Modeling Robust and Reliable Supply Chains

Markus Bundschuh (markus.bundschuh@web.de)
Diego Klabjan (klabjan@uiuc.edu)
Deborah L. Thurston (thurston@uiuc.edu)

University of Illinois at Urbana-Champaign

December 11, 2006

Abstract

We present formulations for the strategic design of robust and reliable supply chains with long-term contracting. The inability to deliver a supply part due to unexpected events in a complex supply chain can significantly impact on the performance of a supply chain. Reliable and robust supply chains leverage cost and risk of not obtaining a supply. Reliable chains are less likely to be disrupted, whereas robust chains still perform well in the case of disrupted supply channels. We consider a multi-echelon inbound supply chain of a manufacturer and we embed aspects of reliability and robustness into traditional supply chain models. Models that embed reliability, consider contingency supply, and use multiple suppliers yield the best trade-off among cost, robustness, and reliability. We provide computational results documenting trade-offs among robustness, reliability, and cost.

1 Introduction

Supply chains are complex, dynamic and in many cases global. Supply chains, particularly global supply chains, are exposed to a large variety of risks, which compromise the performance of suppliers and the supply chain as a whole. These risks include, for example, natural disasters, strikes, and terrorist attacks. A failure of a supplier or a subsystem results in a loss of supply or in the worst case in a total disruption of the supply chain.

In highly competitive environments, supply chain disruptions can have a severe if not existential impact on the success of the companies involved. Competitive advantage implies the ability to provide products to customers at any time. Lost sales, decreased market share and large contractual penalties are possible results of disruptions.

The inability of a supplier to provide the necessary amount of supply can have a major impact on the profitability of the entire supply chain. Martha and Vratimos (2002) and Sheffi (2005) give various examples of companies that encountered severe problems when their supply chains were disrupted. The U.S. car manufacturer Ford experienced severe disruptions in transportation caused by the terror attacks of September 11. Ford had to shut down five manufacturing sites in the U.S. for several days because they ran out of supply. The result was a 13% decrease in manufactured cars in the fourth quarter of 2001. Lester (2002) gives another example of supplier problems where Land Rover was unprepared when a major supplier of a crucial component went bankrupt. An earlier example is the earthquake of September 21, 1999 in Taiwan, which caused severe supply problems to the computer manufacturer Apple. The destruction of major suppliers of semiconductor components delayed the production of the iBook and the Power Macintosh G4 desktop computers during a period of market growth. By contrast, DaimlerChrysler and Continental Teves were better prepared. These two companies had contingency plans and alternative transportation modes for their supplies to which they could resort to when their supply chains were disrupted after September 11. Navas (2003a) gives an example of car manufacturers, which have started to build up pools of secondary suppliers to mitigate the risk of failures of primary suppliers.

These cases illustrate the inability of traditionally-designed supply chains to deal with disruptions due to unanticipated events. Traditional models for the strategic design of supply chains focus on cost-efficiency of the system, thus not considering redundancies in the form of inventories and multiple supplier arrangements and developing long-term relationships with a smaller supplier base, Nahmias (2001). Just-in-time supply chains have become a de facto standard in many industries. These chains, however, are based on the assumption that every element in the supply chain will always perform as planned. But what happens if this were not the case? How severely do supplier failures impact the supply chain efficiency?

While these questions have already been addressed in some other industries (e.g., the telecommunication industry), there are untapped opportunities in supply chain designs. The discussion about reliability and robustness of supply chain networks has gained momentum mainly after September 11, which has led to an increased perception of risk and vulnerability in general as well as in today's production-distribution systems. However, so far, only a few research publications have appeared that present analytical models in this direction. The goal of our work is to fill this gap by exploring approaches and models for the strategic design of robust and reliable supply chains and evaluating them in terms of robustness, reliability, and cost.

We focus on the design of inbound supply chains that incorporate reliability and robustness. To the best of our knowledge, we are the first ones to give analytical models for the inbound supply chain design that embed cost, reliability, and robustness. We introduce two novel concepts:

- supply chains with low probabilities of supplier failures, and
- supply chains with emergency buffers and contingency supply.

We explore the trade-offs among cost, reliability, and robustness.

In Section 2 we present the models for robust and reliable supply chains in detail. In Section 3 we introduce a case study, evaluate the proposed models, and discuss the results of the different models. We conclude the introduction by explaining basic concepts and by giving a review of the related literature.

1.1 Concepts

We define *reliability* as the probability that a system or a component performs its specified function as intended within a given time horizon and environment. A system consisting of different components can only perform as intended if every component fulfils its system-relevant functions. In other words, reliability refers to the probability of the absence of failures affecting the performance of the system over a given time interval and under given environmental conditions, Kuo and Zuo (2003), Andrews and Moss (2002).

In the context of supply chain management, supplier (component) and supply chain (system) reliability have to be distinguished. Supplier reliability refers to the probability that the supplier operates as planned during the planning horizon. In our work, we define failure as the inability of a supplier to ship any required quantity of materials to its customers for a certain duration of time. Failures result from various reasons, such as strikes, destruction of production facilities (e.g., due to a fire), natural disasters, sabotage, terrorism or war. Similarly we define failure of a region or a set of suppliers, i.e., the inability of all suppliers in the set to deliver required quantities. Typically supplier disruptions are dependent and failures of sets or regions of suppliers capture these dependencies.

The term supply chain reliability is used to express the probability that a supply chain can completely fulfill the demand for a final product without any loss of supply resulting from failures of suppliers. Thus, any supplier failure compromises supply chain reliability.

We assume that a supplier either delivers zero or the full amount of its designated supply over a specified time horizon. Let r_v denote the unconditional reliability of supplier v over a given time period. This time period is typically much shorter than the planning time horizon. The unconditional failure probability of supplier v is then $p_v = 1 - r_v$. Let G be the set of all regions and let $\tilde{r}_j$ denote the reliability of region j. A region is a subset of suppliers. The supply chain reliability is defined by expression

$$R = \prod_{\text{suppliers } v} r_v \cdot \prod_{j \in G} \tilde{r}_j \ . \tag{1}$$

We assume that the reliabilities of regions are independent. Then R accurately models reliability, which can be easily established by conditioning.

Robustness, on the other hand, deals with the impact of failures on the performance of a system. The term robustness can be defined in many ways, depending on the specific context. For an overview of working definitions of robustness see for example the report by the Santa-Fe Institute (2001). We define robustness as the extent to which a system is able to perform its intended function relatively well in the presence of failures of components or subsystems. In the context of our work, we use robustness to describe how much the output of a supply chain is affected by supplier failures. Output refers to the amount of products that are manufactured during the planning horizon. The failure of a supplier interrupts the downstream material flow originating from the failed supplier and leads to a reduction of the overall available supply for the production of the final product. Thus, robustness assesses the reduction of the output, whereas reliability can be used to quantify the likelihood of a reduction of any magnitude. Robustness of a supply chain cannot be as easily quantified as reliability. We capture two aspects of supply chain robustness that we also quantify. The first one being the number of supplier failures before a supply chain is completely disrupted. The second is the standard deviation of the output, which is a common measure for risk-induced variability of performance indicators. However, the standard deviation is strongly influenced by reliability as well.

1.2 Literature Review

Supply chains face various sources of risk. Besides manufacturing processes and customer demand, Davis (1993) identifies the performance of suppliers as a major source of risk which influences the efficiency of a supply chain. Van der Vorst et al. (1998) name order forecast horizon, input data, administrative and decision processes as well as inherent uncertainties depending on the typology of the supply chain as major risk clusters. Van Landeghem and Vanmaele (2002) present a list of various sources of uncertainty that endanger the efficiency of global supply chains and indicate the most appropriate supply chain planning level to address them.

In the supply chain management literature, risk has been addressed mainly on the tactical planning level focusing on uncertainty of demand or lead-times. Safety stocks are the means to reduce the effects of these types of uncertainties. For an overview of the vast literature on safety stock see for example the survey articles by Axsäter (1993), Federgruen (1993), Inderfurth (1994), van Houtum et al. (1996) or Diks et al. (1996).

In distribution systems, warehouses between manufacturers and retailers are used to buffer lead-time or demand uncertainties. Schwarz and Weng (2000) provide recent references on the risk pooling literature. A comprehensive review of earlier references on this subject can be found in Schwarz (1989).

Van Landeghem and Vanmaele (2002) introduce a robust planning approach to tactical supply chain planning under uncertainty. Monte Carlo simulation is used to characterize joint distributions of performance outcomes to allow for better decision-making, e.g., in terms of safety stock levels or for the identification of uncertain factors with large impacts on the supply chain performance.

Among the extensive literature on strategic supply chain design only few authors consider the design of supply chains under different aspects of uncertainty. For a literature review on strategic supply chain design, we refer to the survey articles of Vidal and Goetschalckx (1997) and Goetschalckx (2000). Literature on reliability or robustness of supply chain networks is even scarcer. Vidal and Goetschalckx (2000) present a survey of stochastic elements that have been included by various authors in models for global supply chain design. Most of these analytical models address mainly financial risks, such as exchange rate fluctuations or uncertain market prices, see e.g., Hodder and Dincer (1986), Huchzermeier (1991) and Huchzermeier and Cohen (1996).

