

## SIPLIB 2.0

### Stochastic Integer Programming Library version 2.0

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**Abstract** We present a collection of stochastic integer programming problem instances.

**Keywords** Stochastic Integer Programming · Problem Instances

## 1 Introduction

The SIPLIB [1] is an abbreviated term of the Stochastic Integer Programming (SIP) Library firstly constructed in 2002 by Shabbir Ahmed and his colleagues. The library has been providing a collection of test instances to facilitate computational and algorithmic research in SIP. Some new test problems with instances have been added to SIPLIB gradually and now it contains nine different problems in total. The instances are basically given in the standard SMPS format accompanied with additional information including parameter data, size of the instance in terms of the number of rows, columns, and integers, benchmarking information such as best known objective value or bounds, optimality gap, and solution time.

At the time SIPLIB appeared, it provided enough large-sized instances that is reasonable to argue that the performance of algorithm is remarkable if it solves the instances. State-of-the-art in SIP combined with the speedup in computing machinery, however, makes many instances in SIPLIB so easy that we have not enough basis to use them for showing the excellence of

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newly suggested solution methods. At this point, we are motivated to develop the second version of SIPLIB, say SIPLIB 2.0 that provides larger-sized test instances with higher degree of tailorability, e.g., users can easily generate instances of test problems as largely as they want.

(as we include DCLP (data center location problem), this paragraph should be modified) Stochastic programming (SP) is a framework for modeling optimization problems that involve uncertainty. Whereas optimization problems are typically formulated with known parameters, the problems in real world contain some unknown parameters in many cases. For details on SP, see, e.g., [2, 3]. SIP is a branch of SP that indicates any type of SP including at least one integer decision variable. The integers can be placed anywhere in general SIP. However, we restrict our focus on two-stage SIP that contains integer variables (including binary) in its second stage throughout this paper and SIPLIB 2.0. The main reason is that the class of SIP is most widely used to model real world problems. Moreover, two-stage SIP itself has enough difficulties that have not been conquered yet even without any other details like chance-constraints and multi-stages. The main difficulty in solving two-stage SIP is that the second-stage value function is not necessarily convex, but only lower semicontinuous. Thus, the standard decomposition approaches that work nicely for stochastic *linear* programs, break down when the second stage integer variables are present [4]. Hereinafter, we use the term SIP to indicate the two-stage SIP that contains integer variables in its second stage.

We provide the test sets in two formats: SMPS files (\*.cor, \*.tim, \*.stoch) and Julia files (\*.jl). SMPS is widely used to describe stochastic linear and quadratic programs. Once having SMPS files of a problem instance, we can directly solve it using various mixed integer linear program (MILP) solvers such as CPLEX, GUROBI, and CBC. One can also use the existing open-source SIP solvers like DSP [5], PySP [6], and SMI [7] given that SMPS files. A drawback of SMPS format is its low readability by human, which we decided to provide Julia files to let users be able to easily read problems and tailor the instances.

Julia is an open source high-level, high-performance dynamic programming language for numerical computing. It is also known as its good performance, approaching that of statically-compiled languages like C [8]. The syntax of Julia is simple and should feel familiar to anyone who has experienced in another high-level languages like MATLAB or Python. A Julia package called JuMP (Julia for Mathematical Programming [9]) provides a domain-specific modeling language for mathematical optimization embedded in Julia. JuMP enables us to easily translate mathematical model to JuMP.Model-type object. Some structured mathematical models like SIP can also be translated to the JuMP.Model-type object combined with the package StructJuMP [10]. Once we have a Julia code for constructing JuMP.Model-type object, it is easy to generate instances whenever we need to modify the original mathematical model. For each problem in SIPLIB 2.0, we provide a Julia script for constructing JuMP.Model-type object. We also provide a Julia script (SmipsWriter.jl) for converting any JuMP.Model-type objects to SMPS files for users' convenience. Those who feel the given instances are not large enough can simply generate

more scenario data by just modifying the parameter in `Julia` script corresponding to the number of scenarios.

By SIPLIB 2.0, we provide 1) richer collection of test instances for computational and algorithmic research in SIP with benchmarking computational results, 2) not only `SMPS` files but also `Julia` files that are easily readable/tailorable. Hence, the users can obtain as large-sized instances as they need by generating new scenarios and including them into instances. For those who want to utilize the instances in the legacy SIPLIB with strong tailorability provided by SIPLIB 2.0, we include the original SIPLIB instances as well.

(Contents of the paper, not finished yet) In this paper, we provide a detailed description of the test problems in SIPLIB 2.0, including information on the instances, their origin, formal mathematical models with explanation on notations, and scenario data generation procedure. SIPLIB 2.0 classifies problems based on the stages, variables, and constraints. We borrow some classification criteria from the most frequently utilized mixed integer programming (MIP) library, MIPLIB 2010 [21], whenever they are applicable to SIP as well.

## 2 Stochastic integer programming

In this section, we explain general description of SIP. This includes formal mathematical formulation, existing general solution methods to solve the SIPs, and currently available software libraries.

### 2.1 Formulation

In this subsection, we introduce the form of SIP of interest. The notations and dimensional information are summarized in Table 1. We are interested in finding solution for two-stage SIP of the form:

$$z := \min_{x \in X} \{c^\top x + Q(x) : Ax \geq b\}, \quad (1)$$

where  $Q(x) := \mathbb{E}_\xi [\phi(h(\xi) - T(\xi)x)]$  is the recourse function associated with the random variable (r.v.)  $\xi$ . We assume that  $\xi$  follows a known discrete probability distribution with the finite realizations, called *scenarios*,  $\xi_1, \dots, \xi_r$  and respective nonnegative probabilities  $\mathbb{P}(1), \dots, \mathbb{P}(r)$ , i.e.,  $\mathbb{P}(s) \equiv \mathbb{P}[\xi = \xi_s]$  for  $s \in \mathcal{S} := \{1, \dots, r\}$ . When the distribution is continuous, we can approximate it by a suitably discretized distribution. The real-valued map  $\phi_{\xi_s} : \mathbb{R}^{m_2} \rightarrow \mathbb{R}$  is the optimal value of the second-stage problem defined by

