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RISK MANAGEMENT IN SUPPLY NETWORKS USING MONTE-CARLO SIMULATION

Léa A. Deleris
Feryal Erhun

Department of Management Science and Engineering
Stanford University
Stanford, CA 94305 U.S.A.

ABSTRACT

Trends such as (1) globalization, (2) heavy reliance on transportation and communication infrastructures, and (3) lean manufacturing have led to an increase in the vulnerability of supply networks. Due to a large number of interrelated processes and products, disruptions caused by these vulnerabilities propagate rapidly. Firms, however, can partially control the robustness and resilience of their supply networks through strategic and tactical decisions. Therefore, a decision-support tool that assists managers to evaluate the risk exposure of their supply networks can considerably increase the robustness/resilience of these networks. In this study, we present a Monte Carlo simulation based tool designed to assess uncertainty in supply networks. We describe its application and discuss the possible drawbacks of our approach.

1 INTRODUCTION

Events within the past decades have shown the extent to which companies, and subsequently their supply chains, are vulnerable to adverse events (Deleris, Erhun, and Paté-Cornell 2004). This observation should be an expected outcome of recent developments in supply networks. For instance, researchers comment on increasing reliance of corporate supply chains on transportation, utilities, and communication infrastructures (NACFAM report 2003 and Cranfield University report 2002). Trends such as globalization and offshoring further increase the complexities and interdependencies in supply chains which are now predominantly characterized by a large number of interrelated processes and products. However, the strategic and tactical decisions of a firm influence the extent to which its supply network is flexible in the face of uncertainty and able to mitigate – or on the contrary exacerbate – the consequences of these adverse events. Therefore, it is important to provide decision-makers at all levels of an organization with appropriate information for decision support. The study that we present in this paper precisely addresses this issue.

Our study originates from discussions that we had with managers at Seltik, a disguised high-tech company based in the Silicon Valley. Seltik operates a global supply network in order to produce several hundred SKUs (Stock Keeping Units). Our initial analysis revealed that managers at Seltik were concerned by the overall vulnerability of their supply network. They were particularly worried about whether the strategic development of their supply network – in terms of their choice of partners and geographical area – was adequate.

We present a simulation-based tool designed to help Seltik in the risk assessment of their supply network. Because of the size and intricacies of supply networks, simulation is considered to be a suitable approach for their analysis. For example, Ingalls (1998) points out that unlike optimization, simulation enables to identify robust solutions. The author further notes that robustness, not optimality, is the main concern of senior management when dealing with supply chains. Hicks (1999) describes a four-step method based on both simulation and optimization aimed at supply chain strategic planning. In this method, simulation is used to describe the dynamic behavior of a given supply chain structure and to assess the benefits of supply chain policies, such as inventory policies. Ingalls (1999) describes a simulation-based tool for supply chain analysis implemented at Compaq, which incorporates demand forecast errors. Deleris, Elkins and Paté-Cornell (2004) use a Monte Carlo simulation of a dynamic stochastic process to determine the losses caused by fire hazard within a large manufacturing network.

Our approach for supply network risk assessment rests on a flow model of the network and on Monte Carlo simulation. This approach incorporates external events to evaluate uncertainty in supply networks. It accounts for the dependencies between products and facilities, and enables a high-level analysis of "loss of product volume" due to network structure and adverse external events.

The rest of the paper is organized as follows. Section 2 describes our general approach to supply chain risk assessment of which this project is a (partial) application.

Section 3 introduces Seltik's supply network. Section 4 presents the risk assessment tool, with an overview in Section 4.1. Section 4.2 describes the supply network model. This model serves as the basis of the risk assessment, which we discuss in Section 4.3. The application of the tool to Seltik's supply network is described in Section 5. Finally, Section 6 concludes the paper with a summary of the benefits and limitations of the tool presented.