Vidal and Goetschalckx (2000) present an approach that includes supplier reliability as a design criterion. A constraint is formulated which guarantees that the probability of all suppliers of critical materials of being on time satisfies at least a given target probability at each plant in the network. This concept is formulated only for the case that all suppliers directly ship to the manufacturing plants.

Sheffi (2001) suggests dual supply arrangements in a strategic supply chain design. Except for a small illustrative example, no analytical formulations for a strategic supply chain model are provided. The author also opts for the installation of strategic emergency stock in the supply chain. Again, no analytical formulations for the integration of this concept into strategic design models are given.

Snyder and Daskin (2003) introduce a facility location model, which performs well under both normal operating conditions and when distribution centers in the network fail. Retail nodes in a distribution system are assigned to a hierarchy of distribution centers. If a distribution center on a higher level in this hierarchy fails, the retailer will then be served by the one on the next lower stage.

Thiele and Bertsimas (2004) propose a robust model for lot-sizing. The uncertainty is with respect to demand but the underlying model is deterministic.

Numerous business cases related to disruptions in supply chains are given in Sheffi (2005). On several occasions the book illustrates different consequences of companies facing failures of identical suppliers. Companies with contingency plans and adequate processes in place usually capture a significant market share over their less prepared competitors. Several business cases arose after the disaster caused by hurricane Katrina. Wal-Mart's agile and adaptable supply chain enabled the company to access the devastating areas earlier than the Federal Emergency Management Agency and the Red Cross were able to (see e.g., Waller (2005)). Selected well prepared companies were much quicker to shift their logistics operations from the devastated areas.

Though the literature on supply chain management lacks on the topic of network robustness and reliability, this has been discussed extensively in the literature on the design of survivable telecommunication networks. Survivable networks are defined as networks that are still functional after a failure of certain network components (see e.g., Soni and Pirkul (2000)). Network and cost structure of these networks, however, differs significantly from those of supply chain networks. The focus of survivable communication networks is to ensure the connectivity of the network in case of failures, which is clearly not an objective in supply chain design problems.

2 Models for Robust and Reliable Supply Chains

The goal of this work is to create a robust and reliable, yet economical, inbound supply chain for a manufacturer of a given final product. We consider an integrated multi-echelon supply chain comprised of multiple production stages for the components of either the final product or other intermediary components. We focus on long-term contracting of supply arrangements for a strategic planning horizon.

Our models for the strategic design of robust and reliable supply chains build upon a base model, which is a fairly standard model for strategic supply chain design. The objective of the base model is to minimize production and fixed costs subject to constraints for meeting the demand of the final product, flow balancing, and production capacity limitations. This model does not incorporate aspects of reliability or robustness.

A model for supply chains with increased reliability is obtained by adding a constraint to the base model, which specifies that the supply chain reliability (1) be larger than a given target reliability. Robustness of a supply chain can be improved by building redundancy into the system. A model with additional suppliers is obtained by adding constraints, called the *supplier sourcing limits*, to the base model that enforce bounds on the amount of supply a customer can source from a single supplier. These limits impose using several suppliers instead of a single one, which clearly creates more reliable and robust supply chains. In addition, we develop a contingency supply model. This model does not only reduce the risk of failing completely by having additional suppliers, but it also accounts for a partial compensation of the loss.

While the reliability model, according to our definition, focuses only on the occurrence of failures but does not consider the supply reduction, robustness, on the other hand, is primarily concerned with the amount of supply still available in the presence of failures, but it disregards the likelihood of such an event. It is clearly desirable to combine both concepts into a joint reliability-robustness model for the design of supply chains, which is obtained by adding both supplier sourcing limit and target supply chain reliability constraints to the base model.

2.1 Problem Statement

Our main assumptions are as follows.

1. A supplier or a region of suppliers either deliver full quantity or zero.

2. The probability of a supplier or a regional failure over a time period does not depend on the actual time in the planning horizon. For example, if the failure time period is two weeks, then the failure probability is the same in any two week time period.
3. This probability is independent of the history. For example, if the failure time period is two weeks, the failure probability for a two week time period in December is the same as the failure probability for a two week time period in January, regardless of already occurred failures.
4. We focus on a single final product with a single critical component, of which a shortage results in an interruption of the production process.
5. The external demand occurs only at the manufacturing plant and it is assumed to be constant throughout the planning horizon.

The fourth assumption is made for ease of exposition and it can easily be dropped by augmenting the models to allow multiple products and components. On the other hand, the first three assumptions can not be dropped in the current framework. The last assumption is discussed later and it can be dropped.

Given a set of possible suppliers, the task is to design an inbound supply chain for a manufacturer, leveraging reliability, robustness, and cost. We denote by N the set of all suppliers, which for ease of notation includes the manufacturer. N is partitioned in k stages S_i, $i \in \{1, ..., k\}$. A stage consists of all possible suppliers for a specific product, required as a component for the manufactured product on the succeeding stage. We represent the problem on a network. The nodes of the network correspond to suppliers N. We denote by $n \in N$ the final manufacturer node, which by definition is on stage S_k. An arc $e = (u, v)$ corresponds to a feasible supply channel from supplier u to customer v (which is potentially a supplier to other nodes). We denote by A the set of all arcs and let I_v, O_v denote all incoming, outgoing arcs of node v, respectively.

We assume that there is a single manufacturing plant. This is without loss of generality since if there are several manufacturing plants, a new dummy manufacturing plant is added, which is supplied by the true manufacturing plants. Such a transformation allows also to model manufacturing plants that can fail.

Component manufacturers, which consist of the nodes on intermediate stages S_i, $i \in \{2, ..., k-1\}$, are simultaneously suppliers (to the nodes on the next stage) and customers (to the nodes on the previous stage). Thus, a node $u \in S_i$, $i \in \{1, ..., k-1\}$ is connected to the nodes on the succeeding stage S_{i+1}. By definition, $O_n = \emptyset$ and $I_v = \emptyset$ for all $v \in S_1$.

With every arc $e \in A$, a unit cost for production cp_e, a unit cost for transportation ct_e, and fixed costs for an open supply channel f_e are associated. The fixed costs can include, for example, administrative and overhead cost for establishing and maintaining supplier-customer relations. For ease of exposition, we do not consider fixed costs associated with the nodes. In most practical situations, these costs can be included in the supply chain related fixed costs. Such an extension is straightforward. The manufacturer has to meet an aggregated demand of D units of the final product over the strategic planning horizon.

2.2 Base Model

The base model is a deterministic mixed integer programming model. It has two types of decision variables. For every arc $e \in A$, the binary variable Y_e is one, if this link is used in the supply chain and zero, if it is inactive. The continuous variable X_e represents the amount of units flowing along arc e. A flow $X_e > 0$ can only be assigned to an arc if it is active, i.e., $Y_e = 1$.

The objective function of the base model is to minimize the total production, transportation and fixed costs, given by:

$$\sum_{e \in A} \left[\left(cp_e + ct_e \right) \cdot X_e + f_e \cdot Y_e \right]. \tag{2}$$

For every $v \in \bigcup_{i=2}^{k} S_i$, let α_v be the bill-of-materials parameter that expresses how many input units are required for the production of one output unit. The sum of the incoming material flows to the final manufacturer node must equal the aggregated demand D, multiplied by the bill-of-materials parameter, which is expressed as

$$\sum_{e \in \mathrm{I}_n} X_e = \alpha_n \cdot D. \tag{3}$$

Nodes on intermediate stages S_i, $i \in \{2, ..., k-1\}$ are technically transshipment nodes, for which the total flow into each node has to equal the total flow out. The supply inputs to these nodes are transformed into component flows to the next stage, considering the bill-of-materials relationship. The following flow balancing constraints

$$\sum_{e \in \mathrm{I}_v} X_e = \alpha_v \cdot \sum_{e \in \mathrm{O}_v} X_e \quad \text{for all } v \in \bigcup_{i=2}^{k-1} S_i \tag{4}$$

guarantee that there are no additional sources than those on the first stage and no additional sinks except the end manufacturer node. Each supplier v has a production capacity limit m_v that must not be exceeded:

$$\sum_{e \in \mathrm{O}_v} \mathrm{X}_e \le m_v \quad \text{for all } v \in N / \{n\}. \tag{5}$$

Each arc e has a minimum flow q_e. This represents, for example, minimum order quantities demanded by the suppliers and prevents unreasonably low flows.

$$q_{\mathrm{e}} \cdot Y_e \le X_e \quad \text{for all } e \in A \tag{6}$$

The following constraints guarantee that flows can only be assigned to active arcs:

$$X_e \le M \cdot Y_e \quad \text{for all } e \in A, \tag{7}$$

where $M = \min\left\{ \max_{v \in N \setminus \{n\}} m_v, D \cdot \prod_{i \in N \setminus S_1} \alpha_i \right\}$.

In the uncapacitated case, i.e., $m_v = \infty$ for all $v \in N$, it can be shown that the supply chain resulting from the base model is always a serial supply chain. This type of a supply chain has only one supplier per stage and the critical supply items flow along a single path from the supplier on the first stage to the end manufacturer. This makes the supply chain extremely vulnerable to failures of suppliers. The overall performance critically depends on the performance of each and every supplier in the network. The image that a chain can only be as strong as its weakest link applies here: the entire chain can only perform well if each and every supplier performs well. A failure of a single supplier disrupts the entire supply chain. Therefore a serial supply chain is not robust at all.

