEGAL CONTACT IBM

Stochastic Solutions Users Guide

- Overview of Stochastic Solutions
  - Use of the Stochastic Solutions Solver
  - Use of the Stochastic Solutions User Callable Modules
  - Scenarios Data Structure
  - Organization of Storage: the SPL-file
  - Stochastic Models
  - Building Scenario Trees from Simulations
  - User Access to the Stochastic Solution Data Structures
- Stochastic Mathematical Programming System (SMPS) Format
  - Header Line
  - Problem Statement
  - SMPS Format for LPs: Core File Time File
  - Stoch File: Header Line Distributions Linear Transformations Scenarios
- The Flexible Decomposition Solver
- Bottom of Page

Overview of Stochastic Solutions

Stochastic Solutions provides functional support in modeling, solving, and analysing solution data for multiperiod stochastic programs. The modeling phase includes:

- **Core LP.** Specification of a *Core* linear program.
- **Time Stages.** Identification of *Time Stages*.
- **Stochastics.** Definition of the *Stochastic* information for the distribution of the random variables.

The solver phase includes:

- **Model Size.** Identification of the size of the model.
- **Decomposition.** Decomposition of the model into subproblems.
- **Algorithm.** Invocation of the *L-shaped* (Benders) decomposition algorithm.
- **Termination.** Interpretation of the algorithm's termination criteria.

The analysis of solution data is a complex issue -- the number of ways the user can implement the functions of the Stochastic Solution is so great that it is difficult to anticipate every user's requirement. The Solver enables:

- **Activities.** Access to column and row solution activity levels by scenario and stage, and
- **Distribution.** Access to distributions of problem data items (such as the value of the objective).

Complete access to all solution data, including dual information, is enabled through the use of the Callable Modules.

Use of the IBM Stochastic Solutions Solver

Most users will find that the easiest way to use the IBM Stochastic Solution is through the Solver, which is documented in the Solver Reference. The Solver is controlled by command line arguments. By specifying different arguments, different calls to the Solver can perform many functions. Some of the basic functions are invoked as follows.

oslstslv -inputformat=mps -input=<*name*> -modelout=<*modelname*>
: Models a multiperiod stochastic program using the SMPS standard. The dimensions of the multiperiod stochastic program are printed out. The model is stored in a binary file *modelname.spl*.

oslstslv -inputformat=spl -input=<*name*> -sample=100
: Produces a sampled version and examines its dimensions.

oslstslv -inputformat=spl -input=<*name*> -solve=yes
: Solves the problem. Additional flags implement decomposition.

-decompose=yes -cutperiod=3
: Employs the L-shaped decomposition method for a description of the decomposition method, with the tree cut at period 3.

-masteriter=10
: Limits the number of master problem iterations. If the problem is not solved in this number of master iterations, the problem is turned over to the simplex solver.

-subproblems=5
: Limits the number of subproblems (the master problem is one of these). This is a crude method of controlling the subproblem size to achieve more efficient use of processor resources. Generally speaking, the simplex method is faster than decomposition up to a certain problem size. The threshold depends on processor configuration and problem difficulty.

-prtscn=1
: Prints the row and column activities for the given scenario number. This produces no output if the problem has not been solved.

-rowdistn=0
: Prints the distribution of given row activity. The special value of 0 produces the objective distribution. A similar call produces the distribution of a given column.

Additional flags control the destination of output, whether the problem is a maximization or minimization, and so forth. Details are found in the Solver Reference.

The formulation of stochastic programs is a sophisticated undertaking that may require expert advice from application domains, probability and statistics, and the numerical modeling of decision systems. Problem examples are provided that indicate various types of formulations and analyses. These may be useful as templates.

Use of the IBM Stochastic Solutions Callable Modules

The motivating principle of IBM Stochastic Solutions is to free the user from the complex task of managing multistage stochastic data structures common to all stochastic programs. To implement this aim, IBM Stochastic Solutions provides several independent clusters of user callable modules corresponding roughly to initialization and input, tree generation, model formation and data transfer, solution via Benders decomposition, and user-access to data and information. These modules are accessed by writing a driver program. Example drivers are provided. Here we give an overview of the basic structures of a stochastic solution driver.

All information concerning a particular instance of a stochastic program is organized as a structured data type called Stoch_Data. This structure is initialized by a call to subroutine ekks_InitializeApplication, which returns a pointer to the Stoch_Data data type. Every Callable Module uses this pointer to access the data of the stochastic program. Multiple instances of stochastic programs can appear in the same program module, each with their own unique Stoch_Data pointer.

The generic IBM Stochastic Solution driver consists of five subroutine calls:

```
include "ekkstoch.h"
Stoch_Data *stoch_data;
    ekk_Initialize();
ekks_InitializeApplication(&rc,&stoch_data,...);
ekks_CreateCore(&rc,stoch_data,... );
for(s=0;s<max_s;s++)
{
    ekks_AddScenario(&rc,stoch_data,s,...);
}
ekks_BendersLSolve(&rc,stoch_data,osl_dspace,...);
for(s=0;s<max_s;s++)
{
    ekks_GetSolution(&rc,stoch_data,s,soln,...);
    printf( ... ,soln);
}
```

The call to ekks_InitializeApplication initializes the stoch_data pointer to the Stoch_Data object. The calls to ekks_CreateCore (declare core file) and ekks_AddScenario (add a scenario) pass the problem data to the Stoch_Data object. A call to ekks_BendersLSolve declares and solves the stochastic problem with a Benders decomposition method implemented in the IBM Optimization Library subroutines. The subroutine ekks_GetSolution accesses scenario solutions one-by-one after which they may be processed by the user (for example, printed).

Scenarios Data Structure

Scenarios provide the information about the probability distribution and the data needed to define the actual stochastic program in the SMPS standard format. Scenarios are declared one at a time by specifying the node from which it branches, the probability to be attached to the leaf, and the scenario data for the time stages between the branch and the leaf.

Scenario data is defined relative to the core data. For details of this convention, see the documentation of the ekks_AddScenario subroutine.

Organization of Storage: the SPL-file

When stochastic program core and scenario data is passed, the data, consisting of matrix, row and column bounds, and objective function, is sorted into stages and stored in a specially-structured *SPL-file*. Core data is stored first in the file, then the scenario data. A copy of the core data is retained in memory, but all scenario data is left in the SPL-file until needed by an optimization method.

SPL-file storage is managed by IBM Stochastic Solution routines. Users may have access to this information through special purpose data-access routines. The SP-file may be saved (ekks_PutStochasticData), in which case it will contain all information necessary to restore (ekks_GetStochasticData) the stochastic program.

Stochastic Models

The data corresponding to a stochastic program is organized by nodes and arcs of a tree structure and stored in an SPL-file. Many stochastic programs could be defined from the same data--for example, the data defined by one single scenario is itself a linear program complete with objective and bounds.

The data required for the definition of a stochastic program is organized into a structure of type Stoch_Model. A Stoch_Model can be thought of as a selection of a subset of nodes from a Stoch_Data. (They are not the same sort of structure, since the node data for the submodel is obtained by reference to the original Stoch_Data structure.) A stochastic model is created by passing a *list of nodes* to the appropriates IBM Stochastic Solution subroutine ekks_DescribeModel. By default, a Stoch_Data structure is considered to be itself a stochastic model containing all possible nodes.

Building Scenario Trees from Simulations

The IBM Stochastic Solution includes an independent set of routines for the purpose of building a scenario tree out of a sequence of simulations. Each simulation is viewed as an array of *events*, labelled as integers. When a new simulation is added (ekks_AddToTree), its initial sequence is compared against all initial sequences so far received. The longest match found is recorded, and the new simulation is made to branch from the scenario it matched. Weights of unmatched nodes are initialized at one, and weights of the matched nodes are incremented by one. The weights are eventually used to calculate the empirical probability of a node. The result is a scenario tree that describes the empirical distribution of the sequence of simulations. The scenario tree data, together with scenario numbers, branching node, and probability weights can be retrieved (subroutine ekks_GetScenarioFromTree). The example driver exsgbdt illustrates the use of these routines.

User Access to Stochastic Solution Data Structures

The user interfaces, data structures and subroutine declarations, are declared in the header file ekkstoch.h. ekk-stoch This file should be included in every program module that calls IBM Stochastic Solution subroutines.

The data pointed to by the structures Stoch_Data and Stoch_Model is internal and protected from the user. But all stochastic programming data is available to the user via the structures usrCoreData, usrStoch, usrNode, and usrNodeData, as referenced in Data Structures Reference. These must be filled by special subroutine calls: ekks_GetCoreData, ekks_GetScenarioTree and ekks_GetNodeData. The drivers exsdst.c, and exsolv.c contain examples of user data access.

Calls to user access subroutines can have a Stoch_Data or a Stoch_Model pointer in the argument list. In the latter case, the list of nodes returned will be those that appeared in the model's original list, plus the list of appropriately marked virtual nodes. Offsets and probabilities refer to the relevant model.

The node data retrieved by a call to ekks_GetNodeData contains only the stochastic data. It must be combined with the appropriate core data obtained by ekks_GetCoreData. It is important to note is that the data may have been sorted during the input phase. Particular items may have been moved out of their original positions. The usrCoreData structure has pointers to the sort keys used to translate the row and column indices from external (i.e. user) order to internal, and back.

Stochastic Mathematical Programming System (SMPS) Format for Stochastic Linear Programs

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Parts of this article originally appeared in Birge, et al and are reproduced here, with slight updating, by permission of the authors.

This article reprints selections from the paper "A standard input format for multiperiod stochastic linear programs", which introduced a data convention for the automatic input of multiperiod stochastic linear programs based on the MPS standard.

SMPS Header Line.

- columns 1 through 14: indicator code
- columns 15 through 24: name

Most sections contain *data lines*. Data lines are distinguished by a blank in the first column; the first word of a header line must, therefore, begin with a non-blank character. Comment lines are indicated by an asterisk (*) in the first column and may appear anywhere.

Problem Statement

A general form of the multiperiod stochastic linear program is as follows.

$$\begin{aligned} &\text{minimize}_{x1} && \boldsymbol{c}_1{}^T \boldsymbol{x}_1 + E_2\, Q_2(\boldsymbol{x}_1)\,, \\ &\text{subject to:} && \boldsymbol{x}_1 \in \mathbb{R}_{n_1}\,, \\ & && \boldsymbol{l}_1 \le \boldsymbol{x}_1 \le \boldsymbol{u}_1\,, \\ & && \boldsymbol{A}_1\boldsymbol{x}_1 = \boldsymbol{b}\,; \end{aligned}$$

where the functions Q_2, Q_3, **...** , Q_T are defined recursively by:

$$\begin{aligned} Q_2(\boldsymbol{x}_1) = \min_{x2} \quad & \boldsymbol{c}_2{}^T \boldsymbol{x}_2 + E_3\, Q_3(\boldsymbol{x}_1, \boldsymbol{x}_2)\,, \\ \text{subject to:} \quad & \boldsymbol{x}_2 \in \mathbb{R}_{n_2}\,, \\ & \boldsymbol{l}_2 \le \boldsymbol{x}_2 \le \boldsymbol{u}_2\,, \\ & \boldsymbol{A}_{2,1}\boldsymbol{x}_1 + \boldsymbol{A}_{2,2}\boldsymbol{x}_2 = \boldsymbol{b}_2\,, \end{aligned}$$

$$
\begin{aligned}
Q_3(\boldsymbol{x}_1, \boldsymbol{x}_2) = \min_{x3} \quad & \boldsymbol{c}_3^T \boldsymbol{x}_3 + E_4\, Q_4(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3), \\
\text{subject to:} \quad & \boldsymbol{x}_3 \in \mathbb{R}^{n_3}, \\
& \boldsymbol{l}_3 \le \boldsymbol{x}_3 \le \boldsymbol{u}_3, \\
& \boldsymbol{A}_{3,1}\boldsymbol{x}_1 + \boldsymbol{A}_{3,2}\boldsymbol{x}_2 + \boldsymbol{A}_{3,3}\boldsymbol{x}_3 = \boldsymbol{b}_3,
\end{aligned}
$$

and so on, for Q_t, $t = 4, \ldots, T - 1$. In each of the forgoing equations, and in the next (where $t = T$), "E_t" represents the expectation with respect to the random variables in period number t. Finally, Q_T is defined by:

$$
\begin{aligned}
Q_T(\boldsymbol{x}_1, \ldots, x_{T-1}) = \min_{xT} \quad & \boldsymbol{c}_T^T \boldsymbol{x}_T, \\
\text{subject to:} \quad & \boldsymbol{x}_T \in \mathbb{R}^{n_T}, \\
& \boldsymbol{l}_T \le \boldsymbol{x}_T \le \boldsymbol{u}_T, \\
& \boldsymbol{A}_{T,1}\boldsymbol{x}_1 + \boldsymbol{A}_{T,2}\boldsymbol{x}_2 + \ldots + \boldsymbol{A}_{T,T}\boldsymbol{x}_T = \boldsymbol{b}_T.
\end{aligned}
$$

The data defining this problem may be arranged in a LP formulation for a single realization of the random variables:

$$
\begin{aligned}
\text{objective:} \quad & \sum_{j=1}^{T} \boldsymbol{c}_t^T \boldsymbol{x}_t, \\
\text{constraints:} \quad & \boldsymbol{x}_t \in \mathbb{R}^{n_t} && \text{for } t = 1, \ldots, T, \\
& \boldsymbol{l}_t \le \boldsymbol{x}_t \le \boldsymbol{u}_t && \text{for } t = 1, \ldots, T, \\
& \boldsymbol{A}_1\boldsymbol{x}_1 = b_1 \in \mathbb{R}^{m_1}, && \text{and} \\
& \sum_{j=1}^{t} \boldsymbol{A}_{t,j}\boldsymbol{x}_j = b_t \in \mathbb{R}^{m_t}, && \text{for } t = 2, \ldots, T.
\end{aligned}
$$

All entries of the matrices $\boldsymbol{A}_{t,j}$ and vectors: $\boldsymbol{c}_t$, $\boldsymbol{l}_t$, $\boldsymbol{u}_t$, $\boldsymbol{b}_t$ may be random (although in practice all but a few entries will be deterministic). The indices $t = 1, \ldots, T$ signify the periods of the problem; to each period t there corresponds a decision vector $x_t \in \mathbb{R}^{n_t}$. The lower block-triangular constraint system expresses the typical feature of these problems--the decisions of the prior periods constrain the decision of the current period explicitly (since those decisions are known), but the decision of the current period is affected only implicitly by the feasibility and costs of possible future (recourse) decisions.

The proposed format is most easily understood by considering the above multistage LP in stages of gradually increasing levels of detail. First we regard it as a purely deterministic problem and create an input file following the MPS convention, ignoring (non-random) zero entries. This file will identify an objective vector, upper and lower bounds, a right hand side, and a block lower-triangular matrix, all expressed in the usual column-row format; we call this the *core file*.

Next we note the period structure of the problem, that certain decisions are made at certain times. Here it is necessary only to specify which rows and columns from the core file correspond to which periods. It is most simply done by indicating the beginning column and row for each period. This is done in the *time file*. Such a system relies on the proper sequencing of the core file--we require that the list of row names is in order from first period to last period and that the block lower-triangular matrix has been entered in column order: first period columns first, and last period columns last.

Finally there remains the specification of the distributions of the random entries; this takes place in the *stoch file*. The simplest case occurs when all random entries are mutually *independent*. We consider two general types of dependency among the random entries: *blocks* and *scenarios*. A block is a random vector whose realizations are observed in a single, fixed period. A *scenario* is a more general type of stochastic structure which models dependencies across periods.

The organization of the data files is similar to the MPS format. Each data file contains a number of *sections*, some of which are optional. A *header line*, or *header*, marks the beginning of each section and may contain *keywords* to inform the user that the data to follow should be treated in a special way. Each header line is divided into two fields delineated by specific columns.

SMPS Format for Linear Programs

Core File

The *core file* is sketched only briefly since it closely follows the MPS format. The core file consists of sections introduced by header lines. Data lines follow the headers.

MPS Data line for LP

A data line is divided into six fields: three name fields, two numeric fields and one indicator field.

- columns 2 and 3: indicator field
- columns 5-12: name field
- columns 15-22: first data name field
- columns 25-36: first numeric field
- columns 40-47: second data name field
- columns 50-61: second numeric field

A *name* is treated as a character string and may contain any ASCII symbol, except that data name fields must not start with a ($). Numbers with decimal point, or in scientific notation, may appear in numeric fields.

Core file layout in SMPS

1. NAME Required. The second word field is used to identify the problem.
2. ROWS Required. Each data line specifies the names of the objective and rows of the matrix in the first name field, and the type of constraint (E, L, G, N) in the code field. The list of row names must be in order from first period to last, preceded by the objective name(s).
3. COLUMNS Required. Each data line specifies the column names and the nonzero values. This must be done in column order.
4. RHS Required. Starts the RHS section. Data lines specify nonzero entries of the righthand side.
5.

