# Short Papers

## Analytical Framework for the Management of Risk in Supply Chains

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***Abstract*—In this paper, we develop a framework to classify supply chain risk-management problems and approaches for the solution of these problems. We argue that risk-management problems need to be handled at three levels: 1) strategic, 2) operational, and 3) tactical. In addition, risk within the supply chain might manifest itself in the form of deviations, disruptions, and disasters. To handle unforeseen events in the supply chain, there are two obvious approaches: 1) to design chains with built-in risk tolerance and 2) to contain the damage once the undesirable event has occurred. Both of these approaches require a clear understanding of undesirable events that may take place in the supply chain and the associated consequences and impacts from these events. Having described these approaches, we then focus our efforts on mapping out the propagation of events in the supply chain due to supplier nonperformance, and employ our insight to develop two mathematical programming-based preventive models for strategic level deviation and disruption management. The first model, a simple integer quadratic optimization model, adapted from the Markowitz model, determines optimal partner selection with the objective of minimizing both the operational cost and the variability of total operational cost. The second model, a simple mixed integer programming optimization model, adapted from the credit risk minimization model, determines optimal partner selection such that the supply shortfall is minimized even in the face of supplier disruptions. Hence, both of these models offer possible approaches to robust supply chain design.**

***Index Terms*—Cause–consequence diagrams, failure analysis, mean-variance optimization, partner selection, risk management, supply chain design, supply chain planning, supply chain risk management.**

### I. Introduction

Manufacturing supply chains today tend to be global in nature, comprised of complex interactions and flows between tens, even hundreds and thousands of companies and facilities geographically distributed across regions and countries. Such chains are currently in operation in a variety of industries such as electronics, automotive, aerospace, etc. Despite their complexity, most manufacturing supply chains are structurally similar. The member companies in a typical manufacturing supply chain network include the suppliers and their suppliers, assembly plants, distributors, retailers, inbound and outbound logistics providers, and financing institutions. In fact, under the intense competitive scenario prevalent today, competition is no longer between companies but between supply chain networks with similar product offerings, serving the same customer.

The winning supply chain networks are usually characterized by the presence of dominant organizations (also called channel masters), such as Dell, GM, Sun, or Nike that possess strong domain knowledge, design, brand and marketing capabilities, around which they congregate. Furthermore, these supply chains are able to achieve a high level of efficiency through the sophisticated use of pervasive information and logistics networks that hold the supply chain together, and facilitate the easy movement of information and goods throughout the chain. Given their influence and consequentially the role of controller within the supply chain, the channel masters are typically responsible for supply chain planning incorporating [1]:

1) selection of appropriate partners to form the supply chain based on market requirements;
2) synchronization of activities between selected partners for optimal profit.

In a perfect world, the plans generated by the channel master would allow all of the partners to synchronize their activities and business processes leading to greater efficiencies and profits for everyone. For example, components would arrive at the assembler site on time for production to start, adequate inventory of all components would be available before production and demand would be deterministically predictable. However, in the practical world, uncertainty rules. Consequentially, sales routinely deviate from forecasts; components are damaged in transit; production yields fail to meet the plan; and shipments are held up in customs. In truth, schedule execution as per the plans generated by supply chain planning is just a myth.

Because supply chain performance is inherently unpredictable and chaotic, supply chain practitioners often must seek safety mechanisms to protect against unforeseen events. Significant efforts are expended to expedite orders, to check order status at frequent intervals, to deploy inventory "just-in-case," and to add safety margins to lead times. These are some of the creative ways employed to counter the occurrence of unforeseen events. These time and material inventories along with limited communications among supply chain partners hide the problems until they lead to serious consequences. While risk has always been present in the process of reconciling supply with demand, there are a number of factors, which have emerged in the last decade or so, which might be considered to have increased the level of risk. These include a focus on efficiency rather than effectiveness; the globalization of supply chains; focused factories and centralized distribution; the trend toward outsourcing; reduction of the supplier base; volatility of demand; and lack of visibility and control procedures. As a result, it has become extremely important for channel masters to employ risk-management tools in the management of their supply chains.

Supply chain risk is defined by the distribution of the loss resulting from the variation in possible supply chain outcomes, their likelihood, and their subjective values. Supply chain risks comprise risks due to variations in information, material, and product flows, which originate at the original supplier and lead to the delivery of the final product to the end user. Thus, supply chain risks refer to the possibility and effect of a mismatch between supply and demand. Furthermore, risk consequences can also be associated with specific supply chain outcomes, such as supply chain costs or quality. Within this context, we can identify the following basic constructs of supply chain risk management:

1) risk sources;
2) risk consequences;
3) risk drivers;
4) risk mitigating strategies.

An increased awareness of the existence of the disturbances and their sources of origin in the supply chain may enable better preparedness for handling or preventing them.

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While studying risk in a supply chain network context, one also has to remember that a supply chain comprises a network of companies that belong to an industry vertical embedded in a business and social environment. Hence, supply chains are subjected to internal risks resulting from the interaction between firms within the supply chain and to external risks that are felt by all supply chain networks in the industry and within the same environment. Consequentially, supply chain risks can arise at four levels: organizational, network level, industry level, and environmental level, as elaborated in Section II-A. An excellent discussion on this topic may be found in [14].

In terms of existing solutions, the existing ERP, SCM, EAI, and other B2B solutions are designed to improve efficiency of the supply chains and not to enhance their reliability or robustness under uncertainty. Some vendors offer partial solutions to this problem under the name of supply chain event management (SCEM). These offerings include track and trace, supply chain visibility, and alert messaging solutions [2], which merely notify the human operator of unexpected occurrences and leave him or her to resolve the issue. In such a scenario, there is a critical need for a framework and for suitable tools that would allow companies and managers to better understand the presence and significance of various types of risks and allow them to manage it better. In this paper, we attempt to address these needs from the perspective of a channel master.

### A. Previous Work

In a very general sense, research from high-reliability organizations (HROs), networked organizations, and interorganizational systems is relevant in the study of supply chain reliability, trust, and risk (Sections III and IV). Some of the research within this area focuses on risk management in a special breed of organizations, called virtual organizations, which are also a collection of companies under independent ownership that come together for a common purpose, such as fighting forest fires or mitigating the risk of oil spills.

However, in terms of directly relevant work in the area of supply chain risk management, Paulsson [5] provides a good survey of the recent literature in the field. Some of the commonly studied supply chain risks are disruption risk, terrorism risk, and the risks from natural disasters.