$$\phi_{\xi_s}(t) := \min_{y_s \in Y} \{q(\xi_s)^\top y_s : W(\xi_s)y_s \geq t\}, \quad t \in \mathbb{R}^{m_2}, \quad (2)$$

where  $\xi_s$  is an arbitrarily realized scenario. The sets  $X \subseteq \mathbb{R}^{n_1}$  and  $Y \subseteq \mathbb{R}^{n_2}$  represent integer or binary restrictions on a subset of the decision variables  $x$  and  $y_s$ , respectively. The first-stage problem data comprise  $A$ ,  $b$ , and  $c$ . The second-stage data are given by  $T(\xi_s)$ ,  $W(\xi_s)$ ,  $h(\xi_s)$ , and  $q(\xi_s)$  (for dimensional

information refer to Table 1). Hereinafter, we use the simplified notations  $(T_s, W_s, h_s, q_s)$ . The SIP (1) can be rewritten in the extensive form

$$z = \min_{x, y_s} c^\top x + \sum_{s=1}^r \mathbb{P}(s)(q_s^\top y_s), \quad (3a)$$

$$\text{s.t. } Ax \geq b, \quad (3b)$$

$$T_s x + W_s y_s \geq h_s, \quad \forall s \in \{1, \dots, r\}, \quad (3c)$$

$$x \in X, \quad (3d)$$

$$y_s \in Y, \quad \forall s \in \{1, \dots, r\}. \quad (3e)$$

**Table 1** Summary of notations in SIP formulation

<b>Sets:</b>	
$X \subseteq \mathbb{R}^{n_1}$	first-stage polyhedral set (continuous, integer, binary)
$Y \subseteq \mathbb{R}^{n_2}$	second-stage polyhedral set (continuous, integer, binary)
$\mathcal{S} = \{1, \dots, r\}$	index set of realizable scenarios
<b>Scalars:</b>	
$\xi$	r.v. denoting scenario that realizes by one of the set $\{\xi_1, \dots, \xi_r\}$
$z \in \mathbb{R}$	optimal objective value of the SIP
$r \in \mathbb{N}$	number of scenarios
$s \in \mathcal{S}$	index denoting scenario
$\mathbb{P}(s) \in [0, 1]$	probability that scenario $s$ happens, i.e., $\mathbb{P}(s) \equiv \mathbb{P}[\xi = \xi_s]$
<b>Vectors:</b>	
$x \in \mathbb{R}^{n_1}$	first-stage decision vector
$c \in \mathbb{R}^{n_1}$	first-stage cost vector
$b \in \mathbb{R}^{m_1}$	first-stage RHS vector
$y_s \in \mathbb{R}^{n_2}$	second-stage decision vector under scenario $\xi_s$
$q_s \equiv q(\xi_s) \in \mathbb{R}^{n_2}$	second-stage cost vector
$h_s \equiv h(\xi_s) \in \mathbb{R}^{m_2}$	second-stage RHS vector
<b>Matrices:</b>	
$A \in \mathbb{R}^{m_1 \times n_1}$	first-stage constraint matrix corresponds to decision vector $x$
$W_s \equiv W(\xi_s) \in \mathbb{R}^{m_2 \times n_2}$	second-stage constraint matrix corresponds to decision vector $y_s$
$T_s \equiv T(\xi_s) \in \mathbb{R}^{m_2 \times n_1}$	second-stage constraint matrix corresponds to decision vector $x$
<b>Functions:</b>	
$\phi_{\xi_s} : \mathbb{R}^{m_2} \rightarrow \mathbb{R}$	second stage program optimal value under the realization of scenario $\xi_s$
$\mathcal{Q} : \mathbb{R}^{n_1} \rightarrow \mathbb{R}$	recourse function (the expectation of $\phi(h(\xi) - T(\xi)x)$ over the r.v. $\xi$ )

## 2.2 Solution methods

### 2.2.1 Stage-wise decomposition algorithm

### 2.2.2 Scenario-wise decomposition algorithm

## 2.3 Software libraries

### 2.3.1 Modeling languages

### 2.3.2 Solvers

## 3 Summary of the test sets

### 3.1 Type of problems

**Table 2** Types of the problems in SIPLIB 2.0

Problem name	Description	Main reference
DCAP	Dynamic capacity planning with stochastic demand	Ahmed and Garcia [4]
DCLP	Data center location problem	Kim et al. [19]
MPTSPs	Multi-path traveling salesman problem with stochastic travel costs	Tadei et al. [13]
SIZES	Optimal product substitution with stochastic demand	Jorjani et al. [15]
SMKP	Stochastic multiple knapsack problem	Angulo et al. [17]
SSLP	Stochastic server location problem	Ntaimo and Sen [20]
SUCW	Wind power stochastic unit commitment	Papavasiliou and Oren [18]

**Table 3** Components of the problems in SIPLIB 2.0

Problem	1st stage		2nd stage	
	Variable	Constraint	Variable	Constraint
DCAP	C, B	VBB <sup>1</sup>	B	PAR <sup>1</sup> , M01 <sup>1</sup>
DCLP			C	
MPTSPs	C, B	PAR <sup>2</sup> , GEN <sup>1</sup>	B	GEN <sup>2</sup>
SIZES	I	VBD <sup>1</sup> , GEN <sup>2</sup>	B, I	IKN <sup>1</sup>
SMKP	B	KNA <sup>1</sup>	B	KNA <sup>1</sup>
SSLP	B	IVK <sup>1</sup> , GEN <sup>1</sup>	C, I	GEN <sup>2</sup>
SUCW	∅		C, B	

### 3.2 Instance catalog

#### 3.2.1 Instance naming rule

**Table 4** Problem-specific instance naming rules

Problem	Instance name	Description
DCAP		
DCLP		
MPTSPs	MPTSPs_Dx_Ny_Sz	node distribution strategy Dx, number of nodes y, and number of scenarios z
SIZES	SIZESz	number of scenario is z
SMKP		
SSLP		
SUCW		

## 4 How to run a test, generate new instance, and convert to SMPS

We explain the structure of **SIPLIB 2.0**. We explain procedure to generate new instances with user-generated scenario data using **Julia** scripts. The problem-specific descriptions are given in Section 6. We explain how to convert **JuMP.Model**-type object to **SMPS** files.

