Supplier Network Configuration and Contingency Planning Considering Multiple Demand Points and Supplier Failures

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Abstract

This paper deals with the optimal allocation of demand across a set of suppliers given the risk of suppliers' failure to deliver. We consider items that are used in multiple facilities (demand points) and that can be purchased from multiple suppliers with different cost and reliability characteristics. Suppliers have production flexibility that allows them to deliver a contingency quantity in case other suppliers fail. Costs considered include supplier fixed costs and variable costs per unit, while failure to deliver to a demand point results in a financial loss particular to that demand point. The model considers all the possible states of nature when one or more suppliers fail. The model results in a base allocation to one or more of the available suppliers and a state of nature specific delivery contingency plan from the suppliers to each demand point. A numerical example, as well as sensitivity analyses, is presented to illustrate the model and provide insights.

Keywords: Supplier selection, Order allocation, Supply chain risk management, Decision trees, Mathematical programming

1. INTRODUCTION

The emergence of globalization and the extended enterprise has significantly changed the competitive environment in many industries. Initially, many companies responded by setting up manufacturing facilities in low-cost regions. Later, traditional supply sources also started to shift to sources in the low-cost regions. However, the rising wages, tightening regulations and increasing transportation costs in the past few years have resulted in the need to redesign the supply chain of many companies (Lee, 2009).

Several observers and analysts believe that we have entered a new era, referred to as the "multi-polar world" – a world with multiple pockets of demand sources, supply sources, as well as sources of innovation (Foster, 2008; Lee, 2009). In this new era, globalization is no longer a one-way street where the multinational companies based in developed countries view the emerging regions only as sources of low-cost manufacturing and supply. In several emerging economies the middle class has gained critical mass and possesses sufficient disposable income to buy many consumer products. As a result many multinational companies have started to incorporate their facilities in the low-cost regions into the global manufacturing network and building distribution networks to reach millions of consumers in the emerging economies to expand and develop new markets. More recently, the leading multinationals have abandoned their stand-alone business models to pursue the "one-world strategy" by locating research/product development, manufacturing, sourcing, distribution and marketing in the most appropriate locations in the globe (Tse, 2010).

The pursuit of the "one-world strategy" has resulted in new challenges. For example, increasing supply chain risk has emerged as a major concern for both practitioners and researchers. Therefore, supply chain risk management aimed at developing approaches to identify, assess, analyze and develop contingency plans to effectively deal with supply chain disruptions has gained significant importance and attention (Neiger *et al.* 2009). Supply chain risk management approaches generally consider supplier attributes or the supply chain structure to determine appropriate mitigation and response strategies (Oke and Gopalakrishnan, 2009; Trkman and McCormack, 2009). Thus, the ability to identify the suppliers that have the greatest potential for failure and the decision on options to increase the allocation of other suppliers (i.e., emergency production) in case of the failure are both critical in today's turbulent environment.

We consider sourced items that are used in multiple facilities, referred to as demand points, and that can be purchased from multiple suppliers. For example, a smart phone manufacturer that is sourcing batteries could use suppliers in San Diego, Hong Kong and Shanghai to supply its manufacturing plants in Juarez, Manila, Bangalore and Shenzhen. Figure 1 illustrates the considered network configuration of multiple suppliers and demand points.

Each supplier has different cost and reliability characteristics, and the shipping cost is unique for each source-destination combination. The model combines the characteristics of the problems studied by Berger *et al.* (2004) and Ruiz-Torres and Mahmoodi (2007) with the traditional transportation problem and provides contingency plans for each failure scenario. In other words, our model blends decision-tree concepts with mathematical programming. The context and the environment considered is an important research area in the framework of global supply chain design (Meixell and Gargeya, 2005) and relevant to many companies in various industries given today's global sourcing strategies.

< Insert Figure 1 about here >

The remainder of the paper is organized as follows. The literature on supplier selection and order allocation, as well as on supplier risk management is reviewed in the next section. Then, we formally describe the model and our analysis approach in Section 3. This is followed by the presentation of a set of numerical examples used to describe the model and the associated sensitivity analyses to gain further insights in Section 4. Finally, conclusions and managerial implications, as well as directions for further research are presented in Section 5.

2. LITERATURE REVIEW

We classify existing efforts related to our research into two categories: (1) studies that consider both supplier selection and order allocation decisions; and (2) studies that analyze risks associated with supply networks. In what follows we provide a review of the literature.

2.1 Supplier Selection and Order Allocation

The importance of supplier selection and order allocation decisions has consistently attracted a great deal of attention over the past several decades, and the scholars have applied a range of Operations Research (OR) techniques to arrive at optimal solutions under various decision-making configurations. The "order allocation" is alternatively referred to as "lot-sizing" in the literature. A comprehensive review article by Aissaoui *et al*. (2007) surveys and classifies the works that employ OR and computational models to study the final selection stage that consists of determining the best mixture of vendors and allocating orders among them so as to satisfy different purchasing requirements.

Since the publication of this review paper, new efforts have attempted to address the subject by considering more complicated supplier characteristics, demand uncertainty, and costs, as well as utilizing more advanced OR techniques. For example, the work by Burke *et al.* (2008) studies how to allocate order quantity among suppliers that not only have capacity limitations, but also offer alternative discounts. Due to the complexity of the problem, heuristics are developed and extensive computational experiments are conducted to understand the impacts of the supplier's pricing strategy on the order allocation decision. The other effort by Mendoza and Ventura (2008) considers the impact of transportation on both supplier selection and inventory replenishment decisions. The authors propose a mixed integer nonlinear programming model to properly allocate order quantities to the selected set of suppliers while taking into account the purchasing, holding and transportation costs. To account for tangible, intangible, quantitative, and qualitative factors simultaneously in selecting suppliers and defining the optimal order quantity assigned to each, Ozgen *et al.* (2008) use a combination of Analytic Hierarchy Process (AHP) and multi-objective linear programming. Furthermore, to accommodate the uncertain elements of the decision-making process, a fuzzy-based model featured by a possibilistic linear programming (PLP) is adopted for finding the optimal solutions.

Awasthi *et al.* (2009) consider the supplier selection problem with uncertain demands, where each supplier has a unique price and limited capacity. The authors describe the problem properties, propose a solution algorithm, and evaluate the performance of the algorithm in a small experimental set. Basnet and Weintraub (2009) consider the bi-criteria problem of minimizing the number of suppliers and minimizing the acquisition cost. They model the problem as a Mixed Integer Program (MIP) where issues such as quality, demand, capacity, and delivery performance are incorporated as constraints. Given the size of the problem, the authors propose a multi-population, genetic algorithm for generating Pareto-optimal solutions, and then test this algorithm using solutions generated by MIP and Monte Carlo simulation. The study by Lin (2009) develops a comprehensive decision method for identifying top suppliers by considering the effects of interdependence among the selection criteria while achieving optimal allocation of orders among the selected suppliers. The decision method integrates fuzzy theory, analytic network process (ANP), and multi-objective linear programming. Zhang and Ma (2009) present a mixed integer nonlinear programming (MINLP) formulation of the problem, for both single- and multiple-sourcing procurement policies.

More recent research efforts are characterized by developing integrated approaches and by taking multiple criteria into account. Representative studies include Azadeh *et al.* (2010), who formulate a Fuzzy Data Envelopment Analysis (Fuzzy DEA) model and then a multi-objective integer programming with fuzzy objectives and fuzzy constraints to assign an optimal order quantity to each supplier. Also, Ho *et al*. (2010) provide an in-depth review of the multi-criteria decision making approaches for supplier selection. Finally, Razmi and Rafiei (2010) propose a model comprising an analytic network process (ANP) sub-model to qualify and select suppliers, and present a mixed-integer non-linear sub-model to simultaneously allocate order quantities to the chosen suppliers.