With reference to disruption risks, managing such risks in global supply chains includes the following procedures: identifying sources of risk, determining the means by which such risks can take place, estimating the potential consequences, and providing the approaches to mitigating and handling these consequences. Many factors can contribute to disruption risks, including natural disasters, for example, the earthquake in Taiwan in September 21, 1999; and the SARS virus outbreak in 2003; and risks arising from purposeful organizations or individuals, such as the September 11, 2001 terrorist attack and geopolitical risks. Kleindorfer and Wassenhove [11] have also analyzed disruption risk management in global supply chains. On supply chain security, Lee and Wolfe [13] recently discussed the strategic approaches to improving security without jeopardizing supply chain effectiveness.

In the area of terrorism risk, there has been a great deal of interest especially after the September 11, 2001 terrorist attack in the U.S. Consequential to the attacks, the global business environment, together with the world's political and military landscape, has changed greatly and companies have reassessed common strategies for sourcing transportation, demand planning, and management. Sheffi [6] studied supply chain management under the threat of international terrorism and proposed some methods such as setting certain operational redundancies. Martha and Subbakrishna [15] also analyzed supply chains under terrorist attacks and proposed (a so-called) targeting a just-in-case supply chain strategy to face the inevitable next disaster.

Another area of particular interest in supply chain risk management is that of managing risks emanating from natural disasters. Martha and Subbakrishna [15] have investigated the impact of natural disasters on supply chains such as the earthquake in Taiwan (Sept. 21, 1999), outbreaks of mad cow and foot and mouth diseases in Europe (Spring 2001), and proposed the just-in-case supply chain strategy for unexpected disasters in the future. Svensson [19], [20] established conceptual frameworks to analyze the vulnerability in supply chains. Svensson [21] also provided a typology of vulnerability scenarios in supply chains based on perceived time and relationship dependencies toward both suppliers and customers.

In a slightly different area, one of the authors has developed a method based on process capability indices to minimize operational and performance risk through lead-time variance minimization [7]. Chen and Federgruen [24] have also, motivated by the Markowitz model [25], studied risk management through mean-variance minimization in the context of the newsboy problem and inventory management using a base-stock policy. In addition, there are a few commercial software solutions and technology implementations to manage supply chain exceptions and events [2].

Despite these publications, since the area of supply chain risk management is an emerging area of research, there are limited perspectives, theoretical models, and frameworks addressing the area. We wish to exactly provide such a theoretical basis in this paper and attempt to highlight how some analytical tools can be employed to manage risk in supply chains, particularly in the context of supply risk.

### B. Organization of this Paper

In this paper, we present a conceptual framework for the classification of supply chain risks and associated approaches for handling them. In particular, we focus on the design of robust supply chains at the strategic level through the selection of suppliers that minimize the variability of supply chain performance in terms of cost and output. In this manner, we are able to build robustness into the supply chain at the planning stage itself. In Section II, we present a conceptual framework for the classification of supply chain risks and associated approaches for building robustness in the supply chain. In Section III, we develop models for supply chain risk management at the strategic level. In Section IV, we share some of our computational results and observations and, finally, we conclude with Section V with a discussion on the possibilities for future work.

## II. Conceptual Framework to Approach Supply Chain Risk Problems

### A. Nature of Risk in Supply Chains

Risk could arise from faulty processes and uncertainties within an individual company, from interaction between network partners or could be at a higher industry or environment level that impacts supply chain outcomes. At the organizational level, "risk sources" include operational uncertainties, such as employee strikes, communicable diseases, etc. or machine-related failures, raw material shortages due to diseases such as mad cow disease, quality problems, spare part unavailability, etc. Also, organizational risk could emanate from research-and-development activities that result in a delayed product introduction. Opportunistic behavior by the CEO, managers, and other staff is another source of risk.

A number of business trends make supply networks more complex and global. Products and services are customized to better meet the demands of customers. Organizations have outsourced many of their activities to specialists allowing all of them to focus on their own core competencies. Internet-based collaboration is blurring boundaries between manufacturing, logistics, and distribution partners. All of these trends make supply chains very efficient but also highly vulnerable to disruption. Network-related risk sources represent the second category of risk sources, which are the primary focus of this paper. These risks are of two broad kinds:

1) Firms are vulnerable not only to attacks on their own assets, but also to attacks on their suppliers, customers, transportation providers, communication lines, and other elements in their ecosystem.
2) Firms are also vulnerable to irregular behavior of their network partners, such as a supplier sharing a sensitive product design with a competing manufacturer.

In addition, there are also risks for the industry as a whole. These risks could arise due to the emergence of a disruptive technology or a new entrant with a sell direct kind of business model or due to input price, quality, or quantity fluctuations. Environment-related uncertainties affect businesses across all industries in a country or region. These include factors, such as economic slowdown; foreign exchange fluctuations; war; policy changes, such as price controls; free trade zones; financial barriers; terrorist attacks; and, finally, natural calamities, such as earthquakes, storms, drought, etc.

### *B. Classification of SC Risk Problems*

Based on its nature, uncertainty in the supply chain may manifest itself in three broad forms—deviation, disruption, and disaster—as explained below.

*1) Deviation:* A deviation is said to have occurred when one or more parameters, such as cost, demand, lead time, etc., within the supply chain system stray from their expected or mean value, without any changes to the underlying supply chain structure.

*Examples of Deviations:*

1) variations in demand;
2) variations in supply;
3) variations in procurement, production, and logistics costs;
4) variations in transportation and production lead times.

*2) Disruption:* A disruption occurs when the structure of the supply chain system is radically transformed through the nonavailability of certain production, warehousing, and distribution facilities or transportation options due to unexpected events caused by human or natural factors.

*Examples of Disruptions:*

1) Disruptions in production (the Taiwan earthquake resulted in the disruption of integrated-circuit (IC) chip production and component production was disrupted due to a fire in Toyota's supplier's factory in Mexico, resulting in a downstream factory shutdown).
2) Disruptions in supply (meat supply was disrupted due to the spread of foot-and-mouth disease in the U.K.).
3) Disruptions in logistics (U.S. port shutdown disrupted the transportation of components from Asia to the U.S.).

*3) Disaster:* A disaster is defined as a temporary irrecoverable shutdown of the supply chain network due to unforeseen catastrophic system-wide disruptions.