2 OUR APPROACH TO RISK MANAGEMENT IN SUPPLY CHAINS

Risk in a supply network originates from the lack of knowledge about (1) the events that may affect operations, i.e., the *load* on the network, and (2) the ability of the network to endure them, i.e., the network *capacity* at a given point in time. Our approach to risk assessment identifies and models both the load and the capacity of a given network and estimates the probability distribution of a specific set of performance measures. We summarize our framework below in Figure 1.

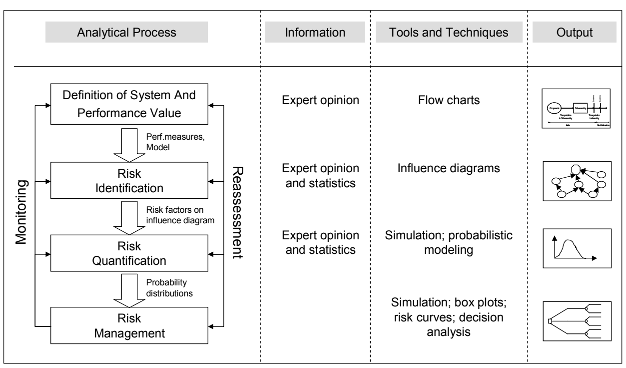

Figure 1: Our Approach to Risk Management in Supply Chains

There are many dimensions to supply network performance. Companies may choose to monitor customer-centric measures such as fill rate and on-time delivery, financial measures such as profit and revenue, process-centric measures, such as efficiency, or a combination of these. In this study, we measure network vulnerability through the "loss of volume," which we then translate into financial loss.

The framework separates the analysis of the adverse events from the analysis of the consequences on the overall network. The analysis of the adverse events (Step 2) includes the identification of these events and the estimation of their probability of occurrence and severity. The analysis of the consequences on the overall network rests on a model of the supply network (Step 1). The two models are combined through Monte Carlo simulation to obtain a quantitative risk assessment (Step 3). This assessment can be communicated through indices, maps, and graphs, which all foster the identification of risk mitigating alternatives, hence, risk management of the supply chain (Step 4).

We would like to highlight that such risk assessments are useful to quantitatively evaluate actions for risk mitigation. In addition, the approach enables to perform sensitivity analysis to study the behavior of the supply network under a range of specific loads, for instance an increase in suppliers' downtime or sudden shifts in end-consumer demand. The sensitivity analysis helps better understand the source of risk and the possible solutions to reduce it.

Deleris, Erhun and Paté-Cornell (2004) applied the framework described in Figure 1 to assess the risk of a supply chain for a single product. While the steps of the risk analysis are similar, the models that serve as the basis of the assessment are of different natures. In that application, the supply chain studied was serial. In the research described in this paper, our objective is to go beyond a serial supply chain and incorporate the additional complexities brought by the network structure.

3 SUPPLY NETWORK: DEFINITION AND EXAMPLE

By supply network, we mean a set of sites connected through an underlying network. Sites can be component suppliers, assembly/sub-assembly facilities, or distribution centers. We often use the term *node* to refer to a site. Similarly, we describe the underlying network as being composed of a set of *arcs* which represent transportation or information links. We use the term *element* to refer to either arcs or nodes within the network. Further, we use the word *path* to denote a set of nodes and arcs such that the nodes are all connected through the arcs in an acyclic chain.

Figure 2 depicts a simplified version of Seltik's supply network; accounting only for its most profitable products.