2.2 Supplier Selection and Order Allocation under Supply Risk

As today's supply chains rely heavily on suppliers and the structure of supply networks is becoming increasingly complex, the risks and uncertainties inherent to each supply network have received a great deal of attention over the past decade. As a result, research on supply risk management has been growing rapidly in recent years. One important issue examined by Kovács and Tatham (2009) is the capabilities of supply networks defined by different resource configurations to manage large-scale attacks. Rao and Goldsby (2009) provide further analysis by synthesizing the diverse literature into a typology of risk sources, consisting of environmental, industry, organizational, problem-specific, and decision-maker related factors. A final typology that can be used by managers to measure and assess the vulnerabilities of their company and supply chain is devised.

Recently, a number of researchers have pursued studies that consider risks in supplier selection and order allocation decision analysis. For example, a study by Shin *et al.* (2009) considers the supplier's risks from two dimensions – quality and delivery performance; in particular, a probabilistic cost model in which suppliers' quality performance is measured by inconformity of the end product measurements and delivery performance is estimated based on the suppliers' expected delivery earliness and tardiness. Such a sourcing policy decision tool can help companies determine an optimum set of suppliers considering the risk factors. Hou, *et al*. (2010) study two kinds of risk – supply disruption and recurrent supply uncertainty, and investigates how to work with a backup supplier through a buy-back contract under each of those risks to ensure continuous flow of supplies. The buy-back contract and the buyer's decision on the optimal order quantity under each risk are obtained and analyzed. Lockamy and McCormack (2010) present a methodology for analyzing risks in supply networks to facilitate outsourcing decisions. The methodology includes the development of a risk profile for a given supplier through the creation of Bayesian networks, which can be used to analyze a supplier's external, operational and network risk probabilities, and the associated revenue impact on the organization. Another recent study by Sawik (2010) investigates the problem of allocating orders for custom parts among suppliers in a make-to-order manufacturing environment, where the selection of suppliers is based on price and quality of purchased parts and supplier's reliability of on-time delivery. The risk of defective or unreliable supplies is controlled by the maximum number of delivery patterns (combinations of suppliers' delivery dates) for which the average defect rate or late delivery rate can be unacceptable, and the quantity or volume discounts offered by the suppliers are also considered. The decision problem is formulated as a single- or multi-objective mixed integer program. Meena et al. (2011) address the problem of determining the number of

suppliers under risks of supplier failure due to catastrophic events disruption considering different failure probability, capacity, and capacity specific compensation potential.
The authors propose an algorithm that finds the optimal number of suppliers assuming an equal allocation among those selected and under two different objective functions; minimizing the total costs subject to a target service level, and maximizing the service level subject to a budget constraint (total costs).

Our paper differs from the existing research in the following three aspects. First, we consider the supplier selection and order allocation problem in the context of a classic transportation network with multiple supply sources and a set of separate demand points, where each supplier not only has limited capacity, but also a probability of failure to provide required quantity when selected. Secondly, we present a decision-tree based method for quantifying and calculating the reliability of the entire supply network given each supplier's probability of failure. Finally, our modeling and analysis approach accommodates and facilitates both decisions in network configuration and contingency planning.

3. MODEL DESCRIPTION

This section provides a formal presentation of the problem and the proposed model. There are s possible suppliers, $S = \{1, \dots s\}$ and n demand points that consume the material being procured, $N = \{1, \dots, n\}$. Each demand point k has a required demand in number of units, d_k, and failure to deliver to a demand point results in a per unit financial loss l_k. Let a_h be the number of units allocated to supplier h. Each supplier has maximum capacity (m_h) and a flexibility factor (i.e. b_h). The maximum capacity limits the number of units that a supplier can produce per cycle, while the flexibility factor is used to model the ability of the suppliers to deliver a larger amount than their allocation when other suppliers fail. For example, if $a_h = 50$, $b_h = 40\%$, and $m_h = 100$, this supplier could produce up to 70 units in a cycle if other suppliers fail (50 x 1.4). However, if m_h = 60, then this supplier could produce up to 60 units.

There is a per-unit cost to transport from supplier h to demand point k, t_{hk}. Each supplier h is characterized by a probability of failure (i.e. p_h) that represents a supplier shutdown (e.g., equipment failure, quality problem, lack of raw materials). Each supplier h is characterized by two costs; a variable cost per unit, c_h, and a fixed cost, f_h, which represent the costs of maintaining the supplier. Furthermore, let e_h be the premium charged by supplier h when delivering units above their baseline allocation. The model considers all the possible states of nature (SN) given the number of possible suppliers, s, and given each supplier can either deliver or fail to deliver the number of possible states of nature is 2^s. Let v be the number of state of nature, $V = \{1, \ldots, v\}$. For a state of nature g, let $w_{gh} = 1$ if supplier h will deliver, and let $w_{gh} = 0$ if it fails to deliver.

Each state of nature has a separate set of flow quantities from the suppliers in S to the demand points in D. Therefore, the amount of material that flows from each supplier to each demand point is particular to each state of nature. Let q_{ghk} be the number of units that flow from supplier h to demand point k for state of nature g. Let u_{gk} represent the number of units not delivered to a demand point k for state of nature g. A list of the notation and symbols used throughout the paper is given below:

- *Decision Variables*

  z_h A binary variable; 1 if supplier h is active, 0 otherwise.

  a_h Allocation of demand to supplier h in number of units.

  q_{ghk} Quantity flowing from supplier h to demand point k during state of nature g.

- *Input Parameters*

p_h Probability that supplier h will not deliver (supplier failure)

m_h Maximum output capacity for supplier h.

b_h Flexibility factor for supplier h.

c_h Variable cost per unit for supplier h.

f_h Fixed management cost for supplier h.

e_h Variable premium cost per unit for supplier h.

d_k Demand in units for demand point k.

t_{hk} Per-unit cost to transport from supplier h to demand point k.

l_k Loss cost per unit for failure to deliver to demand point k.

u_{gk} Unsatisfied demand (in units) for demand point k during state of nature g.

w_{gh} Binary variable related to the delivery condition of supplier h during state of nature g; 1 if the supplier is delivering, 0 if it fails to deliver.

The model considers all the possible state of nature combinations given s suppliers. Each state of nature has a probability r_g determined as:

$$r_g = \prod_{h \in S} [(1 - w_{gh})\ p_h + w_{gh}\ (1 - p_h)]. \tag{1}$$

There are four costs that are state of nature dependent: flow or transportation costs (fc_g), base variable costs (vc_g), premium variable costs (pc_g), and loss costs (lc_g). The flow costs are based on the number of units that flow between each source-demand point combination. The base variable costs consider all the units that are sourced from a particular supplier under a state of nature, including those that are part of the supplier's original allocation and those that were produced due to other supplier failures. The premium variable costs consider those units sourced by a supplier above its baseline allocation. The loss costs consider the number of units not delivered to a demand point, given the particular flow decisions for that state of nature. The flow costs, base variable costs, premium variable costs and loss costs for state of nature g are determined as:

$$fc_g = \sum_{h\in S\, k\in N} t_{hk}\, q_{ghk} \tag{2}$$

$$vc_g = \sum_{h\in S\, k\in N} c_h\, q_{ghk} \tag{3}$$

$$pc_g = \sum_{h\in S} e_h\, w_{gh}\, (\sum_{x\in N} q_{ghk} - a_h) \tag{4}$$

$$lc_g = \sum_{k\in N} u_{gk}\, l_k \tag{5}$$

The only cost that does not depend on the state of nature is the supplier management fixed cost (sc), determined as:

$$sc = \sum_{h\in S} z_h f_h \tag{6}$$

The total costs (tc) for this model are determined as in equation (7). The objective of the model is to minimize total costs.

$$tc = sc + \sum_{g\in V} r_g\, (fc_g + vc_g + pc_g + lc_g) \tag{7}$$

Table 1 presents the model's constraints including a brief explanation. The complexity of the model is defined by 2^s x n x s linear variables and by s binary variables.