## 5 Implementation of SMPS Writer

We describe our **Julia** implementation, how to model **SIP** and generate **SMPS** files..

## 6 Problem descriptions

In this section, we introduce details for each problem in **SIPLIB 2.0**. We also explain the scenario data generation procedures. Due to limited access to the original data in reference papers, we selectively choose the methods from several available references and modify some of them without harming validity. Also, we guess some parameters about scenario generation to make the procedure clear.

### 6.1 DCAP: Dynamic capacity planning with stochastic demand

**DCAP** is the problem of determining a capacity expansion schedule for a set of resources, and the assignment of resource capacity to task with stochastic requirement over a multi-period planning horizon. In **SIPLIB**, 12 instances are available in **SMPS** format with the largest instance comprises of 500 scenarios correspond to the size of 9,012 rows and 18,018 columns. We refer to [4] for writing **Julia** scripts.

### 6.1.1 Mathematical formulation

$$(\text{DCAP}) \min \sum_{t \in T} \sum_{i \in M} (\alpha_{it} x_{it} + \beta_{it} u_{it}) + \sum_{s \in \mathcal{S}} \mathbb{P}(s) \sum_{t \in T} \sum_{i \in M \cup \{0\}} \sum_{j \in N} c_{ijt}^s y_{ij}^s \quad (4a)$$

$$\text{s.t. } x_{it} \leq u_{it}, \quad \forall i \in M, \forall t \in T, \quad (4b)$$

$$\sum_{j \in N} d_{jt}^s y_{ij}^s \leq \sum_{\tau=1}^t x_{i\tau}, \quad \forall i \in M, \forall t \in T, \forall s \in \mathcal{S}, \quad (4c)$$

$$\sum_{i \in M \cup \{0\}} y_{ijt}^s = 1, \quad \forall j \in N, \forall t \in T, \forall s \in \mathcal{S}, \quad (4d)$$

$$x_{it} \geq 0, \quad \forall i \in M \cup \{0\}, \forall t \in T, \quad (4e)$$

$$u_{it} \in \{0, 1\}, \quad \forall i \in M \cup \{0\}, \forall t \in T, \quad (4f)$$

$$y_{ijt}^s \in \{0, 1\}, \quad \forall i \in M \cup \{0\}, \forall j \in N, \forall t \in T, \forall s \in \mathcal{S}, \quad (4g)$$

**Table 5** Notations for DCAP

<b>Index sets:</b>	
$M$	index set of resources ( $i \in M \cup \{0\}$ where 0 is a dummy resource with infinite capacity)
$N$	index set of tasks ( $j \in N$ )
$T$	index set of time periods ( $t \in T$ )
$\mathcal{S}$	index set of scenarios ( $s \in \mathcal{S}$ )
<b>Parameters:</b>	
$\alpha_{it}$	variable cost for expanding capacity of resource $i$
$\beta_{it}$	fixed cost for expanding capacity of resource $i$
$c_{ijt}^s$	cost of processing task $j$ using resource $i$ in period $t$ under scenario $s$
$d_{jt}^s$	processing requirement for task $j$ in period $t$ under scenario $s$
$\mathbb{P}(s)$	the probability of occurrence of scenario $s$
<b>Decision variables:</b>	
$x_{it}$ (1 <sup>st</sup> stage)	capacity acquisition amount of resource $i$ in period $t$
$u_{it}$ (1 <sup>st</sup> stage)	1 if capacity of resource $i$ is expanded in period $t$ , 0 otherwise
$y_{ijt}^s$ (2 <sup>nd</sup> stage)	1 if resource $i$ is assigned to task $j$ in period $t$ under scenario $s$ , 0 otherwise

### 6.1.2 Scenario data generation

## 6.2 DCLP: Data center location problem

### 6.2.1 Mathematical formulation

### 6.2.2 Scenario data generation

## 6.3 SMKP: Stochastic multiple knapsack problem

SMKP is a class of stochastic multiple binary knapsack problems. Unlike typical knapsack problems where the objective is to maximize total profits under the restriction of the weight capacity of each knapsack, SMKP is to minimize total weights while satisfying a certain required profit for each knapsack.

SIPLIB provides 30 instances of **SMKP** in total. The first-stage problems contain 240 binary variables and 50 knapsack constraints. The second-stage problems have 120 binary variables and 5 knapsack constraints. Each instance has 20 scenarios. We refer [17] for writing `Julia` script for **SIPLIB 2.0** and explain the model throughout the following subsections.

### 6.3.1 Mathematical formulation

We have three types of items  $x$ ,  $z$ , and  $y$  where the first two types are of the first-stage and the last one is of the second-stage with stochastic scenarios. For each type, we have  $|I|$  number of items where  $I$  is the index set of the items. Hence, we define the binary variables  $x_i$ ,  $z_i$ , and  $y_i^s$  which are equal to 1 if the  $i^{\text{th}}$  item is decided to be included ( $s$  denotes scenario so only appears in  $y$ -type variables). We consider two types of knapsacks: one associated with  $x$ -type and  $z$ -type items (say **xz**-knapsack) and the other one with  $x$ -type and  $y$ -type items (say **xy**-knapsack). **xz**-knapsacks are indexed by  $j \in J$  and **xy**-knapsacks are indexed by  $k \in K$ . Each knapsack has its own minimum level of profit that should be satisfied by the items of the associated types, e.g., the profit of the  $j^{\text{th}}$  **xz**-type knapsack is calculated based on the inclusion or exclusion of  $x$ -type and  $z$ -type items and should satisfy a certain requirement  $b_j$ . Bear in mind that the inclusion or exclusion of a certain item  $i$  affects all the associated knapsacks.

