On the Resilience of Supply Chain Design under Disruptions

A Thesis Presented for the

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Degree

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I would like to dedicate this thesis to my loving family who have been my backbone all throughout my life. Their emotional and moral support guided me at every step in life. Even being miles away, a conversation with them every night gave me the strength to get through the tough times.

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Abstract

It is not possible to design a system in which there are no failures. To make the system more efficient, it is important to design the system in such a way that once the failure has occurred, the system can be restored to its full functionality in a short span of time. For a system to perform this task, we need to make the system "resilient". The basic idea of resilience is the ability to recover from an occurred failure in a system so that the system is performing at its best level. Resilience can be applied to all types of systems. This study aims at enhancing the resiliency of Supply Chains in the event of disruption at various levels. Supply Chains are one of the most important aspects for the growth and welfare of any business. Supply chain, just like any other system, is prone to disruption. A supply chain disruption is an unanticipated event that slows down the normal flow or even stops the normal flow of materials with hampering effects to the members within the supply chain. For enhancing the resiliency, various tools such as contingency planning, key indicators identification, and simulation have been implemented through the aggregate dimensions. The simulation tool is incredibly helpful for designing different scenarios in the highly complex supply chains. This study also sheds light on how the disruptions are transmitted through the various members of the supply chain and through different levels. The contingency planning plays an important role in the time of disruption by providing alternate sourcing ideology so that the supply chain does not come at a halt and costs the firm losses in terms of money and time.

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Chapter 1

Introduction

In a world full of constant uncertainties and disruptions, it is quintessential to have a sense of awareness and preparedness in order to avoid the losses or keep the losses as minimum as possible. The ability of a firm to withstand such uncertainties/disruptions and maintain the operational performance proves to have an advantage over the competitors. To comprehend the impact of these disruptions in the supply chains of firms, we need to have a fundamental understanding of several concepts first. These concepts include resilience, robustness, SC resilience and robustness, disruption propagation, network structure of the supply chain, and the implementation of simulation in supply chain design. The elaboration on these concepts is made in this chapter in the following sections.

1.1 The Concept of Resilience and Robustness

The fundamental idea of resilience has a foundation in almost all fields. In the article published by (Boin and Comfort, 2010) resilience can be observed in the fields such as engineering, biology, and psychiatry. Even though they have different meanings in their particular domains, the idea of resilience remains the same. Another definition as put by (Westrum, 2006) states that resilience is the ability prevent something bad from happening, ... to prevent something bad from becoming worse, or ... the ability to recover from something bad once it has happened. (Hale, A. & Heijer, 2006) define resilience as, "...the ability in difficult conditions to stay within the safe envelope and avoid accidents".

The resilience triangle is shown in Fig 1.1. The quality of infrastructure percentage can be replaced by system performance to keep it as a generic measure. The main target over here is to keep the triangle as small as possible i.e the length between time t_0 and t_1 should be made as minimum as possible for a system to be highly resilient. There are many strategies that can be implemented to shorten the time length. The strategy that has been used in our study is a mix of contingency planning and key indicators identification. The implementation of these strategies is exhibited in the latter sections of our study.

Robustness has been defined by (Tierney and Bruneau, 2007) as "the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance". In simpler words, if the system is robust, then it should be able to continue its operations in the face of disruptions. The system does not exhibit robustness on its own. There are certain modifications that need to be occurred at the time of disruption at various levels by using methods of forecasting and planning. If these decisions are not taken at the intended time, then the system fails to obtain the state of robustness.

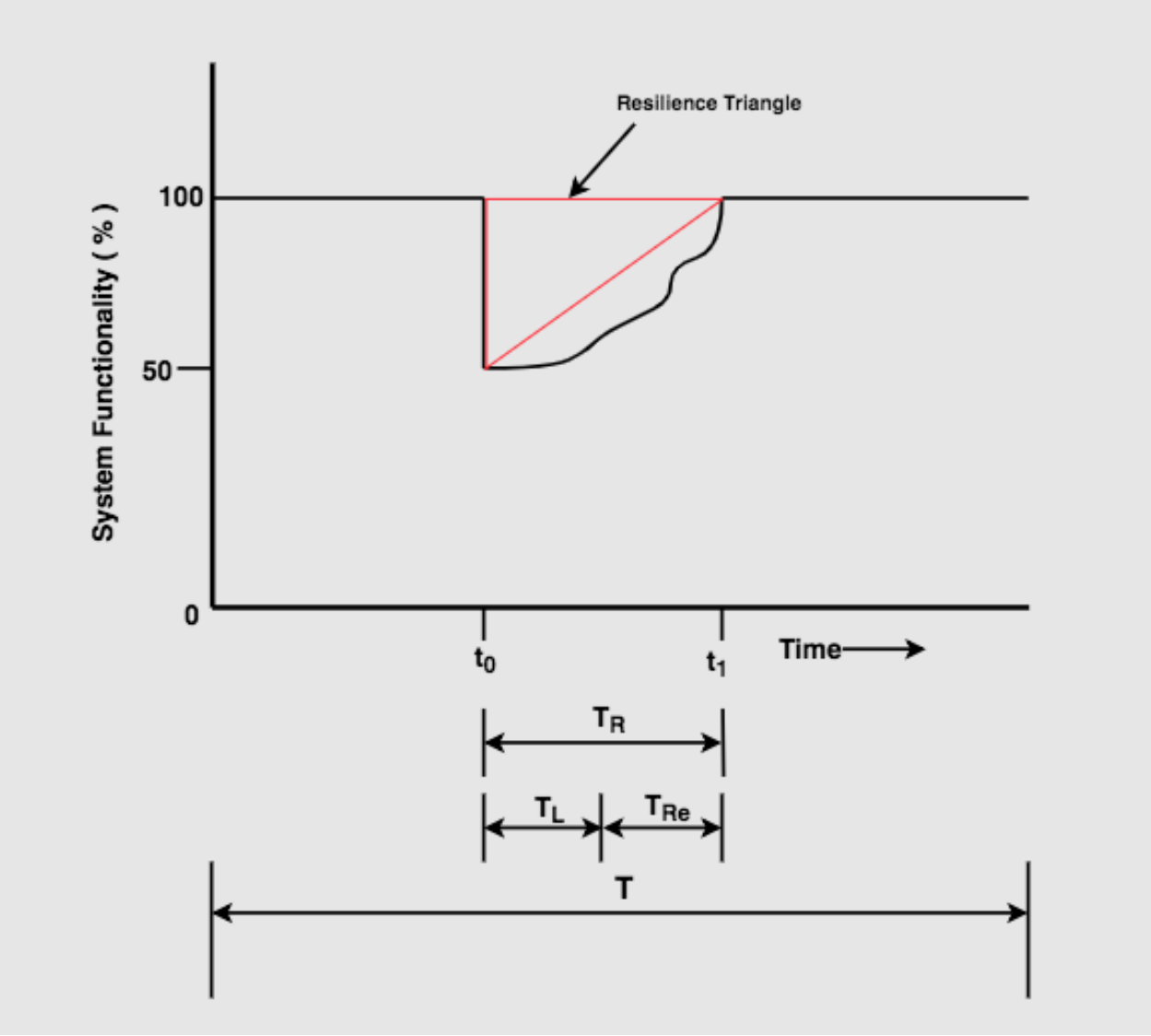


Figure 1.1: Resilience Triangle

1.2 Resilience and Robustness in Supply Chain

Now that the understanding of the concepts of resilience and robustness has been established, let us incorporate these concepts into supply chain and find the significance they hold. The primary definitions for these concepts remain the same, but the supply chain is considered as our system in this case. (Brandon-Jones, E.; Squire, B.; Autry, 2014) have defined SC Resiliency as " the ability of a system to return to its original state, within an acceptable period of time, after being disrupted". Resilience aids in indicating the weakest links of the chain and fortify them such that in the event of a similar disruption in the future, the system would be easily able to deal with it. (Kitano, 2004) defines SC Robustness as "the ability of the supply chain to maintain its function despite internal or external disruptions".