< Insert Table 1 about here >

4. NUMERICAL EXAMPLES AND SENSITIVITY ANALYSES

A numerical example is presented to illustrate the model and provide further insights. The example is loosely based on an observed case for a global manufacturer of appliances. There are three demand points (i.e., manufacturing/assembly plants) and five suppliers with significant geographical dispersion. The supplier information is provided in Table 2, the flow costs and demand information are provided in Table 3.

< Insert Tables 2 & 3 about here >

The proposed model was implemented in Excel ® in combination with Frontline's premium Solver (Frontline Systems, 2011) and Visual Basic for Applications. The Excel/Solver/Visual basic tool found a solution for the described problem case (and all additional instances discussed later in this section) in less than 5 seconds using a personal computer with a Pentium V processor.

As an initial condition let's assume there is no contingency planning in place; therefore shipments from suppliers to demand points do not change if suppliers fail. This further implies there will be no emergency production. In this environment, the best solution is an allocation to two suppliers; 1,500 units to s[4], and 900 units to s[5]. Given two suppliers are selected there are only four possible SN: all suppliers deliver, only s[4] fails, only s[5] fails, and both s[4] and s[5] fail. Figure 2 presents the decision tree representation with the corresponding values for the delivery condition variables (w_{gh}), the non-zero probabilities components of r_g, and the resulting probabilities per state of nature. The resulting flow quantity variables, probabilities, and costs for each state of nature are presented in Figure 3. The expected costs are $72,827.

< Insert Figures 2 and 3 about here>

When all of the contingency characteristics are included; flexibility to ship to any demand point and emergency production, the optimal solution uses four suppliers. The allocations are 533, 557, 839, and 471 units, respectively, for suppliers s[2], s[3], s[4], and s[5] (note that in this discussion we will present allocation results as integer values although the values found by the model were in most cases non-integer values). When four suppliers are used there are a total of sixteen possible SN: all suppliers deliver; s[2] fails; s[3] fails; s[4] fails; s[5] fails; s[2] and s[3] fail; s[2] and s[4] fail; s[2] and s[5] fail; s[3] and s[4] fail; s[3] and s[5] fail; s[4] and s[5] fail; s[2], s[3], and s[4] fail; s[2], s[4], and s[5] fail; s[3], s[4], and s[5] fail; and all fail.

Figure 4 presents five SN (those with 0 or 1 supplier failing), while Figure 5 presents the six SN with two suppliers failing. The remaining four SN are not presented for the sake of brevity and given the total probability for these six states is 0.02%. For each state of nature the figure includes the probability, costs, and units not delivered. Also, note that in all cases where one or more suppliers failed, all "operational suppliers" produced to their maximum flexibility. In other words, when supplier s[2] failed, s[3], s[4], and s[5] produced 56, 336, and 141 extra units, respectively (allocation x flexibility factor).

< Insert Figures 4 and 5 about here>

The expected total cost for this plan is $61,903, a reduction of 17%. As observed in Figure 4, the current set of plans is able to meet the demand requirements in most states of nature with a single supplier failure. In only one of the four states of nature with one supplier failing (presented in Figure 4) the demand is not satisfied (when s[4] fails), although when two suppliers fail (Figure 5) the demand can never be fully satisfied. While not shown, it is obvious that the demand cannot be met when three suppliers fail, and no deliveries occur when all suppliers fail.

4.1 Sensitivity Analysis for Supplier s[1]

This section focuses on how the characteristics of supplier s[1] affect the resulting solutions, in particular its reliability and flexibility characteristics. Figure 6 illustrates the baseline configuration with $p_{s[1]}$ = 9%, 6%, 0.5% and 0.1%. As the reliability of supplier s[1] improves, its baseline assignment increases (as expected). At $p_{s[1]}$ = 6% it replaces supplier s[3] as part of the supplier set and as its reliability increases its allocation increases. It is important to note that even when it becomes the most reliable supplier, allocation of the demand is still distributed across multiple suppliers. Also, as its reliability increases the number of arcs decreases (from 6 to 5 as $p_{s[1]}$ change from 6% to 0.5%), and the number of suppliers decreases (from four to three suppliers; supplier s[5] no longer receives an allocation when $p_{s[1]}$ = 0.1%).

< Insert Figure 6 about here >

The second parameter investigated in the sensitivity analysis was the flexibility factor, focusing on its interaction with the failure probability. Figures 7 and 8 present the effect of this parameters on the allocation to supplier s[1] and the total cost. The effect here is interesting as the allocation to supplier s[1] and the total cost are clearly related to the interaction of flexibility and reliability, and in different tendencies. When supplier s[1] was unreliable ($p_{s[1]}$ = 6%), having more flexibility increased it allocation; from 0 at the low flexibility levels (< 15%) to about 20% of the total requirements (about 500 units) at $b_{s[1]}$ = 40%. This is explained by s[1] being able to provide a larger number of units in contingency situations at the lowest premium cost, reducing expected loss costs. At the next reliability level ($p_{s[1]}$ = 1%), supplier s[1] has an allocation even with 0 flexibility. As the flexibility increased, its allocation increased, however as its flexibility increased beyond the 20% level, its allocation actually decreased. We note that after the 20% flexibility level its “flexible capacity” (allocation x flexibility factor) stayed constant at about 260 units. This indicates the “best flexibility level” for this supplier when considering all the possible SN and the solutions that at this reliability level the number of suppliers used stays constant at 4. We propose that based on this result (and other observations) that loss costs are minimized when suppliers reach a “best flexibility level” based on the probability of the different SN with failures, in particularly those SN with higher probabilities.

< Insert Figures 7 and 8 about here >

When $p_{s[1]} = 0.5\%$, the allocation to supplier s[1] starts at 900 at the 0 flexibility level (it is the supplier with the highest allocation), its allocation increases to 1,524 units at 5% flexibility, and then decreases from this point on until it reaches the 35% flexibility level, where it increases again. As in the $p_{s[1]} = 1\%$ level, the allocation decreases but the flexibility capacity stays constant at about 200 units (flexibility from 15% to 30%). At 35% flexibility, the solution changes from 4 active suppliers to 3, thus the "best flexibility level" for a supplier is based on the number of suppliers in the active set. The final level of reliability ($p_{s[1]} = 0.1\%$) provides another interesting set of insights. Under this condition, supplier s[1] becomes the sole source for the network when it has no flexibility (or 5%), and as its flexibility increased it received a smaller allocation. It is interesting to note that as the flexibility of s[1] increased, the number of active suppliers changed: 1 supplier at $b_{s[1]} = 0\%$ and 5%, 4 suppliers at $b_{s[1]} = 10\%$; 3 suppliers at $b_{s[1]} = 15\%$ to 35%, and 2 suppliers at $b_{s[1]} = 40\%$, and supplier s[1] was in all cases an active supplier. When $p_{s[1]} = 0.1\%$ the loss and premium costs are a very small percentage of the total costs, thus the optimal decision is closely related to the balancing of fixed and transportation costs.