*Examples of Disasters:*

1) Terrorist action. (The entire U.S. economy was temporarily shutdown due to the downturn in consumer spending, closure of international borders, and shutdown of production facilities in the aftermath of the terrorist attacks on September 11, 2001.)

It may be noted that the classification of an event as a disruption or a disaster is dependent on the structure of a specific supply chain and its exposure to the event. Consequently, it is very likely that a particular event might manifest itself as a disruption for one supply chain network and influence another in the form of a disaster. For example, the shutdown of the U.S. trading system, subsequent to the September 11th attacks, would be a disaster for a supply chain completely based in the U.S. But the same event would only be a disruption for a manufacturer, located in Asia, adopting a dual-sourcing strategy for components by procuring parts both in the U.S. and in Europe if the manufacturers are able to keep their supply chains running by switching from U.S. suppliers to European ones.

TABLE I
TYPES OF DEVIATIONS

| Planning Level | Type of Event | Example |
|---|---|---|
| Strategic | Deviation | Logistics/Manufacturing Capacity Reduction |
| | Disruption | Supplier bankruptcy |
| Tactical | Deviation | Order forecast |
| | Disruption | Port strike |
| Operational | Deviation | Lead-time variation |
| | Disruption | Machine/Truck breakdown |

In general, it is possible to design a supply chain that is robust enough to profitably continue operations in the face of expected deviations and unexpected disruptions. However, it is impossible to design a supply chain network that is robust enough to react to disasters. This arises from the constraints of any system design, which is limited by its operational specification.

Furthermore, supply chains need to be robust at three levels: 1) strategic, 2) tactical, and 3) operational, and they need to handle minor regular operating deviations and major disruptions at each of these three levels. For example, at the operational level, companies require decision support systems that can act on information from various partners regarding various deviations and disruptions to reschedule activities so that the business processes are synchronized and deliveries are undertaken within customer delivery windows and cost limitations. At the tactical level, plans need to have redundancies in terms of human and machine resources and also logistics and supply organizations. At the strategic level, more reliable partners with intrinsic capabilities in deviation and disruption handling, and the skills and ability to adapt to changing market conditions will be preferred and selected. A complete classification of risk-management issues, with examples at various levels and of various scopes, is presented below, with examples in Table I.

### *C. Classification of Risk-Management Approaches*

Accepting the fact that uncertainty cannot be completely eliminated and given that there are several possible failure modes that can affect a supply chain network; there are two choices for building "resilient supply chains": supply chains with the ability to maintain, resume, and restore operations after a disruption. The first approach involves the time tested "just in case" way of maintaining inventories all along the chain, employing dual or multisourcing and manufacturing at multiple sites. This is a highly inefficient option. A better option would be to first design a sourcing strategy taking into account the disruption costs for the most relevant failure modes and then putting in place contingency plans for each disruption that include both the description of the procedures to follow and a definition of roles and responsibilities. Furthermore, within this systematic approach to risk management, there can be two types of responses to manage uncertainty: preventive and interceptive (see Fig. 1).

The preventive route to managing uncertainty seeks to reduce the likelihood of occurrence of an undesirable deviation or disruption through the design of a robust chain. The process starts with identifying the set of unexpected events (also commonly known as exceptions) that can occur in the chain including the interfaces. For each event, one can conduct the root cause analysis and devise ways and means to reduce the probability of their occurrence. One can use fault trees or fish bone diagrams for doing this. This would also enable us to compute the probability of occurrence of these undesirable exceptions.

The interceptive approach, on the other hand, attempts to contain the loss by active intervention subsequent to the occurrence of the event (for example, if there is a disruption in the supply of a critical component, buy it in an exchange). This requires a very good understanding of all the available alternatives and their impact on the supply chain.

In both cases, it is first necessary to identify the exceptions that can occur in the chain, estimate the probabilities of their occurrence, map out the chain of immediate and delayed consequential events that propagate through the chain, and quantify their impact. In the preventive approach, the knowledge of exception probabilities and their resulting impact is employed to design chains that are inherently robust and resilient to exceptions. In the interceptive approach, once an exception occurs, based upon the map of consequential events and their impact, actions that minimize the impact of the exception are initiated.

*1) Analytical Approaches:* Within the context of the broad classification of approaches suggested above, a number of different analytical and computational methods and tools can be employed to design robust supply chains.

*a) Mathematical planning models:* Mathematical planning models can be employed to select and schedule processes and partners such that the overall supply chain is by design robust to internal and external stimuli. In particular, portfolio optimization models commonly applied in finance can be used to select a portfolio of suppliers such that the total supply chain cost variability and the consequences from supplier nonperformance are within manageable limits, as demonstrated in the later sections of this paper. In addition, recent works in the area of robust optimization can also be used to generate supply chain solutions that maintain their optimality under minor deviations in environmental conditions.

*b) Adaptive control:* A multilevel adaptive control model can be built that continuously reconfigures the supply chain such that the difference between the actual and desired performance of the supply chain is minimized. The first level of an adaptive control system can be developed from a mathematical programming-based supply chain planning model that determines optimal supply chain configurations and production and logistics schedules, which are then followed by the various participants on the supply chain. The performance of these participants is monitored and input to the second level of the control system which then reconfigures parameters governing the first level of the control system to provide better-designed plans that fall within the performance requirements expected from the entire supply chain. Mathematical programming models can be used to build the second level of the control system. One such model might attempt to identify the optimal manner and location to add and deduct capacity from the supply chain such that the overall leadtimes and work-in-progress inventories lie within certain specified limits. Neural networks can also be employed to build the second level of the control system. The ensuing adaptive planning models will allow supply chains to respond in an agile manner to internal and external performance deviations.

*c) Rule-based control:* An alternative technique to handle exceptions in supply chains is through rule-based expert systems that initiate exception-management processes in the face of disruptions. For example, if a supplier is unable to fulfill an order within the promised time period, a decision support system for the manufacturer can analyze alternative options, such as securing supplies from other suppliers or the market or postponing the delivery of the final product. This technique tends to be interceptive in nature.

*2) Basics of Uncertainty Management:* As mentioned in the above section, for both preventive and interceptive approaches to risk management, it is necessary to identify the exceptions that can occur in the chain, estimate the probabilities of their occurrence, map out the chain of immediate and delayed consequential events that propagate through the chain, and quantify their impact. In this context, it becomes important to identify the possible exceptions in a supply chain and their consequences before proceeding to the development of analytical models.