Each parameter  $c_i$ ,  $d_i$ , and  $q_i^s$  denotes the gain of weight when including items of type  $x$ ,  $z$ , and  $y$ , respectively. Here,  $c_i$  and  $d_i$  are deterministic and  $q_i^s$  is stochastic. Parameters  $a_{ij}$ ,  $e_{ij}$ ,  $t_{ik}$ , and  $w_{ik}$  are all deterministic and denote the profits for including items in the knapsacks. The RHS parameters  $b_j$  and  $h_k$  are the minimum levels of profit requirements for **xz**-knapsacks and **xy**-knapsacks, respectively.

The extensive form of **SMKP** is as follows and the notations used are summarized in Table 6.

$$(\text{SMKP}) \min \sum_{i \in I} (c_i x_i + d_i z_i) + \sum_{s \in \mathcal{S}} \mathbb{P}(s) \sum_{i \in I} q_i^s y_i^s \quad (5a)$$

$$\text{s.t.} \quad \sum_{i \in I} a_{ij} x_i + \sum_{i \in I} e_{ij} z_i \geq b_j, \quad \forall j \in J, \quad (5b)$$

$$\sum_{i \in I} t_{ik} x_i + \sum_{i \in I} w_{ik} y_i^s \geq h_k, \quad \forall k \in K, \forall s \in \mathcal{S}, \quad (5c)$$

$$x_i \in \{0, 1\}, \quad \forall i \in I, \quad (5d)$$

$$z_i \in \{0, 1\}, \quad \forall i \in I, \quad (5e)$$

$$y_i^s \in \{0, 1\}, \quad \forall i \in I, \forall s \in \mathcal{S}. \quad (5f)$$

The objective (5a) is to minimize the expected value of the total weights. Constraint (5b) ensures the minimum levels of profit requirements for all **xz**-knapsacks are satisfied. Constraint (5c) guarantees the minimum levels of



profit requirements are satisfied for all **xy**-knapsacks under every scenario. Constraints (5d)-(5f) are binary restriction of the decision variables.

**Table 6** Notations for SMKP

<b>Index sets:</b>	
$I$	index set of items for each type ( $i \in I$ )
$J$	index set of <b>xz</b> -knapsacks ( $j \in J$ )
$K$	index set of <b>xy</b> -knapsacks ( $k \in K$ )
$S$	index set of scenarios ( $s \in S$ )
<b>Parameters:</b>	
$c_i$	weight of the $i^{\text{th}}$ $x$ -type item
$d_i$	weight of the $i^{\text{th}}$ $z$ -type item
$q_i^s$	weight of the $i^{\text{th}}$ $y$ -type item under scenario $s$
$a_{ij}$	profit of the $j^{\text{th}}$ <b>xz</b> -knapsack for including $i^{\text{th}}$ $x$ -type item
$e_{ij}$	profit of the $j^{\text{th}}$ <b>xz</b> -knapsack for including $i^{\text{th}}$ $z$ -type item
$t_{ik}$	profit of the $k^{\text{th}}$ <b>xy</b> -knapsack for including $i^{\text{th}}$ $x$ -type item
$w_{ik}$	profit of the $k^{\text{th}}$ <b>xy</b> -knapsack for including $i^{\text{th}}$ $y$ -type item
$b_j$	minimum required profit for the $j^{\text{th}}$ <b>xz</b> -knapsack
$h_k$	minimum required profit for the $k^{\text{th}}$ <b>xy</b> -knapsack
$\mathbb{P}(s)$	the probability of occurrence of scenario $s$
<b>Decision variables:</b>	
$x_j$ (1 <sup>st</sup> stage)	1 if the $j^{\text{th}}$ $x$ -type item is decided to be included, 0 otherwise
$z_j$ (1 <sup>st</sup> stage)	1 if the $j^{\text{th}}$ $z$ -type item is decided to be included, 0 otherwise
$y_j^s$ (2 <sup>nd</sup> stage)	1 if the $j^{\text{th}}$ $y$ -type item is decided to be included under scenario $s$ , 0 otherwise

### 6.3.2 Scenario data generation

## 6.4 SSLP: Stochastic server location problem

SSLP is a class of problem that finds the optimal location of servers and the optimal allocation of clients to servers which maximizes the expected net income under uncertain presents of clients. SSLP finds applications in a variety of domains such as network design for electric power, internet services, telecommunications, and water distribution. SIPLIB provides 12 instances with varying number of clients, server locations, and scenarios in SMPS format. The largest instance includes 10 server locations, 50 clients, and 2,000 scenarios which corresponds to 120,001 constraints, 1,000,010 binary variables, and 20,000 continuous variables.

We refer to [20] for mathematical formulation and data generation forthcoming through the following subsections.

### 6.4.1 Mathematical formulation

$$(\text{SSLP}) \min \sum_{j \in J} c_j x_j - \sum_{s \in \mathcal{S}} \mathbb{P}(s) \left( \sum_{i \in I} \sum_{j \in J} q_{ij}^s y_{ij}^s - \sum_{j \in J} q_{0j}^s y_{0j}^s \right) \quad (6a)$$

$$\text{s.t.} \sum_{j \in J} x_j \leq v, \quad (6b)$$

$$\sum_{j \in J_z} x_j \geq w_z, \quad \forall z \in Z, \quad (6c)$$

$$\sum_{i \in I} d_{ij} y_{ij}^s - y_{0j}^s \leq u x_j, \quad \forall j \in J, \quad \forall i \in I, \quad \forall s \in \mathcal{S}, \quad (6d)$$

$$\sum_{j \in J} y_{ij}^s = h_i^s, \quad \forall i \in I, \quad \forall s \in \mathcal{S}, \quad (6e)$$

$$x_j \in \{0, 1\}, \quad \forall j \in J, \quad (6f)$$

$$y_{ij}^s \in \{0, 1\}, \quad \forall i \in I, \quad j \in J, \quad s \in \mathcal{S}, \quad (6g)$$

$$y_{0j}^s \geq 0, \quad \forall j \in J, \quad \forall s \in \mathcal{S}. \quad (6h)$$