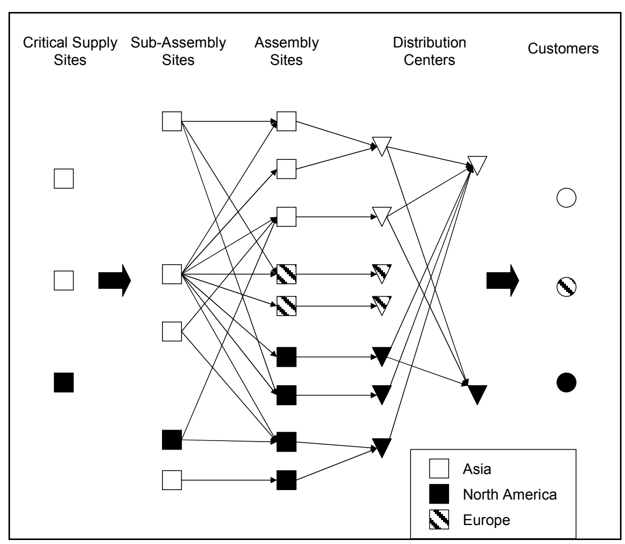

Figure 2: Representation of Seltik's Simplified Supply Network

4 RISK ASSESSMENT TOOL FOR SUPPLY NETWORKS

4.1 Overview

Our approach to risk assessment is based on a model that determines the outgoing flow of products for a given state of the network. In simple words, this flow model analyzes the effect of the state (open or closed) of arcs and nodes on the network performance. When compared with a reference outgoing flow, this yields a measure of "loss of volume," which may in turn be translated into loss of revenues. The model is to be used in a risk analysis exercise in two ways:

1. As a simple loss evaluation tool for what-if scenario analysis during a strategic discussion (Section 4.2)
2. As the basis for a risk assessment of the network based on Monte Carlo simulation (Section 4.3) as per our description in Section 2.

Figure 3 summarizes the overall process, emphasizing the information needed for each step. After gathering data related to the products and their respective network, we identify the risk factors that may affect the flow of the products. We generate disruption scenarios based on these risk factors, considering their severity and frequency. Combining the flow model with these scenarios by using Monte Carlo simulation yields the distribution of the chosen performance measure; i.e., loss of volume in a given supply network.

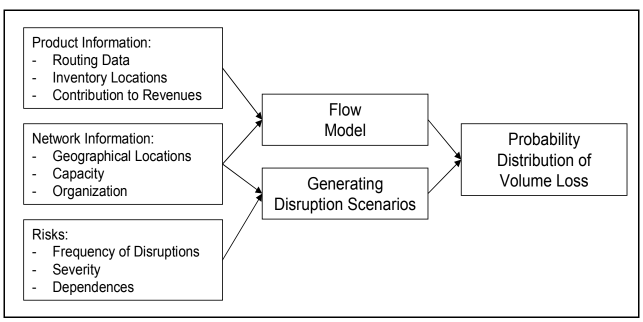

Figure 3: Schematic Representation of the Input Information Used by the Supply Network Risk Assessment Tool

The flow model is aimed at supply chain design decisions at a strategic/tactical level such as capacity development or capacity shifting. In that perspective, day to day variability is ignored: demand is taken as constant and lead time variations and capacity constraints on paths are overlooked. The disruptive events that are considered involve severe interruptions that affect a subset of elements of the supply chain over one or more time units. Inventories are accounted for but only at the level of the number of time units of production that they can replace.

The choice of "loss of volume" as the main measure of performance reflects the fact that the model is oriented towards strategic design decisions of the supply chain. Therefore, many operational aspects and measures related to them are left out of this study. An analysis aimed at estimating operational risks may target customer- and process-centric measures to study the impact of these risks on customer dissatisfaction or system inefficiency.

4.2 Description of Network Flow Model

The underlying idea of the flow model is to identify all the possible paths of the network and to estimate, for each product, how many units flow through each path. Then, accounting for state (open or closed) of each element in the network, one can assess the number of each product actually flowing through the network. (Paths are used to eliminate the possibility of double counting. Consider for instance a single-product network composed of two paths A-**d**-C and B-**e**-C, where capital letters denote nodes and bold lower case letters denote arcs. Each path transports 50% of the product volume. Assume that A is not operating for instance due to a strike, then the loss of volume is 50%. If in addition, the arc **d** is broken, for instance due to a storm, then the loss of volume is unaffected. Yet the naïve approach of summing the loss due to node A and the loss due to arc **d** would yield to an incorrect 100% loss of volume. The same loss is accounted twice. While the error is obvious in this simple network and straightforward to correct, it may not be the case in a more complex network.)

