A Decision Support Framework to Assess Supply Chain Resilience

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ABSTRACT

Our research is aimed at developing a quantitative approach for assessing supply chain resilience to disasters, a topic that has been discussed primarily in a qualitative manner in the literature. For this purpose, we propose a simulation-based framework that incorporates concepts of resilience into the process of supply chain design. In this context, resilience is defined as the ability of a supply chain system to reduce the probabilities of disruptions, to reduce the consequences of those disruptions, and to reduce the time to recover normal performance. The decision framework incorporates three determinants of supply chain resilience (density, complexity, and node criticality) and discusses their relationship to the occurrence of disruptions, to the impacts of those disruptions on the performance of a supply chain system and to the time needed for recovery. Different preliminary strategies for evaluating supply chain resilience to disasters are identified, and directions for future research are discussed.

Keywords

Decision Support Systems, Resilience, Simulation, Supply Chain Design

INTRODUCTION

The topic of supply chain resilience has been discussed primarily in a qualitative manner in the literature. This paper represents an attempt to close the gap between qualitative and quantitative research through the development of a quantitative framework for assessing such resilience.

The concept of resilience is related to the capacity of physical and human systems to respond to and recover from extreme events, and it has gained prominence in recent years as a topic in the field of disaster research (Bruneau, Chang, Eguchi, Lee, O'Rourke, Reinhorn, Shinozuka, Tierney, Wallace and von Winterfeldt, 2003; Rose and Liao, 2005). Resilience can be thought of as an extension of the traditional concept of resistance, defined as the measures that enhance the performance of structures, infrastructure elements, and institutions, in reducing losses from a disaster. While disaster resistance emphasizes the importance of pre-disaster mitigation, the concept of resilience extends those ideas in order to also include improvements in the flexibility and performance of a system both during and after a disaster. Based on those ideas, we therefore can define *supply chain resilience* to be the ability of a supply chain system to reduce the probabilities of a disruption, to reduce the consequences of those disruptions once they occur, and to reduce the time to recover normal performance.

The primary purpose of this study is to develop a model based upon this definition, which can help quantify resilience in the supply chain. For that purpose, a decision support framework that incorporates the concept of resilience into supply chain design is proposed. Our framework incorporates strategic considerations (i.e., network design decisions) to quantify coordinated supply chain resilience and to support decision making in terms of the development of measurable, more effective supply chain configurations. Decision makers will be able to explore different supply chain configurations in order to, for example, analyze the vulnerability of a supply chain as a consequence of the break-down of nodes and links (vulnerability, in the context of our work, can be defined as an exposure to disruptions due to internal and external supply chain risks), assess the impacts of the disruption of a link on the network performance, or evaluate the costs and benefits of alternative measures to increase supply chain resilience (i.e., to absorb a disruption and to reduce the restoration time).

The reader should note that many actions that can increase resilience conflict with "traditional" business goals such as reducing costs and increasing operational efficiency. With this in mind, our decision framework will allow decision makers to model a variety of strategies in order to determine the "price of resilience". Ultimately, decision makers will be able to propose different recommendations for the design, or redesign, of supply chains in view of attaining efficient network resilience.

The remainder of the paper is organized as follows: First we provide a review of the literature related to supply chain resilience. We then provide an overview of our decision framework, followed by a description of the proposed methodology. Finally, we conclude with a discussion of the implications of our research study, and outline directions for future research.

LITERATURE REVIEW

In the supply chain literature, the topic of resilience emerged a few years ago and has recently become more widely recognized (Christopher and Peck, 2004; Craighead et al., 2007; Sheffi and Rice, 2005). Despite the increasing number of papers published on supply chain resilience, however, there has been little application of quantitative modeling techniques to the topic; in general, most papers have simply provided qualitative insights into the problem. In addition, researchers tend to focus on supply chain disruptions from the point-of-view of either mitigation measures or response measures, but typically do not look at both stages simultaneously as we are proposing here.