BOUNDS Optional. Data lines specify the column bounds using the codes LO or UP in the code field.

6. RANGES Optional. Refer to the MPS standard.

7. ENDATA Required. End of problem data.

Core file - example

```
1...5.........15........25.............40........50.............
NAME          problem name
* this is a comment line
ROWS
 N  OBJ
 L  ROW1
 E  ROW2
    -etc-
COLUMNS
1...5.........15........25.............40........50.............
    COL1      ROW1      value          ROW2      value
    COL1      ROW3      value          ROW4      value
    -etc-
    RHS
    RHS       ROW1      value          ROW2      value
    -etc-
BOUNDS
 LO BND       COL1      value
    -etc-
RANGES
    -etc-
ENDATA
```

Integer variables may be indicated by using delimiters as described in the MPS/MIP standard. for those users who want to use mixed integer programming techniques.

Time File

The *time file* contains the information needed to specify the dynamic structure of the problem. It indicates which rows and columns are to be identified with which period. The first line identifies it as a time file and gives a name to the problem. The next header line consists of a single word PERIODS in the first name field, and contains the keyword LP in the second name field to identify the problem as a pure LP. The first two name fields of the data lines identify the beginning row and column names for each period with the corresponding period name in the third name field.

Time file - example

```
1...5.........15........25.............40........50.............
TIME          problem name
PERIODS
    COL1      ROW1                     PERIOD1
    COL6      ROW3                     PERIOD2
    COL8      ROW19                    PERIOD3
ENDATA
```

In this example: Columns COL1 through COL5 are PERIOD1 decision variables and COL6 and COL7 are PERIOD2 variables; rows ROW1 and ROW2 are PERIOD1 constraints and ROW3 through ROW18 are PERIOD2 constraints. All remaining rows and columns belong to PERIOD3.

Stoch File

In the *stoch file* the distributions of the random variables are specified. As mentioned, we consider three varieties of distributions: *independent*, *blocks*, and *scenarios*. Each type will be treated in separate sections of this file; each section consists of a header line followed by data lines.

Stoch file - header lines

1. STOCH - informative. Identifies a new problem with a give name in the second word field.
2. INDEP section - specifies the distribution of all independent random entries in separate sections for each type.
3. BLOCKS section - specifies the joint distribution of all dependent random entries in separate sections for each type.
4. SCENARIOS section - specifies the scenarios.
5. ENDATA - informative. End of problem data.

Each distribution specifies the values that a core file entry takes with a certain probability. This value *replaces* the corresponding core file entry.

Distributions

- Independent Discrete Distributions Format
- Uniform Distribution Format
- Normal Distribution Format
- Block Independent Distributions Format

Independent Discrete Distributions

For each discretely distributed entry one must specify the values and corresponding probabilities. The first two name fields identify the entry, and the first two numeric fields are the value field and probability field respectively. The intervening third name field contains the name of the period in which the random variable is realized. (This information is ignored by the input routine, but it is useful to have it made explicit for data consistency checking).

Independent Discrete format

```
1...5.........15........25.............40........50.............
INDEP         DISCRETE
```

```
    COL1      ROW8      6.0            PERIOD2   0.5
    COL1      ROW8      8.0            PERIOD2   0.5
    RHS       ROW8      1.0            PERIOD2   0.1
    RHS       ROW8      2.0            PERIOD2   0.5
    RHS       ROW8      3.0            PERIOD2   0.4
```

In this example the entry COL1/ROW8 takes value 6.0 with probability 0.5 and 8.0 with probability 0.5; and the righthand side of ROW8 takes values (1.0,2.0,3.0) with probabilities (0.1,0.5,0.4) respectively. Of course the probabilities associated with an entry must total one.

Uniform Distribution

The endpoints of the interval are the only relevant parameters for uniformly distributed entries. These are entered into the first two numeric fields; the third name field is blank.

Uniform Distribution Format

```
1...5.........15........25.............40........50.............
INDEP         UNIFORM
    COL1      ROW8      8.0            PERIOD2   9.0
```

In this example the random entry COL1/ROW8 is uniformly distributed over the interval [8.0,9.0].

Normal Distribution

The normal distribution is specified by mean and variance in the first two numeric fields.

Normal Distribution Format

```
1...5.........15........25.............40........50.............
INDEP         NORMAL
    COL1      ROW8      0.0            PERIOD2   1.0
```

In this example the random variable is normal with mean 0.0 and variance 1.0.

Block Independent Distributions

The "values" of a block are actually vectors of values of the entries that make up the block, and to each value of a block there corresponds a probability. We need two sorts of data lines to describe a block. The first line, distinguished by a BL in the code field, gives the name of the block, the name of the period in which the block is realized, and the probability that the block assumes a given vector value; the following lines identify which entries of the block assume which value.

Independent Block format

```
1...5.........15........25.............40........50.............
BLOCKS        DISCRETE
 BL BLOCK1    PERIOD2   0.5
    COL1      ROW6      83.0
    COL2      ROW8      1.2
 BL BLOCK1    PERIOD2   0.2
    COL1      ROW6      83.0
```

```
    COL2       ROW8       1.3
 BL BLOCK1     PERIOD2    0.3
    COL1       ROW6       84.0
    COL2       ROW8       1.2
ENDATA
```

In this example the block, called BLOCK1, is the vector made up of the entries COL1/ROW6 and COL2/ROW8. It takes values (83.0,1.2) with probability 0.5, (83.0,1.3) with probability 0.2, and (84.0,1.2) with probability 0.3.

Linear Transformations

These are blocks whose distribution is computed as a linear transformation of another random vector with independent components, i.e., The vector v is the block whose distribution is desired; the vector u has independently distributed components of standard type, e.g., normal. We first identify the block as in the subroutine case, then the (marginal) distribution of each (independent) component of the random vector followed immediately by the corresponding column of the matrix H .

Linear Transformation format

```
1...5.........15........25.............40........50.............
BLOCKS         LINTR
 BL V_BLOCK    PERIOD2
    COL1       ROW8
    COL3       ROW6
 RV U1         NORMAL     0.0                      1.0
    COL1       ROW8       11.0
    COL3       ROW6       21.0
 RV U2         UNIFORM    -1.0                     1.0
    COL1       ROW8       12.0
    COL3       ROW6       22.0
 RV U3         CONSTANT
    COL3       ROW6       24.0
```

This example illustrates the file structure. In this case

Note that the "names" U1, U2 and U3 are irrelevant and may be left blank.

Scenarios, An Example - event tree, and the Scenarios Format

To describe *scenarios* one needs a data structure that expresses inter-period dependencies. This is best developed as a description of the distribution of a *process* vector just as one may describe a stochastic process in probability theory. We consider the random entries of the objective, bounds, and matrix as states of a process vector. Given the corresponding (finite dimensional) joint distributions of this process, Kolmogorov's construction yields a probability measure, termed the *process distribution*, on the space of trajectories. Thus, in general, we have the alternatives of describing the distribution of the stochastic process in joint or conditional state distribution form, or as a process distribution over trajectories. In the case under consideration, all this may be given a much simpler, more graphic, characterization.

To describe the process paths in the discrete state case, note that process can assume only finitely many values. A path of the process up to a given time stage may be followed by a finite collection of possible values of the process in the next time period. We think of these as *nodes* in the next period. Following Lane and Hutchinson and Raiffa, we construct an *event tree* representation of the trajectories: Represent the (unique) value of the process in the first period by a single node connected by *oriented arcs* from that node to nodes representing the values of the process in period 2. These are the *descendant* nodes of the first period node in the terminology of Birge. Each node of period 2 is connected to its descendant nodes at period 3 by individual arcs oriented in the direction of the period 3 nodes. This construction is continued by connecting each *ancestor* with its descendant nodes in the next period. Each node of this tree has a single entering arc and multiple departing arcs representing the possible next period events.

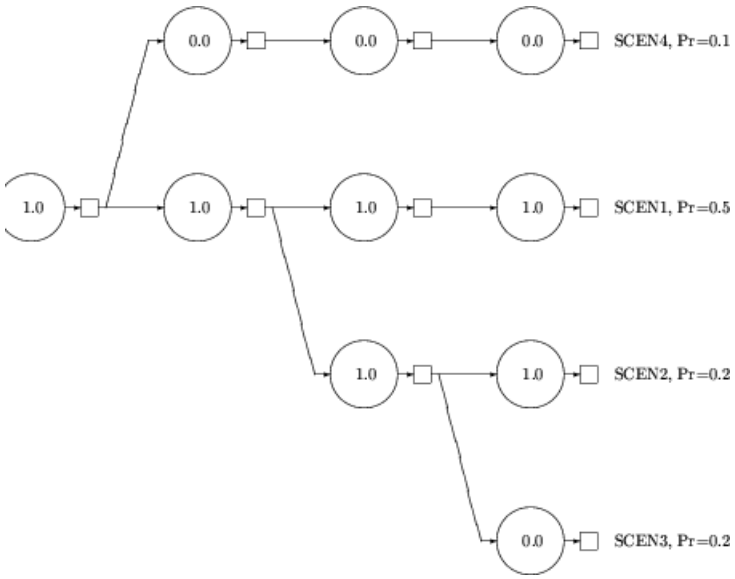
A single trajectory of the process thus corresponds to a *path* from the period 1 node to a single period T node composed of arcs oriented in the direction of increasing time and, moreover, corresponds uniquely to a single node in the last period T. There are only finitely many paths linking nodes in period 1 to nodes in period T and to specify the distribution on the paths one needs only to attach a definite probability to each path. Hence specifying the process distribution in terms of path probabilities can be effected in this context by assigning probabilities to period T nodes of the hyperrefevent treeevent tree, see Figure fig_scenexample.

The topology of this event tree represents the information about the process. To each arc we attach the probability that the terminal node occurs given the initial node has occurred--that is, the conditional probability of the process distribution over a period conditional on the history over all previous periods. These *arc probabilities* can be computed from the path probabilities by summing the probabilities of the paths visiting the terminal node and then dividing by the sum of the probabilities of the paths visiting the initial node.

Conversely, if to each arc in the tree we know the conditional probability that its terminal node occurs given that its initial node has occurred, then the probability of any given path is simply the product of the arc probabilities along the path.

A decision at a given node is made only on the basis of information collected up to and including that node. The uncertainty faced by the decision maker is represented by the collection of paths that branch from this node. Thus in Figure, the decisions occur at the nodes and the scenarios branch after the node.

Figure 1.1: Scenarios example - event tree



In a language more specific to our application, a "path" in the tree analogy is a single "scenario". The nodes visited by the path correspond to certain values assumed by certain entries of the matrices in the core file. Thus a scenario is completely specified by a list of column/row names and values, and a probability value. Once a single given scenario is described, then other scenarios that branch from it may be described by indicating in which period the branch has occurred, and then listing the subsequent column/row names and values. It is best to work through the example of Figure.

There are two types of data lines. The first, signified by SC in the code field, gives the name of the scenario in the first name field and its probability in the first numeric field; and then gives the name of the scenario from which the branch occurred and the name of the period in which the branch occurred--i.e., the first period in which the two scenarios *differ*--in the second name field and third name field, respectively. A scenario that originates in period one is indicated by ROOT in the name field. The next data lines give the column/row values assumed by the scenario.

Scenarios Format

```
1...5.........15........25.............40........50.............
SCENARIOS     DISCRETE
 SC SCEN1     ROOT      0.5            PERIOD1
    COL1      ROW2      1.0
    COL2      ROW3      1.0
    COL3      ROW4      1.0
    COL4      ROW5      1.0
 SC SCEN2     SCEN1     0.2            PERIOD3
    COL3      ROW4      1.0
    COL4      ROW5      1.0
 SC SCEN3     SCEN2     0.2            PERIOD4
    COL4      ROW5      0.0
 SC SCEN4     SCEN1     0.1            PERIOD2
    COL2      ROW3      0.0
    COL3      ROW4      0.0
    COL4      ROW5      0.0
ENDATA
```

This is a description of the distribution of four entries: COL1/ROW2, COL2/ROW3, COL3/ROW4, COL4/ROW5, which for convenience we denote here as d1, d2, d3, and d4, respectively. Note that in PERIOD4 there are two nodes for the "state" d4 equals 0.0 and two for d4 equals 1.0, and similarly in PERIOD3 two nodes for d3 equals 1.0. This is because a node is distinguished by the information that one has collected concerning the path up to and including that node. Thus in PERIOD3 the two nodes are distinguished because in scenario SCEN1 one *knows* that the final state is d4 equals 1.0, whereas in SCEN2 the outcome of d4 is in doubt.

The Flexible Decomposition Solver

The decomposition method implemented in the IBM Stochastic Solution is the L-shaped method of van Slyke and Wets. The actual implementation has been documented in King.

The solution procedure consists of an L-shaped, or Benders, decomposition phase, and if needed, a Simplex method phase. The decomposition often does not terminate in a reasonable number of iterations, for this reason it is often useful to follow Benders with the Simplex method.

In the decomposition phase, the problem is decomposed into master and subproblems at a user-specified stage, the Cut_Stage. All nodes belonging to stages strictly less than the Cut_Stage are put into the master problem. (For this reason, the Cut_Stage should not be less than 2.) The nodes belonging to the Cut_Stage become "root" nodes of subtrees extending to the leaf nodes. These subtrees form the nodelists for the subproblems of the Benders decomposition method.

If there are more subtrees than the maximum number of subproblems allowed, Maximum_Subproblems, then the subtrees are divided among the subproblems as evenly as possible. The first subproblem is joined to the master problem, thus the master consists of the nodes less than Cut_Stage together with the subtrees collected into the first subproblem. This "augmented master" tends to produce better proposals; for example, the master nodes might be unbounded without the influence of some downstream nodes.

Benders cuts are generated for each remaining subproblem. Changing the number Maximum_Subproblems can have a big effect on the performance of Benders decomposition. For example, 100 subproblems will generate 100 different cuts, whereas 1 subproblem will generate 1 cut from the same proposal. The difference is the level of aggregation: the 1 cut from 1 subproblem is in fact the aggregation of the 100 cuts from the 100 subproblems. Generally speaking, aggregated cuts contain less information than the collection of disaggregated cuts, but disaggregated cuts make the master problem grow much faster.

Major iterations of Benders decomposition are performed until either a relative optimality gap of size less than Optimality_Gap is attained, or the maximum number of iterations Benders_Major_Iterations is performed. A major iteration consists of:

1. Solving the master with all optimality and feasibility cuts so far generated, and posting the proposed master solution and master objective value, if one exists.
2. Solving all subproblems with the master proposal and generating subproblem optimality or feasibility cuts. If all subproblems generate optimality cuts, then the subproblem optimal values are summed to form the subproblem objective value.
3.

Testing the relative gap between the sum of the subproblem objective values (the true value at the given master proposal) and the master objective value (a lower bound) for convergence to within Optimality_Gap.

At the termination of the Benders decomposition phase, if optimality was not attained, then the Simplex phase begins.

Experience suggests that the solution progress is most affected by the maximum number of major interations, the cut stage, and the maximum number of subproblems. The setting of the Cut_Stage controls the size of the subproblems and the size of the master. Large subproblems and masters take a long time to solve. A large number of small subproblems generating disaggregated cuts for the master does not seem to present much difficulty.

Those parameters not yet described affect to the solution procedures applied within the Benders decomposition. These procedures are IBM Optimization Library subroutines, and the parameters refer to the calling sequences documented in the OSL manual. A method or type setting of zero means that the procedure will not be called. For example, the parameter EKKCRSH_method refers to the parameter passed to EKKCRSH, which is called at the initial solution of any subproblem, master or subproblem. If this parameter is set to zero, then EKKCRSH would not be called (not recommended!). The actual instantiation is if (icrsh) ekkcrsh(iret,osl_dspace,icrsh);, and similarly for the other procedures.

[**Top of Page | Previous (Roadmap) | Next (Reference Section) | Table of Contents**]

Example Problems and Code

- Sample problems
  KandW3 PROD_MIX LandS HYDRO CAP
- Guide to the Driver Source Codes - Illustrating:
  - Tree Construction Subroutines
  - SMPS Input
  - Direct Solution by exsolv
  - Post Solution Processing
- Sample Driver Coding
  exsmps.c exsgbds.c exsolv.c exsdst.c exsgbdt.c
- Bottom of Page

A collection of sample problems

We describe a collection of 5 small multistage stochastic programming test problems that are available with the IBM Stochastic Solutions. Both the formulation of, and test data for, each problem is described. The SMPS input files for the problems are available in the Stochastic Solutions product directory .\oslstoch\samples\sampc\

- Problem KandW3 Statement Formulation Data Solution
- Problem PROD_MIX Statement Formulation Data Solution
- Problem LandS Statement Formulation Data Solution
- Problem HYDRO Statement Formulation Data Solution
- Problem CAP Statement Formulation Data Solution

Problem KandW3

Statement Formulation Data Solution

This problem has been modified from the production planning example in the text book by Kall and Wallace.