These two concepts are coming into the light and starting to have a pivotal role in the enhancement in the performance of the system due to rise in the number of uncertainties and unanticipated natural disasters. Incorporating these two factors into a supply chain would give the competitive advantage over others in the highly complex market.

SC resiliency and robustness ensures that there is a constant flow of materials and information throughout the supply chain. Even a hold up of materials in any facility within a SC of the firm makes a huge impact in terms of both time and money. Along with this, there are chances that the customer may decide to change to other firms due to the dissatisfaction caused to them. Various big companies such as Proctor and Gamble, Coca-Cola, Boeing, and Cisco have shifted their attention towards the implementation of resilience and robustness in their supply chains.

1.3 Disruption Propagation

Considerable research has been invested in understanding, predicting, preventing, and managing disruptions (Ivanov et al., 2016). The propagation of the disruption within a supply chain directly impacts the outcome. It is of utmost importance to focus on the supply chain disruption propagation because as the disruption spreads, the negative effects disseminate throughout the supply chain until the whole system fails. It is necessary to address the disruption at any level irrespective of its magnitude. A disruption which may seem innocuous has the potential to turn into a critical and harmful disruption by propagating and amplifying through various levels of the supply chain. The factors that affect the propagation of the supply chain disruption should be comprehended for better addressing of the disruptions.

The qualitative analysis made through the Gioia methodology mentioned by (Scheibe and Blackhurst, 2017) validates the data analysis to be done in three different orders. The first order analysis describes and summarizes the data. The second order analysis reduces the data by grouping similar codes and descriptions. The third order analysis consolidates the second-order themes into logical groupings called aggregate dimensions. There are three aggregate dimensions having two second-order themes each. These aggregate dimensions are

1) Nature of the Disruption

2) Supply Chain Structure and Dependence

3) Managerial Decision Making

The nature of the disruption itself affects the severity of the propagation of the disruption. The better understanding of the nature of the disruption poses as the foundation element in managing the disruption propagation. The two second-order themes associated with the nature of the disruption are correlation of risks and compounding effects. The correlation of risks theme states that one risk or even a risk mitigation strategy can inflict another risk. The disruptions never happen in a single member along a supply chain. Due to the strong interdependent and connected nature of the supply chain, disruptions never occur as an isolated event. The compounding effect means the adhering of one disruption to other as it propagates along the supply chain. Due to the compounding effect, the disruptions grow in

size and severity. The decision-making capability of the stakeholders directly contributes to the compounding effect. Self-preservation or measures to mitigate the risk at a personal level increases the severity of the disruption. The structure of the supply chain and the consisting dependencies serve as a source of propagation of disruption along the supply chain.

The two second-ordered themes associated with the supply chain structure and dependence are cyclical linkages and counterparty risk as shown in Fig 1.2. The cyclical linkages are nothing but the inter-dependencies between the nodes of a supply chain. A problem in one node leads to a problem in another node and vice versa. These linkages often go unnoticed until the disruptions occur. The cyclical linkages occur as a reason of one or more members playing different roles at different levels in the same supply chain. To mitigate the supply chain disruption propagation, the cyclical linkages must be carefully observed and studied. Counterparty risk occurs when one supplier supplies to a firm and its competitor at the same time. This means that the risk in one link in the supply chain is dependent on the other link. It is arduous to identify the interconnection through which the disruption can propagate. The firm focuses on one interconnection within a supply chain when the risk through different parts of the supply chain hit the firm without having any knowledge of it. The counterparty risk takes place mainly due to the hiding of information within the supply chain members (Scheibe and Blackhurst, 2017).

The managerial decision-making at the time of disruptions also affect the propagation through the supply chain. The two-second ordered themes associated with this type of aggregate dimension are herding behavior and misaligned incentives as shown in Fig 1.2 (Scheibe and Blackhurst, 2017). The herding behavior is the behavior in which one person behaves the way that others behave even though they are completely different people. In case of a supply chain, during the time of disruption, a firm takes the same measures as others are taking to mitigate the disruption although they have different properties and structure. They just tend to follow the 'herd' without thinking. The easiest example of herding behavior is when food joints adjust their prices based on other food joints which are the competitors. Misaligned incentives are the decisions made by the supply chain decision-makers which benefits one part of the supply chain at the expense of the other parts in the supply chain. These decisions are a result of the inability of the decision-makers to see the

bigger picture and improve the entire supply chain rather than improving just one part of it. One such misaligned incentive is giving more importance to taking actions after a disruption takes place rather than taking actions to avoid the disruption from happening.

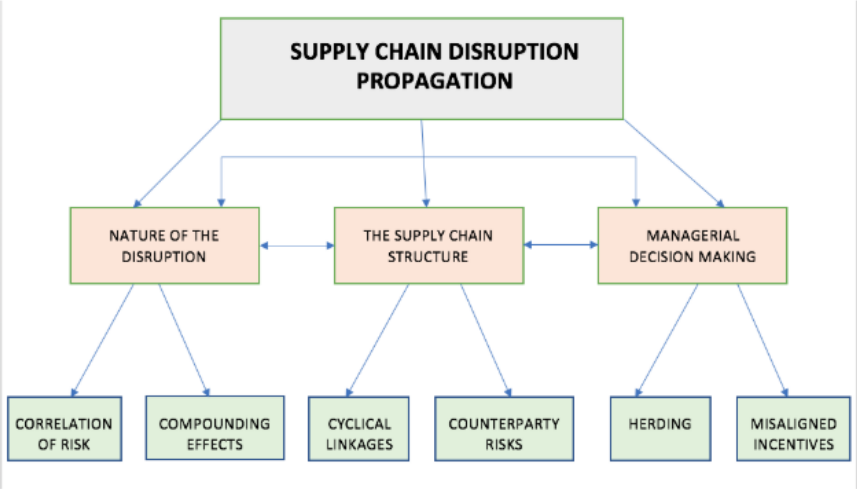


Figure 1.2: Aggregate Dimensions and their Second-order themes.

In a supply chain, the aggregate dimensions are the major source of the disruption propagation. If the risks in these aggregate dimensions are mitigated and the supply chain is designed in such a way that it would avoid any disruption propagation, then the resiliency of the supply chain is increased. There has been ample research related to the identification of the risks associated with the aggregate dimensions but there has not been a lot of research in the field of mitigation of the disruption propagation through the aggregate dimensions (Scheibe and Blackhurst, 2017). The nature of disruption, supply chain structure, and managerial decisions are the aggregate dimensions through which the supply chain disruption propagation can be contained.