Assume there are P different product families indexed by p. Let s index a path through the network and assume that there are S such paths. Let R_s^p denote a *route*, which is the association of a path with a specific product family. Let V_s^p denote the number of products from product family p flowing through route s. Then the outgoing flow for a given state of the network for product family p, V^p, is given by

$$V^p = \sum_{s \in S} 1_{\{R_s^p\ open\}} V_s^p \tag{1}$$

and the total outgoing flow V is therefore

$$V = \sum_{p \in P} V^p = \sum_{p \in P} \sum_{s \in S} 1_{\{R_s^p\ open\}} V_s^p \tag{2}$$

In our application of this model, we have identified the following types of nodes: Component supply location, sub-assembly location, final assembly location, distribution center, and customer location. Arcs represent transportation modes between any two types of the above nodes. A path (R_s) is therefore uniquely characterized by the identification of an element from each of the above groups.

Transportation modes need only be specified when more than one transportation mode is available between two nodes. Note that the maximum number of routes grows exponentially with the number of nodes in the network. It is seldom the case, however, that all elements are connected. In our application we have identified a total of 69 routes for 5 product families.

To estimate Equation 2, it is necessary to identify for each route whether it is open or closed and separately, the number of items of each product family that flow through this route. To assess whether a route is open or not, the logic is to go down to the level of each network element. The rule is simple: a route is open if and only if all of its elements (nodes and arcs) are open. For a given product family, holding inventory acts as a redundancy and protects elements upstream of the inventory. Therefore an element that is protected with inventory is considered closed if the inventory is zero and the node is not operational.

To estimate the number of products that flows through each route, it is necessary to assign a time unit to the network, typically a day or a week. Product volume, V_s^p, would therefore be the (average) number of units of product p that flow through route s during the associated time period. It represents a reference volume for the given route and product pair. It is the result of design decisions of the supply network, hence an input to our model.

4.3 Risk Assessment Based on Monte Carlo Simulation

As described in Section 2, our objective is to go beyond the deterministic estimation of the losses contingent on a given scenario and to account for the likelihood of scenario occurrences. Our goal is to provide decision makers with an aggregate estimation of the risk exposure in the form of the probability distribution of losses. Such measure is useful when contemplating decisions about changing the structure of the supply network or improving its reliability as it accounts for both the severity and the frequency of events.

The analysis is based on repeated simulation of the supply network during an extended time horizon, typically a quarter (respectively a year) when the time unit of the flow model is a day (respectively a week). Based on a probabilistic description of the hazards that affect the network, we generate disruption scenarios that describe the load of the network during the time horizon. Thus, a disruption scenario determines for each time unit in the time horizon what the state of the network is in terms of the state of its elements. One should be careful that dependence between events is accounted for. For instance, one scenario could be that a tornado affects production at nodes 3 and 5 during a four-day time period starting at day 45 and that a national holiday affects all economic activity in some countries between days 67 and 69. The flow model is then used to assess the daily losses which are aggregated over the time horizon. We use Monte Carlo simulation to obtain the probability density function of the losses. To summarize, a disruption scenario translates into failure of elements of the network at the time unit level and finally into routes being open or closed. Based on routes status, we use the flow model to estimate the losses which are aggregated over the time horizon.

The simulation naturally yields numerous statistics about the behavior of the supply network in addition to "loss of volume" measures. For example, it can inform decision makers about node-specific performances. How frequently is a specific node unavailable? For how long is it unavailable on average? What is the correlation between node failures? Decision makers should analyze these statistics in order to identify where the risk resides in the network and to develop mitigating strategies.