**Table 7** Notations for SSLP

<b>Index sets:</b>	
$I$	index set of clients ( $i \in I$ )
$J$	index set of servers ( $j \in J$ )
$Z$	index set of zones ( $z \in Z$ )
$\mathcal{S}$	index set of scenarios ( $s \in \mathcal{S}$ )
<b>Parameters:</b>	
$c_j$	cost of locating a server at location $j$
$q_{ij}^s$	revenue from client $i$ being served by server at location $j$ under scenario $s$
$q_{0j}^s$	rate of revenue loss for overflows that are not served due to limited server capacity under scenario $s$
$d_{ij}$	resource demand of client $i$ from server at location $j$
$u$	server capacity
$v$	upper bound on the total number of servers that can be located
$w_z$	minimum number of servers to be located in zone $z$
$J_z$	subset of server locations that belong to zone $z$
$h_i^s$	1 if client $i$ is present under scenario $s$ , 0 otherwise
$\mathbb{P}(s)$	probability of occurrence for scenario $s$
<b>Decision variables:</b>	
$x_j$ (1 <sup>st</sup> stage)	1 if a server is located at site $j$ , 0 otherwise
$y_{ij}^s$ (2 <sup>nd</sup> stage)	1 if client $i$ is served by a server at location $j$ under scenario $s$ , 0 otherwise
$y_{0j}^s$ (2 <sup>nd</sup> stage)	non-negative amount of overflows that are not served due to limitations in server $j$ 's capacity

### 6.4.2 Scenario data generation

#### 6.5 MPTSPs: Mutli-path Traveling Salesman Problem with Stochastic Travel Times

MPTSPs is a variant of the travelling salesman problem (TSP) where a set of paths exists between any two nodes and each path is chracterized by a random travel time.

In SIPLIB, only limited data (e.g., number of nodes, coordinates of nodes, generated travel times) are provided and no SMPS file is available. We mainly refer to [12] for deriving the mathematical formulation. Due to the malfunction of subtour breaking constraints in the reference model, we refer to another paper [14] to break subtours. Combining the two references, we construct the forthcoming single commodity flow-based formulation MPTSPs that is used for SIPLIB 2.0.

### 6.5.1 Mathematical formulation

We consider a two-stage SIP with recourse. The travel time oscillation  $e_{ij}^k$  by using path  $k$  between nodes  $i$  and  $j$ . We present each realization (scenario) of random travel time oscillation by  $e_{ijk}^s$  where  $s$  indicates the scenario. In MPTSPs, at the first stage, the decision-maker does not have any information about the travel time oscillation. The tour paths among the nodes, however, should be determined before the complete information is available. The first stage decision variable  $y_{ij}$  is represented by the selection of nodes  $i$  and  $j$  to be visited in a tour. In the second stage where the random travel time  $c_{ijk}^s$  are available, the paths  $k$  between each couple of nodes  $i$  and  $j$  under scenario  $s$ ,  $x_{ijk}^s$  can be calculated.

Let  $N$  and  $K_{ij}$ , respectively, be the finite set of nodes of the graph and the set of paths between the pair of nodes  $i, j \in N$ . We denote with  $\mathcal{S}$  the set of scenarios with associated equally distributed probability of each scenario  $\mathbb{P}(s)$ , i.e.,  $\mathbb{P}(s) \equiv 1/|\mathcal{S}|$ . Each path  $k \in K_{ij}$  between nodes  $i, j \in N$  is characterized by a non-negative estimation of the mean unit travel time  $\bar{c}_{ij}$  and a non-negative unit random travel time  $c_{ijk}^s$  under the scenario  $s \in \mathcal{S}$ . Let  $e_{ijk}^s \equiv c_{ijk}^s - \bar{c}_{ij}$  be the error on the travel time estimated for the path  $k \in K_{ij}$  under time scenario  $s \in \mathcal{S}$ .

The first stage binary variables  $y_{ij} = 1$  if node  $j \in N$  is visited right after node  $i \in N$ , 0 otherwise. The second stage binary variables  $x_{ijk}^s = 1$  if path  $k \in K_{ij}$  between nodes  $i, j \in N$  is selected at the second stage, 0 otherwise. We have one more set of first stage variables  $\phi_{ij}$  which is introduced to break the subtours [14]. The non-negative continuous variables  $\phi_{ij}$  describe the flow of a single commodity to node 1 from every other nodes (without loss of generality, 1 is the starting node).

The extensive form of MPTSPs is as follows and the notations used are summarized in Table 8.

$$(\text{MPTSPs}) \min \sum_{i \in N} \sum_{j \in N} \bar{c}_{ij} y_{ij} + \sum_{s \in \mathcal{S}} \mathbb{P}(s) \sum_{i \in N} \sum_{j \in N} \sum_{k \in K_{ij}} e_{ijk}^s x_{ijk}^s \quad (7a)$$

$$\text{s.t.} \quad \sum_{j \in N: j \neq i} y_{ij} = 1, \quad \forall i \in N, \quad (7b)$$

$$\sum_{i \in N: i \neq j} y_{ij} = 1, \quad \forall j \in N, \quad (7c)$$

$$\sum_{j \in N} \phi_{lj} - \sum_{i \in N \setminus \{1\}} \phi_{il} = 1, \quad \forall l \in N \setminus \{1\}, \quad (7d)$$

$$\phi_{ij} \leq (|N| - 1) y_{ij}, \quad \forall i \in N \setminus \{1\}, \forall j \in N, \quad (7e)$$

$$\sum_{k \in K_{ij}} x_{ijk}^s = y_{ij}, \quad \forall i \in N, \forall j \in N, \forall s \in \mathcal{S}, \quad (7f)$$