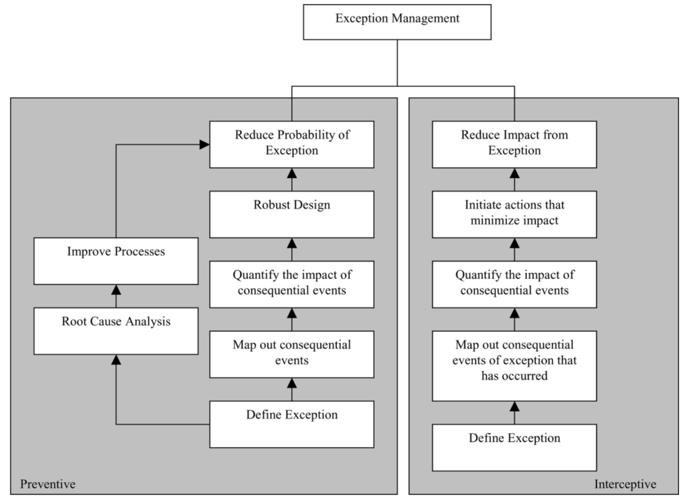


Fig. 1. Exception-management strategies.

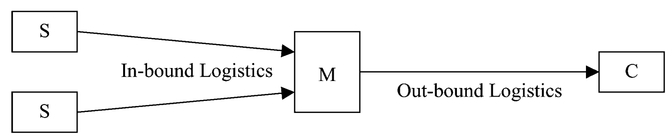


Fig. 2. Simple model for analyzing exceptions.

*3) Supply Chain Exception: Definition:* In attempting to analyze supply chain exceptions, our analysis here is based on a simple two-tier supply chain structure where the customer demand is directly fulfilled by a manufacturer, who, in turn, is supplied various components by a set of suppliers. Logistics service providers handle material movements between all of the parties as shown in Fig. 2.

In trying to differentiate a well-executed supply chain operation from a badly managed operation, we are motivated to adopt the well-accepted classical "Seven Rs" definition for the purpose of logistics, which is:

"To ensure the availability of the right product, in the right quantity, in the right condition, at the right place, at the right time, at the right cost, for the right customer."

We can use this description to define a supply chain exception occurring whenever the supply chain deviates from any one of the above required specifications-either in terms of delivering the wrong product in the wrong quantity, in the wrong condition, at the wrong place, at the wrong time, at the wrong cost and to the wrong customer. Whenever a supply chain delivery fails to stay on specification on any one of these dimensions, we say that an error has been committed in that dimension.

*4) Failure or Disruption Modes:* In a supply chain, exceptions can occur at various nodes—on the supply side, demand side, during transport, or in storage—and due to a variety of different causes. There could be failures of power and communications or employee strikes. There is also a risk of breach of trust by partners, by outside elements. It is not possible to list all of them but we have the following possible modes of disruption.

In this paper, we specifically study supplier nonperformance, in terms of the complete failure of a supplier to deliver components to the manufacturer or the inability of the supplier to deliver components at the promised price.

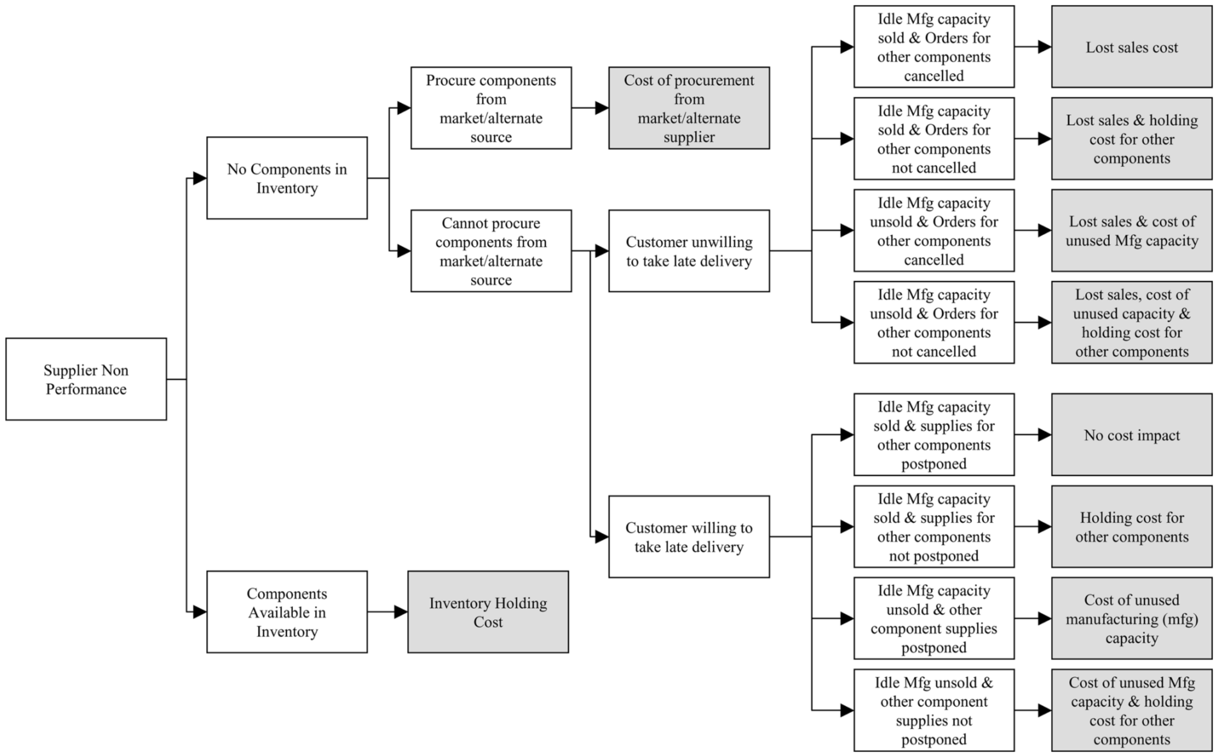


Fig. 3. Cause–consequence diagram for supplier nonperformance and the resulting outcome.