As the presented network design model is based only on lowest possible cost, typically the supply chain reliability is relatively low, too, because the cheapest suppliers are in all likelihood not the most reliable ones. In most cases a negative correlation between reliability and cost is a realistic assumption.

2.3 Reliability Model

We first extend the approach of Vidal and Goetschalckx (2000) to multi-echelon supply chains by adding a new constraint to the base model, which enforces the supply chain reliability to be greater or equal than the desired target supply chain reliability R. For every $v \in N / \{n\}$, let Z_v be a binary variable indicating if the supplier is used or not. In addition, let $\tilde{Z}_j$ be a binary variable indicating if the supply chain has suppliers in region j for $j \in G$. Then based on (1) the reliability of the supply chain is

$$\prod_{v \in N/\{n\}} r_v^{Z_v} \cdot \prod_{j \in G} \tilde{r}_j^{\tilde{Z}_j} \geq R. \tag{8}$$

This nonlinear expression is linearized by applying the logarithm on both sides. This yields the inequality

$$\sum_{v \in N/\{n\}} \log\left(r_v\right) \cdot Z_v + \sum_{j \in G} \log(\tilde{r}_j) \cdot \tilde{Z}_j \geq \log\left(R\right), \tag{9}$$

which is linear.

We link $Z_v, \tilde{Z}_j$, and X_e by

$$M \cdot Z_v \geq X_{(v,u)} \quad \text{for all } (u,v) \in A, \tag{10}$$

$$Z_v \leq \sum_{(v,u)} Y_{(v,u)} \quad \text{for all } v \in N \setminus \{n\}, \tag{11}$$

$$Z_v \leq \tilde{Z}_j \quad \text{for all } j \in G, v \in H_j, \tag{12}$$

where H_j denotes the set of suppliers in region *j*. From the modeling point of view, it suffices to include either (10) or (11). However, we list both to adhere with the definition of Z and to get a formulation with a stronger linear programming relaxation. The *reliability model* consists of the objective function (2), constraints (3)-(7), and (9)-(12).

In the uncapacitated case, it is shown in Bundschuh (2003) that this model yields a serial supply chain. The obtained supply chain now has a lower risk of failing, but the effect of a supplier failure remains the same. If a single element in the serial chain fails, this disrupts the entire chain. To further improve the performance of the supply chain, fail-safe features have to be included.

2.4 Robustness Models

Reducing the impact of failures on the output of the supply chain and thus making it more robust can be achieved by building redundancy into the network, i.e., increasing the number of suppliers on each stage. In case of a failure the remaining unaffected suppliers still provide their share of the total demand of critical supply. The supply chain is now much less likely to be completely disrupted, since for a complete disruption all suppliers on the same stage have to fail simultaneously. On the other hand, using more suppliers increases fixed costs. In addition to using only the cheapest suppliers we have to opt for more expensive ones.

2.4.1 Supplier Sourcing Limit Model

One way of creating a supply chain with redundant suppliers is to add sourcing limit constraints to the base model. The sourcing limits impose an upper bound on the amount of critical supply a node can source from a single supplier. The upper bound is expressed in terms of a given percentage ω of the total demand of the node. The supplier sourcing limit constraints

$$\mathrm{X}_{\mathrm{e}} \leq \omega \cdot \sum_{\bar{\mathrm{e}} \in \mathrm{I}_v} \mathrm{X}_{\bar{\mathrm{e}}} \quad \text{for all } v \in \bigcup_{i=2}^{k} S_i, e \in I_v \tag{13}$$

are added to the model.

We can use the idea at the region levels. In this case, a customer node can only source a given percentage ζ of its total supply from the suppliers in a particular region. For $v \in N$, $j \in G$ let $\tilde{I}_{jv} \subseteq A$ be the set of incoming arcs from region j to node v. We can express the regional sourcing limits as

$$\sum_{\mathrm{e} \in \tilde{I}_{jv}} \mathrm{X}_{\mathrm{e}} \leq \zeta \cdot \sum_{\mathrm{e} \in I_v} \mathrm{X}_{\mathrm{e}} \quad \text{for all } v \in \bigcup_{i=2}^{k} S_i \,. \tag{14}$$

The *supplier sourcing limit model* consists of the objective function (2), constraints (3)-(7), (13), and (14).

The sourcing limit formulation does not consider supplier reliabilities. It is solely concerned with minimizing the magnitude of a supply loss in case of a failure, but not the probability of such a failure. Sourcing limits force the use of more suppliers than a serial supply chain would use, and reliability maybe reduced; every additional supplier increases the risk of a failure. Compared to the reliability model, the supply chain network designed with the sourcing limit constraints has a much higher probability of failure, but suffers less severe effects in the actual case of a failure, because the redundant suppliers leverage the loss.

The core idea of redundancy is to spread risk. Unless all suppliers on a stage fail simultaneously, the loss of one or more suppliers does not lead to a complete shortage of critical supply, but still reduces the total available supply. This shortcoming of supplier sourcing limits can be eliminated by expanding it with features for a partial compensation of the loss, which further improve the mean output and the standard deviation of the output, and increase the degree of robustness of the supply chain.

2.4.2 Contingency supply model

Compensation of supply is achieved by having contingency supply at hand. There are two ways to provide contingency supply in a supply chain. The first is to install strategic emergency buffers as proposed by Sheffi (2001), which are used only in case of a supply disruption. These buffers contain critical supply items needed for the production of additional components to compensate for a loss of supply. Unlike conventional safety stock, the strategic emergency buffers are not used to hedge against stochastic demand. Using solely strategic emergency buffers is very expensive, because the strategic emergency buffer inventory levels would be significant if sufficient loss compensation is to be guaranteed. There is research on placement of safety stock in a supply chain, e.g., Graves and Willems (2003), Shen et al. (2003), however, these authors deal with demand uncertainty and they assume the suppliers to be completely reliable, and we do not.

A second alternative to prevent a large accumulation of emergency inventory is to purchase options on additional supply in case of a loss. In case of a failure, the remaining suppliers provide extra supply in addition to their regular contractual supply to make up for at least a given percentage of the loss. As opposed to the strategic emergency buffers, this form of contingency supply is physically not existent in the supply chain. It only appears if a shortage occurs.

This poses a problem of lead-time of the contingency supply. Every node has a certain production and transportation lead-time until its contingency supply is made available to its customers. After this time, the customers, who themselves are suppliers of contingency supply to their customers in the next stage, can begin the production of the additional units. Thus, even more time elapses until the contingency supply reaches the next stage, and so forth. The total lead-time until the first contingency supply items reach the end manufacturer can be considerable and this may or may not be acceptable, depending on whether excess demand of the final product in case of a supply shortage can be back-ordered or is lost. A reasonable strategy is to combine strategic emergency buffers with options on contingency supply. In this strategy the strategic emergency buffer at a supplier node is used to bridge the lead-time until the suppliers of this node are able to provide additional contingency units. With this combination strategy we are able to compensate in an economical way for the loss of supply due to supplier failures.

In this model we need two new decision variables U_v and W_e. For every $v \in \bigcup_{i=2}^{k} S_i$, U_v is the decision variable for the size of the strategic emergency buffer kept at node v and for every $e \in A$, W_e denotes the amount of contingency supply units for the option between the nodes connected by arc e.

For setting up a supply chain with contingency supply, we suffer additional costs from the strategic emergency buffers and the options on contingency supply. Additional critical supply must be purchased for storage in strategic emergency buffers. Strategic emergency buffers also incur ongoing holding costs. The parameter h_v expresses the per unit holding cost at node v. Purchasing options on contingency can be viewed as buying insurance for a loss of supply. The supplier as insurance provider has to either keep free production capacity in case the contingency supply is needed or be able to free capacity within a certain time.

The price for this service, the risk prime, can be modeled in several ways. For example, it can be expressed as an extra charge on the production cost of the regular units, depending on the amount of contingency supply. If the option on contingency supply has to be exercised, we assume the production cost of these additional supply items is higher than those of the regular units. Since we are dealing with the strategic design of a supply chain, these additional production costs are not captured in the model, because they are only incurred in case of a failure. However, the failure costs are considered implicitly in an extension of this model to a combined reliability-robustness model, described in Section 2.4.3. A much simpler way to model risk prime is by using a standard contract form such as pay-to-delay, quantity-flexibility, or backup agreement for the contingency supply. For simplicity, we assume a simple linear cost on the contingency supply, where cc_e is the per-unit cost of contingency supply on arc e. It is easy to extend the model to handle piecewise linear functions.

We assume that an option for contingency supply can be purchased only in addition to regular supply. A spot market can be modeled by an additional supplier.

The objective function is given by

$$\sum_{e \in A} \left[(cp_e + ct_e) \cdot X_e + f_e \cdot Y_e + cc_e W_e \right] + \sum_{v \in \bigcup_{i=2}^{k} S_i} h_v \cdot U_v \, . \tag{15}$$

The first summation term captures the transportation and production cost as well as the contingency supply cost, and the second summation term expresses the holding cost for the inventoried critical supply in the strategic emergency buffers.