4.2 Sensitivity Analysis: Simultaneous Change for All Suppliers

As a second set of experiments we consider a modification to all of the supplier's characterization. We assume all suppliers now have a flexibility of 5% and we consider three reliability levels. The first level (*base*) is the same as the initial case (values in Table 2), the second called *high* has higher failure probabilities for each supplier than the *base* level and the *low* level where all suppliers have a lower failure probability value than the base case (*high* level: $p_{s[1]} = 15\%$, $p_{s[2]} = 9\%$, $p_{s[3]} = 12\%$, $p_{s[4]} = 7\%$, $p_{s[5]} = 8\%$; *low* level: $p_{s[1]} = 5\%$, $p_{s[2]} = 2\%$, $p_{s[3]} = 3.5\%$, $p_{s[4]} = 1\%$, $p_{s[5]} = 1.5\%$).

The allocation to suppliers in the *base* failure case (with all suppliers at 5% flexibility) is 114, 1386, 900 for s[2], s[4] and s[5], respectively, and resulting in a total expected cost of $71,759. When we compare this solution to the original one (each supplier having independent flexibilities, presented in Figure 3), the cost has increased by 16%, thus the benefit of flexible suppliers is clearly measurable. Figure 9 illustrates the results for the 0 and 1 failure SN. Besides the increase in cost, the change in flexibility resulted in a reduction in the number of active suppliers (from 4 to 3) and in less dispersed distribution as supplier s[4] now receives a significantly larger allocation, while supplier s[2] receives a significantly smaller allocation.

The allocation to the suppliers when we consider the higher failure probability values is 114, 114, 1,386 and 786 for s[2], s[3], s[4] and s[5], respectively, with a total expected cost of $112,174. This significant increase in total cost is expected as less reliable suppliers will result in an increase in expected loss costs. Figure 10 illustrates the results for the 0 and 1 failure SN. Compared to the *base* case with 5% flexibility the number of suppliers increases, with 114 units previously assigned to s[5] now being assigned to s[2]. This result, an increase in the number of suppliers as their reliability decreases, has been described in previous research such as Ruiz-Torres and Mahmoodi (2007) and Sawik (2011). When we compare this solution to the original one it can be noted that while the supplier set is the same, the allocation with less flexibility has a much higher level of dispersion with suppliers s[2] and s[3] receiving relatively small allocations.

The allocation at the *low* failure level is 1,429 and 971 for suppliers s[4] and s[5], respectively, with a total expected cost of $61,451. As expected, more reliable suppliers result in lower total expected costs; in particular as expected loss costs are much lower. Figure 11 illustrates the results for the 0 and 1 failure SN. Compared to the *base* case with 5% flexibility the number of suppliers decrease, with most of s[2]'s allocation given to s[5]. Thus, it is shown that increases in reliability can offset flexibility losses, and as in previous studies, increases in reliability results in fewer suppliers.

< Insert Figures 9-11 about here >

5. CONCLUSIONS AND FUTURE WORK

Global sourcing strategies have enabled many organizations to take advantages of resources and production capacities located in different parts of the world. With numerous perceivable benefits come various pitfalls and challenges when it comes to managing such global supply chains, one of which is how to cope with supplier risks and develop contingency plans when supply failures are noticeably present or readily measurable.

This paper focuses on determining the optimal supply allocation and contingency planning in supply networks with multiple sources and a set of separate demand points, which are frequently observed in today's global supply chains. The capacity of each supplier and demand quantity at each demand point are known information, and the per-unit transportation cost on each supply-demand combination is also available. The optimal supply allocation decision aiming at minimizing the total transportation costs can be solved as classic transportation problems, where each supplier is assumed to be completely reliable. This research expands the traditional transportation model by taking each supplier's failure probability and flexible capacity, as well as more complicated cost structures into consideration. Our model blends decision-tree concepts with mathematical programming and the solutions provide guidelines for multiple decisions, including the allocation quantities that best utilize available suppliers' flexible capacities, the number of suppliers needed to best satisfy the demand quantities, and how to balance between each supplier's reliability and its flexibility.

This work can be extended from at least two directions. The first direction is to study a more complicated network structure; for example, supply chains with intermediate points, and/or with one single demand point (for those products that are assembled in one location). The second research direction is to consider more complicated supplier performance portfolio; for instance, commonly used attributes such as lead time, quality, and price can be included in each supplier's performance metric, in addition to reliability and flexibility considered in this paper.

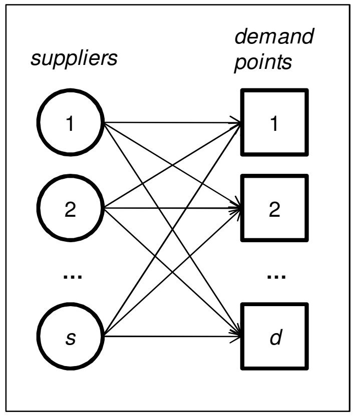

Figure 1: Basic Problem Configuration

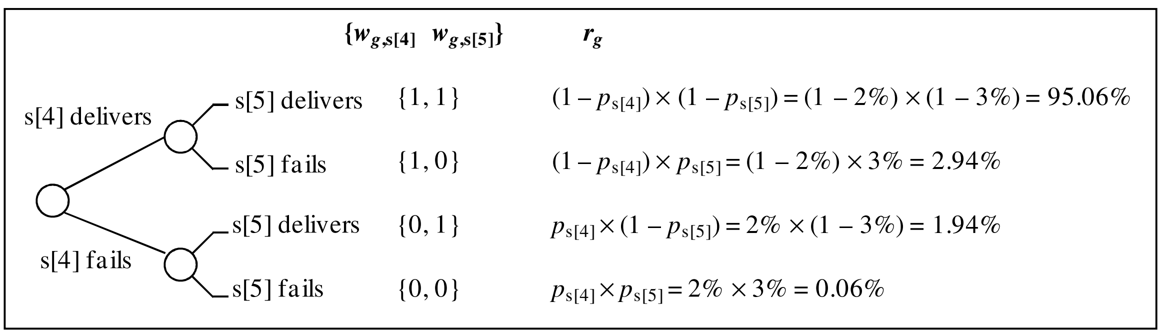

Figure 2: Decision Tree for the Case of No Contingency Planning
($p_{s[4]} = 2\%$, $p_{s[5]} = 3\%$)