In the quantitative modeling arena, only recently has there been work published on the subjects of supply chain disruption and resilience, and the primary focus of this research has been on tactical considerations, i.e., decisions that do not affect the overall design of the supply chain. Tomlin (2006), for example, developed a model to determine the best contingency and mitigation strategies for a firm with a single product and two alternative suppliers. The parameters used by the author include supplier reliability, capacity and costs, transit lead time, volume and response time flexibility, as well as different inventory and demand considerations. Those parameters are then used to determine appropriate tactics for dealing with supply chain disruptions. The resulting model is most relevant to individual members of a supply chain and for tactical decision-making, and it does not explicitly take supply chain design decisions into consideration.

Lodree Jr, and Taskin (2007) introduce an insurance risk management framework for disaster relief and supply chain inventory planning. This framework provides an approach by which decision makers can quantify the risks and benefits of stocking decisions related to supply chain disruptions and disaster relief efforts. The authors introduce different newsvendor problem variants that take into consideration demand uncertainty as well as the uncertainty related to the occurrence of extreme events. Optimal inventory levels are determined and the insurance premium associated with disaster-relief planning is calculated. Once again, the parameters used by the authors are tactical in nature and are most appropriate for individual supply chain members.

In contrast, Huang, Chou and Chang (2007) developed a dynamic system model for supply chains and applied it to the management of disruptive events in full-load states of manufacturing chains. Their model is used to analyze demand shocks and to determine the level of contingent resources that must be synchronously activated by the members of the chain. The authors describe how the model can be used to reduce the impact of disruptive events and thus to enhance risk management. In this case, although the parameters used by the authors are tactical in nature, they are appropriate for coordinating an entire supply chain by assessing the impacts of disruptive events on the entire system and by activating contingency plans for mitigating these impacts.

Datta, Christopher and Allen (2007) present an agent-based framework for studying multi-product, multi-country supply chains subject to demand variability, production, and distribution capacity constraints, with the aim of improving supply chain flexibility and resilience. The model developed by the authors shows the advantages of using a decentralized information structure and flexible decision rules, monitoring key performance indicators at regular intervals, and sharing information across members of the supply chain network. One key limitation of this study, however, is that it does not incorporate cost data into the agents' decision-making functions, limiting the possibilities of performing relevant trade-off analyses. The parameters used by the authors are tactical in nature, since different fundamental structures of the supply chain network are not discussed, but they are appropriate for coordinating an entire supply chain.

There also has been a fairly significant amount of qualitative research that can help to determine parameters appropriate for modeling supply chain resilience (i.e., drivers of supply chain vulnerability, as well as their dependencies and relationships). In this general area, for example, Tang (2006) reviewed various models for managing supply chain risks and related various supply chain risk management strategies examined in the research literature with actual practices.

Kleindorfer and Saad (2005) developed a conceptual framework for managing supply chain disruption risk that includes the tasks of specification, assessment, and mitigation. The authors analyze the relationship among diversification (extended to facility locations, sourcing options, and logistics), weakest link identification, leanness and efficiency, backup systems, contingency plans, information sharing, modularity of process and product designs, and other elements of agility and flexibility in relation to supply chain disruption drivers. Sheffi (2005) discussed the use of safety stocks, extra capacity, redundant suppliers, standardized components and simultaneous processes and analyzed their effect on the resilience of a firm's supply chain in order to derive a series of qualitative insights into the problem. The considerations in both of those papers can be categorized as strategic, and those characteristics are most relevant at the level of individual members of a supply chain.

In a similar manner, Peck (2005) identified different sources and drivers of supply chain vulnerability and developed a multi-level conceptual framework for the analysis of the nature of supply chain vulnerabilities. The drivers identified by the author include products and processes, assets and infrastructure dependencies, organizations and inter-organizational networks, as well as the environment. The considerations in this paper can be categorized as strategic in nature and as appropriate for analyzing an entire supply chain.

More recently, Craighead, Blackhurst, Rungtusanatham and Handfield (2007) used an empirical research design to derive different insights and propositions that relate the severity of supply chain disruptions to three specific supply chain design characteristics (density, complexity, and node criticality) , as well as to the supply chain mitigation capabilities of recovery and warning. The chosen design characteristics can be categorized as strategic in nature, and as appropriate to the study of an entire supply chain, however the authors do not explicitly derive any quantitative relationships between them.