$$x_{ijk}^s \in \{0, 1\}, \quad \forall i \in N, \forall j \in N, \forall k \in K_{ij}, \forall s \in \mathcal{S}, \quad (7g)$$

$$y_{ij} \in \{0, 1\}, \quad \forall i \in N, \forall j \in N, \quad (7h)$$

$$\phi_{ij} \geq 0, \quad \forall i \in N, \forall j \in N. \quad (7i)$$

The first sum in the objective function (7a) represents the first stage travel cost, while the second sum represents the recourse action, consisting in choosing the best path  $k \in K_{ij}$  under scenario  $s \in \mathcal{S}$ . The constraints (7b) and (7c) form the assignment constraints and ensure that each node is visited only once. Given the fixed values of  $y_{ij}$ , constraint (7d) and (7e) form a network flow problem, and therefore the  $\phi_{ij}$  values will be integer. In case the solutions of the above formulation contain at least one subtour, the constraints (7d) and (7e) are violated. Moreover, no tour can exist that does not contain node 1 by the two constraints. For more explanation on the subtour breaking mechanism accompanied with rigorous proof, refer to [16]. The constraint (7f) guarantees that path  $k$  between nodes  $i$  and  $j$  can be chosen at stage 2 only if nodes  $i$  and  $j$  were part of the tour fixed at stage 1. Finally, the constraints (7g)-(7i) restrict the polyhedral sets from which the variables take values.

**Table 8** Notations for MPTSPs

<b>Index sets:</b>	
$N$	index set of nodes ( $i, j, l \in N$ )
$K_{ij}$	index set of paths between nodes $i$ and $j$ ( $k \in K_{ij}$ )
$\mathcal{S}$	index set of scenarios ( $s \in \mathcal{S}$ )
<b>Parameters:</b>	
$c_{ijk}^s$	unit random travel time of path $k$ between nodes $i, j$ under scenario $s$
$\bar{c}_{ij}$	estimation of the mean unit travel time (expectation of $c_{ijk}^s$ over all $s$ and $k$ )
$e_{ijk}^s$	the error on the travel time on estimated for arc $(i, j)$ and path $k$ under scenario $s$
$\mathbb{P}(s)$	the probability of occurrence of scenario $s$
<b>Decision variables:</b>	
$\phi_{ij}$ (1 <sup>st</sup> stage)	the nonnegative real-valued flow on arc $(i, j)$
$y_{ij}$ (1 <sup>st</sup> stage)	1 if path $k$ between nodes $i, j \in N$ is selected at the second stage, 0 otherwise
$x_{ijk}^s$ (2 <sup>nd</sup> stage)	1 if node $j$ is visited just after node $i$ , 0 otherwise

### 6.5.2 Scenario data generation

We follow the scenario generation methods described through the references [11, 12, 13]. For MPTSPs, there are three mainly distinguished characteristics for each instance: the nodes partition strategy ( $D \in \{D0, D1, D2, D3\}$ , explanation on each strategy is forthcoming), the number of nodes ( $|N| \in \{2, 3, \dots\}$ ), and the number of scenarios ( $|S| \in \{1, 2, \dots\}$ ). Another important characteristic  $|K_{ij}| \in \{1, 2, 3, \dots\}$  is the number of paths for each edge which is fixed by 3 as a default following [13]. Once we decide  $D$ ,  $|N|$ , and  $|S|$  by  $D = Dx$ ,  $|N| = y$ , and  $|S| = z$ , each instance is named by MPTSPs\_Dx\_Ny\_Sz.

The nodes are distributed in a circle with radius equal to  $r$  km. We use Cartesian coordinate system where the geometric center of the circle is  $(r, r)$ . The nodes are distinguished by two subsets: *central* and *suburban*. If the Euclidean distance between a node and the geometric center is less than or equal to the half of the radius ( $r/2$ ), then the node is of *central* type. Otherwise, if the Euclidean distance is greater than the half of the radius, the node is of *suburban* type. Each arc between any two nodes  $i$  and  $j$  is either *homogeneous* or *heterogeneous*. If the two nodes are of the same type of node, i.e., both are *central* or both are *suburban*, the type of the arc is *homogeneous*. Otherwise, the type of the arc is *heterogeneous*. Later, the travel time of each path between two nodes are affected by the type of arc.

The nodes are generated by one of the following distribution strategies:

- $D0$ : All the nodes are *central*.
- $D1$ : All the nodes are *suburban*.
- $D2$ :  $3/4$  of the nodes are *central* and the remaining  $1/4$  are *suburban*.
- $D3$ :  $1/2$  of the nodes are *central* and the remaining  $1/2$  are *suburban*.

Given  $D$ ,  $|N|$  and  $|S|$ , the next procedure can be summarized as follows:

1. Generate  $|N|$  nodes based on the predetermined strategy  $D$ . Then, the nodes are generated by acceptance-rejection procedure with uniform random number generation. Again following [13], we fix  $r = 7\text{km}$ .
2. Calculate Euclidean distances between the nodes ( $EC_{ij}$ ).
3. We guess and fix the deterministic velocity profile by  $40\text{km/h}$  for the *central* nodes and  $80\text{km/h}$  for the *suburban* nodes:  $v_{ctr} = 40$  and  $v_{sbrb} = 80$ .
4. Generate random travel times ( $c_{ijk}^s$ ) for each scenario  $s$ .
  - The velocity for traveling arc  $(i, j)$  is affected by its arc type.
  - If the arc is *homogeneous*, the random travel time of all the paths are generated only based on the corresponding velocity profile.
  - If the arc is *heterogeneous*,  $\lceil \frac{|K_{ij}|}{3} \rceil$  paths are generated based on  $v_{ctr} = 40$  and the remaining paths are generated based on  $v_{sbrb} = 80$ .
  - The velocities are distributed by  $Unif(\frac{v}{2}, 2v)$  for  $v = v_{ctr}, v_{sbrb}$ .
  - In summary, if the arc  $(i, j)$  is *homogeneous*,

$$c_{ijk}^s \sim \begin{cases} \frac{EC_{ij}}{Unif(\frac{v_{ctr}}{2}, 2v_{ctr})} & \text{if } i, j \text{ are both } central, \\ \frac{EC_{ij}}{Unif(\frac{v_{sbrb}}{2}, 2v_{sbrb})} & \text{if } i, j \text{ are both } suburban, \end{cases} \quad \forall k \in K_{ij}.$$