Problem statement

A refinery can blend *N* raw materials into *M* different products. At present, the management is trying to decide how much of each of the raw materials to purchase and stock, so that they can be blended to satisfy the demand for the products in future *T* time periods. The demand has to be completely satisfied, and in case of raw material shortage the products can be outsourced at a higher cost. There is an inventory constraint on how much raw material can be stocked in total.

Formulation

Indices:

i	for raw materials (i = 1,...,N).
j	for products (j = 1,...,M).
t	for time periods (t = 1,...,T).

Variables:

x_{it}	Quantity of raw material i purchased for use in period t .
y_{jt}	Quantity of product j outsourced in period t .

Parameters:

c_i	Present cost of raw material i .
a_{ij}	Raw material i required per unit of product j .
f_{jt}	Cost of outsourcing product j in time period t .
b	Inventory capacity.
$\tilde{d}^k_{jt}$	Random demand of product j in time period t .

KandW3 :

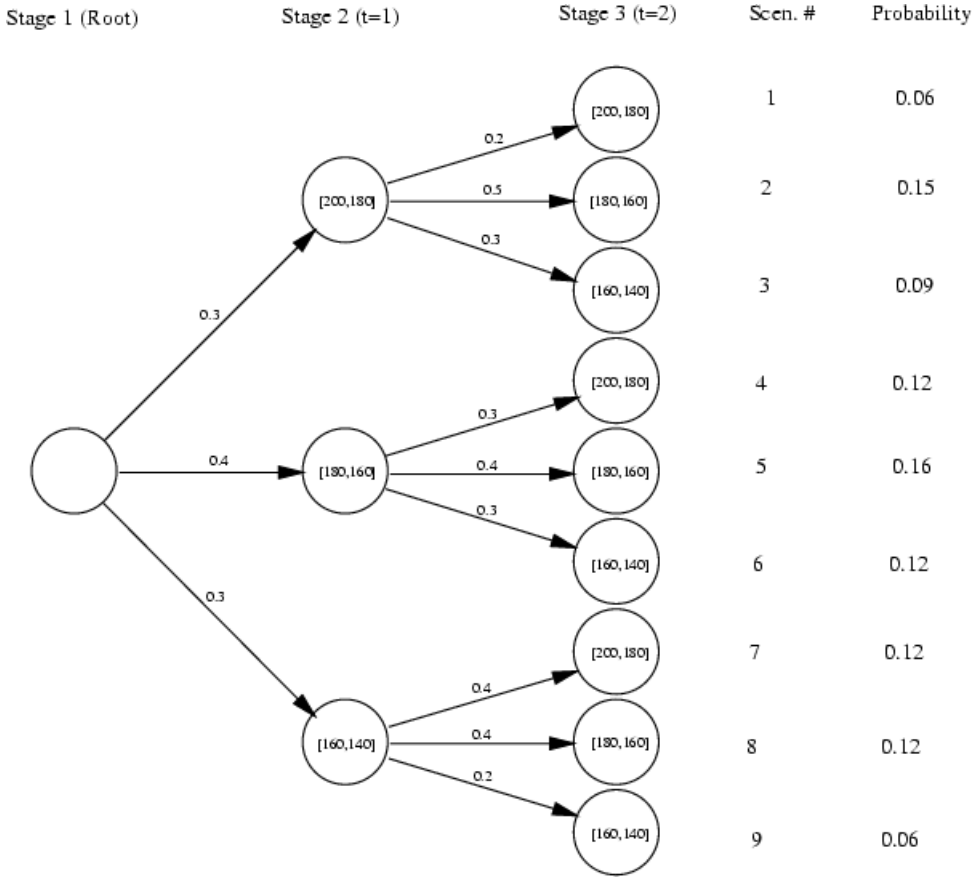
$$
\begin{array}{ll}
\min & \sum_{i,t} c_i x_{it} + \mathrm{E}[\sum_{j,t} f_{jt} y_{jt}] \\
\text{s.t.} & \sum_{i,t} x_{it} \leq b \\
& \sum_i a_{ij} x_{it} + y_{jt} \geq \tilde{d}_{jt} \qquad \forall j,t \\
& x_{it}, y_{jt} \geq 0 \qquad \forall i,j,t
\end{array}
$$

Test problem data

$$
\begin{array}{lcl}
N & = & 2 \\
M & = & 2 \\
T & = & 2 \\
c & = & [2.0, 3.0] \\
a & = & \begin{bmatrix} 2.0 & 6.0 \\ 3.0 & 3.4 \end{bmatrix} \\
f & = & \begin{bmatrix} 7.0 & 10.0 \\ 12.0 & 15.0 \end{bmatrix} \\
b & = & 50
\end{array}
$$

The scenario tree for the demand realizations is shown in Scenario tree for problem KandW3.

Figure 3.1: Scenario tree for problem KandW3



Solution

$$
\begin{array}{rcl}
\text{Objective value} & = & 2613.0 \\
x_{11}^* & = & 0.0 \\
x_{21}^* & = & 20.0 \\
x_{12}^* & = & 0.0 \\
x_{22}^* & = & 30.0
\end{array}
$$

Problem PROD_MIX

Statement Formulation Data Solution

This problem is taken from Examples from the Literature.

Problem statement

The problem consists of determining the product mix for a furniture shop with two workstations: carpentry and finishing. The availability of labor in man-hours at the two stations is limited. There are four product classes, each consuming a certain number of man-hours at the two stations. Each product earns a certain profit and the shop has the option to purchase labor from outside. The objective is to maximize the profit.

Formulation

Indices:

i	for product class (i = 1,...4).
j	for workstation (j=1,2).

Variables:

x_i	Amount of product class j produced.
v_j	Man-hours purchased from outside for workstation j .

Parameters:

c_i	Profit per unit of product class i .
q_j	Cost per man-hour for labor for workstation j .
$\tilde{t}_{ji}$	Random man-hours at work station j required per unit of product class i .
$\tilde{h}_j$	Random man-hours available at workstation j .

PROD_MIX:

$$
\begin{array}{lll}
\max & \sum_i c_i x_i - \mathrm{E}[\sum_j q_j v_j] & \\
\text{s.t.} & \sum_i \tilde{t}_{ji} x_i \le \tilde{h}_j + v_j & \forall j \\
& x_i, v_j \ge 0 & \forall i, j
\end{array}
$$

Note that the problem is in the form of a minimization problem in the data files.

Test problem data

$$
\begin{aligned}
c &= [12.0, 20.0, 18.0, 40.0] \\
q &= [5.0, 10.0] \\
\tilde{h} &= [\mathcal{N}(6000, 100), \mathcal{N}(4000, 50)] \\
\tilde{t} &= \begin{bmatrix} \mathcal{U}(3.5, 4.5) & \mathcal{U}(8.0, 10.0) & \mathcal{U}(6.0, 8.0) & \mathcal{U}(9.0, 11.0) \\ \mathcal{U}(0.8, 1.2) & \mathcal{U}(0.8, 1.2) & \mathcal{U}(2.5, 3.5) & \mathcal{U}(36.0, 44.0) \end{bmatrix}
\end{aligned}
$$

Above $\mathcal{N}(a,b)$ denotes a normal distribution with mean *a* and standard deviation *b* , and denotes a uniform distribution in the range [*a*,*b*] .

Solution

The solution of the above problem for a sample of 300 scenarios is as follows:

$$
\begin{aligned}
\text{Objective value} &= -17730.3 \\
x_1^* &= 1381.86 \\
x_2^* &= 0.0 \\
x_3^* &= 0.0 \\
x_4^* &= 55.92
\end{aligned}
$$

Note that the objective value is negative since the problem was supplied as a minimization problem.

Problem LandS

Statement Formulation Data Solution

The following problem is taken from Louveaux and Smeers.

Problem statement

The following two-stage problem consists of determining the optimal capacity investment in various types of power plants so as to meet next period demands for electricity. Four power plants are considered and they can operate in three different modes. The next period demand for each of the three modes are to be met. There is a budget constraint and also a constraint on the minimum total capacity.

Formulation

Indices:

i	for power plant type (i = 1,...,4).
j	for operating mode (j = 1,...,3).

Variables:

x_i	Installed capacity for power plant of type i .
y_{ij}	Operating level of power plant i in mode j .

Parameters:

c_i	Cost per unit of capacity installed for plant type i .
f_{ij}	Cost per unit operating level of power plant i in mode j .
m	The minimum total capacity to be installed.
b	Budget available for capacity installment.
$\tilde{d}_j$	Random demand for power in mode j .

LandS:

$$
\begin{aligned}
\min \quad & \sum_i c_i x_i + E \sum_{i,j} f_{ij} y_{ij} \\
\text{s.t.} \quad & \sum_i x_i \geq m \\
& \sum_i c_i x_i \leq b \\
& \sum_j y_{ij} \leq x_i \quad \forall i \\
& \sum_i y_{ij} \geq \tilde{d}_j \quad \forall j \\
& x_i, y_{ij} \geq 0 \quad \forall i, j
\end{aligned}
$$

Test problem data

$$
\begin{aligned}
c &= [10.0, 7.0, 16.0, 6.0] \\
f &= \begin{bmatrix} 40.0 & 24.0 & 4.0 \\ 45.0 & 27.0 & 4.5 \\ 32.0 & 19.2 & 3.2 \\ 55.0 & 33.0 & 5.5 \end{bmatrix} \\
m &= 12.0 \\
b &= 120.0 \\
\tilde{d} &= [\xi, 3.0, 2.0]
\end{aligned}
$$

where ξ is a random variable taking the values 3.0,5.0 or 7.0 with probability 0.3, 0.4 and 0.3 respectively.

Solution

$$
\begin{aligned}
\text{Objective value} &= 381.85 \\
x_1^* &= 2.67 \\
x_2^* &= 4.00 \\
x_3^* &= 3.33 \\
x_4^* &= 2.00
\end{aligned}
$$

Problem HYDRO

Statement Formulation Data Solution

The following problem is taken from Pereira and Pinto.

Problem statement

The objective of the problem is to determine a generation schedule for a hydrothermal generating system such that expected operating costs are minimized. These costs are composed of fuel costs for the thermal units and penalties for failure to meet power demand. The hydrothermal system consists of four hydroelectric reservoirs and a thermal generation unit. Constraints to the problem are the mass balance equations for the water supply across the reservoirs and across the stages; the demand constraints and the capacity of the operating units. The schedule has to be developed for three time periods.

Formulation

Indices:

i	for the reservoirs in the system (i = 1,...4).
i'	an alias for i .
t	for the time periods (t = 1,...3).

Variable:

GT_t	Thermal generation in time period t .
D_t	Unmet power demand in time period t .
V_{it}	Water volume at reservoir i at the end of period t .
Q_{it}	Water volume passed through reservoir i turbines in period t .
S_{it}	Water volume spilled from reservoir i in period t .

Parameters:

M_i	The set of reservoirs immediately upstream of reservoir i .
c_t	Cost of thermal generation in period t .
f_t	Penalty for unmet demand in period t .
L_t	Power demand in period t .
ρ_i	Power generated per unit volume turbined at reservoir i .
V_{i0}	Initial volume in reservoir i .
$\overline{V}_i$	Capacity of reservoir i .
$\overline{Q}_i$	Turbine capacity at reservoir i .
$\tilde{A}_{it}$	Random water inflow to reservoir i in period t .

HYDRO:

Test problem data

The reservoir configuration is shown in Reservoir configuration for problem HYDRO.

The scenario tree for the water inflow vectors is given in Scenario tree for problem HYDRO.

Figure 3.2: Reservoir configuration for problem HYDRO

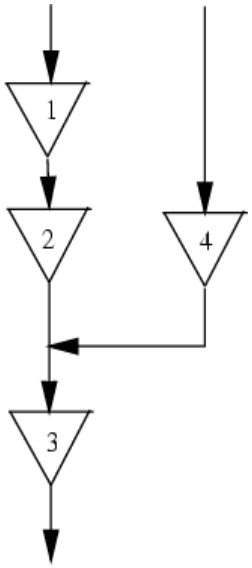
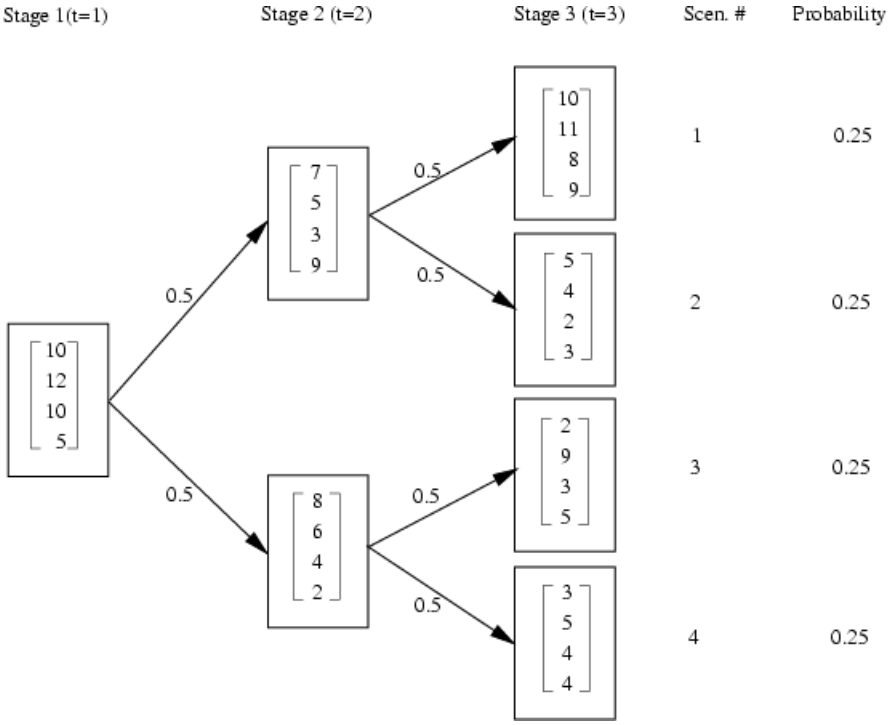


Figure 3.3: Scenario tree for problem HYDRO



Solution

The first stage solutions are reported below. Note that these solutions do not conform to those reported in the original paper Pereira and Pinto.

Objective value $= 265.3$

$GT_1^* = 28.0$

$D_1^* = 0.0$

$V_1^* = [0.0, 112.0, 15.0, 0.0]$

$Q_1^* = [60.0, 0.0, 100.0, 55.0]$

$S_1^* = [0.0, 0.0, 0.0, 0.0]$

Problem CAP

Statement Formulation Data Solution

Problem statement

The following problem consists of designing the capacities of the plants in a chemical processing network in order to maximize expected future profits. The network contains three processes and two chemical products, and a planning horizon of two periods is considered. The profit is the difference between the sales revenue of the chemicals and the capacity installation and operating costs for the plants.

formulation

Indices:

i	for processes (i = 1,...,3).
j	for chemicals (j=1,2).
t	for time periods (t=1,2).
τ	an alias for t .