The specific insights presented by Craighead et al. (2007) fit well within Peck's (2005) conceptual framework for analysis, yet they provide a more focused basis for modeling the relationships that have an effect on the resilience of a supply chain. Even though Craighead et al. (2007) do not explicitly address the notion of resilience, their chosen design characteristics could be useful for a model intended to help quantify coordinated supply chain resilience at a strategic level. These characteristics represent measurable supply chain parameters that can be related to important strategic resilience concepts and are appropriate for modeling the entire supply chain. For this reason, we have chosen these characteristics to serve as the basis for our quantitative decision framework, and the following discussion expands upon each of them (supply chain density, supply chain complexity, and node criticality) within this context.

FRAMEWORK

Determinants of Resilience within the Supply Chain

Supply chain density is defined by the quantity and geographical spacing of nodes within a supply chain (see Figure 1 below). Thus when a large number of nodes within a supply chain are clustered closely together, that portion of the supply chain is said to have a high density level. The relationship of supply chain density to supply chain resilience can be illustrated by the impact of the 1999 earthquake in Taiwan. Because of the high concentration of computer component manufacturers in Hsinchu, Taiwan, the resulting damage caused to all of these manufacturers by the earthquake ended up having a significant effect on the entire global PC supply chain (Papadakis, 2003; Papadakis, 2006). This illustrates how the global nature of many supply chains leads to the possibility, in general, that local events can have far-reaching effects. The overall impact of such an event on the entire supply chain can be substantially increased if a significant portion of that supply chain is located within the same region, as illustrated by the example above.

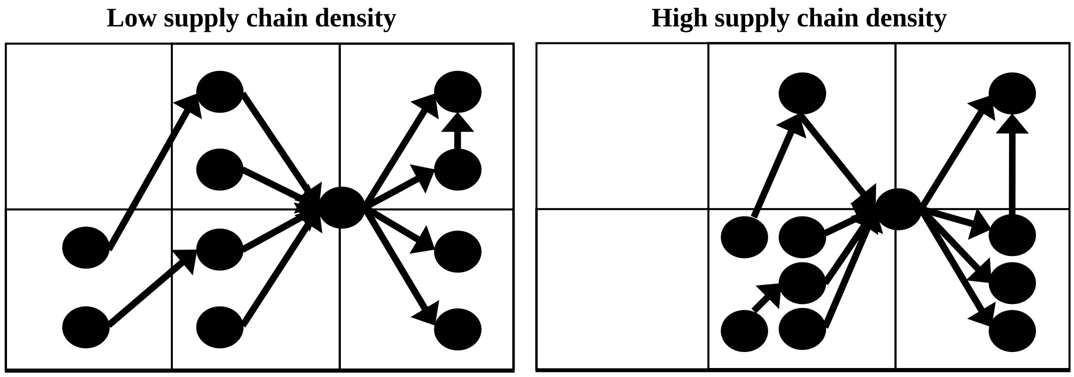

Figure 1. Different degrees of supply chain density

The second factor discussed by Craighead et al. (2007), supply chain complexity, is related both to the number of nodes in a supply chain and to the interconnections between those nodes (see Figure 2 below). Based on this definition, a less complex supply chain would have fewer nodes and/or fewer interconnections between nodes. As a consequence of this simpler structure, one might expect that a disruption in a less complex supply chain would be less significant since fewer nodes might be affected (although the relative importance of each node may therefore be greater, as discussed below). On the other hand, however, there can be a practical advantage to adding extra nodes to a supply chain (for example, contracting with an extra manufacturer of processors in the PC industry), even though this makes the supply chain more complex. Because an additional source of supply can act as a potential "buffer", such added complexity might actually increase the overall supply chain resilience level.