*5) Cause–Consequence Diagrams:* Cause–consequence diagrams or event trees are tools commonly used in reliability analysis to study the overall impact of a particular failure on the entire system. Based on the supply chain configuration, we can develop cause–consequence diagrams for each failure described before. However, given our interest in developing models for the supplier selection, we employ these cause–consequence diagrams to specifically analyze the effect of supplier nonperformance on the supply chain and to estimate the associated shortfalls in supply. For this purpose, we develop the cause–consequence diagram for supplier nonperformance as given below in Fig. 3.

Given the probability of occurrence of the initiating event, which is supplier nonperformance, and the probabilities for the various intermediary events, we can calculate the probability of occurrences for each of the end states or outcomes. Furthermore, each of these end states may result in different levels of supply shortfalls and financial cost. Hence, given the probability of each end state and the supply shortfall or financial cost for each end state, we can calculate the expected shortfall or financial risk for the nonperformance of a given supplier. Such an analysis can be repeated for each supplier, and the least risky supplier can be identified as the one whose nonperformance results in the least expected supply disruption or least expected financial loss.

A similar analysis can be undertaken for the management of supply risk due to transportation disruptions. A cause–consequence diagram for the impact of port closures similar to the U.S. West Coast port shutdown, from the perspective of a U.S.-based manufacturer, is presented in Fig. 4.

## III. Problem Formulations for Strategic Level Supply Risk Management

With the above foundation in the basics of supply chain risk management, we now highlight the above approach by presenting two representative models for strategic level supply chain risk management, from the perspective of the channel master. With reference to our classification presented earlier, the first model falls under the class of strategic-level problems for deviation management and the second falls under the class of strategic-level disruption-management models. Both models employ the preventive approach to risk management based on the use of mathematical modeling techniques as described below.

1) Strategic-level deviation-management model: Given the expected costs and variability (deviation) of costs for all suppliers, the first problem is related to the selection of an optimal group of suppliers such that the expected cost of operating the entire supply chain and the risk of variations in total supply chain costs is minimal.
2) Strategic-level disruption-management model: Given the expected probabilities for various supplier disruption scenarios, such as those presented in Table II, and the supply shortfalls under each of these scenarios, the objective for the manufacturer is to choose a set of suppliers that minimize the expected shortfall during the operation of the supply chain.

It may be noted that depending on the horizon of the risk minimization and the underlying nature of the causal events, the risk parameter can be minimized using a deviation-management model or a disruption-management model. This choice of model will primarily depend on whether the fundamental supply chain has changed. If the underlying supply chain network, described by the linkages between the various supply chain participants, changes for the event studied, a disruption model will be appropriate and, on the other hand, if the supply chain network retains its linkages, a deviation model will be appropriate. This distinction between the influence of the causal events also results in certain modeling differences between the deviation-management models and the disruption-management models. In a deviation-management model, the risk parameter to be minimized (typically, a performance metric such as cost, time, or demand) will invariably be modeled as a continuous variable, possibly defined by its mean and average. On the other hand, in a disruption-management model, the linkage impacting the supply chain network will typically be modeled as a discrete 0 or 1 model representing the existence or absence of the linkage. It may be recognized that even while modeling disruptions,

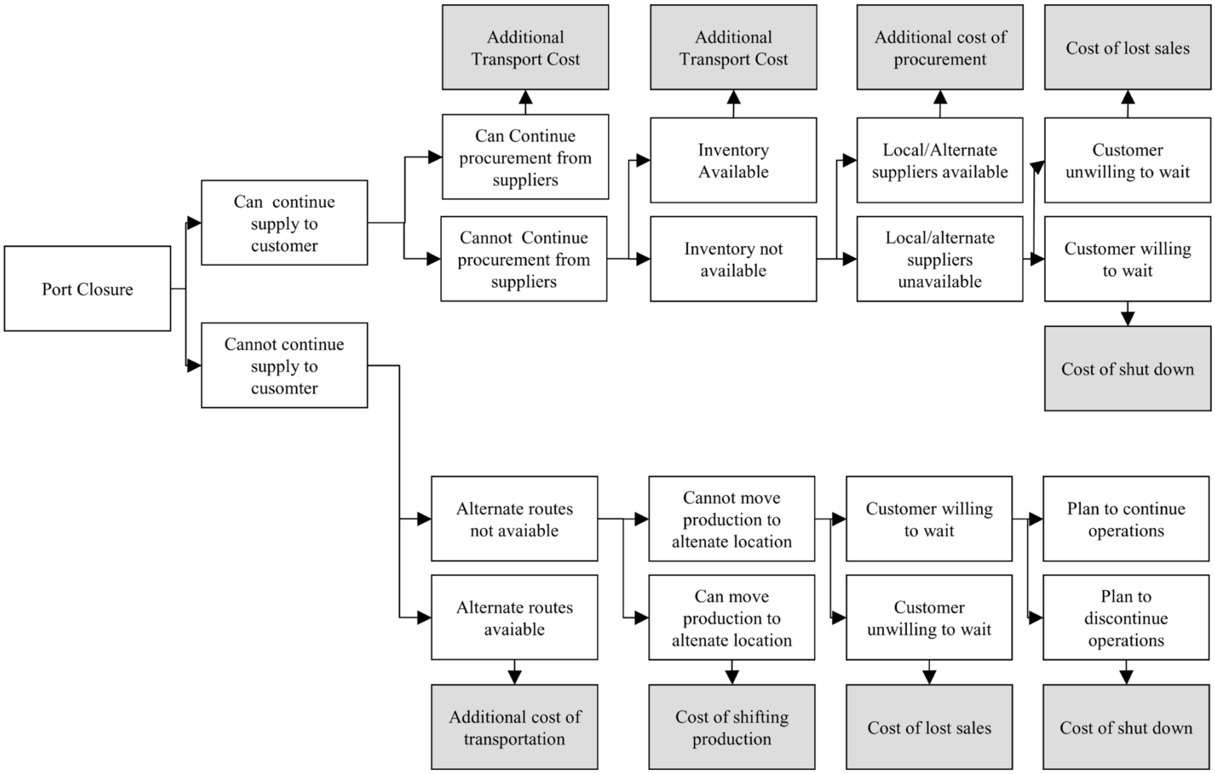


Fig. 4. Cause–consequence diagram for port closure and the resulting outcome as seen from a manufacturer's perspective.