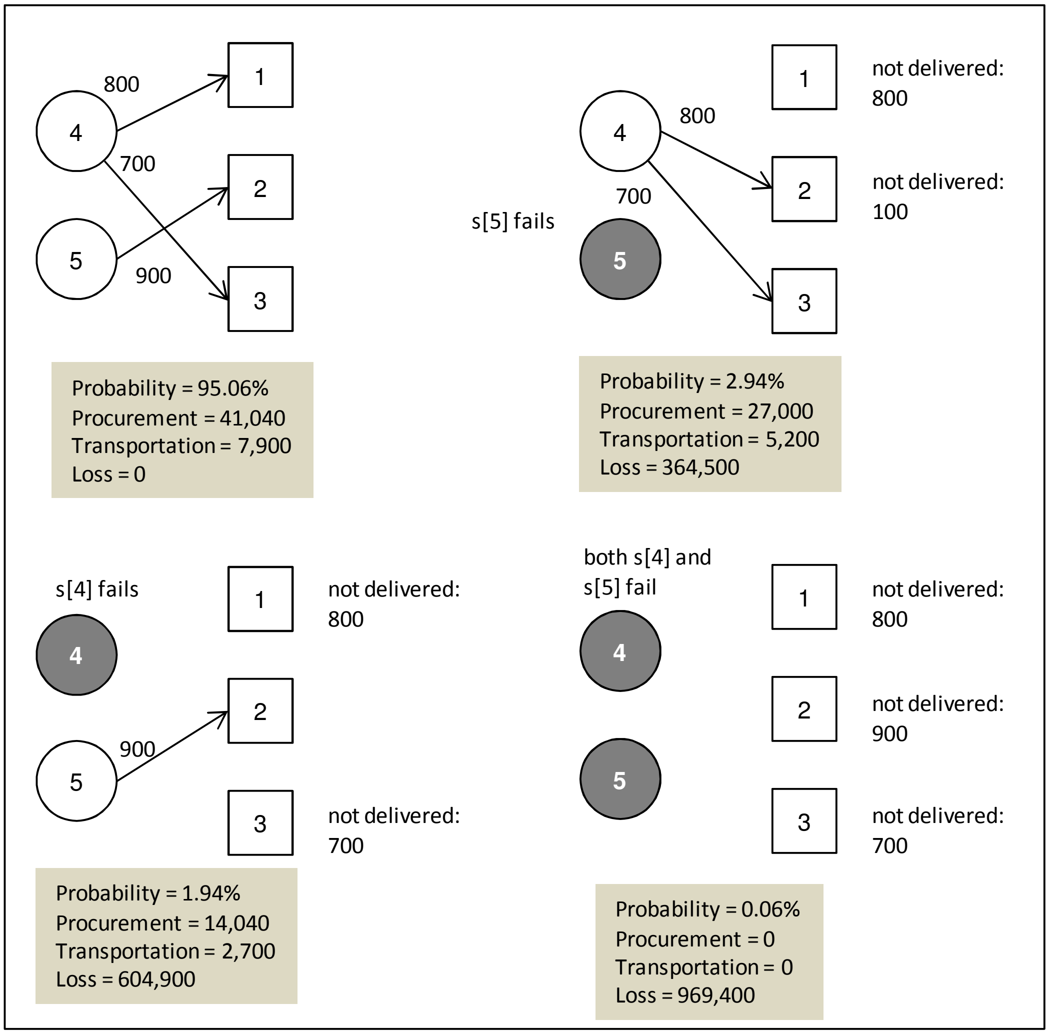

Figure 3: Optimal Solution with No Contingency Planning

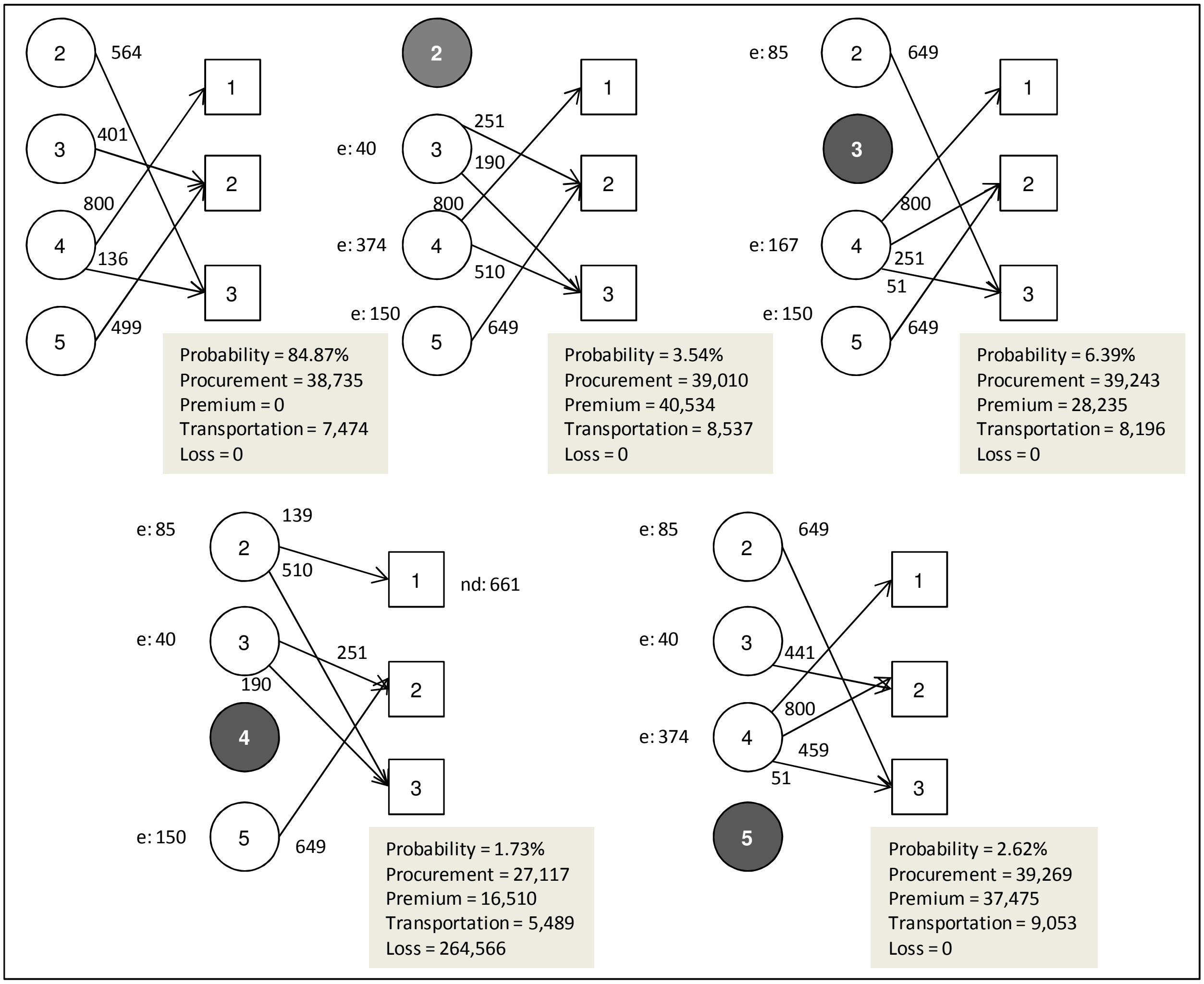

Figure 4: Solution Based on the Proposed Model (States of Nature with 0 or 1 Supplier Failure)