Contingency supply allows us to model a maximum tolerable loss. Because of the relatively low probability of two or more suppliers or an entire region failing, it is reasonable to set a maximum tolerable loss only for the case of a single supplier failure. Assuming a single supplier failure, we would like the loss not to exceed $\mu \cdot D$, where μ is the maximum tolerable loss percentage in terms of the demand of the final product. This means that for a failure of supplier w on stage S_i, the regular flows X_e and the emergency flows W_e of the remaining suppliers on the same stage S_i, in addition to the sum of the strategic emergency buffers kept at nodes on the succeeding stage S_{i+1}, must be at least $1-\mu$ fraction of the total regular output of stage S_i. Formally this is expressed as

$$\sum_{v\in S_i}\sum_{e\in O_v}\left(\mathrm{W_e}+\mathrm{X_e}\right)-\sum_{e\in O_w}\left(\mathrm{W_e}+\mathrm{X_e}\right)+\sum_{u\in S_{i+1}}U_u\geq(1-\mu)\cdot\sum_{v\in S_i}\sum_{e\in O_v}\mathrm{X_e} \tag{16}$$

for all $w\in S_i$, for all $i\in\{1,\ldots,k-1\}$.

An option of contingency supply can only be purchased in addition to regular supply, which is captured by

$$W_e\leq M\cdot Y_e\quad\text{for all } e\in A \tag{17}$$

The contingency output of a node on an intermediary stage has to be covered by its strategic emergency buffer and additional contingency options from its suppliers. A node only needs to purchase enough options on contingency supply from its suppliers to cover that part of its contingency output that is not already stored in the strategic emergency buffer. Thus, the contingency supply output of an intermediate node v must equal the contingency flows into this node in addition to its strategic emergency buffer, considering the bill-of-materials parameter α_v:

$$\sum_{e\in O_v}\mathrm{W_e}=\frac{1}{\alpha_v}\cdot\left(\sum_{e\in I_v}\mathrm{W_e}+U_v\right)\quad\text{for all } v\in\bigcup_{i=2}^{k-1}S_i\,. \tag{18}$$

Outgoing contingency and regular flows out of a node cannot exceed the production capacity. Therefore, the supplier capacity limit (5) from the base model has to be modified to account for the contingency flows as well. The new constraints read

$$\sum_{\mathrm{e}\in\mathrm{O}_v}\left(\mathrm{X}_e+\mathrm{W}_e\right)\leq m_v\quad\text{for all } v\in\bigcup_{i=1}^{k-1}S_i\,. \tag{19}$$

The installation of the strategic emergency buffer requires modifications of (3) and (4). For the final manufacturer node the total inflow of regular supply has to equal the final demand plus the size U_n of the strategic emergency buffer at this node considering the bill-of-materials relationship.

$$\sum_{\mathrm{e}\in I_n}X_e=\alpha_n\cdot D+U_n \tag{20}$$

Similarly, the input of regular supply to node v on an intermediate stage must be equal to its output of regular supply, with respect to the bill-of-materials relationship, plus the amount U_v, needed for the installation of the strategic emergency buffer at this node.

$$\sum_{e\in I_v}X_e=U_v+\alpha_v\cdot\sum_{\mathrm{e}\in\mathrm{O}_v}\mathrm{X}_e\quad\text{for all } v\in\bigcup_{i=2}^{k-1}S_i \tag{21}$$

The strategic emergency buffer at node v on an intermediate stage is used to cover the supply, which is needed for the production of contingency components during the lead-time until the suppliers of this node are able to provide the necessary contingency supply. If τ_v denotes the maximum lead-time until the suppliers on the preceding stage provide the contingency supply to node v, then the requirement for the minimum buffer size of the strategic emergency buffer is expressed as

$$U_v\geq\tau_v\cdot\alpha_v\cdot\sum_{e\in O_v}S_\mathrm{e}\quad\text{for all } v\in\bigcup_{i=2}^{k-1}S_i\,. \tag{22}$$

The minimum buffer size of the final manufacturer node has to cover the supply for the production of at least $1-\mu$ fraction of the demand of final product during the maximum lead-time of its suppliers on stage S_{k-1} and therefore we need

$$U_n \geq \alpha_n \cdot \tau_n \cdot \mu \cdot D \,. \tag{23}$$

Typically, the physical storage of a strategic emergency buffer has an upper bound. If $\hat{U}_v$ denotes the maximum size of the strategic emergency buffer at node v, we add

$$U_v \leq \hat{U}_v \quad \text{for all } v \in \bigcup_{i=2}^{k} S_i \,. \tag{24}$$

In order to reduce the amount of contingency supply, and thus the cost, we limit the number of suppliers per stage. We impose an upper limit N_i on the number of suppliers on stage S_i by adding

$$\sum_{v \in S_i} Z_v \leq N_i \quad \text{for all } i \in \{1, \ldots, k-1\} \,. \tag{25}$$

where binary variable Z_v indicates whether supplier v is used or not. To link Z_v to the rest of the model, constraints (10) and (11) are needed. Finally, as this is an extension of the supplier sourcing limit model the supplier sourcing limit constraints (13) and (14) have to be included. The *contingency supply model* has the objective function (15), constraints (6)-(7), (10)-(14), and (16)-(25)(14)-(23).

It is easy to augment this model to capture fixed costs associated with using the contingency supply on links or strategic emergency buffers. The former is needed if more complex contracts are to be expressed.

Neither the sourcing limit model nor the contingency supply models take supplier reliabilities into account. Choosing cheap but unreliable suppliers leads to a higher expected failure cost, since it is much more likely that the options on contingency supply have to be used and the increased production cost for the additional units have to be paid.

2.4.3 Reliability-Contingency Supply Model

In order to circumvent this, we merge the reliability and contingency supply models. Here the contingency supply model is augmented by the supply chain reliability constraint (9). The result should produce advice in terms of reliability and robustness: flows are better distributed and backed-up with contingency supply, and more reliable suppliers are chosen to guarantee a given target supply chain reliability. However, higher costs are expected for this solution. The *reliability-contingency supply model* consists of objective function (15), constraints (6)-(7), (9)-(14), and (16)-(25)(14)-(23).

3 Computational Experiments

Our computational experiments are carried out on a 550 MHz Pentium III Xeon workstation with 4 GB of RAM and Linux operating system. Our models are written in AMPL and they are solved with ILOG CPLEX 8.0. We impose a time limit of one hour. Most of the models solve within this time limit, a few require some CPLEX parameter tuning and standard ad-hoc techniques such as variable fixing. Only some of the combined reliability-contingency supply models could not be solved to optimality within this time limit. For these problems we return the best feasible solution found in an hour. Model sizes of a typical instance are given in Table 1.

TABLE 1: MODEL SIZES

Model	**Total number of decision variables**	**Number of binary variables**	**Number of constraints**	**Density**
Base model	528	264	561	0.0051
Reliability model	568	304	898	0.0052
Supplier sourcing limit model	561	264	858	0.0049
Contingency supply model	3,402	1,096	4,079	0.0008
Reliability-contingency supply model	3,402	1,096	4,080	0.0009

We analyze a given supply chain with a Monte-Carlo simulation written in MATLAB. In every scenario, we simulate failures of suppliers and determine the output of the supply chain from the "surviving" suppliers. Each reported result is based on a generation of 100,000 scenarios. The different models are compared and evaluated based on the

- deterministic cost (given by the optimal value of the underlying model) for setting-up the supply chain network and contracting the flows,
- mean output,
- standard deviation of the output,
- number of supplier failures (how often the output of the supply chain is reduced due to a failure of one or more suppliers), and
- number of total disruptions (how often the output equals zero due the failures of suppliers).

The last four performance indicators are drawn from the simulation.

We generate the following instance: a manufacturer is located in North-America; its suppliers form 6 stages ($k = 6$) and 4 geographical regions, which are North-America, Europe, South-America and South-East-Asia. Stages 1 through 5 consist of 8 suppliers each and the last stage contains only the manufacturer node. The most reliable suppliers, but at the same time with the highest cost, are located in North-America and Europe. The suppliers in South-East-Asia are the least reliable with the lowest supply price. Overall there are 41 nodes and 264 arcs. In figures that follow, the dots represent the supplier nodes and the triangle the final manufacturer. Additional information about this instance can be found in Bundschuh (2003).

Applying the base model, we obtain a supply chain with the cheapest, but unreliable suppliers, all of which are located either in South-America or South-East-Asia. This chain is shown in Figure 1.