TABLE II
EXAMPLES OF FAILURE OR DISRUPTION MODES

| Mode of Disruptions | Description |
|---|---|
| Supply side | Delay or unavailability of materials from suppliers, leading to a shortage of inputs that could paralyze the production. |
| Transportation | Delay or unavailability of either inbound and outbound transportation to move goods due to carrier breakdown or weather problems |
| Facilities | Breakdown of machines, power or water failure leading to delay or unavailability of plants, warehouses and office buildings. |
| Breaches in freight or partnerships | Violation of the integrity of cargoes, products (can be due either to theft or tampering with criminal purpose, e.g. smuggling weapons inside containers) or company proprietary information. |
| Failed Communications | Failure of information and communication infrastructure due to line, computer hardware or software failures or virus attacks, leading to the inability to coordinate operations and execute transactions. |
| Wild demand fluctuations | Sudden loss of demand due to economic downturn, company bankruptcies, war, etc. |

the performance metrics themselves may be continuous at the system level.

In addition, for our models presented here, we make the assumption that the supply chain is distributed globally and each player within the chain has its own goals, policies, and cultures. The channel master who occupies a dominant position in the chain has all of the information on its partners, including costs and schedules of the suppliers, the logistics providers, etc., to be able to make a rational decision in the interest of minimizing risk.

### A. *Strategic-Level Deviation-Management Model*

We propose an integer quadratic programming model for partner selection that tries to minimize the overall cost impact from the deviation in supplier costs. Such a model will be very useful to supply chain owners and channel masters. The model is an adaptation of the Markowitz model for financial portfolio management, for the purpose of managing a portfolio of suppliers. For this model, we define the impact in terms of the risk as given by the deviation of the total supply chain cost from its expected mean value. Given the expected costs and the variability of costs for all suppliers and manufacturers, the objective is to choose a set of suppliers and manufacturers that minimize the expected cost of operating the entire supply chain and, at the same time, minimize the risk of variations in the total supply chain cost. The selection of these partners also considers the allocation of orders between these selected partners.

The mean costs and variability of the costs for each supplier can be obtained from an analysis of their historical performance or by considering the probabilities of their nonperformance and the associated costs of handling the consequent impacts. Furthermore, due to the stochastic nature of events in the cause–consequence diagram, we can safely assume that, in general, the final outcomes and associated costs of supplier nonperformance will be normally distributed.

*Identifiers:*

$\mathrm{m} \in M$ manufacturer identifier;

$\mathrm{i} \in I$ component identifier;

$\mathrm{s} \in \mathrm{S}_{mi}$ supplier identifier among the set of suppliers for component i to a specific manufacturer $m$.

*Parameters:*

$C$ mean cost of the supply chain entity;

$V$ cost variability for the supply chain entity;

$N$ minimum number of entities to procure from;

$\mu$ risk aversion parameter $(0 < \mu < \infty)$. Large values for $\mu$ emphasize risk minimization and small values cost minimization.

*Variables:*

$X$ fraction of orders and, hence, costs allocated between manufacturers $(0 < \mathrm{x} < 1)$;
$Y$ fraction of orders and, hence, costs allocated between suppliers for a specific manufacturer $(0 < \mathrm{y} < 1)$;
$F$ 0 if the supply chain entity is not selected and 1 if selected.

*Model:* Minimize

$$\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{s=1}^{S_{mi}} y_s C_s F_s + \sum_{m=1}^{M} x_m C_m Y_m + \mu\left(\sum_{m=1}^{M}\sum_{i=1}^{I}\sum_{s=1}^{S_{mi}} y_s^2 V_s F_s + \sum_{m=1}^{M} x_m^2 V_m Y_m\right). \quad (1)$$

Subject to

$$\sum_{m=1}^{M} x_m F_m = 1 \quad (2)$$

$$\sum_{s=1}^{S_{mi}} y_s F_s = F_m \quad \text{forall} \quad m \in M \& i \in I \quad (3)$$

$$F_m \geqslant F_s \quad \text{forall} \quad m \in M \& s \in S_{mi} \quad (4)$$

$$\sum_{m=1}^{M} F_m \geqslant N_m \quad (5)$$

$$\sum_{s=1}^{S_{mi}} F_s \geqslant N_{mi} \quad \text{forall} \quad m \in M \& i \in I. \quad (6)$$

The objective of the model is to choose manufacturers and their suppliers and allocate order quantities between them in a manner such that the expected cost of operating the supply chain is minimized and also the variability of the overall costs is minimized as well. This is subject to the constraint that the selected set of manufacturers, between them, fulfill the order (2) and that the selected set of suppliers for these manufacturers, between them, fulfill the demand for all components (3). Suppliers are part of the supply chain only when the manufacturers they supply to are involved (4). Furthermore, there might be other policies that require a minimum number of manufacturers or suppliers to be engaged at each level of the chain for the sake of redundancy and greater reliability (5), (6).

### B. Strategic-Level Disruption-Management Model

With the probabilities for supplier nonperformance and knowledge of supply shortfalls under various resulting end states (as obtained from the cause–consequence diagram), we propose a mixed integer-programming model for partner selection that tries to minimize the overall impact on the supply shortfall consequential from the exception of supplier nonperformance. Such a model will be very useful to manufacturers, supply chain owners, and channel masters who want to incorporate robustness into their supply chains. The model is an adaptation of the credit risk minimization model employed in financial portfolio management for the purpose of managing a portfolio of suppliers. For this model, we define the impact in terms of the risk as given by the expected shortfall in the total supply from its expected value. Given the expected probabilities for various exception scenarios and the supply shortfalls under each of these scenarios, the objective of the manufacturer is to choose a set of suppliers that minimize the expected shortfall during the operation of the supply chain.

*Identifiers:*

$s \in S$ supplier identifier;
$i \in I$ scenario (state) identifier. $I$ is the set of all supply scenarios (states), which is obtained as a mix of all combinations of supplier nonperformance events for all of the suppliers in the set $J$.

*Parameters:*

$K$ quantity required by the manufacturer;
$x_{\mathrm{i}}$ quantity supplied by supplier $i$;
$R_{\mathrm{j}}$ relation cost of including supplier $j$ into the supply chain;
$C_{\mathrm{j}}$ capacity of supplier $j$.

*Variables:*

$F_{\mathrm{j}}$ 0 if supplier $j$ is not selected and 1 if selected;
$y_{\mathrm{i}}$ shortfall in total supply to manufacturer in scenario $i$.