The Figure 1.2 represents the aggregate dimensions on which the supply chain disruption propagation is dependent on. It also shows the second order themes which contribute to the aggregate dimensions. Out of these, correlation of risk and cyclical linkages have a significant impact on the disruption propagation. Hence, the main focus of this paper would be to model a supply chain in such a manner that the problems arising in the supply chain due to these factors could be anticipated and mitigated at the initial stages to avoid cascading of the failure through the supply chain.

1.3.1 Correlation of Risks

The supply chain is a network of strongly interconnected nodes which function together in coordination for getting the desired output. If there is a disruption occurring at any level in the supply chain, it is plausible to affect the performance of the supply chain. It is observed that this disruption does not just affect the point of occurrence, but it may be propagated throughout the SC because of the inter-connectivity. The disruption may travel upstream as well as downstream the SC. This phenomenon is called as the ripple effect in the supply chain (Ivanov, 2017). It is highly unlikely for a disruption to occur in isolation. It is not just the risk that can cause another risk, but the strategy to mitigate one risk can also lead to risk in a different node in the SC. Thus, the risk mitigation strategy should not be focused only on reducing the risk at a certain point, but it should also pay close attention towards the effects of the risk as well as the effects of the mitigation technique on other elements of the SC.

The Figure 1.3 represents the ripple effect in a supply chain structure. It can be evidently seen that the disruption is going to propagate in both directions. It is important to minimize the risk caused due to the disruption. At the same time, the risks associated with the mitigation strategy should also be taken into consideration. The decisions that are taken once the disruption occurs play a vital role in the degree of recovery of the SC. The managerial decisions during disruption about these decision variables and the ripple effect analysis throughout the SC will contribute towards the resilience of the SC.

The methodology that has been suggested for limiting the propagation of risks due to the correlation of risks is the ripple effect modeling. With the help of this methodology, the effect of the disruption and the effect of the strategies devised to reduce the risks due to the disruption can be found out throughout the supply chain structure. This will help in making the supply chain more resilient by reducing the risks after the disruption has occurred.

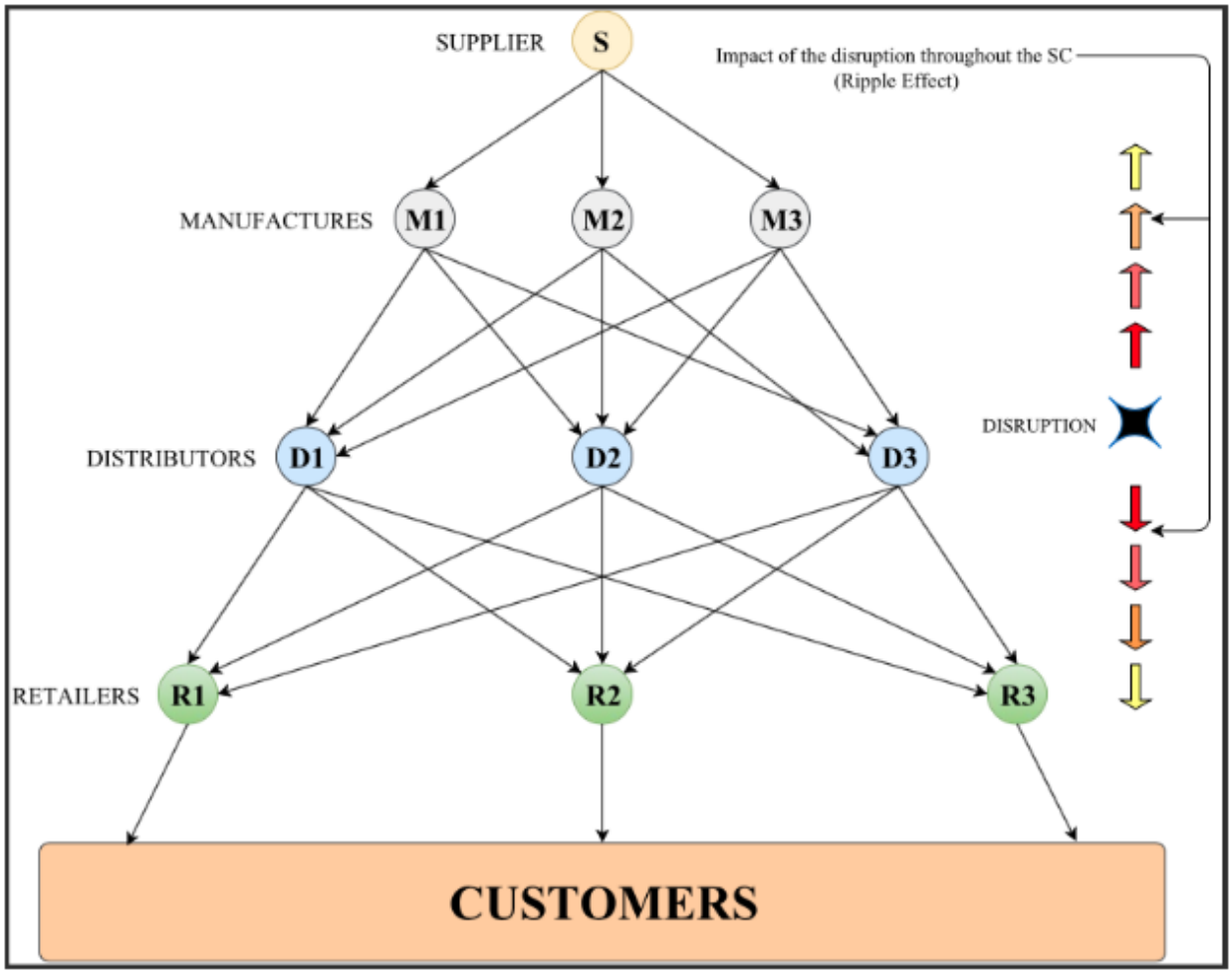


Figure 1.3: Ripple effect in the Supply Chain Structure.

1.3.2 Cyclical Linkages

In a supply chain, all the nodes are inter-connected and are inter-dependent. This aids in the desired functioning of the supply chain. At the same time, if there is any disruption in the SC, the same inter-connectivity and inter-dependence will become disadvantageous. Suppose that there are three nodes in a supply chain. If there is a problem in node 1, then it can transmit a problem to node 2. Similarly, if there is a problem in node 2, it may propagate to node 3. The problem in node 3 can have a feedback effect on the first node. This is called as the cyclical linkage in supply chain and is shown in Fig 1.4. A disruption in one of the stages of trade-off can lead to a disruption in the other stages due to the cyclical linkage. Thus affecting the entire supply chain at different levels.