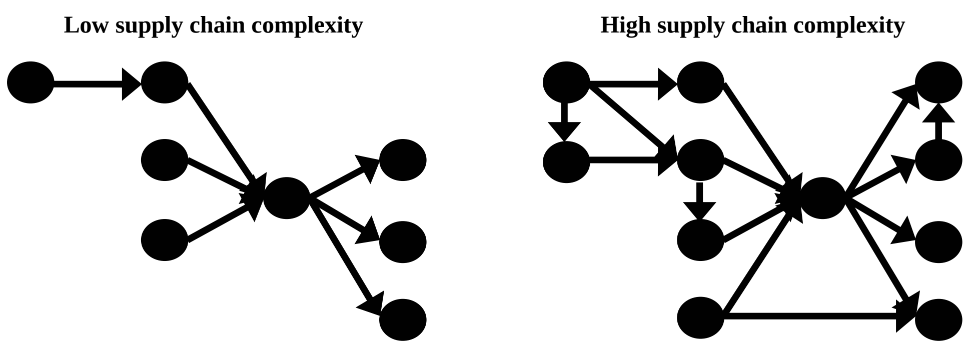

Figure 2. Different degrees of supply chain complexity

The third determinant of supply chain resilience is the number of critical nodes in a supply chain. Node criticality is defined as the relative importance of a given node or set of nodes within a supply chain (Craighead et al., 2007). For example, within the PC industry supply chain, a disruption that affects Intel (probably the most critical node in the entire supply chain) has a different impact on supply chain performance than does a disruption that affects a supplier of generic keyboards. A supply chain that contains a large number of critical nodes would have a greater potential for disruption than one within which support for critical processes is distributed among several different nodes (see Figure 3 below). The performance of supply chains with highly critical nodes is strongly dependent on the existence of nodes that represent hubs. If just one of these hubs is removed, a supply chain network (such as the one presented on the right in the figure below) can be reduced to a series of unconnected subnets.

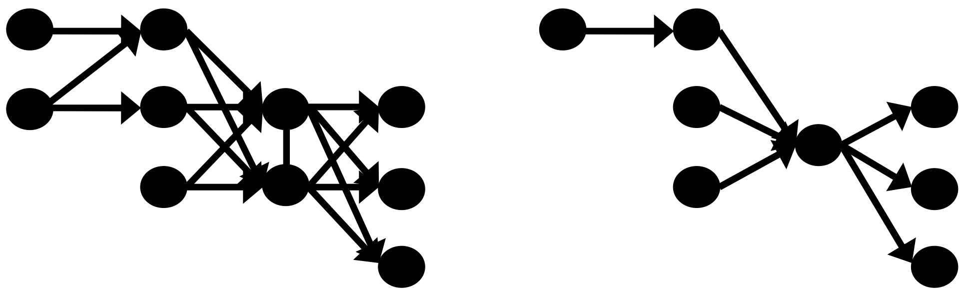

Figure 3. Different degrees of supply chain node criticality

There is a fairly complex relationship between each of these three supply chain design characteristics and the level of resilience of a given supply chain. For example, although a "simple" solution to increasing the resilience of a dense supply chain might be to redistribute the nodes (and thus to distribute the risk associated with those nodes), there may be competing cost or efficiency considerations that advocate the concentration of resources in one location. Depending on the circumstances, therefore, it actually might be better to maintain the density level (and the associated efficiencies) and to concentrate mitigation efforts within that particular location (i.e., density implies need for greater focus).

Similarly, although a higher degree of supply chain complexity implies that there is potential for more portions of the supply chain to be affected by a hazard (i.e., more interconnections imply more possible disruptions), a higher complexity level also implies more redundancy and, consequently, the potential for higher resilience. Under different situations, therefore, a decision maker might be able to improve resilience either by eliminating unnecessary complexity or by focusing her resilience efforts on non-redundant portions of the supply chain.

Similar considerations exist for the node criticality criterion. Although a large number of critical nodes in a supply chain implies the potential for less resilience, there may be underlying reasons (such as improved efficiency) why each of those nodes are included. Adding additional nodes may be a viable option for reducing criticality (at the cost of greater complexity, and perhaps greater density), however, simply identifying that a given node has a critical impact on the supply chain can lead to the opportunity to concentrate one's resources on that node and its associated links, in order to directly impact the overall resilience of the supply chain.

Measuring Determinants of Supply Chain Resilience

In order to quantify the potential relationships discussed above, we propose that the first two determinants of supply chain resilience be measured or estimated in the following way:

Supply chain density can be measured by the number of nodes divided by the average inter-node distance.