*Model:* Minimize

$$\sum_{i=1}^{I} p_i y_i + \sum_{s=1}^{S} R_s F_s. \quad (1)$$

Subject to

$$K - \sum_{s=1}^{S} x_s = y_i \quad \text{forall} \quad i \in I \quad (3)$$

$$x_s = F_s * C_s \quad \text{forall} \quad s \in S. \quad (4)$$

The objective of the model is to choose suppliers such that the expected shortfall in supply, in the face of supplier disruptions, is minimized. This is subject to the constraint (2) which calculates the shortfall for each possible supply scenario. Also, the quantity supplied by any supplier is dependent on its capacity and on the decision whether the supplier is included into the supply chain network (3). When suppliers are included into the supply chain network, their supplies are equivalent to their capacity. This may be visualized as representing the capacity that is contracted or is expected to be contracted with the supplier.

## IV. Computational Results

For representative purposes, both the models described above were formulated in Microsoft Excel and solved using the Solver add-in.

### A. Strategic-Level Deviation-Management Model

This model was solved for a problem with 5 manufacturers, dealing with 5 suppliers each, for each of the two components required in their manufacturing. The risk aversion factor was taken as 25 and it was required that at least 2 manufacturers be selected for fulfilling the orders.

Due to the nonlinear nature of the problem, the final solution obtained depends very much on the initial values of the variables, considered in Table III. Moreover, the choice of manufacturers is the most critical decision since it also decides to a large extent the choice of suppliers. Hence, the model was solved for various initial solutions corresponding to all of the possible combinations of supplier selection. The optimal solution obtained as a result is given below, in Table IV

### B. Strategic-Level Disruption-Management Model

This model was solved for a problem with a single manufacturer (located in the U.S.), dealing with 5 suppliers. The probabilities of supplier disruption for all of the suppliers (individually and in various combinations) were considered as given. The relation cost was taken as U.S.$5000 and the quantity required by the manufacturer was 520

TABLE III
COST AND VARIANCE OF COST FOR EACH PARTNER

| Manufacturer | | | Component 1 | | | Component 2 | | |
|---|---|---|---|---|---|---|---|---|
| Mfg | C | V | Sup | C | V | Sup | C | V |
| Mfg 1 | 90 | 8 | S 1 | 10 | 4 | S 1 | 44 | 7 |
| | | | S 2 | 15 | 3 | S 2 | 45 | 6 |
| | | | S 3 | 25 | 1 | S 3 | 47 | 5 |
| | | | S 4 | 20 | 2 | S 4 | 43 | 6 |
| | | | S 5 | 12 | 2 | S 5 | 45 | 6 |
| Mfg 2 | 81 | 7 | S 1 | 13 | 3 | S 1 | 50 | 4 |
| | | | S 2 | 17 | 2 | S 2 | 45 | 6 |
| | | | S 3 | 19 | 1 | S 3 | 44 | 6 |
| | | | S 4 | 15 | 3 | S 4 | 47 | 5 |
| | | | S 5 | 10 | 3 | S 5 | 43 | 7 |
| Mfg 3 | 84 | 8 | S 1 | 14 | 2 | S 1 | 42 | 7 |
| | | | S 2 | 16 | 3 | S 2 | 46 | 5 |
| | | | S 3 | 15 | 2 | S 3 | 49 | 4 |
| | | | S 4 | 11 | 4 | S 4 | 48 | 4 |
| | | | S 5 | 15 | 2 | S 5 | 44 | 6 |
| Mfg 4 | 93 | 6 | S 1 | 12 | 3 | S 1 | 45 | 5 |
| | | | S 2 | 10 | 3 | S 2 | 45 | 6 |
| | | | S 3 | 20 | 3 | S 3 | 48 | 4 |
| | | | S 4 | 19 | 2 | S 4 | 46 | 6 |
| | | | S 5 | 18 | 2 | S 5 | 50 | 3 |
| Mfg 5 | 99 | 5 | S 1 | 16 | 2 | S 1 | 48 | 5 |
| | | | S 2 | 18 | 2 | S 2 | 47 | 6 |
| | | | S 3 | 21 | 1 | S 3 | 51 | 4 |
| | | | S 4 | 14 | 2 | S 4 | 51 | 5 |
| | | | S 5 | 12 | 3 | S 5 | 48 | 5 |

C = Mean Cost ; V = Variance of Cost; Mfg = Manufacturer ; Sup = Supplier

TABLE IV
COST AND VARIANCE OF COST FOR EACH PARTNER

| Manufacturers | | Component 1 | | Component 2 | |
|---|---|---|---|---|---|
| Mfg Selected | Share | Sup | Share | Sup | Share |
| Mfg 4 | 0.46 | S 1 | 0.167 | S 1 | 0.179 |
| | | S 2 | 0.167 | S 2 | 0.149 |
| | | S 3 | 0.167 | S 3 | 0.224 |
| | | S 4 | 0.25 | S 4 | 0.149 |
| | | S 5 | 0.25 | S 5 | 0.299 |
| Mfg 5 | 0.54 | S 1 | 0.176 | S 1 | 0.197 |
| | | S 2 | 0.176 | S 2 | 0.164 |
| | | S 3 | 0.353 | S 3 | 0.246 |
| | | S 4 | 0.176 | S 4 | 0.197 |
| | | S 5 | 0.118 | S 5 | 0.197 |

Sup = Supplier Selected;
Share = Fractional allocation of demand

TABLE V
SUPPLIER POOL

| Supplier | Location | Capacities | Risks exposed to |
|---|---|---|---|
| Supplier 1 | Ireland | 250 | Terrorist Attacks<br>Union Strikes |
| Supplier 2 | Taiwan | 250 | Earthquakes<br>US East Coast Port Closure |
| Supplier 3 | Malaysia | 280 | Lower Quality (Non-reliable)<br>US East Coast Port Closure |
| Supplier 4 | Singapore | 340 | US East Coast Port Closure |
| Supplier 5 | USA | 250 | |

units. The location, capacities, and risks facing each supplier are listed below in Table V.