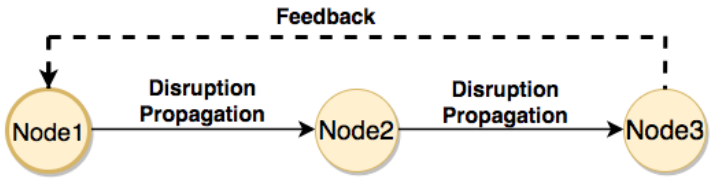


Figure 1.4: Cyclical Linkage Representation

The disruptions occurring in the cyclical linkages are the most underestimated in the entire supply chain. But, these have a very significant impact on the supply chain. These linkages should be considered from all the perspectives. There exists different cyclical linkages between different levels of the supply chain. There is a customer order cycle between the customer and the retailer; a replenishment cycle between the retailer and the distributor; a manufacturing cycle between distributor and the manufacturer; a procurement cycle between the manufacturer and the supplier. Any disruption in one of these cycles can lead to the disruption of the whole supply chain.

The customer order cycle consists of 4 distinctive activities. These are customer arrival, customer order entry, customer order fulfillment, and customer order receiving. The replenishment cycle consists of retail order trigger, retail order entry, retail order fulfillment, and retail order receiving. The manufacturing cycle consists of order arrival, production scheduling, manufacturing and shipping, and receiving. The procurement cycle

consists of order based on manufacturer's production schedule or supplier's stocking method, supplier production scheduling, component manufacturing and shipping, and receiving at manufacturer.

1.4 Network Structure

(Kim et al., 2015) have considered the network structural perspective for the supply network disruption and resilience. It can be inferred that in a network, the prime cause of interruption of the movement of the unit is the malfunction in the node or arc. Although it is the prime reason for the cause of interruption, it does not help in detecting the network-level disruption. In this paper, the methodology that has been used for the purpose of designing the supply chain network is the graph theory. It has been applied to a great extent to the complex networks like the World Wide Web, power grids, and the food chains (Gross and Yellen, 2005). If we implement the graph theory in the field of supply chain, then the facilities would be a representation of the nodes, whereas, the logistics between the facilities would be represented by the arcs.

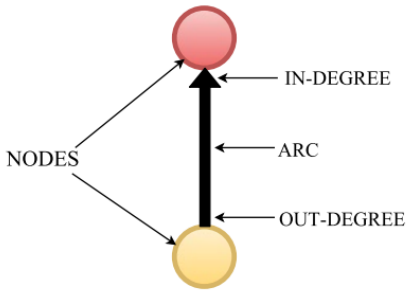


Figure 1.5: The structure of nodes and arcs according to the graph theory.

The latent structure of a supply chain network can be explained by the graph theory in a suitable manner. Instead of using the notations G = (V, E) (Emden-Weinert et al., 1997) ,the notation G=(N, A) is used in terms of supply chain design (Kim et al., 2015). The set N contains the nodes while the set A contains the arcs of the supply chain network. It glances at the correlation between the nodes and arcs at a structural level from a meticulous perspective. The in-degree and out-degree are the elements that describe the amount of the supplier and customer present in the node in consideration. The in-degree resembles the number of arcs whose head connects to a node, and the out-degree resembles the number of arcs whose tail connects to the node.

In the event of an arc or node level disruption, it has been observed that the supply chain may still continue to function normally, as there exists multiple walks from the initial node to the final node. The disruption does not seem to be affecting the supply chain network, since the materials are being delivered to their required final point from its initial point. But, the network level disruption can cause the system to fail or the process to remain incomplete.

For determining the performance of the network structure, a theoretical framework is provided by the complex adaptive systems (CAS) theory (Kim et al., 2015). According to this theory, the analytic frameworks have been developed for the better understanding of the correlations between all the elements within the system. It sheds light on how these correlations affect the overall performance of the system. The structures that have been taken into consideration in this research paper are the ones that take place in the real-life SC scenario. These are as following:

- Block-diagonal network structures
- Scale-free network structures
- Centralized network structures
- Diagonal network structures

The block-diagonal network structure is the one in which the nodes are clumped up between the initial and final node, where there are connections within the clumps but not between the clumps. The scale-free network pattern exhibits a biased nature, where a certain few nodes have most of the connections, while most of the other nodes obtain the merest of connections. This type of network pattern has node degree distribution which is highly distorted and seems to follow a power-law or Pareto distribution. The centralized structure is an accurate illustration of highly central nodes. In this, the high-level suppliers assume authority as a representative of the customer firm in the design and development processes. The diagonal supply structure follows a certain pecking order in which the materials are moved only in one direction (from the lower-level nodes to the higher-level node). These network structures are as shown Fig 1.6, Fig 1.7, Fig 1.8, and Fig 1.9.