Supply chain complexity can be measured as a function of the total number of nodes plus the total number of forward flows in the supply chain (plus the total number of backward flows and the total number of within-tier flows, if any, in the supply chain).

The third determinant, node criticality, is somewhat more difficult to characterize. We believe that three different sub-measures, used in combination, can help describe node criticality within a given supply chain. Node criticality can then be measured as a combination of these sub-measures.

1. The relative importance of a given node (i.e., nodes responsible for “critical” components or large amounts of throughput should receive higher criticality scores).
2. The number of non-redundant inbound flows to a given node (i.e., all other things held equal, a node that integrates many parts is more critical than one that integrates fewer parts).
3. The number of non-redundant outbound flows from a given node (i.e., all other things held equal, a node that delivers several parts/products to many other nodes is more critical than one that delivers parts/products to fewer nodes).

Each inbound and outbound flow to a given node can thus be weighted by the critical nature of the components that it represents, and the resulting sum used to indicate the total criticality of that node.

Quantifying Resilience

Over time, the performance of a system such as a supply chain can change. Normal fluctuations will present minor fluctuations in performance. Man-made or natural disasters, on the other hand, will bring about abrupt changes in performance. These events will be followed by a gradual restoration to normal performance levels that will be a function of the measures implemented (Bruneau et al., 2003).

As pointed out by Sheffi and Rice (2005), the disruption and the dynamics of a system's response can be characterized by different phases. Therefore, since serious disruptions will have a distinctive profile in terms of their effect on system performance, the plotting of any relevant performance metric (e.g., sales, production level, profits, customer service, etc.) over time will reveal those different phases.

The concept of the resilience triangle, as discussed by Tierney and Bruneau (2007), can be used to illustrate the loss of functionality of a system over time due to disruptions, as well as the pattern of restoration and recovery (see Figure 4 below). The resilience triangle represents a measure of both the loss of functionality of a system after a disaster and the amount of time it takes for the system to return to normal performance levels.

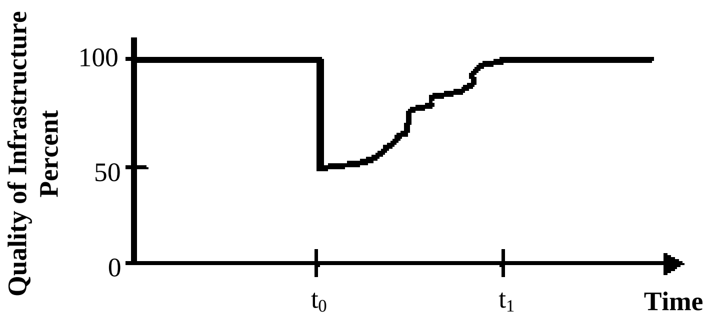

Figure 4. The Resilience Triangle (Tierney and Bruneau, 2007)

In the context of our discussion, supply chain resilience to disasters can thus be thought of as the ability of a supply chain system to (1) reduce the probabilities of such disruptions, (2) reduce the consequences of those disruptions once they occur, and (3) reduce the time to recover normal performance. The resilience triangle provides a simple, high-level means of representing the performance loss of a supply chain system, together with the time to recovery.

Supply Chain Resilience Framework

Craighead et al. (2007) imply that the severity of a supply chain disruption is a function of the number of entities within a supply chain whose outbound and inbound flow is affected by an unanticipated event. We propose the addition of the dimension of time (i.e., time to recover) in order to come up with a more useful measure of supply chain resilience. Thus, we can integrate the three determinants discussed above with the concept of the resilience triangle. A graphical representation of the proposed high-level framework is presented in Figure 5.