FIGURE 1: BASE MODEL SUPPLY CHAIN

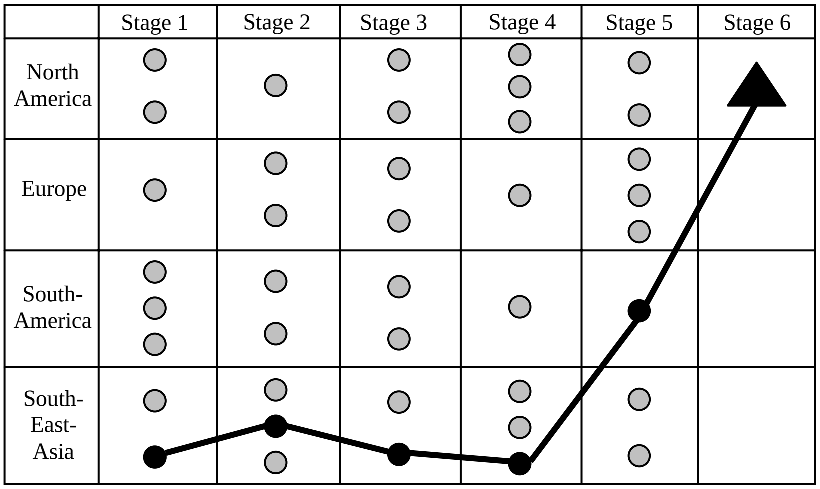


TABLE 2: BASE MODEL RESULTS

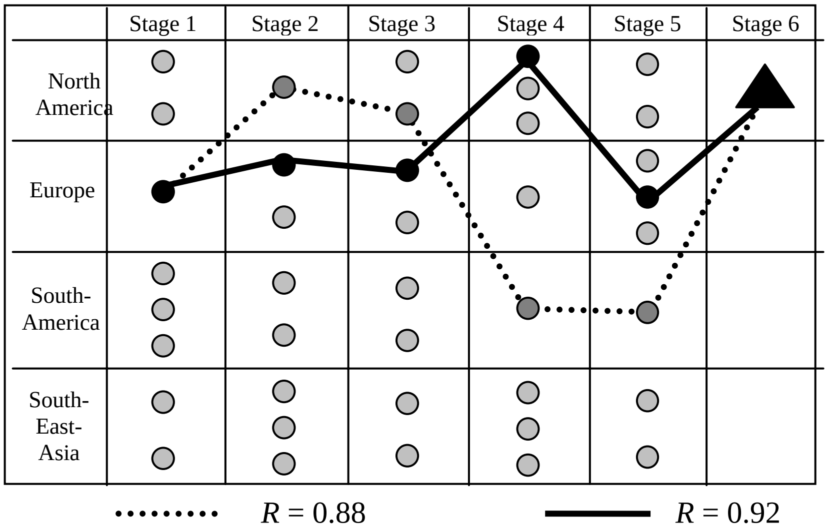
Cost	$ 146,750,000
Number of total failures	18,386
Number of supplier failures	18,386
Mean output	816,140
Standard deviation of output	387,372
Supply chain reliability (analytical)	0.8158

The low reliabilities of the suppliers compromise the supply chain stability greatly and expose it to a significant risk of disruption. Table 2 shows the results of this solution based on the simulation. In what follows, these values are set to 100% and the other models are compared with respect to these base model results.

Though most cost-efficient, the base model supply chain exhibits a high probability of approximately 18.4% of a complete disruption. In every serial supply chain the number of supplier failures equals the number of total supply chain disruptions, because the failure of any single supplier disrupts the only path to the manufacturer. The low mean output of 816,140 units and the high standard deviation of 387,372 units also reflect the questionable performance of the traditionally-designed supply chains under the risk of supplier failures. The empirical reliability of 0.8161 obtained from the simulation is very close to the analytically calculated value of 0.8151 obtained from (1), implying the correctness of the simulation based results.

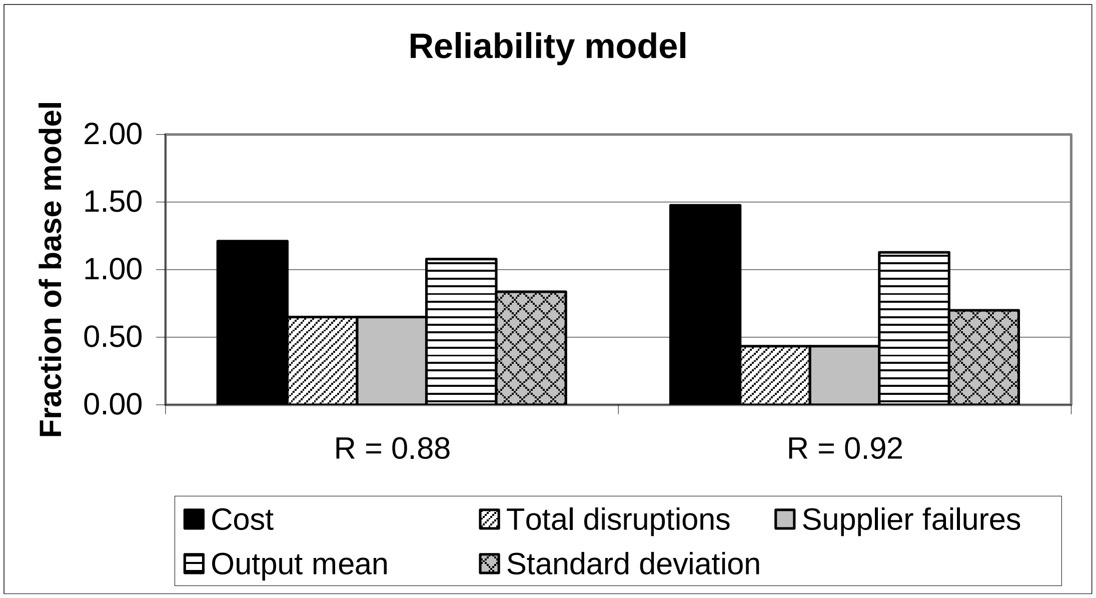
Using the reliability model, the high rate of total disruptions and thus the mean output and the standard deviation of the output can be improved drastically. Figure 2 shows the supply chains for a target supply chain reliability of $R = 0.88$ and for the maximum possible target supply chain reliability of $R = 0.92$.

FIGURE 2: RELIABILITY MODEL SUPPLY CHAIN



As anticipated, in order to improve reliability of the supply chain, suppliers from more reliable regions are selected. The results of these supply chains, relative to the base model, are displayed in Figure 3.

FIGURE 3: RELIABILITY MODEL RESULTS

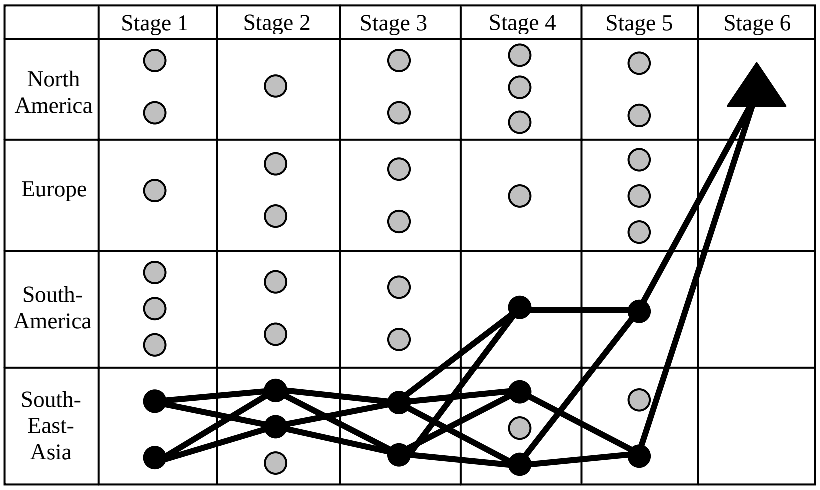


For $R = 0.88$ and $R = 0.92$, the number of total disruptions and the number of supplier failures decrease by 35% and 57% respectively. Due to the higher reliability the mean output increases by 8% and 12%, respectively and the standard deviation of the output is reduced respectively by 16% and 30%. The costs increase by 21% and 48%, respectively. Though now less cost-efficient, these supply chains are much less likely subject to a failure. However, robustness has not improved, because any supplier failure in this serial supply chain still disrupts the entire chain.

Using the supplier sourcing limit model, the resilience of the supply chain can be improved enormously. The supply chain with a sourcing limit of $\omega = 0.6$ is depicted in Figure 4. Stages 1 through 5 now have at least 2 suppliers each.

Figure 5 shows the results of the model with supplier sourcing limits of $\omega = 0.4$, $\omega = 0.6$ and $\omega = 0.8$. The improvement in the number of total disruptions is striking: a 96% reduction from 18,386 failures to 669 for $\omega = 0.8$, by 97% to 533 for $\omega = 0.6$, and even by 99.87% to 24 total failures in the case of $\omega = 0.4$. The supply chain is only totally disrupted if all suppliers on at least one stage fail simultaneously, and the probability of this event is lower the more suppliers are used per stage. But, because at least twice as many suppliers are used, reliability of the supply chain is reduced considerably, because every additional supplier increases the chance of a failure. Hence, the number of supplier failures increases by 70% for $\omega = 0.8$, 84% for $\omega = 0.6$, and up to 135% in the case of $\omega = 0.4$. The average output stays approximately the same as in the base model, which means that most of the supplier failures are leveraged by the remaining suppliers on the same stage. The supply chain is now much more tolerant to failures and thus much more robust. This increased stability is also indicated by a reduction of the output standard deviation of 20% for $\omega = 0.8$, 31% for $\omega = 0.6$, and 44% for $\omega = 0.4$, which in this case is not attributed to improved reliability, as seen in the results of the reliability model. Because supplier reliabilities are not yet considered at this stage, the suppliers are chosen only according to minimum cost, and therefore they are all located in the low cost and reliability regions. For this reason, the cost increase of these supply chain networks of 3% for $\omega = 0.8$, 4% for $\omega = 0.6$, and 10% for $\omega = 0.4$ is less significant than in the case of the reliability model.