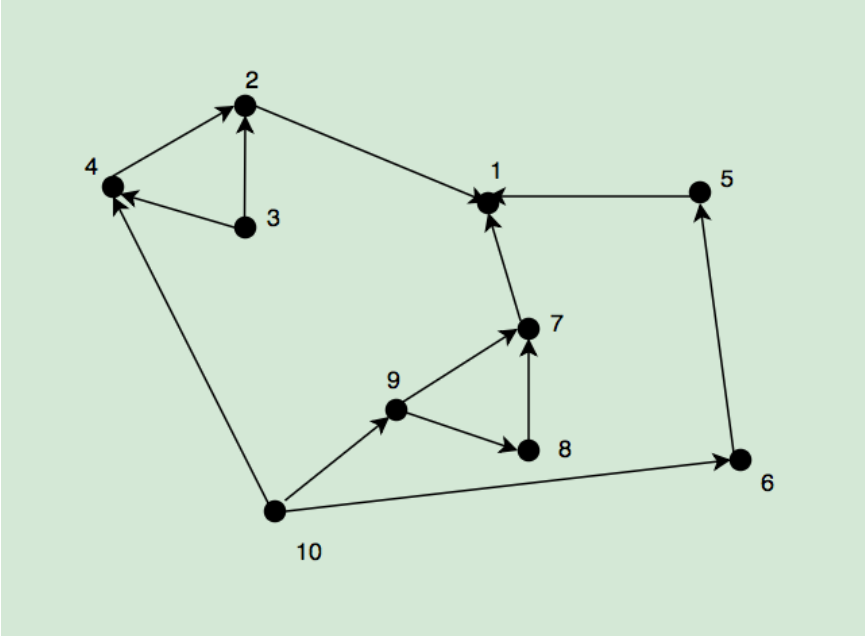


Figure 1.6: Block-Diagonal Network Structure

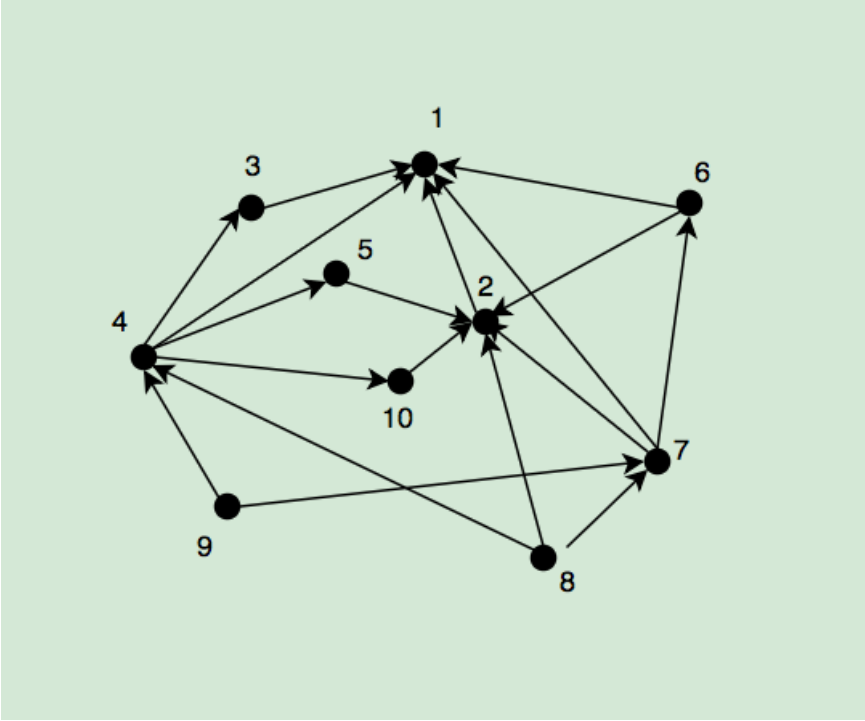


Figure 1.7: Scale-free Network Structure

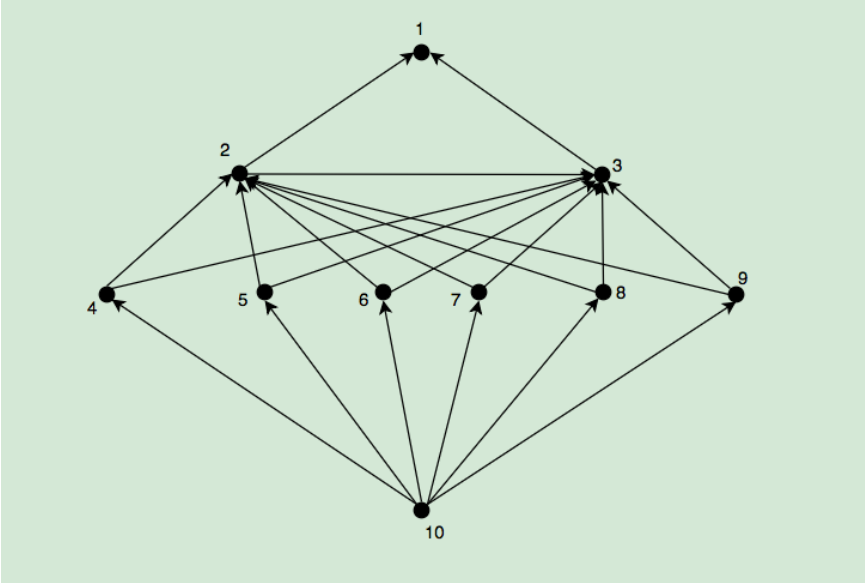


Figure 1.8: Centralized Network Structure

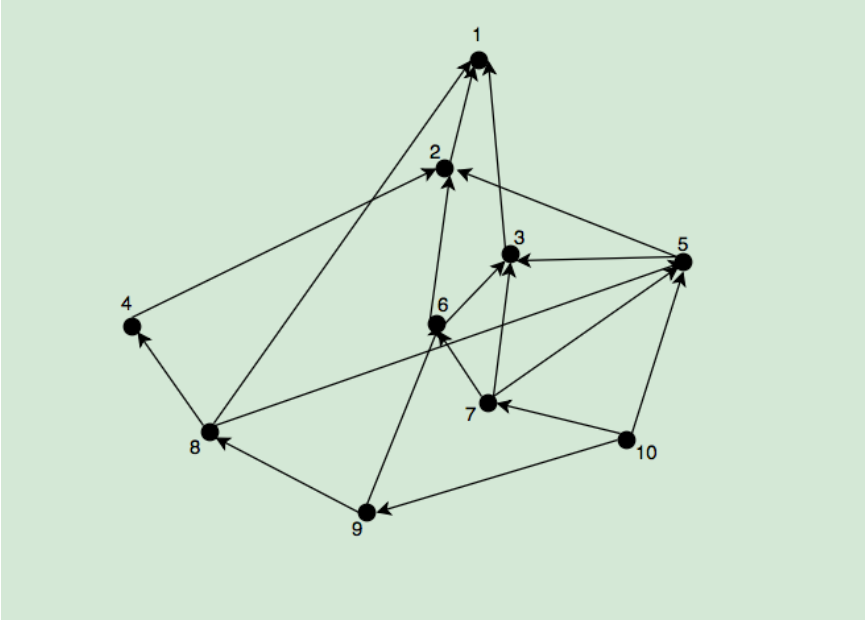


Figure 1.9: Diagonal Network Structure

For the evaluation of the best network structure, certain metrics are required to be defined and measured for all the structures. Based on these metrics, the resiliency of the structure can be determined. In this paper, the authors have defined and measured some resilience metrics that would be helpful in determining the resiliency of the network structures in consideration.

These resilience metrics are as follows:

Network Density (N_{D}) :

$$N_D = \frac{N_T}{N_P} \tag{1.1}$$

Where,

N_{T} = No. of total existing arcs

N_{P} = No. of possible arcs

Average In-Degree: It is the mean of the number of arcs having their heads connected to the nodes throughout the network.

Average Out-Degree: It is the mean of the number of arcs having their tails connected to the nodes throughout the network.

Connectivity: It is the minimum number of nodes and/or arcs which when removed will disengage the network.

A supply network disruption occurs when the network is incomplete between the initial and final node due to the disruptions in the nodes/arcs. The supply network resilience can be determined by evaluating the probability that in case of a removal of a random node/arc between the nodes, then the network is still being completed between the initial and the final node.

Thus, the supply network resilience (R_{S}) can be written down mathematically as

$$R_S = \frac{N_U}{N_D} \tag{1.2}$$

Where,

N_{U} = Total no. of node/arc disruptions, which do not lead to disruption

N_{D} = Total no. of node/arc disruptions

On calculating and comparing these metrics for the structures that have been considered for the study, it is observed that the scale-free network structure has the highest score on the resilience index. It can be inferred from the calculations that the higher resilience does not necessarily come from the networks that are closely-packed or intricate. From the viewpoint of the network structures, a plethora of network does not yield an increase in resilience. In case of unanticipated disruptions, the network that has various tiers has a better chance of survival. The manner in which the nodes and arcs are connected to each other in a network influences the disruption risk and its resilience against the disruption.

Thus, from the aforementioned research it can be extrapolated that the network structure has a significant impact on the resiliency of the entire system. The resiliency of the supply chain network is impacted by the number of nodes and arcs it is made up of. The metrics such as network density, average in-degree, average out-degree, connectivity, and resilience can be further applied to the concepts of cyclical linkages and the correlation of risks in the supply chain. Thus, these two concepts can be further worked on for aiding the improvement of the resilience of the supply chain.