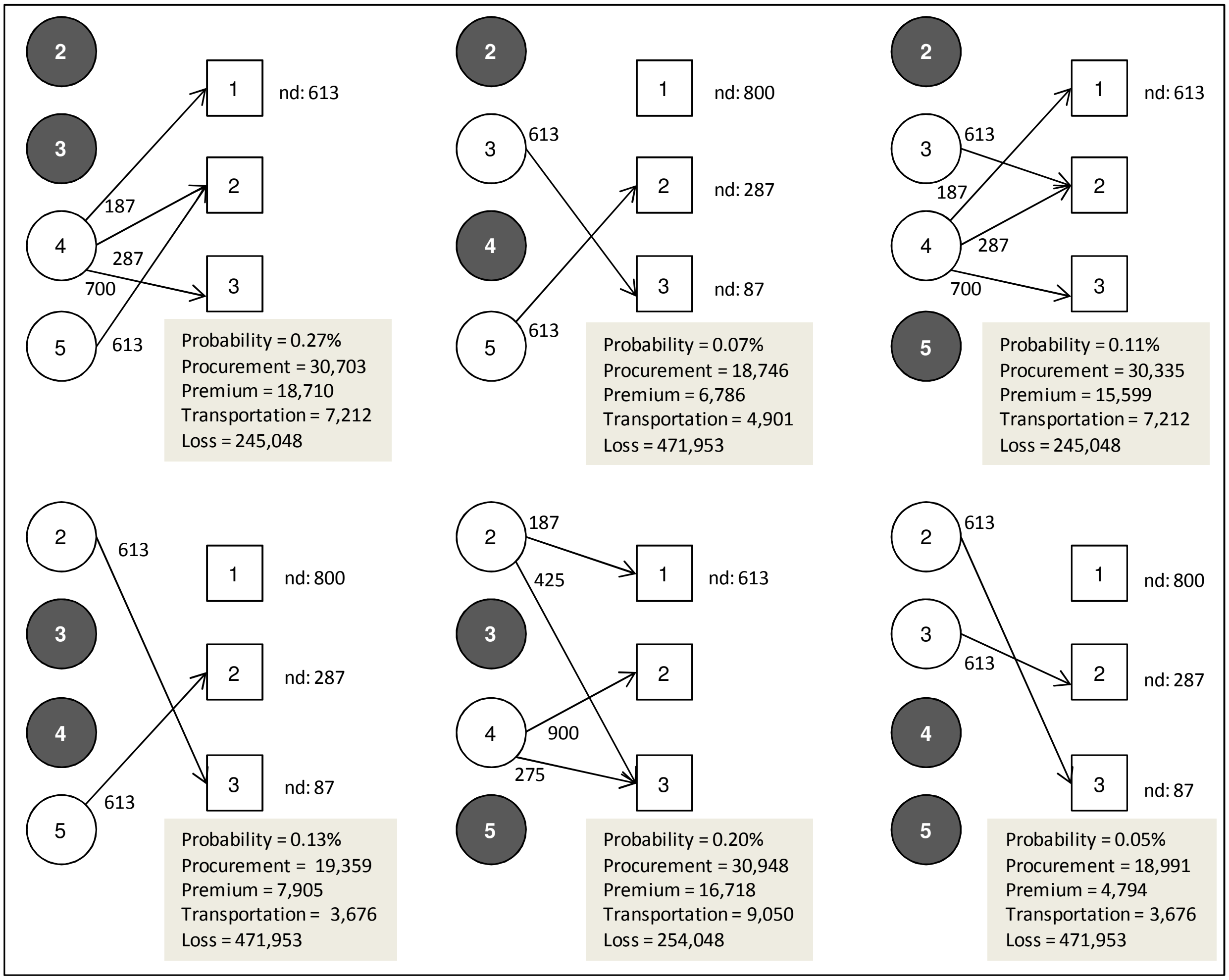

Figure 5: Solution Based on the Proposed Model (States of Nature with 2 Suppliers Failing)

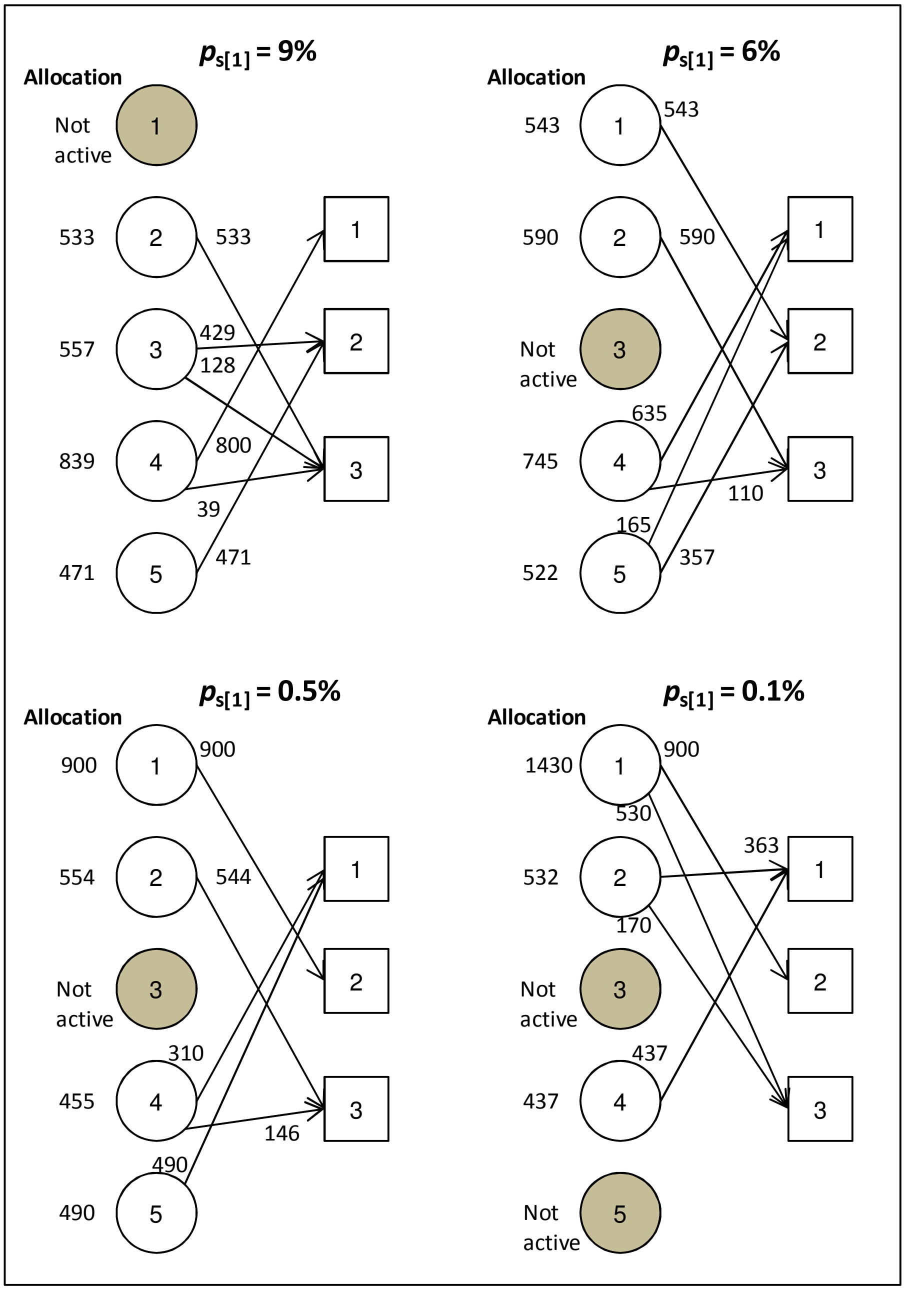

Figure 6: Baseline Configurations as the Reliability of Supplier s[1] is Changed

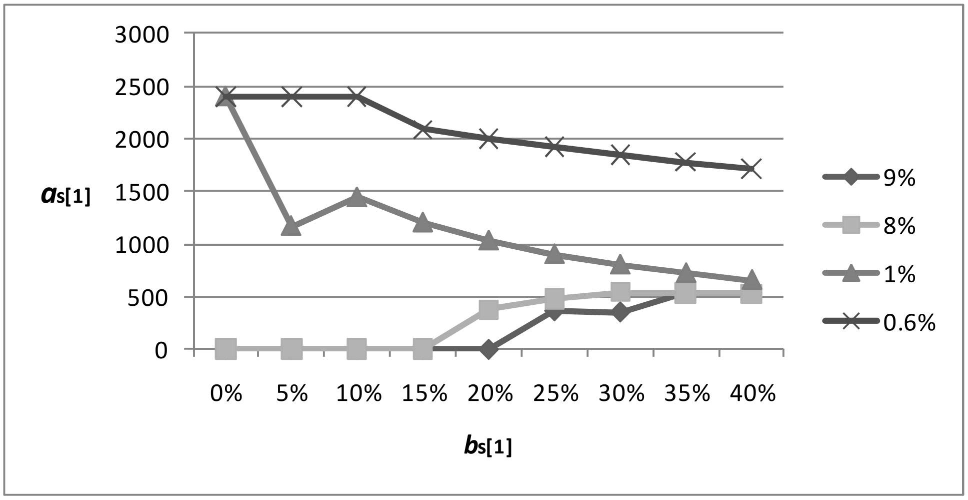

Figure 7: Allocation to Supplier s[1] vs. the Flexibility and Reliability of Supplier s[1]