FIGURE 4: SUPPLIER SOURCING LIMIT MODEL SUPPLY CHAIN



The redundant supply arrangements created with the sourcing limit approach form the basis of the contingency supply model. The contingency supply arrangements further increase robustness of the supply chain and thus improve the mean output and the standard deviation of the output. The network structure given in Figure 6 of a supply chain with a maximum tolerated loss of $\mu = 0.1$ and a supplier sourcing limit of $\omega = 0.6$ is very similar to the one created by only enforcing a supplier sourcing limit of the same value. To minimize cost, this model tries to keep the amount of contingency supply as low as possible by distributing and balancing the flows. Therefore, an additional supplier node on stage 5 is added.

FIGURE 5: SUPPLIER SOURCING LIMIT MODEL RESULTS

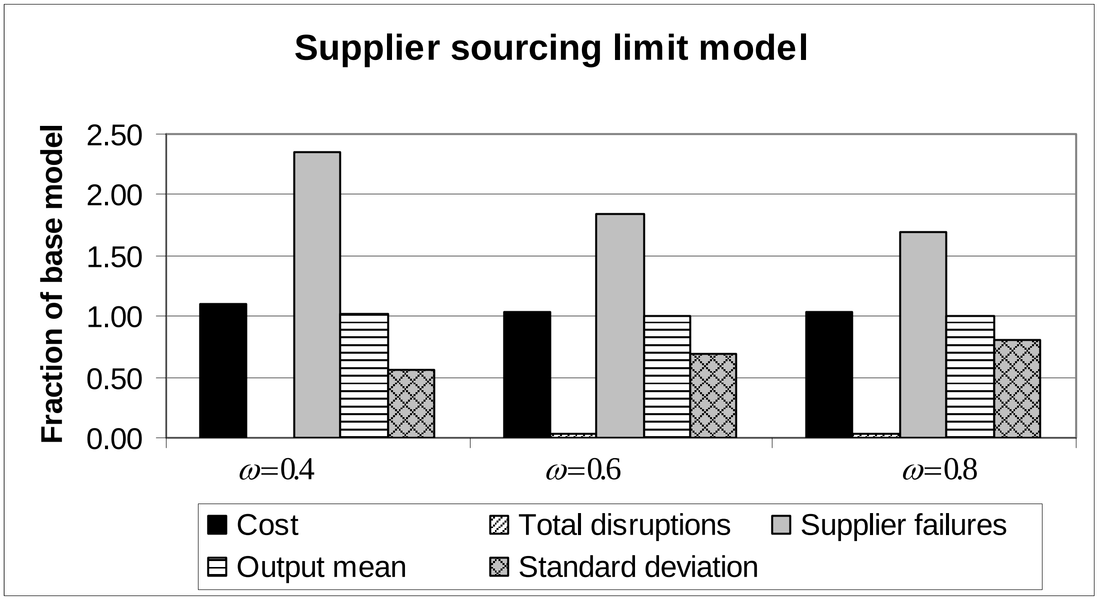


FIGURE 6: CONTINGENCY MODEL SUPPLY CHAIN

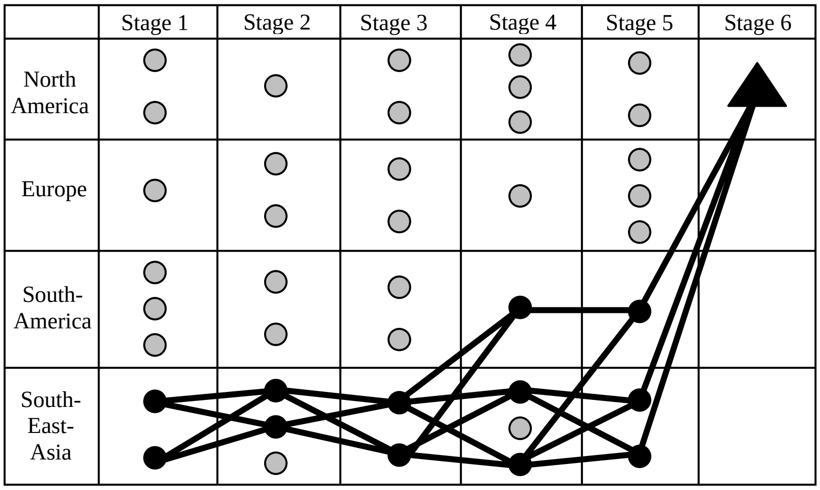


Figure 7 compares the results of this contingency supply model to the corresponding supplier sourcing limit model. Because of the similarity of the two networks, the number of total disruptions is nearly equal in both cases and the increase in supplier failures is less pronounced. The stabilizing effect of the contingency supply is reflected in significantly higher average output and lower standard deviation of the output than in the supplier sourcing limit model. The increased total costs of this solution compared to the respective supplier sourcing limit model is mainly from option prices as well as costs for the installation and holding of the buffers.

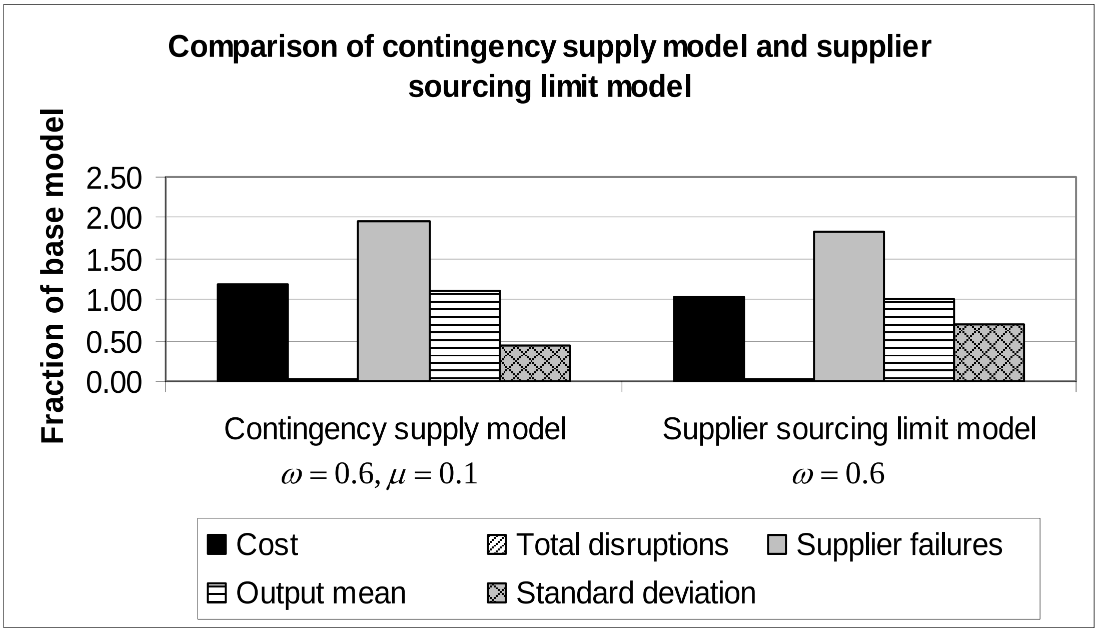
Though the effect of failures is now reduced by having both supplier sourcing limits and contingency supply arrangements, the supply chain reliability is still unsatisfactory since all suppliers are located in the low reliability and cost regions. In case of a failure, the option on contingency supply has to be realized and higher production cost for these units is incurred. The more unreliable a supply chain is, the more often these options have to be used, which increases the failure costs.

The best results in terms of reliability and robustness are obtained from the combination of the reliability and the contingency supply model. The reliability-contingency model produces the highest output mean, the lowest standard deviation, very few total disruptions and the highest supply chain reliability for distributed (non-serial) networks. Figure 8 depicts the supply chain for a sourcing limit of $\omega = 0.60$, a maximum tolerated loss of $\mu = 0.1$ and a target supply chain reliability of $R = 0.77$.

In Figure 9 we give the results for two instances of this type of model: the one already mentioned above and one with the same sourcing limit, same maximum tolerated loss, but a target supply chain reliability of $R = 0.75$.

In the cases of $R = 0.75$ and $R = 0.77$, the mean increases by 15% and 16% respectively, and the standard deviation decreases by 63% and 69%, respectively. The number of total disruptions is decreased by 98.46% to 284 and 99.10% to 165 respectively. With the average supplier reliability in the first case being 0.974 and in the second case 0.978, the number of supplier failures increases now only by 34% and 20% respectively, much less than in the previous cases with dispersed networks. However, the increase in cost is relatively steep: 44% for $R = 0.75$ and 66% for $R = 0.77$.

FIGURE 7: RESULTS OF COMPARISON BETWEEN CONTINGENCY SUPPLY MODEL AND SUPPLIER SOURCING LIMIT MODEL



Next we discuss trade-offs. Figure 10 shows the trade-off between cost and mean output. In many cases contingency supply yields a considerably higher mean output for slightly higher or even less costs. For example, the reliability-contingency supply model with a target supply chain reliability of $R = 0.7$ clearly outperforms the reliability model with the maximum possible supply chain reliability of $R = 0.92$. In contrast, the performance of the pure supplier sourcing limit models in terms of the output mean is not satisfactory.