1.5 Implementation of Simulation in Supply Chain Design

In today's world the nature of the supply chain has become very complex both in size and structure. There are multiple players and facilities present in them. Due to inter-connectivity and inter-dependencies present in them, the supply chains are prone to have disruptions that may disseminate throughout the network. If the supply chains are relatively small, then the uncertainties can be easily mitigated through the techniques of communication and managerial decisions due to the involvement of few players. On the other hand, if the supply chain is considerably large, then the same techniques would prove to be useless. A lot of significant information would be lost somewhere along the communication. Thus, there arises a need for using simulation software that provide an environment to model supply chains having any number of players and facilities and in real time. It is possible to model

the supply chain at individual levels so that each player can be considered very carefully. This aids us in making modifications in the parameters at the individual level in the face of disruption, such that there is a sense of continuity maintained throughout the supply chain. Thus, making the supply chain resilient and robust. The simulation software helps us in quantifying our methodology. Alternate facility selection can be easily achieved through the simulation software. The facilities are selected in such a manner that they can fulfill the needs of the disrupted facility in less time and less cost. Simulation allows us the flexibility to work with different alternatives to resolve the impact of disruptions on the supply chain. It also helps us in understanding the ripple effect of disruptions and its impact throughout the supply chain.

Chapter 2

Literature Review

There has been research in the comprehension of the concepts of resiliency and robustness in the supply chain and its significance to a certain extent. Many firms have faced the adverse effects of disruption on the performance of their supply chains. The loss in terms of money, time, and the trust of the customers have forced the managers and owners to turn to the recourse of having resiliency and robustness incorporated in their initial design phase of the supply chain. The structure of the literature review body is in the following manner: a brief discussion about the ramifications of disruption, the significance of resilience in the supply chain, and the implementation of simulation in supply chain as a tool for evaluation of the resilience strategies.

2.1 The Ramifications of Disruption

The management of disruptions and the decisions that are made during the occurrence of a disruption plays a pivotal role in defining the performance and quality of the system. This can prove to have an advantage over the competitors. An example of this is the approach and decision-making skills of Nokia when the radio frequency chip manufacturing plant of Philips electronics was caught on fire (Latour, 2001). The management personnel of Nokia addressed the ripple effect of the disruption and prevented the spreading of disruption. Due to the proactive decision making and identifying the implications of the disruption, the Nokia achieved profit and the trust of customers over their rivals Ericsson.

In a network design for supply chain , it is of utmost importance to identify the sources of the disruptions for enhancing the strategic operations (Klibi et al., 2010). They have stated that there is no modeling done on the comprehension of intensity of disruption in the supply chain network. There are two types of uncertainties that can affect the performance of the supply chain : Natural, and targeted attacks. The behavior and intensity of the disruption are directly associated with the density, complexity and nodes criticality of the supply chain (Craighead et al., 2007). The cost for facility rebuilding is taken care of through the insurance. The focus should not be on the repairing of the facility, but it should be towards the alternatives for keeping the supply chain to maintain a continuous operation. The damages incurred to the supply chain should be determined in terms of parameters such as capacity loss, supply loss or demand surge (Sheffi et al., 2005).

2.2 Previous work in Supply Chain Resilience

The importance of having a resilient supply chain can be understood from the case of the 1995 earthquake in Japan (Fujimoto, 2011). The earthquake had massive impacts on the supply chains of Toyota and other companies in the affected areas. Toyota helped in providing personnel to the restoration process and simultaneously searched for alternate suppliers to keep the production continuous. The responsiveness is of utmost importance in enhancing the resilience when the customer vs. seller trade-offs are a crucial part of the supply chain (Sáenz et al., 2018). In a supply chain, the resilience can be considered as a concoction of operational capabilities, integration capabilities, flexibility capabilities, and external capabilities (Brusset and Teller, 2017). Although these capabilities aid in making the supply chain resilient for a specific case study, it does not help in devising the generic solution for implementing resiliency. The resilience can be incorporated in the supply chain through integrating engineering recoverability into the system the same way engineering resilience is incorporated (Li and Xi, 2014). The recoverability and resilience of a system are directly related to each other. The fail safe mechanism (Brandon-Jones, E.; Squire, B.; Autry, 2014) makes the supply chain both adaptive and highly responsive to uncertainties. Thus, the supply chain becomes resilient as well as robust. The drawback to this approach

is the costs incurred due to additional inventory being held up at every facility. The supply chain resilience can be linked with logistics capabilities for improving the performance of the supply chain (Ponomarov and Holcomb, 2009). If the supply chain has the right logistics capabilities, then it can make the supply chain capable of responding to unprecedented events. The resilience in a supply chain can be considered from a network perspective where the disruptions affect the nodes/arcs within a supply network (Kim et al., 2015).

2.3 Supply Chain Simulation Literature

The simulation tool can be implemented to evaluate the behavior of supply chains under conditions of uncertainties (Carvalho et al., 2012). The drawbacks of this paper is the consideration of redundancy as a strategy for resiliency. It does not mitigate the negative effects of the disruption while suffering monetary losses. There was a lack of flexibility considerations while designing the supply chain. Also, this approach is just suitable for the case study they have considered and is not applicable for generic supply chain design purposes. The importance of a flexible supply chain has been well expressed for making the system resilient (Christopher and Holweg,2011). As the uncertainty increases in the future, the value for flexibility will be increasing. It is an essential component to be considered while designing the supply chain. They have not mentioned any model which consists of flexibility incorporated in the designing aspect of the supply chain. Implementing the tool of simulation to exhibit the benefits of the flexible supply chain over a normal supply chain would reinforce the reason to shift to a flexible supply chain. The aspects of node density, node complexity, and node criticality are the three pillars that define the supply chain structure (Falasca et al., 2008). If the disruption occurs in any of these pillars of the supply chain, then the entire supply chain would tremble. It has also been mentioned that disruptions are more likely to take place in the supply chains having a significant amount of critical nodes. The cause-effect analysis of the measures taken to make the supply chain resilient can be obtained through the use of simulation. The supply chain redesign (Carvalho et al., 2012) has been evaluated in the face of disruption and the performance measures which are used for comparing the different designs are lead time and total cost. The simulation tool helped in experimenting

with various supply chain designs. An agent-based simulation model has been developed which focuses on fortifying the facility within a supply chain during disruptions (Li et al., 2018). The p-median problem model has been used for choosing the facility which has the least distance for transportation. The RIMF method has been used to select the protective resources at the lowest costs in order to have the least impact during the disruption. The most noteworthy points to be taken from this study is the use of agent-based simulation to study the effect of disruptions on the supply chain, the most cost effective method to resolve the disruptions, and the alternate facility selection having the least distance travelled.

The importance of the resilience and robustness can be easily observed from the research papers. Also, the role that simulation software plays an important role in quantifying the significance of these two terms in supply chain by giving the visual representation of the supply chain under disruptive conditions. Thus, we have made use of agent-based simulation in our study.

Chapter 3

Methodology

The variables for resilience can be represented in the form of a digraph for exhibiting the inter-dependencies between them in terms of nodes and arcs (Soni et al., 2014). These variables are assigned a value and are put in a matrix. The value obtained from the matrix is compared to the predetermined ideal resilience index to obtain the relative resilience index of the supply chain. The limitation of this research is that it only provides a methodology for measuring the existing resilience of a supply chain, but it does not account for improving the resilience of the supply chain. The methodology proposed in our study aims at improving the existing resilience of a supply chain for better performance under the conditions of uncertainties.