Variables:

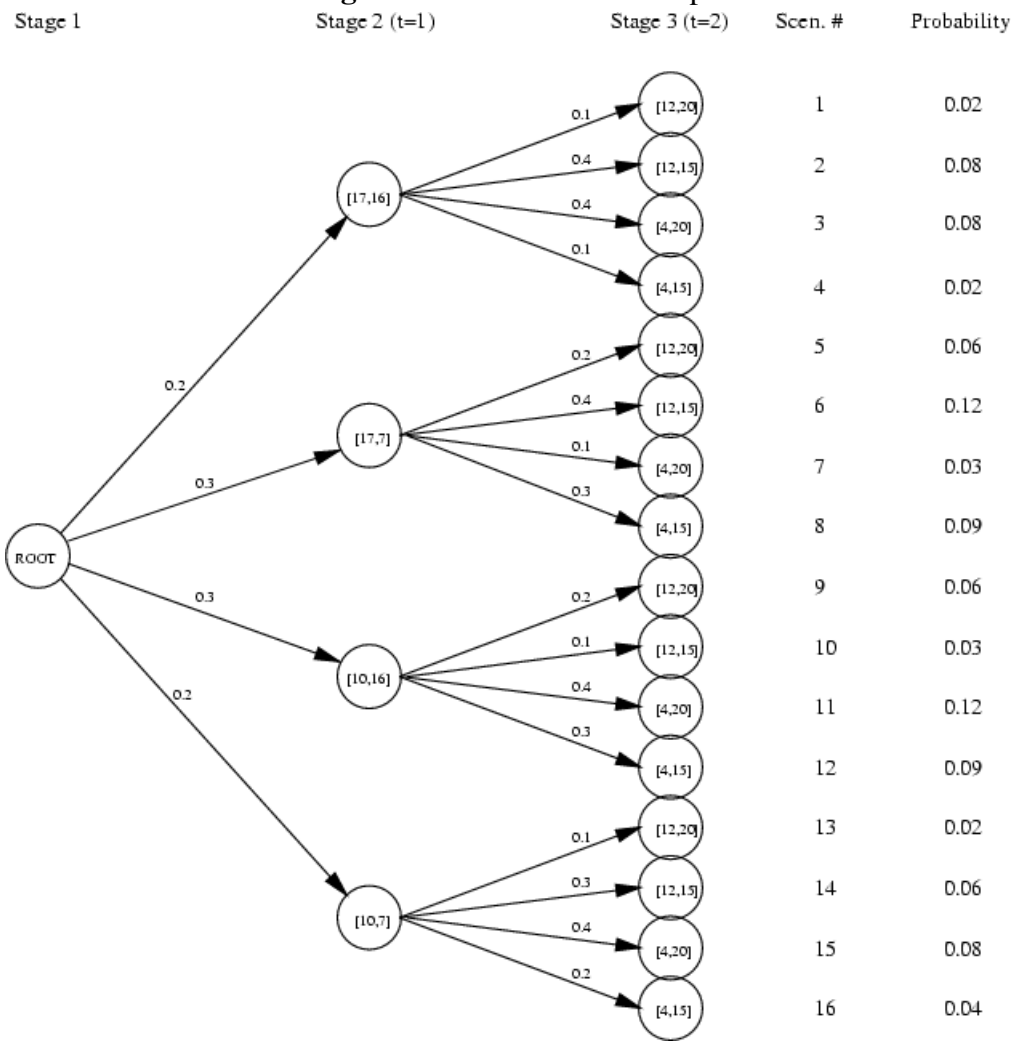
x_{i0}	Design capacity of process i .
x_{it}	Capacity installed for process i in time period t .
w_{it}	Operating level of process i in period t .

Parameters:

c_{i0}	Cost per unit of design capacity for process i .
c_{it}	Cost per unit of capacity installed in process i in period t .
q_{it}	Operating cost of process i in period t .
r_{jt}	Sales price for chemical j in period t .
a_{ij}	Production of chemical j per unit operating level of process i .
$\tilde{d}^L_{jt}, \tilde{d}^U_{jt}$	Demand upper and lower bounds for chemical j in period t .

CAP:

Figure 3.4: Scenario tree for problem CAP



Test problem data

The demand lower bounds are assumed to be zero. The scenario tree for the demand upper bounds is given in Scenario tree for problem CAP.

Solution

Objective value $= -272.83$

$x_0 = [7.083, 0.0, 0.0]$

Note that the objective value is negative since the problem was recast into the minimization form.

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Guide to the Driver Source Codes

The driver programs in the following sections illustrate the use of some of the options for input, solution and data access available in the IBM Stochastic Solution user callable modules. The C-language coding for the examples may be found in the ./examples directory. This code is reproduced in the Sample Driver Coding section.

All the input examples create an SPL-file <file>.spl, where the string <file> is input from the command line (except sgbd, which creates a file called sgbd.spl). The solver examples restore the stochastic program from <file>.spl, then proceed to solve the problem. For example, to solve the problem app0110 found in the ./data directory in SMPS format, execute the commands:

```
> exsmps data/app0110
> exsolv data/app0110
```

Driver illustrating Tree Construction Subroutines

Driver exsgbdt is an example based on the aircraft allocation example of exsgbds. In this example, the distribution is sampled and the tree built up using ekks_AddToTree and ekks_GetScenarioFromTree subroutines. This is only a one-period example, nevertheless, multiperiod examples can easily be constructed on the basis of this code. The exsgbdt call produces the SP file sgbd_smpl.spl.

Driver Illustrating SMPS Input

The driver exsmps reads the SMPS input format. To use the driver, invoke it as follows:

```
> exsmps data/app0110
```

The application name app0110 is one of the applications found in the ./data directory. The smps call produces the SP file ../data/app0110.spl.

Direct Solution by exsolv

Driver exsolv restores the stochastic program from the SPL-file <file>.spl and solves it using decomposition. For instance,

```
> exsolv data/app0110
```

solves the problem generated by the invocation of exsmps in the example given above.

Post Solution Processing

Driver exsdst restores the stochastic program from the SP-file <file>.spl and solves the problem using decomposition. The optimal value along each scenario is then computed by using the user-access routines ekks_GetCoreData, ekks_GetScenarioTree and ekks_GetNodeData, and the results are displayed as a distribution. For instance,

```
> exsdst data/app0110
```

solves the problem generated by the invocation of smps in the example given above, and produces the distribution of objective values.

Sample Driver Coding

exsmps.c

Read SMPS formatted files and save SP file.

```
/*
 *
 * exsmps.c:  Main driver for reading SMPS files.
 *
 *          Usage:   exsmps <file>
 *
 *          Reads CORE, TIME, and STOCH files from
 *          <file>.core, <file>.time, and <file>.stoch.
 *          Writes the SP-file as <file>.spl.
 *
 *          Implements INDEPENDENT DISCRETE, as well as SCENARIOS
 *          versions of the standard input format.
 *
 *          Demonstrates coding for taking SAMPLES from the independent
 *          distribution.
 *
 *         (compile w/ /DOSLMSDLL on INTEL platforms.
 */

#include <stdlib.h>
#include <string.h>
#include "ekkstoch.h"

#define SAMPLE 0                        /* (0,1) means (don't, do) sample */

#define MXSCN 400

void main( long argc, char *argv[] ) {

    Stoch_Data *s_data=NULL;                    /* Stoch_Data pointer */
    Tree *tree=NULL;
    long type;                                  /* distribution type */
    long replace;              ;                /* set by ekks_ReadMPS() */
    long rc=0;                                  /* return code */


/* filenames from argument list */
    char *kspc,*corefile,*timefile,*stocfile,*splfile;
    long nsize,nchar;
    long len;

/* get application name from command line */
    if ( argc != 2 ) {
      printf(" Usage:  smps <file>  , where "
             "{file.core,file.time,file.stoch} is a valid "
             "SMPS triple\n");
```

```
      return;
    }
    nchar = (long) strlen( argv[1] );

/*
 *  make file names:
 *      "app".core
 *      "app".time
 *      "app".stoch
 */
    nsize = 4*(nchar+1)+(5+5+6+3+5);
    kspc = (char *) malloc(sizeof(char)*nsize);
    if ( kspc==NULL ) {
      printf(" ERROR: smps is unable to store input file-names\n");
      return;
    }
    corefile = kspc; kspc += (nchar+1)+5;
     strcpy( corefile,argv[1] ); strcat( corefile,".core" );
    timefile = kspc; kspc += (nchar+1)+5;
     strcpy( timefile,argv[1] ); strcat( timefile,".time" );
    stocfile = kspc; kspc += (nchar+1)+6;
     strcpy( stocfile,argv[1] ); strcat( stocfile,".stoch" );
    splfile  = kspc; kspc += (nchar+1)+3;
     strcpy( splfile,argv[1] ); strcat( splfile,".spl" );

/* Initialize OSL environments */
    rc = ekks_InitializeOSL();           if(rc>0) return;

/* initialize Stoch_Data with maximum MXSCN scenarios */
    ekks_InitializeApplication( &rc,&s_data,MXSCN );
        if ( rc>1 ) return;

/* Process MPS file + Process STOCH file + Process TIME file  */
    ekks_ReadMPS( &rc,s_data,&type,&replace, corefile, timefile, stocfile);
    if ( rc>1 ) return;

/* Process discrete distribution (if that's what it is) */
    if ( type==INDEP_DISCRETE || type==BLOCK_DISCRETE ){

        Independent *s_indp = NULL;
        long *indx;

/* ...get pointer to independent distribution structure */
        ekks_GetPointerToDistribution( &rc,s_data,&s_indp );
                if ( rc>1 ) return;

/* ...malloc indexing arrays */
        nsize = (s_indp->nrvar) * sizeof(long);
        indx = (long *) malloc( nsize );        if (!indx) return;

/* ...loop for sampling independent distributions: */
        if (1==SAMPLE) {
                long jj,irand,ev_indx;
                long ns;
 ;               double *dprobs;
                double dp,ds;
                Discrete *pdist;
                long nindp = s_indp->nrvar;
```

```
                ds = 1.0e0;
                ds /= MXSCN;
                for (ns=0;ns < MXSCN;ns++) {

/*   ...for each indep rv, process random number to get index */
                   for (jj=0;jj<nindp;jj++) {
                           ev_indx = 0;
                           pdist = s_indp->rvar[jj]->dist;
                           dprobs = pdist->dprb;
                           dp = dprobs[ev_indx];
                           irand = rand();
                   ;        while ( irand > dp*RAND_MAX )
                                   dp += dprobs[++ev_indx];
                           indx[jj] = ev_indx;
                   }

/*   ...add event */
                   ekks_AddEvent( &rc,s_data,&tree,indx,ds,replace );
                        if ( rc>1 ) return;

                }

        } /* end if(SAMPLE) */

/* ...if NOT SAMPLE then we add all events: */
        if (0==SAMPLE) {
           long jj,ii,iii;
           long ns;
           double dp;
           long *incr;
           Discrete *pdist;

/* ... malloc increments array */
           incr = (long *) malloc( nsize );     if (!incr) return;

/* ...initialize the event increment to 1 and event index to 0 */
           for (jj=0;jj<s_indp->nrvar;jj++) incr[jj] = 1;
           memset(indx,0,nsize);

/* ...compute probability of first event */
           dp = 1.0;
           for (jj=0;jj<s_indp->nrvar;jj++) {
                pdist = s_indp->rvar[jj]->dist;
                dp *= pdist->dprb[ indx[jj] ];
           }

/* ...add first event */
                   ekks_AddEvent( &rc,s_data,&tree,indx,dp,replace );
                if ( rc>1 ) return;

/* ...main loop
        The logic of this loop is as follows:

        - If nevent[jj] divides the scenario index ii,
            reverse the increment direction incr[jj],
            and increase the random variable index jj by 1.
        - Increment the jj'th random variable by incr[jj]
            and call ekks_AddScenario with the new event.
```

```
        This works because the total number of events is
        the product of the number for each independent RV.
*/

           ns = 1;
           for (ii=0;ii<s_indp->nrvar;ii++) {
                pdist = s_indp->rvar[ii]->dist;
                ns *= pdist->nevt;
           }

           for (ii=1;ii<ns;ii++) {
                iii=ii; jj=0;
                pdist = s_indp->rvar[jj]->dist;
                while ( !(iii%pdist->nevt) ) {
                        iii /= pdist->nevt;
                        incr[jj] = -incr[jj];
                        jj++;
                        pdist = s_indp->rvar[jj]->dist;
                }

/* ...  adjust probability */
                dp /= pdist->dprb[ indx[jj] ];
                indx[jj] += incr[jj];
                dp *= pdist->dprb[ indx[jj] ];

/* ...  add event */
                   ekks_AddEvent( &rc,s_data,&tree,indx,dp,replace );
       ;                                          if ( rc>1 ) return;

           } /* end for */
        } /* end if(!SAMPLE) */

    } /* end if ( type==INDEP_DISCRETE || type==BLOCK_DISCRETE ) */

/* Save SP-file */
    ekks_PutStochasticData( &rc,s_data,splfile );

/* Free Stoch_Data structures */
    ekks_FreeStructure(s_data);
}
```

exsgbds.c

Generate aircraft allocation problem using ekks_AddScenario.

```
/*
 *
 * exsgbds.c:  Generic driver using ekks_AddScenario.
 *
 *         Implements G.B. Dantzig's Aircraft Allocation model,
 *         in: G.B. Dantzig, Linear Programming and Extensions
 *         (Princeton U. Press, 1963) pp. 572-597.
 *
 *         See also: A.J. King, "Stochastic programming problems:
 *         examples from the literature",
 *          in: Yu. Ermoliev and R.J-B Wets, eds, Numerical Techniques for
 *         Stochastic Optimization (Springer-Verlag, 1988) pp. 543-567.
```

```
 *          (compile w/  /DOSLMSDLL on INTEL platforms.
 */

#include  <stdlib.h>
#include "ekkstoch.h"

#define INF 1.0e31

void main( long argc, char *argv[] ) {

    Stoch_Data *s_data;                     /* Stoch_Data pointer */

/* Model dimensions */
    long ncol=27, nrow=9, nels=44;

/* Sparse matrix data...organized by row */
    long mrow[]={ 1, 1, 1, 1, 1,
            2, 2, 2, 2,
            3, 3, 3,
            4, 4, 4, 4, 4,
            5, 5, 5, 5,
            6, 6, 6, 6, 6, 6,
            7, 7, 7, 7, 7,
        ;    8, 8, 8, 8, 8, 8,
            9, 9, 9, 9, 9, 9 };
    long mcol[]={ 1, 2, 3, 4, 5,
            6, 7, 8, 9,
            10, 11, 12,
            13, 14, 15, 16, 17,
            1,         13, 18, 19,
            2, 6, 10, 14, 20, 21,
            3, 7,      15, 22, 23,
            4, 8, 11, 16, 24, 25,
            5, 9, 12, 17, 26, 27 };
    double dels[] = { 1.0, 1.0, 1.0, 1.0, 1.0,
                1.0, 1.0, 1.0, 1.0,
                1.0, 1.0, 1.0,
                1.0, 1.0, 1.0, 1.0, 1.0,
                16.0,               9.0, -1.0, 1.0,
                15.0, 10.0,  5.0, 11.0, -1.0, 1.0,
                28.0, 14.0,       22.0, -1.0, 1.0,
                23.0, 15.0,  7.0, 17.0, -1.0, 1.0,
                81.0, 57.0, 29.0, 55.0, -1.0, 1.0 };

/* Objective */
    double dobj[]={ 18.0, 21.0, 18.0, 16.0, 10.0, 15.0, 16.0, 14.0, 9.0,
              10.0,  9.0,  6.0, 17.0, 16.0, 17.0, 15.0, 10.0, 0.0,
              13.0,  0.0, 13.0,  0.0,  7.0,  0.0,  7.0,  0.0, 1.0 };

/* Column bounds */
    double dclo[]={ 0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,
              0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,
              0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0 };
    double dcup[]={ INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,
              INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,
              INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF };

/* Row bounds */
```

```
    double drlo[]={ -INF, -INF, -INF, -INF,  0.0, 0.0, 0.0, 0.0, 0.0 };
    double drup[]={ 10.0, 19.0, 25.0, 15.0,  0.0, 0.0, 0.0, 0.0, 0.0 };

/* Stages */
    long nstg=2;
    long n_first_stg_rows=4;
    long n_first_stg_cols=17;
    long rstg[]={ 1,1,1,1,2,2,2,2,2 };
    long cstg[]={ 1,1,1,1,1,1,1,1,1,
            1,1,1,1,1,1,1,1,2,
            2,2,2,2,2,2,2,2,2 };

/* Stochastic data */
    long nindp=5;
    long nsamp[]={ 5, 2, 5, 5, 3 };
    double demand[]={ 200, 220, 250, 270, 300,
                50, 150,
                140, 160, 180, 200, 220,
                10, 50, 80, 100, 340,
                580, 600, 620 };
    double dprobs[]={ 0.2, 0.05, 0.35, 0.2, 0.2,
                0.3, 0.7,
                0.1, 0.2, 0.4, 0.2, 0.1,
                0.2, 0.2, 0.3, 0.2, 0.1,
                0.1, 0.8, 0.1 };

/* local variables */
    long rc,ns=1,ii,iii,jj,*indx,*incr;
    double dd,dp=1.0;

/* Initialize OSL environments */
   rc = ekks_InitializeOSL();
     if (rc > 0) return;

/* compute number of scenarios */
    for (ii=0;ii<nindp;ii++) ns *= nsamp[ii];
/* initialize Stoch_Data with ns scenarios */
    ekks_InitializeApplication( &rc,&s_data,ns );
    if ( rc>1 ) return;

/* Create Core */
    ekks_CreateCore( &rc,s_data,nstg,rstg,cstg,nrow,ncol,nels,
          dobj,drlo,drup,dclo,dcup,mrow,mcol,dels,0 );

/* Generate Scenarios */

/* ...zero everything */
    memset( dobj,0,ncol*sizeof(double) );
    memset( drlo,0,nrow*sizeof(double) );
    memset( drup,0,nrow*sizeof(double) );
    memset( dclo,0,ncol*sizeof(double) );
    memset( dcup,0,ncol*sizeof(double) );
    nels = 0;

/* ...initialization -- indx points to first sample of each rv */
    indx = (long *) malloc( (1+nindp)*sizeof(long) );
    memset( indx,0,(1+nindp)*sizeof(long));
    for (jj=0;jj<nindp;jj++) {
```

```
     indx[jj+1] += indx[jj] + nsamp[jj];
     dp *= dprobs[ indx[jj] ];
     drlo[ n_first_stg_rows + jj ] = demand[ indx[jj] ];
     drup[ n_first_stg_rows + jj ] = demand[ indx[jj] ];
    }

/* ...add first sample */
    ekks_AddScenario( &rc,s_data,1,0,2,dp,1,
          nrow,ncol,nels,dobj,drlo,drup,dclo,dcup,
          mrow,mcol,dels,ADD_TO_CORE_VALUES );

/* ...initialize the sample space increment for each rv to 1 */
    incr = (long *) malloc( nindp*sizeof(long) );
    for (jj=0;jj<nindp;jj++) incr[jj] = 1;

/* ...main loop
     The logic of this loop is as follows:
       While the sample size nsamp[jj] divides the scenario index ii,
         reverse the increment direction incr[jj],
          and increase the random variable index jj by 1.
       Increment the jj'th random variable by incr[jj]
         and call ekks_AddScenario with the new sample.
*/

    for (ii=1;ii<ns;ii++) {
     iii=ii; jj=0;
     while ( !(iii%nsamp[jj]) ) {
          iii /= nsamp[jj];
          incr[jj] = -incr[jj];
          jj++;
     }
     dd = dprobs[ indx[jj] ];
     indx[jj] += incr[jj];
     dp = dp* dprobs[ indx[jj] ]/dd;
     drlo[ n_first_stg_rows + jj ] = demand[ indx[jj] ];
     drup[ n_first_stg_rows + jj ] = demand[ indx[jj] ];
     ekks_AddScenario( &rc,s_data,ii+1,0,2,dp,1,
               nrow,ncol,nels,dobj,drlo,drup,dclo,dcup,
               mrow,mcol,dels,ADD_TO_CORE_VALUES );
    }

/* Save SP-file as "sgbd.spl" */
    ekks_PutStochasticData( &rc,s_data,"sgbd.spl" );

/* Free Stoch_Data structures */
    ekks_FreeStructure(s_data);
}
```