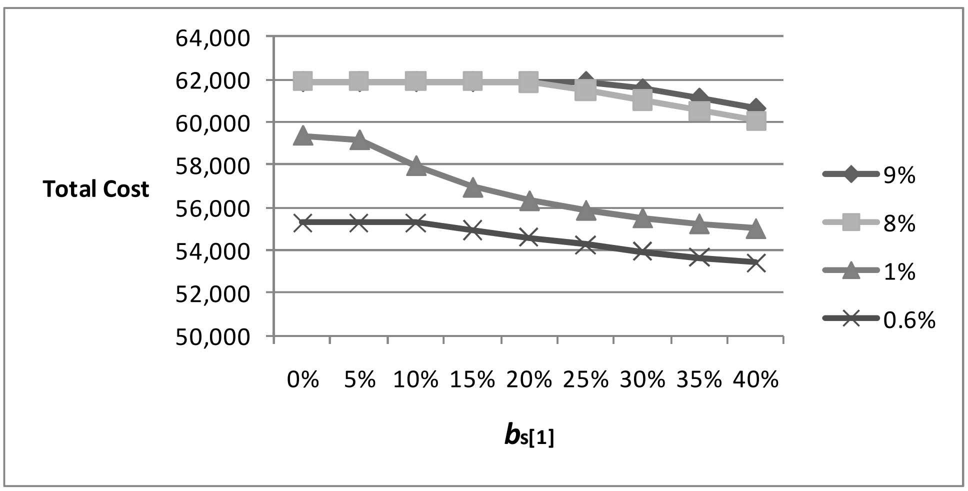

Figure 8: Total Expected Costs vs. the Flexibility and Reliability of Supplier s[1]

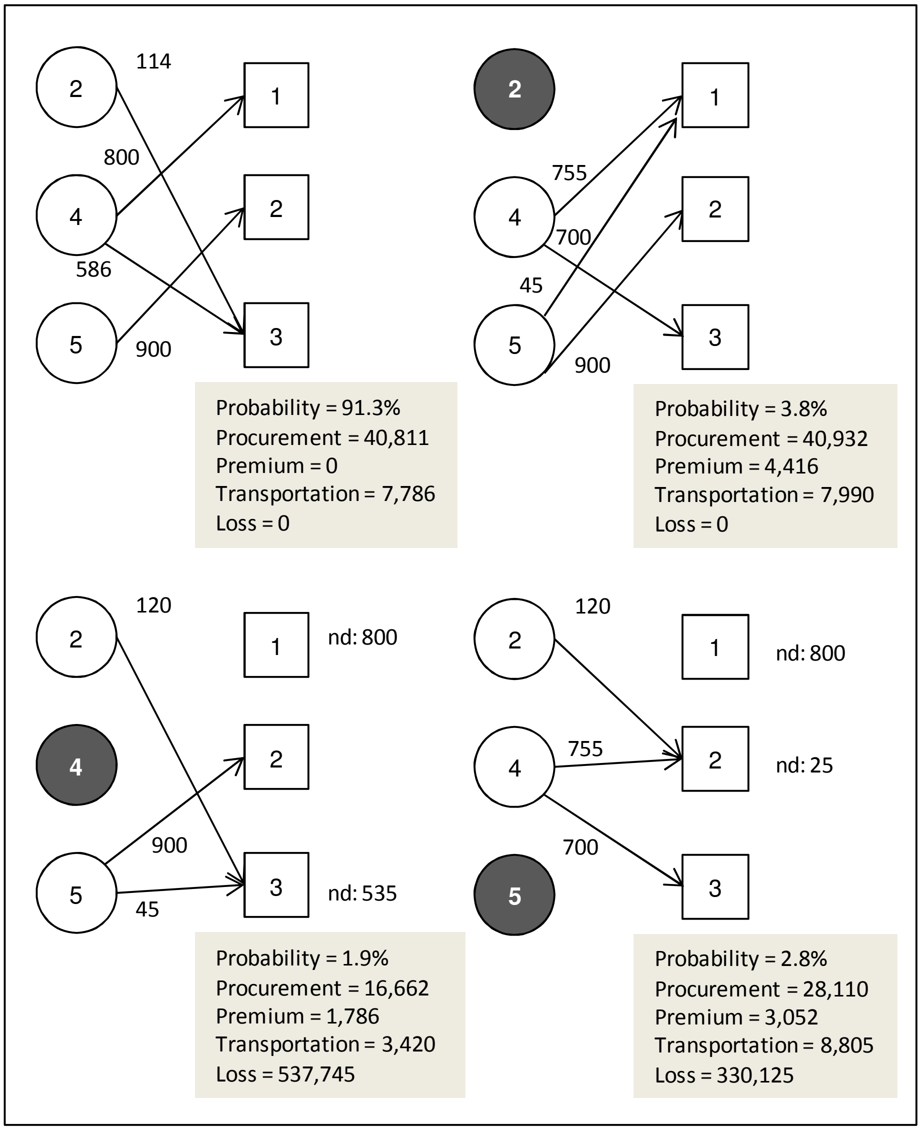

Figure 9: Solution with the *Base* Failure Level and All suppliers at 5% Flexibility (States of Nature with 0 or 1 Supplier Failure)