In our study, we have considered the Agent-based simulation as our primary methodology for illustrating our supply chain model and accounting for disruptions. The supply chain model consists of 'S' Suppliers, 'M' Manufacturers, 'D' Distributors, and 'R' Retailers. Each facility acts as an individual agent which has been placed across the United States. The model represents the supply chain of one company having different facilities throughout the country. In the event of disruption, if any of the facilities gets shut down, then they have an alternative facility to turn to in order to get their demands satisfied. In the meantime, the facility that has been affected by the disruption is revived by taking the correct measures to increase the resiliency. Each facility has been assigned certain parameters of cost, time and demand fulfillment rate. There is a constant flow of materials downwards through the agents in the supply chain, while there is a constant flow of information upwards through the

agents in the supply chain. It is important that this flow is never interrupted for the efficient performance of the system. In order to maintain this flow during disruption, alternate facilities are selected. The alternate facility gets selected based on the best parameter values amongst the available lists of facilities. There are a total of 5 scenarios depicting the source of disruption in the supply chain. The different strategies that need to be taken as per the source of the disruption are encompassed in the model for the purpose of restoration of the disrupted facility. The most efficient and appropriate strategy makes a massive impact on the resiliency of the system.

3.1 Vulnerabilities and Capabilities

There a lot of reasons for the disruptions to occur in the supply chain. Some may arise due to unfavorable natural conditions such as adverse weather, while some may be targeted attacks on firms. The knowledge of the source of disruption is very critical in order to devise proper mitigation strategies. If we know the reason of the disruption, then we can shift our focus on the repairing the most affected factors due to the disruption rather than doing the analysis of all the factors. (Pettit et al., 2010) have jotted down these sources and factors as vulnerabilities and capabilities respectively. They have mentioned 6 vulnerabilities that lead to a disruption in the system. A firm should design its supply chain keeping in mind the relation between the vulnerabilities and capabilities. It should not have more capabilities as well as less capabilities. It should have just the perfect number of capabilities. If the company has enforced more capabilities, then there is a loss in capital. Also, if there are less capabilities, then the supply chain is left vulnerable to the disruptions.

We have implemented 5 out of the 6 vulnerabilities that act as a source of disruption. These vulnerabilities are as shown in the Fig 3.1. The major problem that occurs during resolving a disruption in a system is the time taken for thorough analysis of the root cause of the problem.

TURBULENCE	• Natural disasters • Geopolitical disruptions • Unpredictability of demand • Technological failures
DELIBERATE THREATS	• Theft • Terrorism/Sabotage • Labor disputes
RESOURCE LIMITS	• Supplier, Production and Distribution capacity • Raw materials and Utilities availability • Human Resources
SENSITIVITY	• Reliability of equipment
CONNECTIVITY	• Scale of network • Reliance upon information • Degree of outsourcing
SUPPLIER/CUSTOMER DISRUPTIONS	• Supplier reliability • Customer disruptions

Figure 3.1: Vulnerabilities and their various sources.

FLEXIBILITY IN SOURCING	• Part commonality • Multiple sources
FLEXIBILITY IN ORDER FULFILLMENT	• Alternate distribution channels • Multi-sourcing • Inventory management
CAPACITY	• Reserve capacity • Redundancy
EFFICIENCY	• Asset utilization • Product variability reduction • Failure prevention
VISIBILITY	• Information technology • Information exchange
ADAPTABILITY	• Lead time reduction • Alternative technology development
ANTICIPATION	• Monitoring early warning signals • Forecasting • Contingency planning • Preparedness • Risk management
RECOVERY	• Crisis management • Resource mobilization • Communications strategy • Consequence mitigation
COLLABORATION	• Collaborative forecasting • Customer management
SECURITY	• Layered defenses • Access restrictions • Employee involvement • Cyber-security • Personnel security

Figure 3.2: Capabilities and their various types.

If the managers are well aware of the most common and recurring sources of disruption, they might be able to take preventive and reactive measures during disruptions of similar type in the future. By implementing these vulnerabilities in our supply chain design, we are not only providing ready measures of repair but also reducing the impact of disruption. Thus, making the system both resilient and robust in nature.

Once that the vulnerabilities are addressed, the next step is to glance at the capabilities (factors) that are most likely to be useful for the recovery from the damage from a certain kind of disruption rather looking at all the factors. This will help in reducing the time to find out where the exact problem lies. The list of capabilities that affect the performance of the supply chain system is as shown in Fig 3.2. These capabilities are the measures that help to mitigate the damages that take place because of the disruption. The vulnerabilities that are closely associated with the capabilities are as shown in the Fig 3.3. These prove to be beneficial in identifying the key factors that can help in improving the speed of recovery of the system back to its functioning state.

CONNECTIVITY	• Visibility • Adaptability • Recovery • Security
RESOURCE LIMITS	• Flexibility in sourcing • Flexibility in order fulfillment • Capacity • Efficiency • Visibility • Adaptability • Anticipation • Recovery
SUPPLIER/CUSTOMER DISRUPTIONS	• Flexibility in sourcing • Flexibility in order fulfillment • Capacity • Efficiency • Collaboration • Adaptability • Anticipation
TURBULENCE	• Flexibility in sourcing • Flexibility in order fulfillment • Recovery • Anticipation • Adaptability
DELIBERATE THREATS	• Security • Anticipation • Collaboration

Figure 3.3: Capabilities vs Vulnerabilities.

3.2 Agent-Based Modeling

The main reason for developing the supply chain model as an agent-based simulation was due to the freedom to express the interaction between agents which is absolutely necessary to consider in our model. The complex nature of the supply chains makes it difficult to design models using the basic simulation models. Agent-based simulation helps in exhibiting the exact nature of a supply chain and all its players. The decision-making, information sharing, uncertainties, trade-offs, and coordination can be accurately represented by the agent-based simulation. It proves as the perfect platform to analyze different strategies and select the best one by implementing in the already existing model. The results are obtained at a fast rate and at an higher accuracy.

3.2.1 The Agents involved

The model that we have developed for the purpose of our study contains four different agent types and are connected to each other for maintaining a sense of completion. Each agent type has a number of agents that are positioned across the United States of America. If the connections are lost, that means the supply chain has faced a disruption at some point in the network. The description of these agent types and the parameters associated with them are as follows.

I. Supplier Agent

These are the facilities that provide the raw materials to the manufacturing facility. The nomenclature for the suppliers has been done as S_1, S_2, ..., S_n. The parameters associated with them are response time (time required to fulfill the demands of the manufacturer) and the raw material handling costs. The costs such as raw material handling cost and inventory holding costs are usually a percentage of the total costs. The percentage value for these costs lies between the range 40 to 60 percent of the total costs (Lee and Billington, 1992). The values corresponding to the response time have ranking from 1 to 3. The rank 1 means that the response time is low, which is highly favorable for the selection criteria. Rank 2 and Rank 3 are the response time medium and high respectively. In the event of disruption, if a

supplier is down, then alternate supplier is selected in such a way that the response time is either low or medium, and the raw material handling cost is the minimum.

II. Manufacturer Agent

Once the raw material has been acquired from the supplier, it comes to the manufacturer where it is converted into the final product. These manufactures are positioned around the country and their nomenclature is done as M_1, M_2, ..., M_{n}. The parameters associated with the manufacturer agents are inventory holding cost and response time. In the event of disruption, if any of the manufacturer that fulfills the demands of the distributors associated with it is down, then the alternate manufacturer is selected in such a way that the inventory holding cost is minimum, and the response time is either low or medium.