exsolv.c

Read an SP file and solve using decomposition.

```
/*
 * exsolv.c:  Main driver for reading SP-files and solving.
 *
 *         Reads problem from file .spl and solves using
```

```
 *         exsolv().
 *         (compile with  /DOSLMSDLL on INTEL platforms.)
 */

#include
#include
#include
#include "ekkstoch.h"

#define MXSCN 750              /* maximum scenarios */

#define TARG_OPT_GAP  1.0e-8   /* default target optimality gap */

#define abs(a) (a>0?a:-(a))

void main( long argc, char *argv[] ) {

    Stoch_Data *s_data=NULL;            /* Stoch_Data pointer */
    Stoch_Model *s_model=NULL;          /* Stoch_Model pointer */
    usrCoreData *u_core=NULL;           /* usrCoreData pointer */
    double *solution;                   /* space for solution */
    long *osl_indx;                     /* space for osl indices */
    long rc, nf, ii, nblks, nmod=1;     /* local variables */
    long Stage, Scenario;               /* Stage#, Scenario# */
    long colbeg, colindex;              /* Column start, column index */

    /* filenames */
    char *splfile,*outfile;
    char myfile[80];
    long nchar,nsize;

    /* get application name from command line */
    if ( argc != 2 ) {
         printf(" Usage:  solv   , where "
             "{file.spl} is a valid SPL file.\n");
         return;
    }
    nchar = (long) strlen( argv[1] );
    nsize = (nchar+1)+4;
    splfile = (char *) malloc(sizeof(char)*nsize);
    if ( splfile==NULL ) {
         printf(" ERROR: solv is unable to store input file-name\n");
         return;
    }
    outfile = (char *) malloc(sizeof(char)*nsize);
    if ( outfile==NULL ) {
         printf(" ERROR: solv is unable to store output file-name\n");
         return;
    }
    strcpy( splfile,argv[1] );
    strcat( splfile,".spl" );
    sprintf(myfile,"%s",splfile);

    strcpy( outfile,argv[1] );
    strcat( outfile,".out" );

/* initialize OSL environment */
    rc = ekks_InitializeOSL();  if (rc>0) return;
```

```
/* initialize Stoch_Data with maximum MXSCN scenarios */
    ekks_InitializeApplication( &rc,&s_data,MXSCN );
     if ( rc>1 ) return;

/* Read SP-file */
    sprintf(splfile,"%s",myfile);
    ekks_GetStochasticData( &rc,s_data,splfile );
     if ( rc>1 ) return;

/* Declare stochastic model (full model) */
    ekks_DescribeModel( &rc,s_data,0,0,&s_model,&nblks,1 );
     if ( rc>1 ) return;

/* Solve -- using ekks_BendersLSolve */
    {
        long subproblems=10,iterations=100;
        long ipcut=2, inwmt=0, icrsh=3, ilpdc=0, iscal=0, iprsl=0,
                iprsltype=0, iprslunit=0, isalg=1;
        long large_bounds=0;
        long status;
        double optmaxmin=1.0, optgap=TARG_OPT_GAP;  /*  optmaxmin= 1.0:
minimize
                                                        optmaxmin=-1.0:
maximize */

        /* Solve */

        long bndrrtcod;
        ekks_BendersLSolve( &bndrrtcod, s_model, ipcut,
            subproblems, iterations, optmaxmin,
            inwmt, icrsh, ilpdc,
            iscal,
            iprsl, iprsltype, iprslunit,
            isalg, large_bounds,
            &status,&optgap );
        if ((rc = bndrrtcod) > 1) return;

    }

/* Get core data */
    ekks_GetCoreData(&rc, s_data, &u_core );
    if ( rc>1 ) return;

/* Get stage/scenario solution */
    Scenario = 3;
    Stage = 2;
/* Malloc space for solution and index arrays */
    solution = (double *) malloc( u_core->ncol*sizeof(double) );
    osl_indx = (long *) malloc( u_core->ncol*sizeof(long) );
    colbeg = u_core->colstart[Stage-1]-1;
    nf = u_core->colstart[Stage] - u_core->colstart[Stage-1];

/* Get the solution */
    ekks_GetSolution( &rc,s_model,Scenario,0,solution,osl_indx);
    if ( rc>1 ) return;

/* Print scenario/stage solution */
```

```
    printf("\n\nScenario %d has %d columns in stage %d\n\n",Scenario, nf,
Stage);
    for (ii=0;iisortin2exc[ii+colbeg]-1;
     if ( abs(solution[colindex]) < 1.0e-10 ) solution[colindex] = 0.0;
     printf(" Column[%d] = %g\n",osl_indx[colindex], solution[colindex]);
    }

/* Free data structures */
    ekks_FreeStructure( s_model ); ekks_FreeStructure( s_data );
        return;
}
```

exsdst.c

Solve and compute distribution of optimal values.

```
/*
 *
 * exsdst.c:  Present distribution of optimal values.
 *
 *         Usage:  exsdst <file>
 *
 *         Reads problem from file <file>.spl and solves using
 *         ekks_BenderLsolve().  Then, as an example of user coding,
computes
 *         the distribution of the optimal value.
 *         (compile w/ /DOSLMSDLL on INTEL platforms.
 */

#include <stdio.h>
#include <math.h>
#include <string.h>
#include "ekkstoch.h"

#define MXSCN 750               /* maximum scenarios */

#define TARG_OPT_GAP  1.0e-8   /* default target optimality gap */

void main( long argc, char *argv[] ) {

    Stoch_Data *s_data=NULL;             /* Stoch_Data pointer */
    Stoch_Model *s_model=NULL;           /* Stoch_Model pointer */
    usrCoreData *u_core=NULL;            /* usrCoreData pointer */
    double *solution=NULL;               /* space for solution */
    long rc, rtcod=0, nf, ii, nblks, nmod=1;        /* local variables */

     /* filenames */
     char *splfile;
     char myfile[80];
     long nsize,nchar;
     long len;

     /* get application name from command line */
     if ( argc != 2 ) {
          printf(" Usage:  exsdst <file>  , where "
              "{file.spl} is a valid SPL file.\n");
          return;
```

```
     }
     nchar = (long) strlen( argv[1] );
     nsize = (nchar+1)+3;
     splfile = (char *) malloc(sizeof(char)*nsize);
     if ( splfile==NULL ) {
          printf(" ERROR: exsdst is unable to store input file-name\n");
          return;
     }
         strcpy( splfile,argv[1] );
     strcat( splfile,".spl" );
     sprintf(myfile,"%s",splfile);


/*  Initialize OSL environments */
    rc = ekks_InitializeOSL();  if (rc > 0) return;

/* initialize Stoch_Data with maximum MXSCN scenarios */
    ekks_InitializeApplication( &rc,&s_data,MXSCN );
     if ( rc>1 ) return;

/* Read SP-file */
    sprintf(splfile,"%s",myfile);
    ekks_GetStochasticData( &rc,s_data,splfile );
     if ( rc>1 ) return;

/* Declare stochastic model (full model) */
    ekks_DescribeModel( &rc,s_data,0,0,&s_model,&nblks,1 );
     if ( rc>1 ) return;

/* Solve -- using ekks_BenderLSolve */
    {
        long subproblems=10,iterations=1;
        long ipcut=2, inwmt=0, icrsh=3, ilpdc=0, iscal=0, iprsl=0,
                iprsltype=0, iprslunit=0, isalg=1;
        long large_bounds=0;
        long status;
        double optmaxmin=1.0, optgap=TARG_OPT_GAP;
                /* optmaxmin=  1.0: minimize
                            = -1.0: maximize */


        /* Solve */

        long bndrrtcod;
        ekks_BenderLSolve( &bndrrtcod, s_model, ipcut,
            subproblems, iterations, optmaxmin,
            inwmt, icrsh, ilpdc,
            iscal,
            iprsl, iprsltype, iprslunit,
            isalg, large_bounds,
            &status,&optgap );
        if ((rc = bndrrtcod) > 1) return;

    }

/*
 * Example of User computation using scenario tree and OSL
 *
```

```
 */

     {
          usrStoch *stree = NULL;
          usrNodeData *ndata = NULL;
          usrCoreData *cdata = NULL;
          usrNode *pnode = NULL;
          double *node_obj = NULL;

          /* locals */
          long in, il, ibas, jj;
          double nodvalue, scenvalue, mean=0.0, variance=0.0;
          long ii, is, it;
          double *dnobj, *dcobj, *dsoln, dprob;

          /* get core data */
          ekks_GetCoreData( &rc,s_model,&cdata );   if ( rc>1 ) return;

          /* get stochdata information */
          ekks_GetScenarioTree( &rc, s_model, &stree ); if ( rc>1 ) return;

          /* malloc node objective value array */
          node_obj = (double *) malloc ( stree->nnode*sizeof(double));
          memset(node_obj,0,stree->nnode*sizeof(double));

          /* get OSL pointers to solution array */
          dsoln = (double *) malloc ( stree->node->ncol  * sizeof(double));
          if (dsoln == NULL) {
                     printf("\n Not enough memory available");
                         return;
                 }

          ekks_GetPointerToSolution(&rc, s_model, &nmod, &dsoln);
          if (rc > 1) return;

/*
 * Loop over nodes and compute objective value
 * once for each node.
 */
          for (ii=0;ii<stree->nnode;ii++) {
               pnode = stree->node + ii;

               /* get core objective */
               it = pnode->stag;
               dcobj = cdata->dobj + cdata->colstart[it-1]-1;

               /* node offset in OSL model */
               ibas = pnode->cbas;

               for(jj=0;jj<pnode->ncol;jj++){
                    node_obj[ii] += dsoln[ibas+jj] * dcobj[jj];
               }
               if ( ii > 0 ) {
                  /* get node objective */
                  ekks_GetNodeData( &rc, s_model, ii, &ndata );
                  dnobj = ndata->dobj;
```

```
                if(dnobj!=NULL)
                        for(jj=0;jj<pnode->ncol;jj++){
                                node_obj[ii] += dsoln[ibas+jj] * dnobj[jj];
                }
           }
          }


/*
 * For each leaf node,
 *      go up the tree adding in node_obj value along the way.
 */

          printf(" \n \t Distribution of Optimal Values \n \n");

          for(ii=0;ii<stree->nleaf;ii++) {

               scenvalue = 0.0;

               in = stree->leaf[ii];          /* name of leaf node */

               pnode = stree->node + in-1;     /* pointer to leaf info */
               is = pnode->scen;          /* leaf scenario */
               dprob = pnode->prob;          /* leaf probability */

               while (in>0) {

                    scenvalue += node_obj[in-1];

                    in = pnode->par;     /* parent pos'n in list */
                    if (in>0) pnode = stree->node + in - 1;
               }

               printf(" \t Scenario %d value %f probability %f \n",
                   is,scenvalue,dprob);

               mean += dprob*scenvalue;
               variance += dprob*scenvalue*scenvalue;

          }

          variance -= mean*mean;
          if (variance < 0.0) variance=0.0;

          printf(" \t \t Mean Value: \t \t %f \n",mean);
          printf(" \t \t Standard Deviation: \t %f \n",sqrt(variance));

    }

/* Free data structures */
    ekks_FreeStructure( s_model ); ekks_FreeStructure( s_data );

}
```