TABLE VI
PROBABILITIES OF VARIOUS SUPPLY SITUATIONS

| Scenarios | Explanation | Probability |
|---|---|---|
| 1 | Supplier 1 Disrupted | 0.05 |
| 2 | Supplier 2 Disrupted | 0.04 |
| 3 | Supplier 3 Disrupted | 0.08 |
| 4 | Supplier 4 Disrupted | 0.01 |
| 5 | Supplier 5 Disrupted | 0.02 |
| 6 | Suppliers 1 & 2 Disrupted | 0.0015 |
| 7 | Suppliers 1 & 3 Disrupted | 0.0015 |
| 8 | Suppliers 1 & 4 Disrupted | 0.0005 |
| 9 | Suppliers 1 & 5 Disrupted | 0.0015 |
| 10 | Suppliers 2 & 3 Disrupted | 0.0016 |
| 11 | Suppliers 2 & 4 Disrupted | 0.0004 |
| 12 | Suppliers 2 & 5 Disrupted | 0.0008 |
| 13 | Suppliers 3 & 4 Disrupted | 0.0008 |
| 14 | Suppliers 3 & 5 Disrupted | 0.0048 |
| 15 | Suppliers 4 & 5 Disrupted | 0.0001 |
| 16 | Suppliers 1, 2 & 3 Disrupted | 0.0045 |
| 17 | Suppliers 1, 2 & 4 Disrupted | 0.0015 |
| 18 | Suppliers 1, 2 & 5 Disrupted | 0.0045 |
| 19 | Suppliers 1, 3 & 4 Disrupted | 0.0015 |
| 20 | Suppliers 1, 3 & 5 Disrupted | 0.0045 |
| 21 | Suppliers 1, 4 & 5 Disrupted | 0.0015 |
| 22 | Suppliers 2, 3 & 4 Disrupted | 0.0016 |
| 23 | Suppliers 2, 3 & 5 Disrupted | 0.0032 |
| 24 | Suppliers 2, 4 & 5 Disrupted | 0.0008 |
| 25 | Suppliers 3, 4 & 5 Disrupted | 0.0048 |
| 26 | Suppliers 1, 2, 3 & 4 Disrupted | 0.000045 |
| 27 | Suppliers 1, 2, 3 & 5 Disrupted | 0.000135 |
| 28 | Suppliers 1, 2, 4 & 5 Disrupted | 0.000045 |
| 29 | Suppliers 1, 3, 4 & 5 Disrupted | 0.000045 |
| 30 | Suppliers 2, 3, 4 & 5 Disrupted | 0.000032 |
| 31 | All Suppliers Disrupted | 0.00000135 |
| 32 | None Disrupted | 0.75779665 |

As may be seen from Table V, the third supplier is a nonreliable supplier based in Malaysia and the fourth is a reliable supplier in Singapore, both of whom are susceptible to the risk resulting from the closure of U.S. ports. The fifth supplier is assumed to be a local supplier and is exposed to relatively insignificant risks as compared to the other four overseas-based suppliers. Based on the above characteristics of the various suppliers, the probabilities for various disruption scenarios were calculated in Table VI. Due to the lack of real-world data, our calculations are based on simulated data. However, it should be possible to perform the same analysis with detailed practical data such as the country risk index and supplier rating data.

The model was solved with the above data. The optimal selection of suppliers included Suppliers 4 and 5, with an objective value of 10017. It might be noticed that these two suppliers are the most reliable.

## V. CONCLUSION

We have developed a conceptual framework for the classification of supply chain risks and associated approaches for handling them. In particular, we focus on the design of robust supply chains, at the strategic level, that are resilient to deviations and disruptions that may occur at the supplier end. Our analysis is based on the identification of unforeseen events that may occur at the supplier end propagating down the supply chain leading to cost variability and supply shortfalls. Robustness is built into our supply chain design by selecting a portfolio of suppliers that minimize the variability of supply chain performance in terms of cost and output. The models we develop are preventive in nature and employ mathematical programming tools. Our efforts here are an attempt to formulate and solve problems in the emerging area of supply chain risk management. For example, using our algorithm, the value of reliable suppliers and of adopting dual sourcing strategies in a supply chain can be easily determined. Finally, we may mention that our mapping of exceptions and their associated consequences can also be used to build decision support systems for exception management.

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# Fast Nesting of 2-D Sheet Parts With Arbitrary Shapes Using a Greedy Method and Semi-Discrete Representations

Heng Ma and Chia-Cheng Liu

***Abstract*—An efficient approach for 2-D sheet part nesting, incorporating a novel space encoding scheme and a greedy method for placing parts, is presented. The space encoding scheme denotes the occupancy of the part and the vacancy of the material sheet by discrete strip segments with an equal width and utilizes real-number coordinates on each segment for representing the occupancy and the vacancy. The greedy method operates in an iterative fashion by generating a part sequence and searching for the best position and orientation of each part in the part sequence. The part sequences are generated by a genetic algorithm with appropriate operators. The searching, based on bound settings, results in a stable searching process that is independent of the number of the parts involved. Experimental results show that the approach proposed is able to operate in an efficient manner and the final placements for the parts are more economical in comparison with a benchmark. The greedy method is particularly efficient in cases containing parts with multiple pieces because the range of the bounds for searching is gradually reduced as the method progresses.**

***Note to Practitioners*—This paper was motivated by observing sheetmetal parts in various shapes that are arranged on a rectangular sheet manually to minimize the usage of the sheet. The manual arrangements are highly dependent on one's expertise and experience but the results may vary from case to case. Existing approaches to arrange the parts automatically are usually time-consuming for dealing with parts in complicated shapes. This paper suggests a simple approach using a new decomposition method to describe the parts and the sheet, and a part placing method to efficiently decide the position of each part in a sequence. The part sequences are automatically generated by a known searching algorithm. The proposed approach has been tested in many industrial cases and the results suggest its feasibility and efficiency. In future research, we will address the cases requiring "offsets" among parts.**

***Index Terms*—Genetic algorithms (GAs), geometric representations, nesting, search methods.**

## I. INTRODUCTION

Nesting is an important process for numerous industries, such as sheet metals, garment, shoe, and furniture. The purpose of nesting is to determine an arrangement, (i.e., positions and orientations) of a number of 2-D parts with various shapes on a 2-D material sheet so that the usage of the sheet is minimized. Since more uncertainties are expected in modern manufacturing (e.g., changes in design), it becomes an emerging need that nesting must be performed within a tolerable period of computer time. The computer time, however, becomes more intensive when the nesting problem becomes more complex. It is therefore the objective of this paper to efficiently find a "good" solution to solve a more complex nesting problem.

The complexity of the nesting problem can be realized in two aspects, namely the part geometry and the part placing process. In the part geometry aspect, the boundary of a part can be composed of nonlinear

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