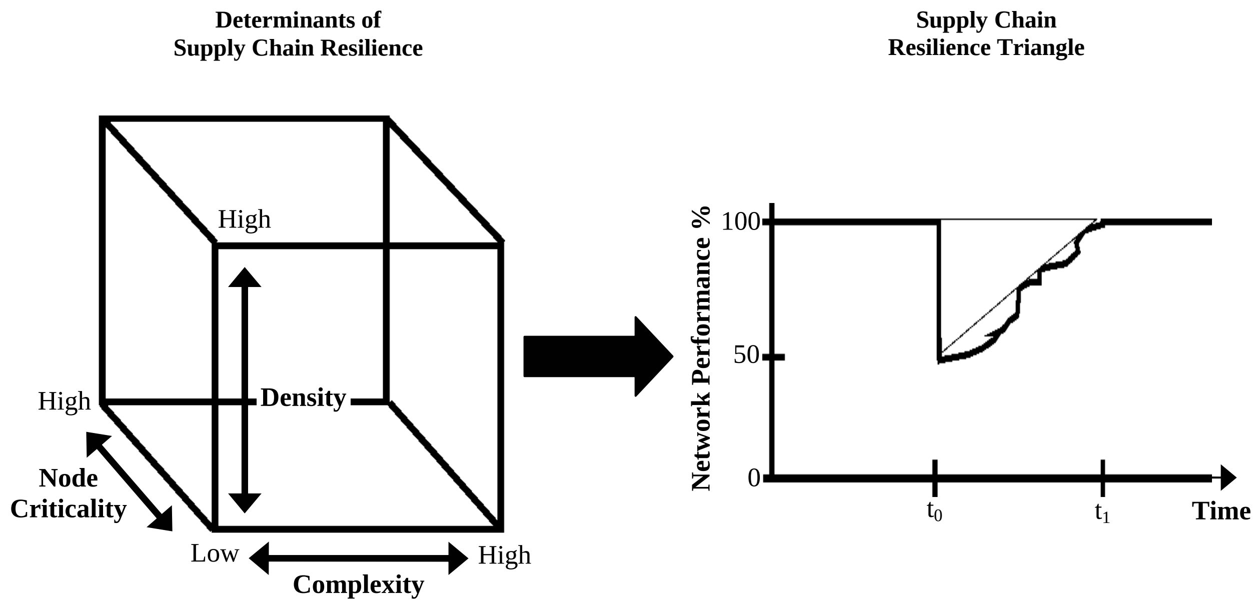

Figure 5. Supply Chain Resilience Framework

The overall objective of our decision support framework is to "reduce the size of the triangle" by supporting the development of supply chain design strategies that, taking into consideration the determinants of supply chain resilience discussed above, result in reduced impacts on total supply chain performance as well as in shorter recovery times should a disaster occur. Thus, this framework can allow the decision maker to display how different supply chain resilience strategies work and to compare the results. Such analysis ultimately can be used to propose recommendations for the design of supply chains in view of attaining network resilience.

PROPOSED METHODOLOGY

In order to characterize and measure the relationship between each of the determinants and the associated resilience of a supply chain, a simulation model can be used to represent the underlying supply chain. The main benefit of simulation in the context of supply chain resilience is that it can capture and model uncertainty, and thus it can allow for a good representation both of the risk of disasters and the overall response of a supply chain over time.

Simulation has been widely applied to study both supply chain phenomena (e.g., Swaminathan, Smith and Sadeh, 1998; Umeda and Zhang, 2006) and disaster management (see Cagnan and Davidson, 2007; Kanno, Morimoto and Furuta, 2006). A good application of simulation in the disaster planning domain is provided by the Critical Infrastructure Protection Decision Support System (CIP/DSS) project, an initiative aimed at studying the human, economic, and environmental effects of disturbances to critical infrastructure systems. The CIP/DSS project helps to demonstrate that one of the most effective ways to analyze tradeoffs between mitigation and the costs of protective actions is to utilize simulation to incorporate disaster data, vulnerability assessments, and disruption consequences in quantitative form (Bush, DeLand and Samsa, 2004).