exsgbdt.c

Assemble tree using ekks_*Tree() subroutines.

```
/*
 *
 * exsgbdt.c:  Generic driver using ekks_*Tree() subroutines.
 *
 *         Input distribution is sampled and processed by
 *         ekks_*Tree() subroutines.
 *
 *         Implements G.B. Dantzig's Aircraft Allocation model,
 *         in: G.B. Dantzig, Linear Programming and Extensions
 *         (Princeton U. Press, 1963) pp. 572-597.
 *
 *         See also: A.J. King, "Stochastic programming problems:
 *         examples from the literature",
 *          in: Yu. Ermoliev and R.J-B Wets, eds, Numerical Techniques for
 *         Stochastic Optimization (Springer-Verlag, 1988) pp. 543-567.
 *         (compile w/ /DOSLMSDLL on INTEL platforms.
 */

#include <stdlib.h>
#include "ekkstoch.h"

#define INF 1.0e31

#define N_SAMPLES  300      /* number of samples to be generated */

void main( long argc, char *argv[] ) {

    Stoch_Data *s_data;                     /* Stoch_Data pointer */

/* Model dimensions */
    long ncol=27, nrow=9, nels=44;

/* Sparse matrix data...organized by row */
    long mrow[]={ 1, 1, 1, 1, 1,
            2, 2, 2, 2,
            3, 3, 3,
            4, 4, 4, 4, 4,
            5, 5, 5, 5,
            6, 6, 6, 6, 6, 6,
            7, 7, 7, 7, 7,
            8, 8, 8, 8, 8, 8,
            9, 9, 9, 9, 9, 9 };
    long mcol[]={ 1, 2, 3, 4, 5,
            6, 7, 8, 9,
            10, 11, 12,
            13, 14, 15, 16, 17,
            1,         13, 18, 19,
            2, 6, 10, 14, 20, 21,
            3, 7,      15, 22, 23,
            4, 8, 11, 16, 24, 25,
            5, 9, 12, 17, 26, 27 };
    double dels[] = { 1.0, 1.0, 1.0, 1.0, 1.0,
                1.0, 1.0, 1.0, 1.0,
                1.0, 1.0, 1.0,
                1.0, 1.0, 1.0, 1.0, 1.0,
```

```
                16.0,               9.0, -1.0, 1.0,
                15.0, 10.0,  5.0, 11.0, -1.0, 1.0,
                28.0, 14.0,       22.0, -1.0, 1.0,
                23.0, 15.0,  7.0, 17.0, -1.0, 1.0,
                81.0, 57.0, 29.0, 55.0, -1.0, 1.0 };

/* Objective */
    double dobj[]={ 18.0, 21.0, 18.0, 16.0, 10.0, 15.0, 16.0, 14.0, 9.0,
              10.0,  9.0,  6.0, 17.0, 16.0, 17.0, 15.0, 10.0, 0.0,
              13.0,  0.0, 13.0,  0.0,  7.0,  0.0,  7.0,  0.0, 1.0 };
        double dqdg[]={ 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
              0.0,  0.0,  0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
              13.0,  0.0, 13.0,  0.0,  7.0,  0.0,  7.0,  0.0, 1.0 };


/* Column bounds */
    double dclo[]={ 0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,
              0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,
              0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0,  0.0 };
    double dcup[]={ INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,
              INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,
              INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF,  INF };

/* Row bounds */
    double drlo[]={ -INF, -INF, -INF, -INF,  0.0, 0.0, 0.0, 0.0, 0.0 };
    double drup[]={ 10.0, 19.0, 25.0, 15.0,  0.0, 0.0, 0.0, 0.0, 0.0 };

/* Stages */
    long nstg=2;
    long n_first_stg_rows=4;
    long n_first_stg_cols=17;
    long rstg[]={ 1,1,1,1,2,2,2,2,2 };
    long cstg[]={ 1,1,1,1,1,1,1,1,1,
            1,1,1,1,1,1,1,1,2,
            2,2,2,2,2,2,2,2,2 };

/* Stochastic data */
    long nindp=5;
    long nsamp[]={ 5, 2, 5, 5, 3 };
    double demand[]={ 200, 220, 250, 270, 300,
                50, 150,
                140, 160, 180, 200, 220,
                10, 50, 80, 100, 340,
                580, 600, 620 };
    double dprobs[]={ 0.2, 0.05, 0.35, 0.2, 0.2,
                0.3, 0.7,
                0.1, 0.2, 0.4, 0.2, 0.1,
                0.2, 0.2, 0.3, 0.2, 0.1,
                0.1, 0.8, 0.1 };

/* Tree structure */
    Tree *tree=NULL;

/* local variables */
    long rc,ns=1,ii,iii,jj,*indx,*incr;
    double dd,dp=1.0,dwgt;
    long irand,indx_beg,ev_indx;
    long nscen,ianc,istg;
```

```
    long *label;
    long evoffset;



/*  Initialize OSL environments */
    rc = ekks_InitializeOSL();
    if(rc > 0) return;

/* initialize Stoch_Data with ns scenarios */
    ekks_InitializeApplication( &rc,&s_data,N_SAMPLES );
        if ( rc>1 ) return;

    ekks_ProblemType( &rc,s_data,quadratic);
        if ( rc>1 ) return;

/* Create Core */
    ekks_CreateCore( &rc,s_data,nstg,rstg,cstg,nrow,ncol,nels,
          dobj,drlo,drup,dclo,dcup,mrow,mcol,dels,dqdg );


/* ...zero everything */
    memset( dobj,0,ncol*sizeof(double) );
    memset( drlo,0,nrow*sizeof(double) );
    memset( drup,0,nrow*sizeof(double) );
    memset( dclo,0,ncol*sizeof(double) );
    memset( dcup,0,ncol*sizeof(double) );
    nels = 0;

/* ...malloc event indexing array */
    indx = (long *) malloc( (1+nindp)*sizeof(long) );
    memset( indx,0,(1+nindp)*sizeof(long) );

/* ...malloc label array */
    label = (long *) malloc( (nstg-1)*sizeof(long) );

/* Generate Scenarios from sampling */

    for (ns=0;ns < N_SAMPLES;ns++) {

/*   ...for each indep rv, process random number to get index */
       indx_beg = 0;
       for (jj=0;jj<nindp;jj++) {
                ev_indx = 0;
                irand = rand();
                dd = (double)irand/(double)RAND_MAX;
                dp = dprobs[indx_beg+ev_indx];
                while ( irand > dp*RAND_MAX )
                        dp += dprobs[++ev_indx + indx_beg];
                indx[jj] = ev_indx;
                indx_beg += nsamp[jj];
       }

/*   ...process indep events into a unique "event label"
       (there should be one such label for each stage in the simulation
       -- this example has only one stage ) */
```

```
        label[0]= indx[0];
        for (jj=1;jj<nindp;jj++)
                label[0] = label[0]*nsamp[jj] + indx[jj];

        dp = 1.0e0;
        dp /= N_SAMPLES;

/*   ...initialize tree if necessary, or add event to tree */
        if (!tree)
                ekks_InitializeTree( &rc,&tree,label,nstg-1,N_SAMPLES,dp );
        else
                ekks_AddToTree( &rc,tree,label,nstg-1,dp);
        if (rc>0) return;

/*   ...get scenario branching information from tree */
        ekks_GetScenarioFromTree( &rc,tree,ns,&ianc,&istg,&dwgt,

&nscen,&label );
        if (rc>0) return;

        if ( istg == 1 )        /* always true in this example */
                ianc = 0;

        istg++;                 /* always need to do this */

/*   ...assign values to right-hand sides based on index */
        evoffset=0;
        for (jj=0;jj<nindp;jj++) {
                drlo[ n_first_stg_rows + jj ] = demand[ indx[jj]+evoffset ];
                drup[ n_first_stg_rows + jj ] = demand[ indx[jj]+evoffset ];
                evoffset += nsamp[jj];
        }

/* ...add sample */
        ekks_AddScenario( &rc,s_data,nscen,ianc,istg,dwgt,1,
                nrow,ncol,nels,dobj,drlo,drup,dclo,dcup,
                mrow,mcol,dels,ADD_TO_CORE_VALUES );
        if (rc>1) return;
    }


/* Save SP-file as "sgbd_smpl.spl" */
    ekks_PutStochasticData( &rc,s_data,"sgbd_smpl.spl" );

/* Free Stoch_Data structures */
    ekks_FreeStructure(s_data);
}
```

[**Top of Page | Previous (Reference Section) | Next (Bibliography) | Roadmap**]

IBM Stochastic Solutions Reference

- Stochastic Solutions Solver
- Data Structures

usrCoreDatausrStochusrNodeusrNodeData
- User Callable Modules
- Messages
- History and Acknowledgements
- Bottom of Page

Stochastic Solutions Solver

```
Usage: oslstslv ["?"] [-keyword=value] [...] [@keyword_file]

keyword_file: Name of file containing "-keyword=value" strings.
Each "-keyword=value" string in this file must be on a separate line.

Example : oslstslv -maxmin=max -presolve=no @optionf.001 -input=test01
                   -inputformat=spl
The file "optionf.001" may contain additional options such as:


-input=app0110
-inputformat=mps
-scale=no
-crash=yes
-masteriter=20

================================================================================

Valid keywords are:

  maxmin=min|max          - default: min
  inputformat=mps|spl     - default: none - a format type must be specified
  input=filename          - default: none - a file name must be specified
  output=listing_file     - default: standard output
  solve=yes|no            - default: no
  alg=primal|dual|osl     - default: primal
  presolve=yes|no         - default: yes
  presolvetype=0|1|2|3    - default: 3
  scale=yes|no            - default: no
  crash=yes|no            - default: yes
  decompose=yes|no        - default: no
  samples=value           - default: 0
  masteriter=value        - default: 1
  cutperiod=value         - default: 2
  subproblems=value       - default: 10
  warnlevel=value         - default: 100
  largebounds=yes|no      - default: no
  modelout=filename       - default: none
```

```
  print=distn|stage       - default: distn
  stage=value             - default: 1
  scenario=value          - default: 1
  roworcol=row|col        - default: col
------------------------------------------------------------------------------

  maxmin       : Solve as a maximization or minimization problem.
  inputformat  : Format of file containing input stochastic data
                 = mps   : MPS format
                 = spl   : Optimization Library internal format
  input        : Name(s) of file(s) containing input data
                 if inputformat = mps, there are 3 input files:
<filename>.core
                                        <filename>.time, and <filename>.stoch
                 if inputformat = spl, there is 1 input file: <filename>.spl
  output       : Name of file to receive OSL messages.
  solve        : Whether or not to solve the problem.
 ; alg          : Simplex algorithm to be used.
                 = primal : primal algorithm
                 = dual   : dual algorithm
                 = osl    : algorithm to be selected by OSL
  presolve     : Use EKKPRSL function to pre-solve problem.
  presolvetype : Type of reduction to be performed by EKKPRSL.
                 = 0   : the redundant rows are eliminated, the variables
                         summing to zero are fixed.
                 = 1   : type 0 reductions are done and the doubleton rows
                         are eliminated.
                 = 2   : type 0 reductions are done and variable
substitutions
                         performed.
                 = 3   : all of type 0, 1, and 2 reductions are performed.
  scale        : Use EKKSCAL function to scale the coefficient matrix.
  crash        : Use EKKCRSH function to create a starting basis.
  decompose    : Use EKKLPDC function to create a starting basis.
  samples      : Maximum number of scenarios to be formed.
                 = 0   : Explode the tree
                 > 0   : Number of scenarios to be generated
  masteriter   : The maximum number of Master iterations that OSL will
perform.
  cutperiod    : Period at which Benders' cuts are made.
  subproblems  : The maximum number of Benders' subproblems.
  warnlevel    : Number of scenarios beyond which the user is to be warned.
  largebounds  : Use large bounds to avoid unboundedness.
  modelout     : Name of file to store SP/OSL model.
  print        : Type of solution to be generated.
                 = stage  : the stage solution
                 = distn  : the scenario distribution of objective values
  stage        : Number of the stage for which solution is to be generated.
  scenario     : Number of the scenario for which solution is to be
generated.
  roworcol     : Row or column activities to be generated.

==============================================================================
```

Data Structures

IBM Stochastic Solutions internal data structures are not accessible to the user. The user gains access to copies of the structures in the format described in the file ekkstoch.h by the functions ekks_GetCoreData (get usrCoreData structure), ekks_GetScenarioTree (get usrStoch structure) and ekks_GetNodeData (get usrNode data). This section describes the data structures.

usrCoreData

The usrCoreData structure contains all information about the core model and its time stage decomposition. It is accessed by a call to the subroutine ekks_GetCoreData.

```
typedef struct {
     long nrow;             /* number of rows */
     long ncol;             /* number of columns */
     long nels;             /* number of matrix elements */
     long nstg;             /* number of stages */
     long nblocks;          /* number of blocks in matrix */
     double *drlo,*drup;    /* row bounds */
     double *dclo,*dcup;    /* column bounds */
     double *dobj;          /* objective */
     long *mrow;            /* matrix row indices */
     long *mcol;            /* matrix column indices */
     double *dels;          /* matrix elements */
     long *rowstart;        /* starts for stage partition of rows */
     long *colstart;        /* starts for stage partition of cols */
     long *elemstart;       /* starts for stage partition of matrix
                               Matrix is partitioned by row blocks
                                and then by column blocks
                               thus t*(t+1)/2-1 is the matrix index for
                               the start of the t-th stage node block
                               (as would be obtained by numbering blocks
                               starting from the top and moving left to
                               right).  The matrix is assumed full lower
                               block triangular. */
     long *sortin2exr;      /* in-to-external row index translation */
     long *sortin2exc;      /* in-to-external col index translation */
} usrCoreData;
```

The three arrays rowstart, colstart and elemstart identify the starting indices for each time stage in the list of row, column, and matrix entry indices respectively. Index numbering for matrix elements always begins from one (for compatibility with IBM Optimization Library).

For example, if then the row indices 1,2,3,4 are first stage rows, and 5,6,7,8,9,10 are second stage rows. The first four entries in the row bounds arrays drlo and drup are the bounds for the first stage rows, and the second six entries are the second stage row bounds. Of course, the ordering here may not correspond to the user's original ordering in the calling sequence for the ekks_CreateCore subroutine that created the core data structure. The array sortin2exr provides the original row indices. Thus, the first element of sortin2exr gives the original index for the first row, etc. Similar comments hold for the column arrays colstart and sortin2exc.

The elemstart array has a more complex structure. The core matrix is sorted first into row blocks, within which each row belongs to the same stage, and then each row block sorted into column blocks, within which each column belongs to the same stage. For example, if the problem has 4 stages, then this method sorts the matrix into lower block triangular form with up to ten blocks in the following order: In

this case the elemstart array has 11 entries. For example, if then the diagonal block 6 has 9 entries starting at the 26th entry of the matrix triple (mrow, mcol, dels), and the off-diagonal blocks 4, 7 and 8 have no entries at all. The matrix triple is stored "by indices," and thus the 26th entry has value dels[25] (using the indexing convention of the C programming language) row index mrow[25] and column index mcol[25].

usrStoch

The usrStoch structure identifies the nodes of a stochastic model. The Stoch and Node structures are filled by a call to ekks_GetScenarioTree.

```
typedef struct {
     long nnode;        /* number of nodes */
     usrNode *node;     /* array of node structures */
     long nleaf;        /* number of leaves */
     long *leaf;        /* list of leaf positions in node array (beg=1) */
     void *user;        /* (optional) pointer to user structure */
} usrStoch;
```

The nodes are described by an array of Node structures. The leaves of the tree are identified by the leaf array. For example, if one has then there are three scenarios in the model and the terminal nodes of the scenarios are described by the 4th, 8th, and 9th entries in the node array. A pointer is provided to point to a user structure, if needed (this information is for the user's purposes only; at this time it cannot be stored or retrieved).

usrNode

The Node structure describes all the information relating to a node in a scenario tree.

```
typedef struct {
     double prob;     /* probability of node in model */
     long orig;       /* original node name (numbered from 1) */
     long par;        /* parent's position in list (beg=1) */
     long child;      /* next-stage child (end=0) */
     long sib_cous;   /* same-stage sibling or cousin (end=0) */
     long stag;       /* original time stage */
     long scen;       /* original scenario number */
     long rbas;       /* row offset in matrix */
     long cbas;       /* column offset in matrix */
     long nrow;       /* number of rows */
     long ncol;       /* number of columns */
     long virtual;    /* = 1 if node not actually in model */
     void *user;      /* (optional) pointer to user structure */
} usrNode;
```

A node points to all information and data corresponding to a given time stage along a given scenario. The prob field contains the node's probability in the stochastic model. This probability multiplies the node's objective in the stochastic model. The orig field identifies the node's original numbering in the Stoch_Data structure, and must be used when accessing the LP data for the node.

The next three fields allow the user to move around the tree. The numbers refer to the ordering in the node array of the Stoch structure. The par field identifies the node's parent, that is, the node from which it branched in the stage immediately preceding. If the node happens to be a root, then its par field is set equal to zero. The child field identifies one of the children of the node. If there are no children (i.e. this is a leaf node) the field is set to zero. The sib_cous field identifies one sibling (that is, sharing a common parent) or cousin (merely share the same time stage). The sib_cous fields of nodes sharing a common time stage are arranged in a *ring*. All children of a node node can be found by following the sib_cous fields of the child, checking to see that they all share the same parent. All nodes of a given stage can be found by following the sib_cous fields around until the starting point is reached again.

The stag field identifies the node's stage and the scen field the original scenario number. The two fields rbas and cbas are the row and column bases that give the node's offset in the (deterministic equivalent) stochastic model. Finally, the virtual field identifies whether the node was (=0) or was not (=1) included in the nodelist which generated the stochastic model. Nodes whose descendents are in a model but that do not themselves appear in the nodelist generating the model need to be identified as such when constructing the LP for the stochastic model, so that offsets may be allocated for the virtual node columns. A pointer is provided to point to a user structure, if needed (this information is for the user's purposes only; at this time it cannot be stored or retrieved).

usrNodeData

The NodeData structure describes the *stochastic* LP data of a node. The data is accessed by *original* node number, as found in the usrNode structure describing the node (in the field orig), by the subroutine ekks_GetNodeData.

```
typedef struct {
     long stg;                /* stage of node ( = number of partitions) */
     long nrow;               /* number of rows */
     long ncol;               /* number of columns */
     long nels;               /* number of node block elements */
     double *drlo,*drup;      /* row bounds */
     double *dclo,*dcup;      /* column bounds */
     double *dobj;            /* objective */
     long *mrow;              /* block row indices */
     long *mcol;              /* block column indices */
     double *dels;            /* block elements */
     long *elemstart;         /* starts for stage partition of node block:
                                 thus t-1 is the index for the start of the
                                 t-th stage arc block and stg-1 is the
                                 index for the start of the node block.
                                 The node block has (poss.  empty) arc
                                 blocks for all stages t < istg. */
} usrNodeData;
```

This data must be combined with the core data to construct the actual node LP data. The convention in IBM Stochastic Solution is to *add* the core and stochastic data.

When a user accesses node data, the incoming arc matrices are copied over in the same subroutine call. This should be taken into consideration when transferring large amounts of data from the SP-file into memory.

The matrix associated with a node is the stochastic *row-block*; that is, all the stochastic row data in the given time stage in the given scenario are found in this matrix. Of course, there may not be any elements in the stochastic row-block. The matrix is structured in similar fashion as that of the matrix in the CoreData stucture, that is, it has been sorted into column blocks, by stage. The column indices in each of the column-blocks have been normalized to begin with index 1. The actual column index of an off-diagonal block is found by locating the node's ancestor for that stage and adding the ancestor's column offset cbas to the matrix column index. The actual column index of the diagonal block is found by adding the current node's column offset cbas to the column index. The actual row index of all entries is found by adding the current node's row offset rbas.