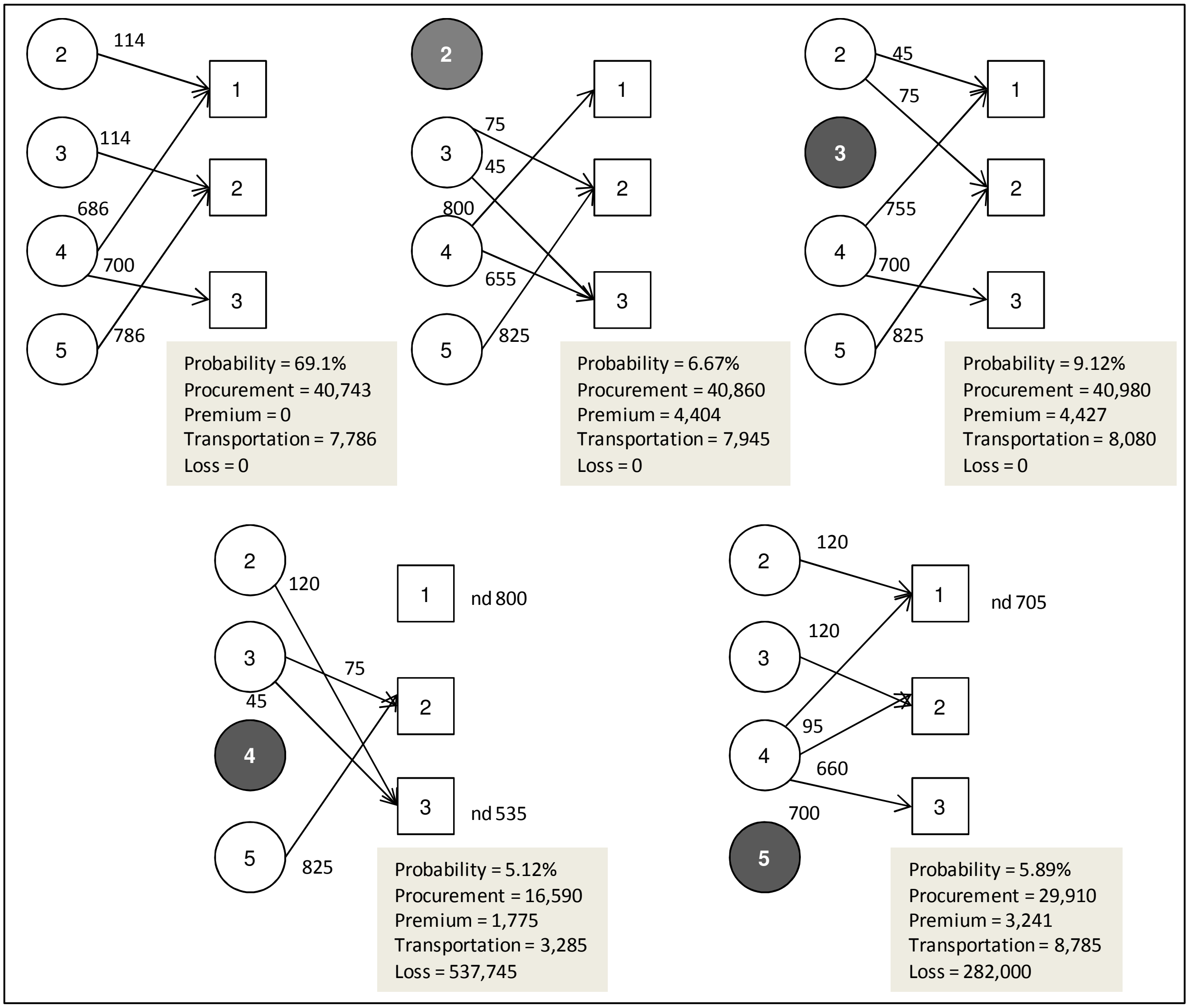

Figure 10: Solution with the *High* Failure Level and All Suppliers at 5% Flexibility (States of Nature with 0 or 1 Supplier Failure).

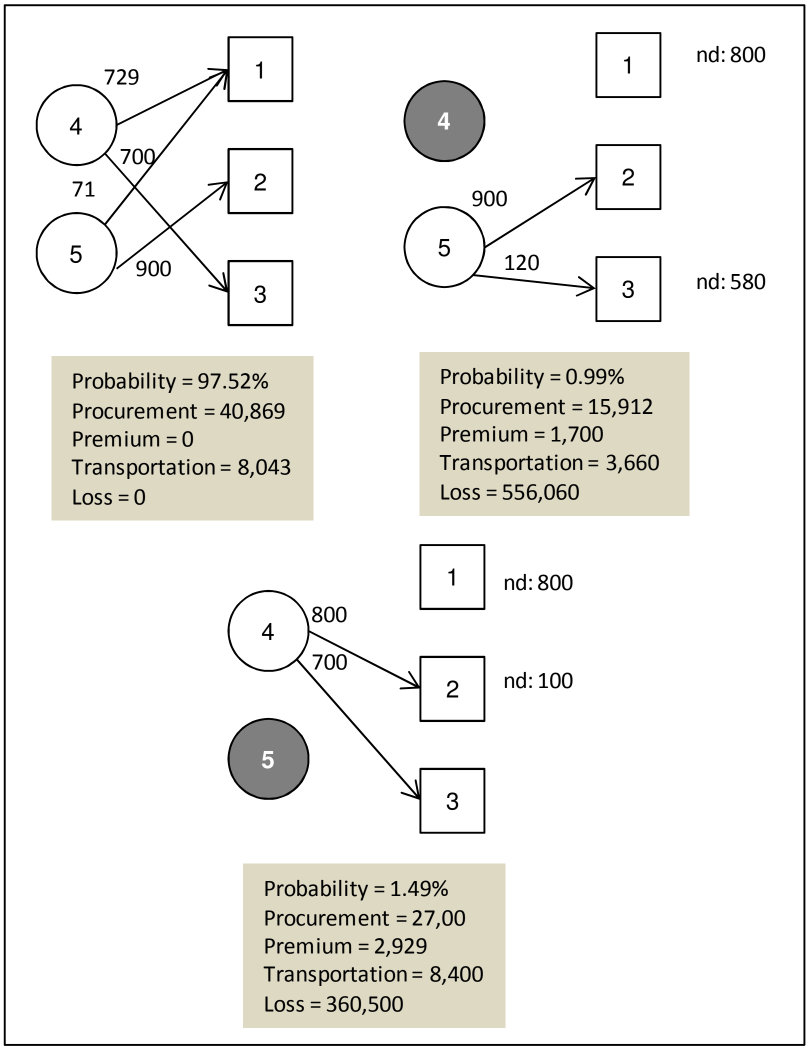

Figure 11: Solution with the *Low* Failure Level and All Suppliers at 5% Flexibility (States of Nature with 0 or 1 Supplier Failure).

Table 1: Model Constraints

Constraint		Description
$\sum_{k\in N} q_{ghk} \leq m_h\, w_{gh}$	$\forall\, g \in V, \forall\, h \in S$	Outflow from a supplier cannot exceed its capacity; if a supplier does not delivery in that state of nature ($w_{gy} = 0$), then it has 0 capacity.
$a_h\,(1 + b_h) \leq m_h\, w_{gh}$	$\forall\, g \in V, \forall\, h \in S$	The allocation to a supplier modified by the flexibility factor cannot exceed its capacity; if a supplier will not delivery in that state of nature ($w_{gy} = 0$), then it has 0 capacity.
$\sum_{k\in N} q_{ghk} \leq a_h\,(1 + b_h)$	$\forall\, g \in V, \forall\, h \in S$	Outflow from a supplier cannot exceed the allocation modified by the flexibility factor.
$\sum_{x\in N} q_{ghk} \geq\ a_h\, w_{gh}$	$\forall\, g \in V, \forall\, h \in S$	Outflow from a supplier must be at least the allocation if the supplier is delivering.
$\sum_{h\in S} q_{ghk} =\ u_{gk} + d_k$	$\forall\, g \in V, \forall\, k \in N$	Inflow to a demand point equals the demand and the unsatisfied demand.
$a_h \leq\ z_h\, m_h$	$\forall\, h \in S$	Used to determine the active suppliers based on an allocation greater than zero.
$\sum_{h\in S} a_h =\ \sum_{k\in N} d_k$		Sum of the assignment to the suppliers must equal the sum of the demands.
$z_h = \{0,1\}$	$\forall\, h \in S$	Binary variable.
$q_{ghk} \geq 0$	$\forall\, g \in V, \forall\, h \in S, \forall\, k \in N$	Non negativity.
$u_{gx} \geq 0$	$\forall\, g \in V, \forall\, k \in N$	
$a_y \geq 0$	$\forall\, h \in S$	

Table 2: Supplier Information

	Supplier				
	s[1]	s[2]	s[3]	s[4]	s[5]
Maximum output	2,500	1,500	2,000	1,500	2,000
Per item cost ($/unit)	14.5	16	15	17	15.6
Flexibility rate	25%	15%	10%	40%	30%
Premium rate ($/unit)	30	37	33	41	35
Failure probability	10%	4%	7%	2%	3%
Fixed costs	1,000				

Table 3: Flow Costs and Demand Information

	Supplier						
Demand Point	s[1]	s[2]	s[3]	s[4]	s[5]	Requirements	Unit Loss
d[1]	11	2	5	3	5	800	400
d[2]	5	6	3	7	3	900	405
d[3]	9	3	5	4	8	700	407

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