5 ILLUSTRATION ON SELTIK SAMPLE NETWORK

We revisit the example presented in Section 2 and apply the tool to evaluate the risk exposure of the network.

5.1 Product and Network Information

Figure 2 displays the supply network that we use in our pilot project. We analyze Seltik's supply network for the company's five most profitable product families. This leads to the identification of a total of 69 routes. We use a day as the time unit of the flow model and a 90-day quarter as the time unit of the simulation.

We limit our analysis to end-consumers in North America, Europe, and Asia. In Seltik's case, components are either commodities or critical (sole or single-sourced) components. For the purpose of the risk analysis, we neglect commodity components (which are often bought in bulk and kept in inventory) and focus solely on the critical ones.

As the Figure 2 highlights, the supply sites and subassembly sites are heavily located in Asia, with two exceptions, where the sites are located in North America. The assembly sites, distribution centers, and naturally the end-consumers are distributed to all three geographies. The diagram emphasizes the complexity of the network even with the simplifying assumptions we made: there are critical dependencies between supply and demand nodes which span three continents.

5.2 Risk Events

We deliberately choose a diverse and limited subset of the risks faced by the company. Our goal is to illustrate the flexibility of the approach with regard to the nature of the risks that can be included in the analysis. We model operational problems such as component shortages along with geo-political crises and natural catastrophes. The results provided are therefore illustrative and do not reflect the actual risk exposure as many risks were omitted.

Specifically, we include the following risks into our analysis:

- the possibility of employee strikes,
- the shortage of components,
- severe political instability in the various regions, and
- disruptions caused by hurricanes.

After the identification of the risk factors, we need to describe their probability of occurrence, the set of nodes and arcs that they affect and the duration of the disruption that they cause. Our choice of models and parameters to represent the occurrences and severity of those risks are described in the Appendix. While we rely on ad-hoc estimations, we suggest that firms build a database of risk factors. This database would ensure consistency across the company about the various risk assessments performed. It is difficult to capture the probability of occurrence of rare events because of the lack of statistical data. The database of risk factors that we suggest should represent a collective effort by experts in relevant areas and should not solely be a matter of data collection and processing. It should also provide qualitative and quantitative information about those factors. To be truly valuable, this database needs to be updated on a regular basis. In parallel, for risk events for which data are scarce, we recommend performing sensitivity analysis on the problem parameters to ascertain that the results are robust to reasonable changes in their values.

5.3 Results

The flow model is implemented in Excel and we use @Risk to perform the simulation. In the simulation, we monitor the loss of volume for each product family. We then transform volume loss into revenue loss by assigning a revenue amount to each product family. This enables to compute the aggregated quarterly losses (in terms of revenues). In addition to quarterly losses, we monitor for each product family the number of days during the quarter where the volume losses are greater than or equal to 5% of the benchmark volume.

We run 20000 simulations of a 90-day quarter each. Each simulation yields slightly different results due to different initial random seeds. Figure 4 below plots the mean the standard deviation, the 95 and the 99 percentile of quarterly losses over n runs. We observe that the mean and standard deviation converge quickly at around 500 runs. Both the 99 and 95 percentiles fluctuate significantly up until approximately 18000 runs, although they are both flat between a few hundred runs and 8000 runs. We have no explanation for this behavior except to invoke randomness. The probability distribution of the quarterly loss (our chosen performance measure) is estimated over the full experimental setting.