User Callable Modules

- ekks_InitializeOSL - ekks_Initialize
- ekks_AddEvent
- ekks_AddScenario
- ekks_AddToTree
- ekks_BendersLSolve
- ekks_CreateCore
- ekks_ChangeProbability
- ekks_GetCoreData
- ekks_GetPointerToDistribution
- ekks_DescribeModel
- ekks_FreeStructure
- ekks_GetNodeData
- ekks_GetPointerToSolution
- ekks_GetScenarioFromTree
- ekks_GetScenarioTree
- ekks_GetSolution
- ekks_GetStochasticData
- ekks_InitializeApplication
- ekks_InitializeTree
- ekks_ProblemType
- ekks_PutStochasticData
- ekks_ReadMPS

ekks_InitializeOSL - ekks_Initialize

Initializes Optimization Library data structures. The ekks_InitializeOSL routine will be removed in the next release level of the Stochastic Solutions. Until then, it remains for compatibility. Use ekks_Initialize instead.

```
extern int ekks_InitializeOSL();
extern int ekks_Initialize();
/*
 * Both initialize data structures.
 *
 * Returns:
 *  integer return code
 ****************************************************************/
```

ekks_AddEvent

Takes an event for a INDEP_DISCRETE distribution and adds it as a scenario.

```
extern void ekks_AddEvent( long *rc, Stoch_Data *stoch, Tree **treep,
                long *index, double dp, long replace );
/*
 * ekks_AddEvent.
 *
 *  Takes an event for a INDEP_DISCRETE distribution and adds it
 *  as a scenario.
 **
 *
 * Input:
 *  Stoch_Data *sdata   -- pointer to a Stoch_Data structure.
 *  Tree **treep        -- address of pointer to event tree under
 *                         construction (pointer must be NULL for first
call)
 *  long *index         -- event indices.
 *  double dp           -- probability
 *  long replace        -- (0,1) means (add to, replace) core values
 *
 * Returns:
 *  long *rc            -- return code (2 is fatal)
 ***********************************************************************/
```

ekks_AddScenario

Adds a scenario to stochastic problem, sets the scenario probability, the branching information, and stores the scenario data by node in an SP-file.

```
extern void ekks_AddScenario( long *rc, Stoch_Data *stoch,
                     long nscn, long ianc, long istg,
                     double dprob, long itype,
                     long nrow,long ncol,long nels,
                     double *dobj, double *drlo, double *drup,
                     double *dclo, double *dcup,
                     long *mrow, long *mcol, double *dels, long replace );
/*
 * ekks_AddScenario.
 *
 *      Adds a scenario to stochastic problem, sets the scenario
 *      probability, the branching information, and stores the scenario data
 *      by node in an SP-file.
 **
 *      Errors occur when branching information is inconsistent
 *      or when dimensions are inconsistent with the core.
 *
 *      If this call is repeated for the same scenario, the scenario
 *      probability is incremented by the amount of the new probability.
 *      No other data is changed.
 *
 *      All scenario LP data is ADDED to the corresponding core data when
 *      forming an LP.  This requires a convention for dealing with infinite
 *      bounds in the core.  If the core value is infinite and the incoming
```

```
 *      scenario value is nonzero, then a warning message is issued and the
 *      incoming scenario value is set to zero.
 *
 *      CORE VALUE      SCENARIO VALUE     ACTION              MESSAGE    RC
 *
 *      finite          infinite           none                none        0
 *      infinite        nonzero            scen value zeroed   warning     1
 *
 *      The LP data is NOT kept in core memory.  (It may be retrieved for
 *      the user by a call to ekks_GetNodeData.)  The LP matrix must be in
 *      "indices" sparse format.
 *
 *   If replace = 0:
 *
 *      LP data should be the "difference" of the intended scenario LP data
 *      with the core LP data.
 *
 *   If replace = 1:
 *
 *      Scenario LP data should "replace" the core LP data.  In this case,
 *      the subroutine calculates the difference for you.
 *
 *
 * Input:
 *      Stoch_Data *stoch       - pointer initialized by
 *
ekks_InitializeApplication
 *      long nscn               - scenario number (1,2,...)
 *      long ianc               - ancestor scenario number
 *      long istg               - branching stage number
 *      double dprob            - probability of scenario
 *      long itype              - matrix type (MUST be 1 - by indices
format)
 *      long nrow               - number of rows (must match core model)
 *      long ncol               - number of columns (must match core model)
 *      long nels               - number of elements in scenario matrix
 *      double *dobj            - array of objective entries
 *      double *drlo           - array of row lower bound entries
 *      double *drup            - array of row upper bound entries
 *      double *dclo            - array of column lower bound entries
 *      double *drup            - array of column upper bound entries
 *      long *mrow              - array of matrix row indices
 *      long *mcol              - array of matrix column indices
 *      double *dels            - array of matrix entries
 *      long replace            - (0,1) means (add to, replace) core values
 *
 * Output:
 *      long *rc                - return code (2 is fatal)
 *
 * Returns:
 *      void
 *
 ************************************************************************/
```

ekks_BendersLSolve

Applies Benders/L-shaped decomposition to the stochastic model, with cut made at the stage number IPCUT.

```
extern void ekks_BendersLSolve( long *rc, Stoch_Model *omodel, long ipcut,
                     long maxmod, long maxits, double rmaxmin,
                     long inwmt, long icrsh, long ilpdc,
                     long iscal,
                     long iprsl, long iprsltype, long iprslunit,
                     long isalg, long largebounds,
                     long *optimal, double *optgap );
/*
 * ekks_BendersLSolve.
 *
 *  Applies Benders/L-shaped decomposition to the stochastic model,
 *  with cut made at the stage number IPCUT.
 **
 *
 * Methodology:
 *
 *  A single master problem is created and up to MAXMOD subproblems
 *  corresponding to a cut made at stage IPCUT; that is, the master
 *  problem contains all rows and columns for stages prior to IPCUT.
 *  These problems are created in the same DSPACE as oModel.  If MAXMOD
 *  is not sufficient to hold all the subproblems, the subproblems are
 *  distributed as evenly as possible among MAXMOD models.
 *
 *  The program performs MAXITS iterations of Benders decomposition,
 *  terminating if optimality, infeasibility, or unboundedness is
 *  detected.
 *
 *  At termination, the master and subproblem solution data is
 *  transferred to the OSL model for oModel as appropriate, and the
 *  local structures are freed.
 *
 *  EKKSSLV (IRET,ds,1,3) is the appropriate continuation.
 *
 * Input:
 *
 *  Stoch_Model *oModel - stochastic model created by OSL.
 *  long ipcut          - period at which Benders cuts are made
 *  long maxmod         - maximum number of subproblems
 *  long maxits         - maximum number of Master iterations
 *  double rmaxmin      - direction of optimization - max (-1.0) or min
(1.0)
 *  long inwmt          - EKKNWMT type (0 => none EKKNWMT) for all problems
 *  long iscal          - (0,1) means (don't, do) call EKKSCAL for each
                                                      submodel
 *  long icrsh          - EKKCRSH type (0 => none) for first solution of
                                                      submodels
 *  long ilpdc          - (0,1) means (don't, do) call EKKLPDC for each
                                                         submodel
 *  long iprsl          - (0,1) means (don't, do) call EKKPRSL for each
                                                      submodel
 *  long iprsltype      - type of presolve
 *  long iprslunit      - presolve unit
 *  long isalg          - EKKSSLV algorithm for first solution of submodels
 *  long large_bounds   - (0,1) means (don't, do) add large bounds to master
```

```
 *  double *optgap      - Benders terminates when gap is less than optgap
 *
 * Output:
 *
 *  long *iret          - return code >= 2 indicates fatal error.
 *  long *status        - (0,1,2,3) means
 (optimal,infeasible,unbounded,unfinished).
 *  double *optgap      - Optimality gap at termination
 *
 ***************************************************************/
```

ekks_GetCoreData

Copy core data pointers into the usrCoreData structure.

```
extern void ekks_GetCoreData( long *rc, Stoch_Data *stoch,
                                                        usrCoreData
**pcore);
/*
 * ekks_GetCoreData.
 *
 *   Copy core data pointers into the usrCoreData structure.
 **
 *   If *pcore is NULL, then a new usrCoreData structure is malloc'ed
 *   and the pointer returned.
 *
 *   The data pointed to by usrCoreData pointers is stable.
 *   (It is the original data as formed by ekks_CreateCore.)
 *
 *  Input:
 *   Stoch_Data *stoch    - pointer initialized by
ekks_InitializeApplication
 and ekks_CreateCore
 *
 *  Output:
 *   usrCoreData **pcore   - address of pointer to type usrCoreData.
 *
 ***************************************************************/
```

ekks_CreateCore

Sorts core model row and column indices by stages, groups core model data into blocks corresponding to stages, and stores all model information, sort keys, and grouped data into a SPL file.

```
extern void ekks_CreateCore( long *rc, Stoch_Data *stoch,
                     long nstg, long *Rstag, long *Cstag,
                     long irow, long icol, long iels,
                     double *dobj, double *drlo, double *drup,
                     double *dclo, double *dcup,
                     long *mrow, long *mcol, double *dels, double *dqdg);
/*
 * ekks_CreateCore.
 *
 * Sorts core model row and column indices by stages, groups
 * core model data into blocks corresponding to stages, and stores
```

```
 * all model information, sort keys, and grouped data into a
 * SPL file.
 **
 *
 * The data is held in core, and may be accessed by a ekks_GetCoreData call.
 *
 * Input:
 *
 *      Stoch_Data stoch        - pointer initialized by
 ekks_InitializeApplication
 *      long nstg       - number of stages in the core model
 *      long *Rstag     - array of stage numbers for rows
 *      long *Cstag     - array of stage numbers for columns
 *      long irow       - number of rows in core model
 *      long icol       - number of columns in core model
 *      long iels       - number of matrix elements in core model
 *      double *dobj    - array of objective entries
 *      double *drlo    - array of row lower bound entries
 *      double *drup    - array of row upper bound entries
 *      double *dclo    - array of column lower bound entries
 *      double *drup    - array of column upper bound entries
 *      long *mrow      - array of matrix row indices
 *      long *mcol      - array of matrix column indices
 *      double *dels    - array of matrix entries
 *      double *dqdg    - array of quadratic matrix diagonal entries
 *
 * Output:
 *
 *      long *rc        - return code (2 is fatal).
 *
 * Returns:
 *      void
 ************************************************************************/
```

ekks_ChangeProbability

Updates leaf node probabilities with new scenario probabilities.

```
extern void ekks_ChangeProbability( long *rc, Stoch_Data *stoch, double
*usrProb );
/* ekks_ChangeProbability.
 *
 *  Updates leaf node probabilities with new scenario probabilities.
 *
 *  Note: The original scenario probabilities are unaffected.
 *        These can be restored by a call to ekks_ChangeProbability with a
NULL
 *        usrProb parameter.
 *
 * Input:
 *  Stoch_Data *stoch   -- pointer initialized by
ekks_InitializeApplication.
 *  double *usrProb     -- points to array of new probabilities.
 *
 * Returns:
 *   long *rc           -- return code (2 is fatal)
 ************************************************************************/
```

ekks_GetPointerToDistribution

Mallocs an independent data structure and sets it to point to the information collected in a ekks_ReadMPS reading of a INDEPENDENT/DISCRETE format.

```
extern void ekks_GetPointerToDistribution( long *rc, Stoch_Data *stoch,

           Independent **s_indep );
/*
 * ekks_GetPointerToDistribution.
 *
 *  Mallocs an independent data structure and sets it to point to the
 *  information collected in a ekks_ReadMPS reading of a
INDEPENDENT/DISCRETE
 *  format.
 **
 * Input:
 *  Stoch_Data *sdata   -- pointer to a Stoch_Data structure.
 *  long type           -- type of distribution pointed to (at the moment
 *                         only INDEP_DISCRETE implented)
 *
 * Output:
 *  usrIndep **s_indp   -- pointer to a usrIndep structure.
 *
 * Returns:
 *  long *rc            -- return code (2 is fatal)
 ***********************************************************************/
```

ekks_DescribeModel

Creates model node information structures and offsets from user-supplied nodelist.

```
extern void ekks_DescribeModel( long *rc, Stoch_Data *stoch,
                long nnodes, long *usrndlist,
                Stoch_Model **smodel, long *nblocks, long calcprob );
/*
 * ekks_DescribeModel.
 *
 *      Creates model node information structures and offsets from
 *      user-supplied nodelist.
 **
 *      If nodelist is empty (nnodes=0)
 *      then all nodes in the Stoch_Data structure are included.
 *
 *      Node probabilities are inherited from StochData structure.
 *      Zero probability nodes (and their incoming arcs) are removed.
 *
 *      Virtual nodes (ancestors not in model one of whose children are)
 *      are recorded and are offset by the total number of real node
columns.
 *
 *      If calcprob is set, the probabilities for each node are
 *      recomputed and normalized so that the probability totals to one.
 *
 *      No matrix data is passed.
```

```
 *      The number of blocks to be passed is returned.
 *
 * Input:
 *      Stoch_Data *stoch       -- stochastic data
 *      long nnodes             -- number of nodes
 *      long *usrndlist         -- list of nodes to be included in model
 *      long calcprob ;          -- (0,1) means (don't, do) recompute
 *                                 node probabilities.
 *
 * Output:
 *      Stoch_Model **smodel    -- pointer to new stochastic model
 *      long *nblocks           -- number of blocks in model
 *
 * Returns:
 *      void
 *
 ************************************************************************/
```

ekks_GetPointerToSolution

Gets a pointer to the solution region for the stochastic model nmod.

```
extern void ekks_GetPointerToSolution( long *rc, Stoch *stoch,
                long *nmod, double **dsoln);
/*
 * ekks_GetPointerToSolution.
 *
 *  Gets a pointer to the solution region for the stochastic model nmod.
 **
 *
 * Input:
 *  Stoch *stoch        -- Stoch_Model or Stoch_Data pointer to be deleted
 *  long *nmod          -- number of the model
 *
 * Output:
 *  long *rc            -- return code
 *  double **dsoln      -- pointer to the solutions region
 *
 * Returns:
 *      void
 *
 ************************************************************************/
```

ekks_GetSolution

Gets a solution for a scenario.

```
extern void  ekks_GetSolution(long *rc, Stoch_Model *stoch,long s,
                                    long colrowtype, double *solution,
long
                                    *indx);
/*
 * ekks_GetSolution.
 *
 *  Gets a solution for a scenario.
 **
```

```
 *
 * Input:
 *  Stoch_Model *stoch  -- Stoch_Model or Stoch_Data pointer
 *  long s              -- Scenario whose solution is to be retreived
 *  long colrowtype     -- type of solution (columns/rows) to be retrieved
 *
 * Output:
 *  long *rc            -- return code
 *  double *solution    -- pointer to the solution
 *  long *indx          -- pointer to the indices
 *
 * Returns:
 *      void
 *
 ************************************************************************/
```

ekks_FreeStructure

Free all data structures and temporary files.

```
extern void ekks_FreeStructure( Stoch *stoch);
/*
 * ekks_FreeStructure.
 *
 *  Free all data structures and temporary files.
 **
 *  If a Stoch_Model structure is passed, then only structures created
 *  for this model are deleted.
 *
 * Input:
 *  Stoch *stoch        -- Stoch_Model or Stoch_Data pointer to be deleted
 *
 ************************************************************************/
```

ekks_GetStochasticData

Copies stochastic data structures from SPL file.

```
extern void ekks_GetStochasticData( long *rc, Stoch_Data *stoch,
                                                                    const
char *filename );
/*
 * ekks_GetStochasticData.
 *
 *   Copies Stoch_Data structures from SPL file.
 **
 * Input:
 *   Stoch_Data *stoch  -- stochastic data pointer initialized by
 ekks_InitializeApplication.
 *   char *filename     -- name of SPL file.
 *
 * Output:
 *   long *rc           -- return code (2 is fatal)
 *
 * Returns:
 *   void
```

```
 *
 ************************************************************************/
```

ekks_InitializeApplication

Allocates pointers for stochastic data structures, opens SPL file, returns Stoch_Data pointer.

```
extern void ekks_InitializeApplication( long *rc, Stoch_Data **stoch,

   long maxscn );
/*
 * ekks_InitializeApplication.
 *
 *      Allocates pointers for stochastic data structures,
 *      opens SPL file, returns Stoch_Data pointer.
 **
 *  Input:
 *      long maxscn             - maximum number of scenarios
 *
 *  Output:
 *      Stoch_Data **stochdata  -  pointer to stochastic data structure
 *      long *rc                -  return code (2 is fatal)
 *
 *  Returns:
 *      void
 *
 ************************************************************************/
```