- Otherwise, if  $(i, j)$  is *heterogeneous*,

$$c_{ijk}^s \sim \begin{cases} \frac{EC_{ij}}{Unif(\frac{v_{cntr}}{2}, 2v_{cntr})} & \text{for } k \in \left\{1, \dots, \left\lceil \frac{|K_{ij}|}{3} \right\rceil\right\}, \\ \frac{EC_{ij}}{Unif(\frac{v_{sbrb}}{2}, 2v_{sbrb})} & \text{for } k \in \left\{\left\lceil \frac{|K_{ij}|}{3} \right\rceil + 1, \dots, |K_{ij}|\right\}. \end{cases}$$

5. Finally, we multiply 3600 for each component of  $c_{ijk}^s$  to convert the unit from *hours* to *seconds*.

## 6.6 SIZES: Selection of an optimal subset of sizes

SIZES is a simplified version of the cutting stock problem with multi-period stochastic demand. In this problem, the term *period* can be exchangeably used with *stage*. The first period (first stage) demand is deterministic whereas demands for the other periods (stages) are stochastic with scenarios. We only consider the two-periods (i.e., two stage) model to follow [15] as well as the SIP of interest discussed in Section 2. In SIPLIB, only three instances are available in SMPS files. We refer to the mathematical formulation in [15] to construct JuMP.Model1. Due to some unclear explanations (or typo), we slightly modify the formulation and use it for SIPLIB 2.0.

### 6.6.1 Mathematical formulation

**Table 9** Notations for SIZES

Index sets	
$N$	index set of items $(i, j \in N)$
$T$	index set of time periods $(t \in T)$
$\mathcal{L}$	index set of scenarios $(l \in \mathcal{L})$
Parameters	
$d_{it}^l$	demand for item $i$ at time $t$ under scenario $l$
$p_i$	unit production cost for item $i$
$s$	setup cost for producing any item
$r$	unit cutting cost
$c_t^l$	production capacity at time $t$ under scenario $l$
$\mathbb{P}(l)$	the probability of occurrence of scenario $l$
Decision variables	
$y_{it}$ (1 <sup>st</sup> stage)	number of units of size $i$ produced at time $t$
$x_{ijt}^l$ (2 <sup>nd</sup> stage)	number of units of size $i$ cut to meet demand for smaller size $j$ at time $t$ under scenario $l$
$z_{it}^l$ (2 <sup>nd</sup> stage)	1 if we produce size $i$ at time $t$ under scenario $l$ , 0 otherwise

$$(\text{SIZES}) \min \sum_{t \in T} \sum_{i \in N} p_i y_{it} + \sum_{l \in \mathcal{L}} \mathbb{P}(l) \sum_{t \in T} \left( \sum_{i \in N} s z_{it}^l + r \sum_{i \in N \setminus \{1\}} \sum_{j=1}^{i-1} x_{ijt}^l \right) \quad (8a)$$

$$\text{s.t.} \sum_{i \in N} y_{it} \leq c_t^l, \quad \forall t \in T, \forall l \in \mathcal{L}, \quad (8b)$$

$$\sum_{i=j}^{|N|} x_{ijt}^l \geq d_{jt}^l, \quad \forall j \in N, \forall t \in T, \forall l \in \mathcal{L}, \quad (8c)$$

$$\sum_{t'=1}^t \sum_{j=1}^i x_{ijt'}^l \leq \sum_{t'=1}^t y_{it'}, \quad \forall i \in N, \forall t \in T, \forall l \in \mathcal{L}, \quad (8d)$$

$$y_{it} \leq c_t^l z_{it}^l, \quad \forall i \in N, \forall t \in T, \forall l \in \mathcal{L}, \quad (8e)$$

$$y_{it} \in \mathbb{Z}_+, \quad \forall j \in N, \forall t \in T, \quad (8f)$$

$$x_{ijt}^l \in \mathbb{Z}_+, \quad \forall i \in N, \forall j \in N, \forall t \in T, \forall l \in \mathcal{L}, \quad (8g)$$

$$z_{it}^l \in \{0, 1\}, \quad \forall i \in N, \forall t \in T, \forall l \in \mathcal{L}. \quad (8h)$$





### 6.6.2 Scenario data generation

## 6.7 SUCW: Stochastic unit commitment problem with wind power

### 6.7.1 Mathematical formulation

$$\min \sum_{\sigma \in \mathcal{S}} \mathbb{P}(\sigma) \sum_{t \in T} \sum_{g \in G} \left( C_g^{\text{fx}} x_{gt}^\sigma + C_g^{\text{up}} u_{gt}^\sigma + C_g^{\text{dn}} v_{gt}^\sigma + \sum_{k \in K} C_{gk}^{\text{mar}} q_{gkt}^\sigma \right) \quad (9a)$$

$$\text{s.t. } 1 - x_{g(t-1)}^\sigma \geq u_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9b)$$

$$x_{g(t-1)}^\sigma \geq v_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9c)$$

$$x_{gt}^\sigma - x_{g(t-1)}^\sigma = u_{gt}^\sigma - v_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9d)$$

$$x_{gt}^\sigma \geq \sum_{\tau=\max\{1, t-UT_g+1\}}^t u_{g\tau}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9e)$$

$$1 - x_{gt}^\sigma \geq \sum_{\tau=\max\{1, t-DT_g+1\}}^t u_{g\tau}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9f)$$

$$-RD_g \leq p_{gt}^\sigma - p_{g(t-1)}^\sigma \leq RU_g - s_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9g)$$

$$s_{gt}^\sigma \leq RC_g x_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9h)$$