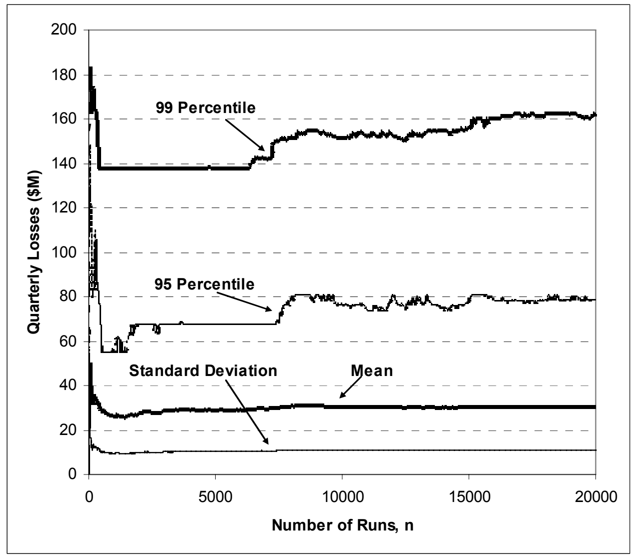

Figure 4: Probability Density Function for Quarterly Losses for Seltik's Simplified Network

Our results show that, for the risk events considered, there is a 0.75 probability that no losses are incurred during a quarter. Figure 5 below displays the probability density function of quarterly losses *conditional* on losses being strictly positive, which happens with probability of approximately 0.25. As can be seen on that graph, the probability of the losses is roughly inversely proportional to their amounts.

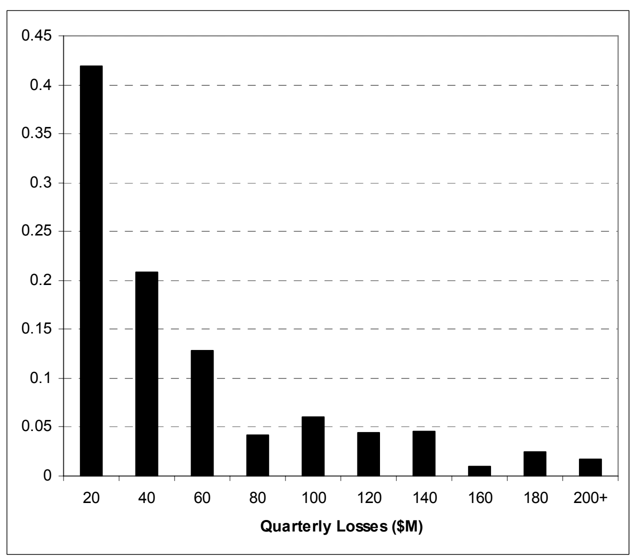

Figure 5: Probability Density Function for Quarterly Losses for Seltik's Simplified Network

6 CONCLUSION

In this paper, we present a tool for risk assessment in a given supply network. The analysis, which is based on a simple flow model paired with Monte Carlo simulation, fits in a more generic approach to risk management in supply chains, which we described in Section 2.

The flow model represents a high-level description of the network, and therefore does not go into details and everyday variability. The objective of this model is to assess the risk from events that affect some elements of the network over a significant amount of time (e.g., several days). Such events include among others political instability, large natural catastrophe that disrupts economic activity, strikes, or component shortages.

It is important to understand that the flow model bears several limitations. First, the model is a static representation of the network, which implies that it does not generate any lead time estimation. Second, the model constitutes a rough approximation of the flow: it does not incorporate yield problems at manufacturing sites, and assume that sites and transportation links are either operational (open) or failed (closed). A solution to overcome these limitations is to rely on discrete-event simulation such as models built with the Extend software. Such models can incorporate operational risks as well as the ones that we study in the flow model. The challenge with discrete-event simulation lies in the scalability of the model to a medium-sized network and in the input data requirements. This is a direction of research that we are currently investigating (Ayvaci, Deleris, and Erhun, 2005).

One of the goals of risk analysis is to provide relevant information to decision makers. The information obtained through the analysis presented in this paper is useful for both executives and supply chain managers. Our perception is that executives may be interested in using the flow model on its own for loss estimations in a what-if exercise whereas supply chain managers would favor obtaining a risk assessment of the supply network through the Monte Carlo simulation. Such a risk assessment is essential to better appreciate the robustness and the resilience of the network.