ekks_GetNodeData

Get stochastic node data into usrNodeData structure.

```
extern void ekks_GetNodeData( long *rc, Stoch_Data *stoch, long node,
                                                              usrNodeData
**punode );
/*
 * ekks_GetNodeData.
 *
 *   Get stochastic node data into usrNodeData structure.
 **
 *   Allocates new usrNodeData structure.
 *   Accesses stochastic matrix and costs/bounds data from SPL file
 *   and places them in volatile working memory.  Costs and bounds are
 *   expanded to their dense form.  usrNodeData pointers are appropriately
 *   set.
 *
 *   NB: ALL matrix and costs/bounds arrays are volatile!  The next call
 *       to an SP/OSL routine WILL OVERWRITE THEM!  (To protect
 *       yourself, copy them to a memory region that you maintain.)
 *
 *   NB: The matrix and costs/bounds arrays contain only the stochastic
 *       part of the data.  They must be ADDED to the relevant core data.
 *
 *   Bug: returns NULL pointers for root node (node=1)
 *
 * Input:
```

```
 *   Stoch_Data *stoch  -- stochastic data pointer initialized by
 ekks_InitializeApplication
 *   long node          -- node number to be accessed
 *
 * Output:
 *  usrNodeData **punode        -- pointer to usrNodeData
 *  long *rc                    -- return code (2 is fatal)
 *
 * Returns:
 *  void
 ************************************************************************/
```

ekks_PutStochasticData

Puts the Stoch_Data structure into an SPL file to be called "filename".

```
extern void ekks_PutStochasticData( long *rc, Stoch *stoch, char *filename
);
/*
 * ekks_PutStochasticData.
 *
 *  Puts the Stoch_Data structure into an SPL file to be called "filename".
 **
 *  Opens the file as a buffered direct access file, writes the data and
 *  then closes it.
 *
 *  File may be read by a call to ekks_GetStochasticData().
 *
 * Input:
 *   Stoch_Data *sdata  -- stochastic data pointer initialized by

ekks_InitializeApplication.
 *   char *filename     -- name of SPL file.
 *
 * Output:
 *   long iret                  -- return code (2 is fatal)
 *
 * Returns:
 *   void
 ************************************************************************/
```

ekks_GetScenarioTree

Creates a user accessible stochastic structure.

```
extern void ekks_GetScenarioTree( long *rc, Stoch *stoch, usrStoch **pstree
);
/*
 * ekks_GetScenarioTree.
 *
 *  Creates a user accessible stochastic structure.
 **
 *  The user needs to copy over the information
 *  to preserve it beyond the next Stochastic Solution call.
 *
 *  The input can be either a Stoch_Data structure or a Stoch_Model
```

```
 *  structure, in which case information for only those nodes in the
 *  model is compiled.
 *
 * Input:
 *  Stoch *stoch        -- pointer to a Stoch_Data or a Stoch_Model
structure.
 * Output:
 *  usrStoch **pstree   -- pointer to a usrStoch structure.
 *       NB: arrays pointed to by pstree are volatile!
 *
 * Returns:
 *  long *rc            -- return code (2 is fatal)
 ************************************************************************/
```

ekks_ReadMPS

Processes the Stochastic MPS files <app>.core, <app>.time and <app>.stoch, creates scenario data and stores it in the StochData structure.

```
extern void ekks_ReadMPS( long *rc, Stoch_Data *stoch, long *smpstype,
                     long *replace, char *corefile, char *timefile, char
                     *stochfile );
/*
 * ekks_ReadMPS.
 *
 * Processes the Stochastic MPS files <app>.core, <app>.time and
<app>.stoch,
 * creates scenario data and stores it in the StochData structure.
 **
 * The value of replace is set to 0 if STOCH file contains 'ADD' at
 * position 40 in the first line.
 *
 * Input:
 *
 *   Stoch_Data *sdata  -- pointer to Stoch_Data structure processed by
 ekks_ReadMPS.
 *   char *corefile     -- pointer to the core MPS filename.
 *   char *timefile     -- pointer to the time MPS filename.
 *   char *stochfile     -- pointer to the stoch MPS filename.
 *
 * Output:
 *   long *smpstype     -- integer identifying type of SMPS distribution.
 *   long *replace      -- (0,1) means (add to, replace) core values
 *   rc - return code (2 is fatal).
 *
 * Returns:
 *   void
 ************************************************************************/
```

ekks_ProblemType

Sets type of core model. Valid arguments are: linear, quadratic.

```
extern void ekks_ProblemType( long *iret, Stoch_Data *stoch, CoreType type
);
```

```
/*
 * ekks_ProblemType:
 *
 *      Sets type of core model.  Valid arguments are
 *              linear
 *              quadratic
 *
 * Input:
 *      CoreType type                   --      type of core model
 *      Stoch_Data *stochdata   --  pointer to stochastic data structure
 *
 * Output:
 *      long *iret              -  return code (2 is fatal)
 *
 * Returns:
 *      void
 *
 *
 ************************************************************************/
```

ekks_InitializeTree

Creates tree and initializes structures. Creates first scenario from data values in arr[].

```
extern void ekks_InitializeTree (long *rc, Tree **tree, long *arr, long
narr,
                        long mxsmp, double dp );
/*
 * ekks_InitializeTree.
 *
 * Creates tree and initializes structures.
 * Creates first scenario from data values in arr[].
 **
 * Input:
 *              arr[]   - integer array of data values
 *              narr    - number of data values (stages) in arr[]
 *              mxsmp   - maximum number of samples to be stored
 *              dp      - probability of events
 *
 * Output:
 *              *tree   - pointer to tree structure
 *              rc      - return code 0
 *
 * Returns:
 *              return value = 1
 ************************************************************************/
```

ekks_AddToTree

Updates scenario tree with data values in arr[].

```
extern long ekks_AddToTree (long *rc, Tree *tree, long *arr, long narr,
                                                        double dp);
/*
 * ekks_AddToTree.
 *
```

```
 * Updates scenario tree with data values in arr[].
 **
 * If arr[] is already in tree, then it increments counters
 * and returns the original scenario number,
 * otherwise it creates new scenario from data values in arr[]
 * and returns the newly created scenario number.
 *
 * Input:
 *              tree    - pointer to tree initialize by ekks_InitializeTree.
 *              arr[]   - integer array of data values
 *              narr    - number of data values (stages) in arr[]
 *              dp      - probability of events
 *
 * Output:
 *              rc      - return codes:
 *                              1 if maximum number of samples exceeded
 *                              2 if tree not initialized or corrupted
 *
 * Returns:
 *              scenario number as described above,
 ************************************************************************/
```

ekks_GetScenarioFromTree

Finds scenario information for sample number nsmp.

```
extern void ekks_GetScenarioFromTree(long *rc, Tree *tree, long nsmp,

long *ianc,
                        long *istg, double *wgt, long *nscn, long **arr);
/*
 * ekks_GetScenarioFromTree.
 *
 * Finds scenario information for sample number nsmp.
 **
 * NB: if branching stage, "istg", has value 1, this means
 *     that the scenario branches from the root (ianc=0).
 *
 * Input:
 *              tree    - pointer to tree initialized by
ekks_InitializeTree.
 *              nsmp    - sample number (first sample is 0, etc)
 *
 * Output:
 *              ianc    - ancestor scenario number.
 *              istg    - branching stage number
 *              wgt     - scenario weight
 *              nscn    - scenario number
 *              arr     - pointer to data array for scenario
 *              rc      - return codes:
 *                              1 if maximum number of samples exceeded
 *                              2 if tree not initialized or corrupted
 *
 ************************************************************************/
```

Messages

EKK0402	*Informational.*	Entering Stochastic Solutions function M01.
EKK0403	*Informational.*	Core model has I01 rows, I02 columns, and I03 stages.
EKK0404	*Informational.*	Scenario I01 Ancestor I02 Stage I03 Probability D01.
EKK0405	*Informational.*	Declaring stochastic model in OSL. Number of rows I01, number of columns I02.
EKK0406	*Informational.*	Total number of blocks declared to OSL is I01.
EKK0407	*Informational.*	Total number of C01 is I01.
EKK0408	*Informational.*	Constructing stochastic model from original node list.
EKK0409	*Informational.*	Process time for C01 is D01 seconds.
EKK0410	*Informational.*	Beginning C01.
EKK0411	*Informational.*	C01 C02 I01 ...
EKK0412	*Informational.*	C01 C02 ...
EKK0413	*Informational.*	C01 D01 ...
EKK0414	*Informational.*	Beginning first pass of Benders decomposition.
EKK0415	*Informational.*	Subproblem I01 did not solve. Exiting.
EKK0416	*Informational.*	Master infeasible. Terminating.
EKK0417	*Informational.*	Master unbounded. Generating ray.
EKK0418	*Informational.*	Estimated subproblem value at new master proposal is E0126.
EKK0419	*Informational.*	Beginning cycle I01.
EKK0420	*Informational.*	Solving subproblem I01.
EKK0421	*Informational.*	Unboundedness detected in subproblem I01 in cycle I02.
EKK0422	*Informational.*	Subproblem actual value at master proposal E0126.
EKK0423	*Informational.*	Problem is unbounded. Terminating.
EKK0424	*Informational.*	Optimality gap for current master proposal is E0114.
EKK0425	*Informational.*	Relative optimality gap is E0114.
EKK0426	*Informational.*	Optimal solution found to within relative optimality gap E0114.
EKK0427	*Informational.*	No new cuts from subproblems. Terminating.
EKK0428	*Informational.*	Maximum cycles exceeded. Terminating.
EKK0429	*Informational.*	No quadratic terms found in model. Resetting type to linear.
EKK0430	*Informational.*	Master problem value is E0126.
EKK3401	*Warning.*	Scenario I01 has already been defined. Probability is changed to D01.
EKK3402	*Warning.*	Scenarios that branch from the root have branching stage = 2.
EKK3403	*Warning.*	Scenario I01 branches prior to ancestor's branch stage: true ancestor is I02.
EKK3404	*Warning.*	Data for current model-block contains elements for earlier stages.
EKK3405	*Warning.*	SPL file is already opened for this application. No action taken.
EKK3406	*Warning.*	No filename supplied. Opening temporary SPL file in /tmp.

EKK3407	*Warning.*	Core C01 value at index I01 is infinite. Nonzero value in scenario I02 ignored.
EKK3408	*Warning.*	Node list is non-empty. Ignored.
EKK3409	*Warning.*	I01 zero probability nodes have been removed from model node list.
EKK3410	*Warning.*	No ENDATA card in C01 file. Ignored.
EKK3416	*Warning.*	Warning! No scenario C01.
EKK3417	*Warning.*	Warning! No stage C01.
EKK3418	*Warning.*	Warning! No column C01.
EKK3419	*Warning.*	Warning! No row C01.
EKK3420	*Warning.*	Warning! Ignored LB of Col I01 Scn I02.
EKK3421	*Warning.*	Warning! Ignored UB of Col I01 Scn I02.
EKK3422	*Warning.*	Warning! Ignored UB of Row I01 Scn I02.
EKK3423	*Warning.*	Warning! End of File.
EKK7401	*Error.*	Malloc failed in subroutine M01. Check maximum memory allocation for user.
EKK7402	*Error.*	Zero allocation attempted in subroutine M01. Check subroutine arguments.
EKK7403	*Error.*	C01 structures not initialized or corrupted. This was detected in subroutine M01.
EKK7404	*Error.*	Sort of C01 failed in subroutine M01.
EKK7405	*Error.*	Error detected while trying to open SPL file C01 in subroutine M01.
EKK7406	*Error.*	Error detected while trying to close SPL file C01 in subroutine M01.
EKK7407	*Error.*	Attempt to reposition within SPL file C01 failed in subroutine M01.
EKK7408	*Error.*	Error detected in subroutine M01 while writing to SPL file C01.
EKK7409	*Error.*	Error detected in subroutine M01 while reading from SPL file C01.
EKK7410	*Error.*	Invalid mode specified in subroutine M01 for opening SPL file C01.
EKK7411	*Error.*	Invalid mode specified in subroutine M01 for closing SPL file C01.
EKK7412	*Error.*	Unable to allocate file pointer for SPL file C01 in subroutine M01.
EKK7413	*Error.*	Unable to allocate filename storage for SPL file C01 in subroutine M01.
EKK7414	*Error.*	Invalid SPL file pointer specified in subroutine M01.
EKK7415	*Error.*	Error detected in subroutine M01 while attaching SPL file C01.
EKK7416	*Error.*	Error detected in subroutine M01 while detaching SPL file C01.
EKK7417	*Error.*	Invalid virtual record specified in subroutine M01 for SPL file C01.
EKK7418	*Error.*	Negative virtual record size specified in subroutine M01 for SPL file C01.
EKK7419	*Error.*	Empty string specified for SPL filename in subroutine M01.
EKK7420	*Error.*	Existing SPL file C01 opened in subroutine M01 is improperly initialized.
EKK7421	*Error.*	Error detected in subroutine M01 while deleting SPL file C01.
EKK7422	*Error.*	File-size discrepancy for SPL file C01 detected in subroutine M01.

EKK7423	*Error.*	Unknown error code for SPL file access used in subroutine M01.
EKK7424	*Error.*	Unable to initialize C01 for SPL file C02 in subroutine M01.
EKK7425	*Error.*	Error detected while attempting to save SPL file with name C01.
EKK7426	*Error.*	Number of C01 requested, I01 exceeds declared maximum I02.
EKK7427	*Error.*	Branching stage out of bounds.
EKK7428	*Error.*	Scenario has negative probability.
EKK7429	*Error.*	Ancestor scenario I01 does not exist.
EKK7430	*Error.*	Number of C01 in CORE model I01 does not match number I02 in scenario.
EKK7431	*Error.*	Data for current model-block is not block lower-triangular.
EKK7432	*Error.*	Total probability in model is zero.
EKK7433	*Error.*	Node list is empty. Cannot construct model.
EKK7434	*Error.*	Error creating hash tables for C01 names.
EKK7435	*Error.*	Not enough space in dspace for C01 file processing.
EKK7436	*Error.*	Index error in C01 file.
EKK7437	*Error.*	Error reading C01 file.
EKK7438	*Error.*	Distribution type not implemented.
EKK7439	*Error.*	Premature EOF reached in C01 file.
EKK7440	*Error.*	Expecting C01 card in C02 file.
EKK7441	*Error.*	Too many elements in scenario I01. Consider revising CORE file, so that more of these elements appear there.
EKK7442	*Error.*	Ranges not implemented in SMPS format.
EKK7443	*Error.*	OSL not initialized or corrupted. This was detected in subroutine M01.
EKK7444	*Error.*	Not enough space in OSL for matrix. Need at least I01 more doublewords.
EKK7445	*Error.*	Duplicate root node dhiscovered in model node tree.
EKK7446	*Error.*	Master status is confused. Exiting.
EKK7447	*Error.*	Bad return code from OSL solving subproblem I01 in cycle I02.

History and Acknowledgements

The precursor of the IBM Stochastic Solution is the *Stochastic Programming Interface to the Optimization Subroutine Library*, also known as SP/OSL, which was an experimental software library developed over the period 1990-1995 by Alan King and colleagues at the IBM Thomas J. Watson Research Center.

Stephen E. Wright (now at Miami University of Ohio) was co-developer of SP/OSL during his postdoc years 1991-3 and during a summer visit in 1994. The elegant SP-file object and the flexible and robust implementation of the parallel decomposition were entirely designed and written by him.

Robert Entriken (now a consultant with PG&E) wrote the first version of SP/OSL, a matrix generator, in early 1990. The important node/arc metaphor basic to SP/OSL data structures is due to him. Hercules Vladimirou (now at University of Cyprus) developed and tested an early parallel implementation of single-cut Benders during his postdoc in 1991-2. Chris Donohue (University of Michigan) developed the prototype tree-generation software during his stint as a summer student in 1992. Shabbir Ahmed (now at the University of Illinois, Urbana Champaign) prepared the section on examples in this documentation. Special acknowledgement also is due to Roger Wets, for inspiration, guidance and support during his frequent visits throughout the development period.

Two significant corporate consulting engagements played a major role in the development of SP/OSL.

In 1990, the Frank Russell Corporation asked IBM Research to assess the solvability of certain stochastic programs generated by an asset/liability management system. In response, Robert Entriken quickly built a matrix generator capable of translating SMPS format to OSL problem structures, and Alan King and Robert Entriken working together solved the problem during several overnight runs on an IBM mainframe computer.

In 1992, the Allstate Corporation's Palo Alto Research Center asked IBM to assist them in the development of a multiperiod asset allocation pilot for their property and casualty portfolio. This relationship spurred major development of SP/OSL both as a model generator and as a decomposition solver.

In the period 1993 to 1997, SP/OSL was distributed under special agreement with principal investigators at selected universities and corporate research centers for field testing.

[**Top of Page | Previous (Users Guide) | Next (Examples) | Roadmap**]

Bibliography

Bottom of Page

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[**Top of Page** | **Previous (Examples)** | **Next (Table of Contents)** | **Roadmap**]