The specific simulation model that will be used for characterizing the relationships between the three supply chain characteristics and the resulting level of resilience is based on Arena® as a software platform, with the addition of Visual Basic for Applications (VBA) for providing additional automation and data analysis capabilities. Arena® is a tool that has been utilized by a variety of other researchers in the supply chain domain (Vieira, 2004; Jain, Workman, Collins and Ervin, 2001; Jain and Leong, 2005; Jeong, Hastak and Syal, 2006), and the ability to augment its capabilities with VBA makes it a part of a very powerful and visually interactive modeling environment for building decision support systems

Supply chain design strategies for resilience

Our modeling approach involves simulating the occurrence of a disaster within the supply chain, and then combining the downstream effects on individual nodes and links in order to generate overall measures of both immediate impact and time to recovery for the system. We may thus characterize the effect of different levels of the determinants on the behavior of specific portions of the supply chain, as well as on the entire system. The system will support decision-making by providing the ability to perform "what-if" analyses and to see the effect of different supply chain configurations on the expected resilience behavior of the system. Ultimately, the costs and benefits of using alternative measures to increase supply chain resilience (i.e., to absorb disruption and to reduce the restoration time) can be evaluated.

As discussed above, many of the actions that can increase resilience conflict with “traditional” business goals such as efficiency and lean manufacturing. The decision maker therefore may need to model several different strategies to determine the “price of resilience”. It may be useful to look at specific tradeoffs such as:

- lowest cost supply network vs. resilient supply network,
- centralization (high density) vs. dispersion (low density), or
- flexibility and redundancy (e.g., extra nodes and/or redundant links) vs. efficiency

within the context of the supply chain model, in order to fully characterize the system behavior in response to a disaster.

An example of applying the model would be in the context of analyzing the idea of redundant components. Adding redundant components to back up a failure of critical parts in a system can increase system reliability and resilience. In terms of supply chains, companies can prevent disruptions in material flow by, for example, having redundant suppliers. In this scenario, we have suppliers of critical components that operate in parallel and in different regions in order to reduce the impact of a disaster. Using simulation, we can study the behavior of the supply chain network with and without those redundant critical components and evaluate how much the performance of the network is affected..

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Peck (2005) concludes her discussion of a proposed multi-level supply chain framework by indicating the need for a more quantitative approach to analyzing the effects of specific actions on dynamic supply chain networks. Similarly, Craighead et al. (2007) advocate the use of simulation-based studies to help quantify the relationship between supply chain disruptions and relevant design characteristics at a strategic level. The simulation model that we have described above provides the foundation for a quantitative framework which can begin to help addressing those needs.

Our decision framework is unique in that it incorporates a quantitative and measurable definition of resilience, as defined by Tierney and Bruneau (2007), and extends it to the study of supply chains. It then uses the three supply chain design characteristics identified by Craighead et al. (2007) as inputs, and looks at characterizing the relationships between these characteristics and the overall resilience of the supply chain. The complexity of these relationships and the need to clearly communicate the impact of design decisions on the performance of the supply chain makes necessary the use of a computer-aided decision support tool such as that within which the simulation is embedded (van der Zee and van der Vorst, 2005).

The current focus of the model is on design considerations concerning the flow of materials within the supply chain, as impacted by disruptive changes in the environment that propagate through the physical infrastructure of the supply chain. Future extensions of this initial work include modeling more specific aspects of the infrastructure and the inter-organizational layers, as well as the idea of modeling the "local" behavior of sub-networks and their impact on the overall supply chain (Peck, 2005).

Simulation has been proven to be a practical tool to test supply chain responses to different strategies for improving disaster resilience. Another natural extension to our work would be to look at the determination of an "optimal" strategy under different conditions, through an approach such as simulation-optimization (see, for example, Joines, Gupta, Gokce, King and Kay, 2002). Given an appropriately formulated model, this would further strengthen the applicability and importance of this work in the context of providing computer-aided decision support.

REFERENCES

1. Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O’Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A. and von Winterfeldt, D. (2003) A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities, *Earthquake Spectra*, 19, 733.
2. Bush, B., DeLand, S. and Samsa, M. (2004) Report no. LA-UR-04-5319. Los Alamos, NM: Los Alamos National Laboratory.