In this paper, we focus on a method to estimate the losses in a supply network. We do not address the critical issues of risk identification or risk mitigation. We refer the readers to Deleris, Erhun, and Paté-Cornell (2004) for a more extensive treatment of the framework. We would like to note that, once the users of the tool (executives or supply chain managers alike) generate a list of mitigation actions, the approach in this paper can be used to estimate the distribution of the benefits of each of them. Decision makers can then quantitatively compare the alternatives and choose the best one.

ACKNOWLEDGMENTS

To protect the company in this study, we refer to it as Seltik. Additionally, all data and information provided here are either publicly available or has been sufficiently disguised without removing the essence of the situation and the results. The authors thank all parties at Seltik for allowing them to use this information.

The authors also wish to thank the two anonymous reviewers who provided constructive comments that improved the clarity of the paper.

APPENDIX: INPUT DISTRIBUTIONS FOR THE RISK EVENTS

1. Employee Strike

The supply network described relies on five different business partners. We have assumed that each business partner can suffer an employee strike independently with probability 0.05 during a 90-day quarter. Given a strike occurs at one of the business partners, all elements of the network that are operated by this business partner are assumed not to be operating. The duration of a strike is sampled from a triangular distribution with a minimum value of 1 day, a most likely value of 3 days, and a maximum value of 10 days for four of the business partners and a triangular distribution with parameters minimum 1 day, most likely 5 days, maximum 20 days for the last one which has a history of longer strikes. Finally, given a strike occurs during a quarter, the day where it begins is obtained from sampling a uniform distribution between 1 and 90.

2. Component Shortage

Only one of the critical components that appear in the supply network is assumed to be subject to shortages, with probability 0.4. The length of the shortage is drawn from a discrete distribution as described in Table A1 and the day when the shortage begins is obtained from sampling a uniform distribution between 1 and 90.

Table A1: Distribution of Length of Component Shortage

Length of Shortage	Probability
2 days	0.625
5 days	0.1875
10 days	0.125
20 days	0.0625

3. Severe Political Instability

Political instability is assumed to be either regional (Asia, Europe, or America), affecting all countries in the region or simply affecting a single country. For Asia and Europe, there is a 0.001 probability of regional political instability per 90-day quarter. This value is assumed to be 0.0001 for America. At the country level, the probability of political instability (given no regional event) are either 0.001 or 0.0001 except for one country which is assumed as less stable and whose probability of political disruption is assumed to be 0.01. Given a disruption, its duration is sampled (independently) from a scaled beta distribution, with values ranging from 5 days to 130 days, a mean value of approximately 8 days and a standard deviation of about 2 days. As for the other events, the starting is sampled from a uniform distribution between 1 and 90.

4. Disruption from Hurricanes

The two regions that we assume to be susceptible to hurricanes are Florida and Mexico. We assume that there is a 0.25 probability of hurricane during any quarter. Furthermore, we assume that 0.7 of the hurricanes affect Florida and 0.3 Mexico. The length of the disruption caused by a hurricane is drawn from a discrete distribution as described in Table A2. Its starting date is sampled from a uniform distribution between 1 and 90.

Table A2: Distribution of Duration of Hurricane Disruption

Length of Disruption	Probability
1 day	0.735
2 days	0.147
3 days	0.074
4 days	0.029
5 days	0.015

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AUTHOR BIOGRAPHIES

LÉA A. DELERIS is a Ph.D. candidate in the Department of Management Science and Engineering at Stanford University. She received her Master of Science degree from the same department. Her research interests lie in probabilistic risk analysis and decision analysis. Her email address is `ldeleris@stanford.edu`.

FERYAL ERHUN is an Assistant Professor in the Department of Management Science and Engineering at Stanford University. She received her Ph.D. in Production and Operations Management from Carnegie Mellon University. Her research interests include the design, analysis, and optimization of supply chains under uncertainty. Her e-mail address is `ferhun@stanford.edu` and her web address is `www.stanford.edu/~ferhun`.