$$\sum_{g \in G} s_{gt}^\sigma \geq SR_t, \quad \forall \sigma \in \mathcal{S}, t \in T, \quad (9i)$$

$$p_{gt}^\sigma = P_g^{\min} x_{gt}^\sigma + \sum_{k \in K} q_{gkt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9j)$$

$$p_{gt}^\sigma + s_{gt}^\sigma \leq P_g^{\max} x_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9k)$$

$$q_{gkt}^\sigma \leq Q_{gk}^{\max} x_{gt}^\sigma, \quad \forall \sigma \in \mathcal{S}, g \in G, k \in K, t \in T, \quad (9l)$$

$$\sum_{g \in G} p_{gt}^\sigma = \sum_{n \in N} D_{nt}^\sigma - \sum_{w \in W} W_{wt}^\sigma, \quad \forall \sigma \in \mathcal{S}, t \in T, \quad (9m)$$

$$\begin{aligned} -F_l^{\max} &\leq \sum_{g \in G} LSF_{lg} p_{gt}^\sigma - \sum_{n \in N} LSF_{ln} D_{nt}^\sigma \\ &\quad + \sum_{w \in W} LSF_{lw} W_{wt}^\sigma \leq F_l^{\max}, \quad \forall \sigma \in \mathcal{S}, l \in L, t \in T, \end{aligned} \quad (9n)$$

$$x_{gt}^{\sigma_1} = x_{gt}^{\sigma_2}, u_{gt}^{\sigma_1} = u_{gt}^{\sigma_2}, v_{gt}^{\sigma_1} = v_{gt}^{\sigma_2}, \quad \forall \sigma_1, \sigma_2 \in \mathcal{S}, g \in G, t \in T, \quad (9o)$$

$$x_{g0}^\sigma = X_g^{\text{init}}, \quad \forall \sigma \in \mathcal{S}, g \in G, \quad (9p)$$

$$x_{gt}^\sigma = 1, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in \{1, \dots, UT_g^{\text{init}}\}, \quad (9q)$$

$$x_{gt}^\sigma = 0, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in \{1, \dots, DT_g^{\text{init}}\}, \quad (9r)$$

$$p_{g0}^\sigma = P_g^{\text{init}}, \quad \forall \sigma \in \mathcal{S}, g \in G, \quad (9s)$$

$$x_{gt}^\sigma, u_{gt}^\sigma, v_{gt}^\sigma \in \{0, 1\}, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T, \quad (9t)$$

$$p_{gt}^\sigma, q_{gkt}^\sigma, s_{gt}^\sigma \geq 0, \quad \forall \sigma \in \mathcal{S}, g \in G, t \in T. \quad (9u)$$

**Table 10** Notations for the SUCW

<b>Index sets:</b>	
$G$	index set of all generators ( $g \in G$ )
$G_s$	index set of slow generators ( $g \in G_s$ )
$G_f$	index set of fast generators ( $g \in G_f$ )
$K$	index set of linear segments of the piece-wise linear power generation cost ( $k \in K$ )
$L$	index set of transmission lines ( $l \in L$ )
$N$	index set of buses ( $n \in N$ )
$T$	index set of time periods ( $t \in T$ )
$W$	index set of wind power generators ( $w \in W$ )
$S$	index set of scenarios ( $\sigma \in S$ )
<b>Parameters:</b>	
$C_g^{\text{up}}$	start-up cost of generator $g$
$C_g^{\text{dn}}$	shut-down cost of generator $g$
$C_g^{\text{fix}}$	fixed cost of operating the generator $g$
$C_g^{\text{mar}}$	$k^{\text{th}}$ marginal cost of production of generator $g$
$X_g^{\text{init}}$	initial on/off status of generator $g$
$UT_g^{\text{init}}$	initial minimum uptime of generator $g$
$UT_g$	minimum uptime of generator $g$
$DT_g^{\text{init}}$	initial minimum downtime of generator $g$
$DT_g$	minimum downtime of generator $g$
$RU_g$	ramp-up limit of generator $g$
$RD_g$	ramp-down limit of generator $g$
$RC_g$	ramping capacity of generator $g$
$P_g^{\text{init}}$	initial power output of generator $g$
$P_g^{\text{min}}$	minimum power output of generator $g$
$P_g^{\text{max}}$	maximum power output of generator $g$
$Q_{gk}^{\text{max}}$	maximum power output of generator $g$ with the $k^{\text{th}}$ marginal cost
$SR_t$	spinning reserve required at time $t$
$F_l^{\text{max}}$	maximum power flow of transmission line $l$
$LSF_{ln}$	load-shift factor of transmission line $l$ with respect to bus $n$
$\mathbb{P}(\sigma)$	probability of scenario $\sigma$
$D_{nt}^{\sigma}$	demand load at bus $n$ at time $t$ in scenario $\sigma$
$W_{wt}^{\sigma}$	wind power generation from generator $w$ at time $t$ in scenario $\sigma$
<b>Decision variables:</b>	
$x_{gt}^{\sigma}$	on/off indicator of generator $g$ at time $t$ in scenario $\sigma$
$u_{gt}^{\sigma}$	start-up indicator of generator $g$ at time $t$ in scenario $\sigma$
$v_{gt}^{\sigma}$	shut-down indicator of generator $g$ at time $t$ in scenario $\sigma$
$p_{gt}^{\sigma}$	power output of generator $g$ at time $t$ in scenario $\sigma$
$q_{gkt}^{\sigma}$	power output of generator $g$ at time $t$ with the $k^{\text{th}}$ marginal cost in scenario $\sigma$
$s_{gt}^{\sigma}$	spinning reserve of generator $g$ at time $t$ in scenario $\sigma$

### 6.7.2 Scenario data generation

## 7 Solution report

## 8 Concluding remarks

(not finished yet) Any further contribution or suggestions for SIPLIB 2.0 are always welcomed. Better solutions than discovered so far, more functions, more

problems with Julia scripts for instance generation, more effective classification rules, etc.

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