FIGURE 8: RELIABILITY-CONTINGENCY SUPPLY MODEL SUPPLY CHAIN

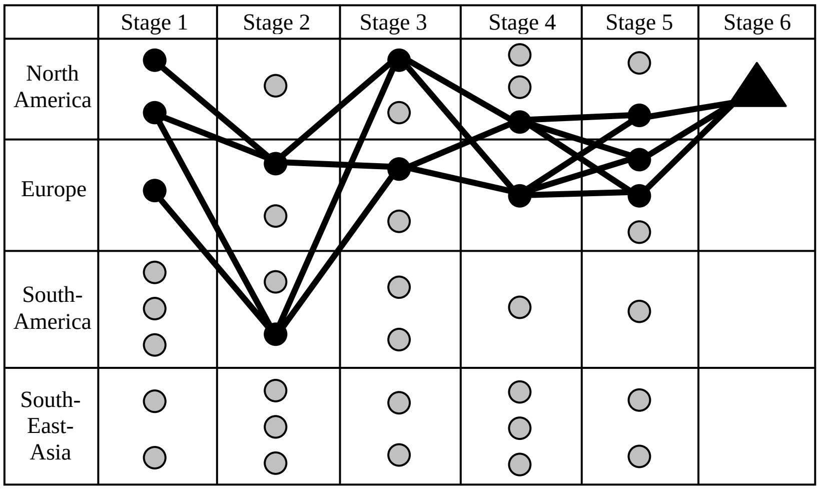


FIGURE 9: RELIABILITY-CONTINGENCY SUPPLY MODEL RESULTS

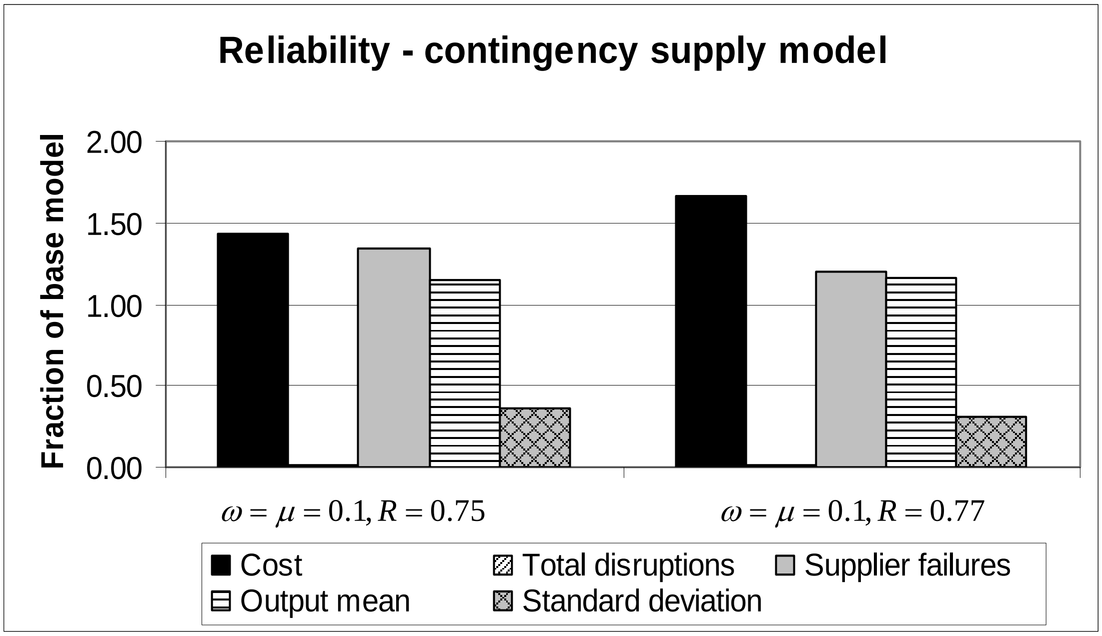


Figure 11 displays the trade-off between cost and the standard deviation of the output. The contingency based model outperforms many other models, in the sense that it yields much lower standard deviations for minor cost increases or even lower cost (e.g., compare again the reliability-contingency supply model with $R = 0.7$ to the reliability model with $R = 0.92$). The supplier sourcing limit model with $\omega = 0.4$ outperforms the reliability models.

Considering the trade-off between cost and total supply chain disruptions, we showed that with all models, except the pure reliability models, large reductions in the number of total disruptions can be achieved.

4 Conclusions and Future Research

We show that traditional strategic supply chain design does not cope with the risk of supplier failures. Disregarding considerations about reliability and robustness of the supply chain and merely focusing on minimum cost can lead to a high likelihood of supplier failures and to severe supply problems. In the uncapacitated design problem, the failure of any supplier causes a total disruption of the supply chain.

We introduce a succession of models to respectively improve reliability and robustness of a supply chain. Pursuing only robustness or reliability can improve performance significantly, but the lack of the other aspect still produces overall insufficient results for a stable supply chain. The reliability-contingency supply model presents a way of improving both reliability and robustness and we show that it can lead to significant performance improvements of a supply chain under the risk of supplier failures. However, the cost for a high level of stability can be significant. We conclude that the reliability-contingency supply model is the most promising one for the strategic design of an inbound supply chain. An additional model named the expected service level model that captures both reliability and robustness is presented in Bundschuh (2003). This model is inferior to the reliability-contingency model. Additional instances and results related to alternative recourse actions (i.e., lost sales, backlogging) can also be found in this publication.

Managing supplier relationships (e.g., "supplier relationship management" (SRM)), is a very important part of a supply chain, Navas (2003). Recently, software tools have emerged that assist companies with SRM. Our models fit naturally in such software packages and they would enhance SRM by embedding robustness and reliability.

FIGURE 10: TRADE-OFF BETWEEN COST AND MEAN OUTPUT

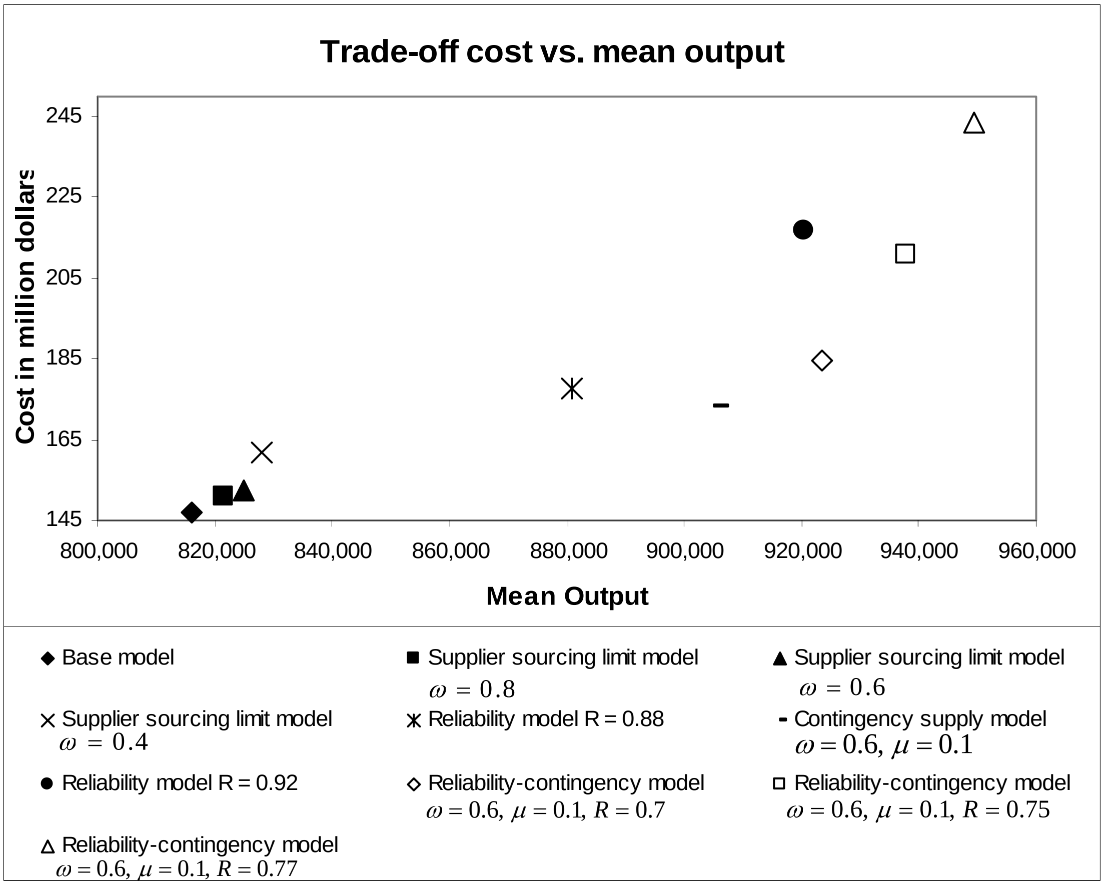
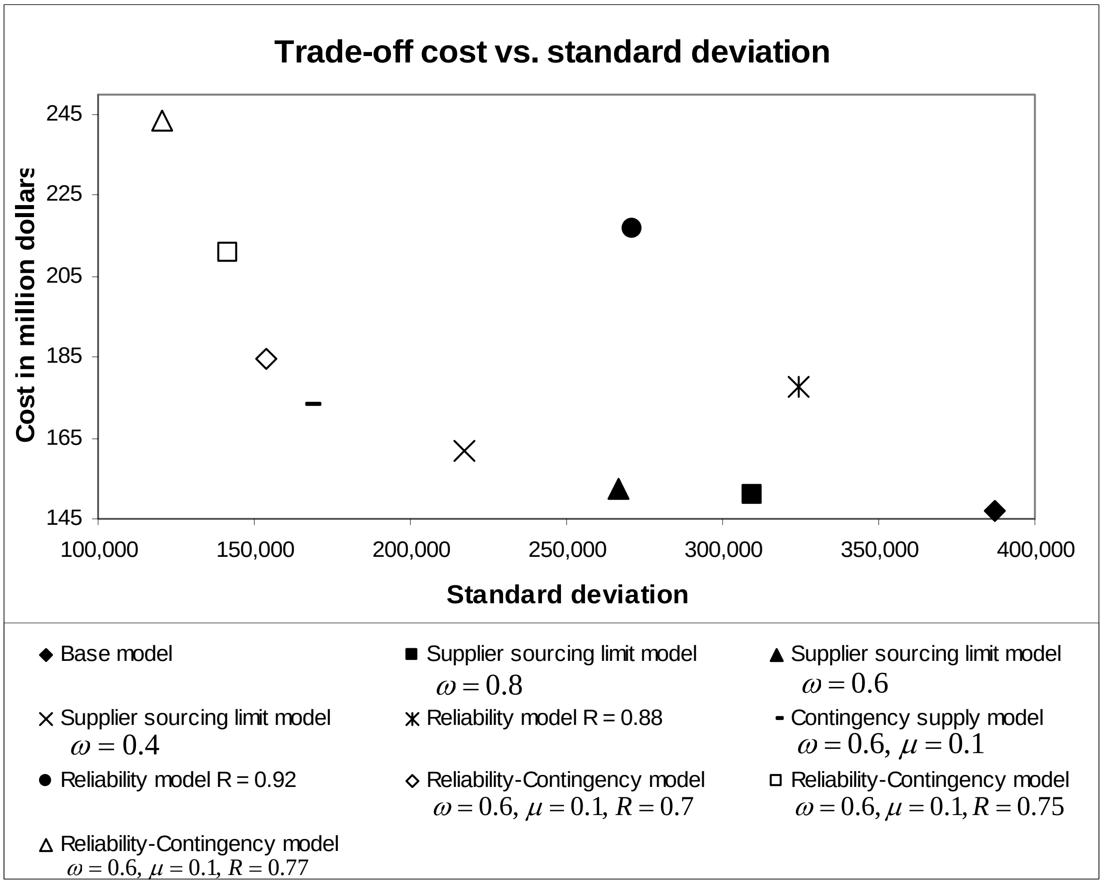