3. Cagnan, Z. and Davidson, R. A. (2007) Discrete event simulation of the post-earthquake restoration process for electric power systems, *International Journal of Risk Assessment and Management,* 7, 8, 1138.
4. Christopher, M. and Peck, H. (2004) Building the Resilient Supply Chain, *International Journal of Logistics Management,* 15, 2, 1.
5. Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J. and Handfield, R. B. (2007) The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities, *Decision Sciences*, 38, 1, 131.
6. Datta, P. P., Christopher, M. and Allen, P. (2007) Agent-based modelling of complex production/distribution systems to improve resilience, *International Journal of Logistics Research and Applications,* 10, 3, 187 - 203.
7. Huang, H. Y., Chou, Y. C. and Chang, S. (2007) A dynamic system model for proactive control of dynamic events in full-load states of manufacturing chains, *International Journal of Production Research,* 1, 1 - 22.
8. Jain, S. and Leong, S. (2005) Stress Testing a Supply Chain Using Simulation, Proceedings of the 2005 Winter Simulation Conference, 1650-1657.
9. Jain, S., Workman, R. W., Collins, L. M. and Ervin, E. C. (2001) Development of a high-level supply chain simulation model, Proceedings of the 2001 Winter Simulation Conference, 1129-1137.
10. Jeong, J. G., Hastak, M. and Syal, M. (2006) Supply Chain Analysis and Modeling for the Manufactured Housing Industry, Journal of Urban Planning and Development, 132, 1.
11. Joines, J. A., Gupta, D., Gokce, M. A., King, R. E. and Kay, M. G. (2002) Supply chain multi-objective simulation optimization, Proceedings of the 2002 Winter Simulation Conference, 1306-1314.
12. Kanno, T., Morimoto, Y. and Furuta, K. (2006) A distributed multi-agent simulation system for the assessment of disaster management systems, *International Journal of Risk Assessment and Management,* 6, 4-6, 528.
13. Kleindorfer, P. R. and Saad, G. H. (2005) Managing Disruption Risks in Supply Chains, *Production and Operations Management,* 14, 1, 53.
14. Lodree Jr, E. J. and Taskin, S. (2007) An insurance risk management framework for disaster relief and supply chain disruption inventory planning, *Journal of the Operational Research Society*, 1-11.
15. Papadakis, I. S. (2003) On the sensitivity of configure-to-order supply chains for personal computers after component market disruptions, *International Journal of Physical Distribution & Logistics Management,* 33, 9/10, 934.
16. Papadakis, I. S. (2006) Financial performance of supply chains after disruptions: an event study, *Supply Chain Management*, 11, 1, 25.
17. Peck, H. (2005) Drivers of supply chain vulnerability: an integrated framework, *International Journal of Physical Distribution & Logistics Management,* 35, 3/4, 210.
18. Rose, A. and Liao, S.-Y. (2005) Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Model of Water Service Disruptions., *Journal of Regional Science*, 48, 1, 75-112.
19. Sheffi, Y. (2005) Building a resilient supply Chain, *Harvard Business Review Supply Chain Strategy,* 1, 8, 1.
20. Sheffi, Y. and Rice, J. B. (2005) A Supply Chain View of the Resilient Enterprise, *MIT Sloan Management Review,* 47, 1, 41.
21. Swaminathan, J. M., Smith, S. F. and Sadeh, N. M. (1998) Modeling supply chain dynamics: A multiagent approach, *Decision Sciences,* 29, 3, 607.
22. Tang, C. S. (2006) Perspectives in supply chain risk management, *International Journal of Production Economics*, 103, 2, 451.
23. Tierney, K. and Bruneau, M. (2007) Conceptualizing and Measuring Resilience: A Key to Disaster Loss Reduction, *TR News, May-June*, 250, 14-17.
24. Tomlin, B. (2006) On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks, *Management Science,* 52, 5, 639.

25. Umeda, S. and Zhang, F. (2006) Supply chain simulation: generic models and application examples, *Production Planning & Control*, 17, 2, 155.
26. van der Zee, D. J. and van der Vorst, J. (2005) A Modeling Framework for Supply Chain Simulation: Opportunities for Improved Decision Making, Decision Sciences, 36, 1, 65-95.
27. Vieira, G. E. (2004) Ideas for modeling and simulation of supply chains with Arena, Proceedings of the 36th conference on Winter simulation, 1418-1427.