FIGURE 11: TRADE-OFF COST VS. STANDARD DEVIATION



References

AMPL. Available at: http://www.ampl.com.

ANDREWS, J. D. and MOSS, T. R. 2002. *Reliability and Risk Assessment*. ASME Press. New York.

AXSÄTER, S. 1993. Continuous Review Policies for Multi-Level Inventory Systems with Stochastic Demand. In: Graves, S. C., Rinnooy Kan, A. H., Zipkin, P. H., (Eds). *Logistics of Production and Inventory*. North-Holland Publishing Company, Amsterdam.

BUNDSCHUH, M. 2003. Modeling Robust and Reliable Supply Chains. Studienarbeit at Fachgebiet Fertigungs- und Materialwirtschaft, Darmstadt University of Technology, Germany.

DAVIS, T. 1993. Effective Supply Chain Management. *Sloan Management Review*, Summer 1993, 35-46.

DIKS, E. B., DE KOK, A. G. and LAGODIMOS, A. G. 1996. Multi-Echelon Systems: A Service Measure Perspective. *European Journal of Operational Research*, **95**, 241-263.

FEDERGRUEN, A. 1993. Centralized Planning Models for Multi-echelon Inventory Systems under Uncertainty. In: Graves, S. C., Rinnooy Kan, A. H. and Zipkin, P. H., (Eds). *Logistics of Production and Inventory*. North-Holland Publishing Company, Amsterdam.

GOETSCHALCKX, M. 2000. Strategic Network Planning. In: Stadtler, H. and Kilger, C., (Eds.). *Supply Chain Management and Advanced Planning: Concepts, Models, Software and Case Studies*. Springer, Berlin. 79-95.

GRAVES, S. C. and WILLEMS, S. P. 2003. Supply Chain Design: Safety Stock Placement and Supply Chain Configuration. In: de Kok, A. G. and Graves, S. C., (Eds). *Supply Chain Management: Design, Coordination and Operations*. Elsevier, Amsterdam.

HODDER, J. E. and DINCER, M. C. 1986. A Multifactor Model for International Plant Location and Financing under Uncertainty. *Computers & Operations Research,* **13**, 601-609.

HUCHZERMEIER, A. 1991. Global Manufacturing Strategy Planning under Exchange Rate Uncertainty. Ph.D. Dissertation, Decision Sciences Department, Wharton School, University of Pennsylvania, Philadelphia.

HUCHZERMEIER, A. and COHEN, M. A. 1996. Valuing Operational Flexibility under Exchange Rate Uncertainty. *Operations Research*, **44**, 100-113.

ILOG CPLEX 8.0. 2002. *User's Manual*.

INDEFURTH, K. 1994. Safety Stocks in Multistage, Divergent Inventory Systems: A Survey. *International Journal of Production Economics*, **35**, 321-329.

KUO W. and ZUO, M. J. 2003. *Optimal Reliability Modeling: Principles and Applications*. John Wiley & Sons, Hoboken.

LESTER, T. 2002. Making it Safe to Rely on a Single Partner: Supply Chain Management. *Financial Times*, April Issue.

MARTHA, J. and VRATIMOS, E. 2002. Creating a Just-in-Case Supply Chain for the Inevitable Next Disaster. *Mercer Management Journal*, **14,** 70-77.

NAHMIAS, S. 2001. *Production and Operations Analysis*. McGraw-Hill, Boston.

NAVAS, D. 2003. SRM: Where Co-dependency Succeeds. *Supply Chain Systems Magazine*, **23**, 20-27.

NAVAS, D. 2003a. Automotive Embraces Volatility. *Supply Chain Systems Magazine*, **23**, 12-16.

SANTA-FE INSTITUTE. 2001. Working Definitions of Robustness. Internal report RS-2001-009. Available at: http://discuss.santafe.edu/robustness/stories/storyReader$9.

SCHWARZ, L. B. 1989. A Model for Assessing the Value of Warehouse Risk-Pooling: Risk-Pooling over Outside-Supplier Leadtimes. *Management Science*, **35**, 828-842.

SCHWARZ, L. B. and WENG, Z. K. 2000. The Design of a JIT Supply Chain: The Effect of Leadtime Uncertainty on Safety Stock. *Journal of Business Logistics*, **21**, 231-253.

SHEFFI, Y. 2001. Supply Chain Management under the Threat of International Terrorism. *The International Journal of Logistics Management*, **12**, 1-11.

SHEFFI, Y. 2005. *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage*. The MIT Press.

SHEN, Z.-J., COULLARD, M. C., and DASKIN, M. S. 2003. A Joint Location-inventory Model. *Transportation Science*, **37**, 40-55.

SNYDER, L. V. and DASKIN, M. S. 2003. Reliability Models for Facility Location: The Expected Failure Cost Case. Technical report. Department of Industrial and Systems Engineering, Lehigh University, Bethlehem, PA. Available from www.lehigh.edu/~lvs2.

SONI, S. and PIRKUL, H. 2002. Design of Survivable Networks with Connectivity Requirements. *Telecommunication Systems*, **20**, 133-149.

THIELE, A. and BERTSIMAS, D. 2004. A Robust Optimization Approach to Inventory Theory. Technical Report, MIT, MA.

VAN DER FORST, J. G. A. J., BEULENS, A. J. M., DE WIT, W. and VAN BEEK, P. 1998. Supply Chain Management in Food Chains: Improving Performance by Reducing Uncertainty. *International Transactions in Operational Research*, **5**, 487-499.

VAN HOUTUM, G. J., INDERFURTH, K. and ZIJM, W. H. J. 1996. Materials Coordination in Stochastic Multi-echelon Systems. *European Journal of Operational Research*, **95**, 1-23.

VAN LANDEGHEM, H. and VANMAELE, H. 2002. Robust Planning: A New Paradigm for Demand Chain Planning. *Journal of Operations Management*, **20**, 769-783.

VIDAL, C. J. and GOETSCHALCKX, M. 2000. Modeling the Effect of Uncertainties on Global Logistics Systems. *Journal of Business Logistics*, **21**, 95-120.

VIDAL, C. J. and GOETSCHALCKX, M. 1997. Strategic Production-Distribution Models: A Critical Review with Emphasis on Global Supply Chain Models. *European Journal of Operational Research*, **98**, 1-1.

WALLER, M. 2005. Hurricane Katrina Showed Critical Importance of Logistics and Supply-Chain Management. Available at: http://dailyheadlines.uark.edu/5471.htm.