III. Distributor Agent

The next agent is the distributor agent where the finished goods are collected from the manufacturer and are forwarded to the retailers. The nomenclature for these distributors is done as follows D_1, D_2, ..., D_{n}. The parameters associated with the distributors are inventory holding cost, order fulfillment rate, and response time. The selection of alternate distributor facility during disruption is done in such a way that the inventory holding cost should be minimum, order fulfillment rate should be high, and the response time should be low or medium.

IV. Retailer Agent

The fourth and final agent in our simulation model is the retailer agent. The retailers accrue the finished products from the distributors depending on the market trends and demands in their respective regions. Some regions have multiple retailers because of the high volume demand of the product from the customers. The nomenclature for the retailers are R_1, R_2, ..., R_{n}. A number of different retailer agents are connected to the same distributor agent. The parameter associated with the retailer agent is the response time (to the customers).

3.3 Scenarios in the model

In a typical supply chain, disruption can occur at any of the levels. Thus, we have developed the scenarios in such a way that the disruptions are occurring at the distributor level, manufacturer level, and the supplier. Also, for all the three events, we have considered the scenarios in which the disruptions are occurring due to the vulnerabilities that have been mentioned earlier. In total, there are 3 different scenarios to quantify the need for our study.

The flow chart of the our methodology is as show in the Fig 3.4. According to the logic, whenever the disruption occurs, the initial step is to identify the source of the disruption. The next step in the process is to check for the capabilities associated with the source of disruption that is most likely to get affected. During a disruption, it is not necessary that all the capabilities get damaged. Only a certain few capabilities get damaged which hinder with the performance of the system. The final step is to revive those damaged capabilities for getting the system functioning again.

The time between the occurrence of disruption and the identification of the key factors is called as the lost time (T_{L}). The time between the identification of the key factors and the total recovery of the disrupted facility is called as the repair time (T_{N}). The time for recovery (T_{R}) is the sum of the lost time (T_{L}) and the time to repair (T_{N}). The total time of the system (T) is the sum of the total cycle time (T_{C}) and the recovery time (T_{R}). The ratio of the total time to the recovery time yields the resiliency value (R_{S}) of the supply chain.

$$R_S = \frac{T}{T_R} \tag{3.1}$$

The higher the value of the resiliency, lesser is the length of recovery of the supply chain during disruption. The percentage change in the resilience value is given by,

$$\%changeinresilience = \frac{R_S(new) - R_S(existing)}{R_S(existing)} * 100 \tag{3.2}$$

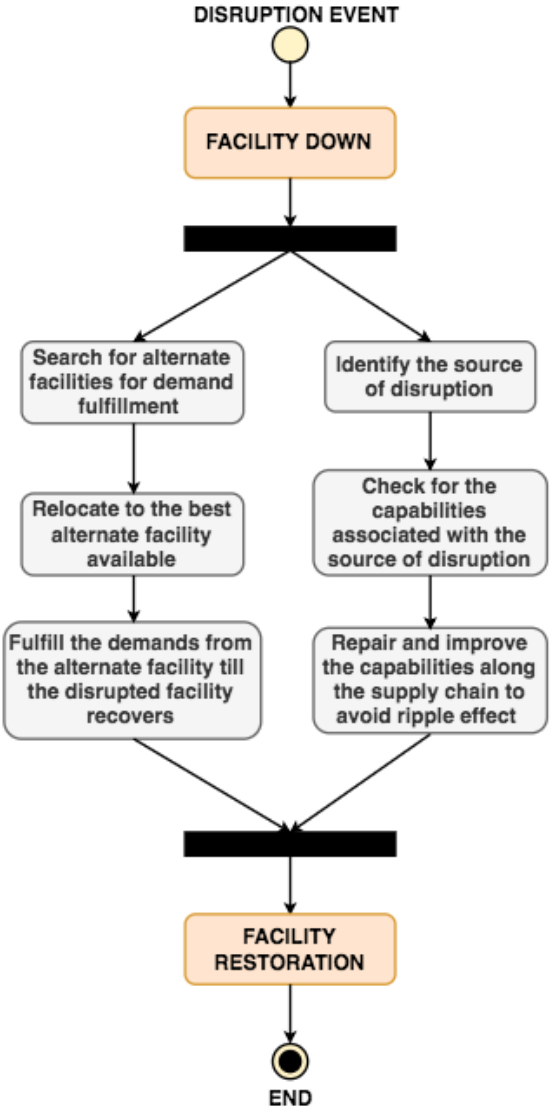


Figure 3.4: Flowchart of Methodology.

Chapter 4

Case Study

In the supply chain model as mentioned in the methodology section, we are considering the supply chain consisting of 5 Suppliers, 7 Manufacturers, 10 Distributors, and 20 Retailers as our case study. This supply chain model is then subjected to different sources of disruption. The results of the resilience value for modeling with and without the resiliency and robustness enhancers are compared for quantifying the methodology. This case study can be considered for generic design purposes as well. The values of the parameters for the Suppliers are as shown in the Table 4.1. The parameters for the manufacturer agent and their corresponding values are shown in the Table 4.2. The parameters for the distributor agent and the values associated with them are as shown in the Table 4.3. The values corresponding to this parameter for the retailer agent is as shown in the Table 4.4. The costs such as inventory holding cost and backlog cost together make the total cost (lost) in the supply chain. Theses costs are used for the quantification of our methodology.

Table 4.1: Parameters of the Supplier

Supplier	Raw Material Handling Cost	Response Time
S1	0.45	High
S2	0.52	Medium
S3	0.44	High
S4	0.58	Low
S5	0.56	Medium

Table 4.2: Parameters of the Manufacturer

Manufacturer	Inventory Holding Cost	Response Time
M1	0.51	Low
M2	0.41	Medium
M3	0.43	Medium
M4	0.57	High
M5	0.49	Low
M6	0.55	High
M7	0.48	Low

Table 4.3: Parameters of the Distributor

Distributor	Inventory Holding Cost	Order Fulfillment Rate	Response Time
D1	0.46	High	Medium
D2	0.51	High	High
D3	0.44	Low	Low
D4	0.52	High	High
D5	0.48	Low	Medium
D6	0.49	Low	Low
D7	0.57	High	Low
D8	0.41	High	Medium
D9	0.48	High	High
D10	0.53	Low	Low

Table 4.4: Parameters of the Retailer

Retailer	Response Time
R1	Low
R2	Medium
R3	Low
R4	High
R5	High
R6	Medium
R7	High
R8	Low
R9	Low
R10	Medium
R11	High
R12	Low
R13	Medium
R14	Medium
R15	High
R16	High
R17	High
R18	Low
R19	High
R20	Medium

4.1 The Base Model Connections

The four agent types are connected to each other to form 5 supply chains in the different regions throughout the country for a company. In the base model, the connections of the agents is as shown in the Fig 4.1. It can be observed from the Fig 4.1 that the distributor D1 is shared by three retailers R3, R5 and R15. If there is a disruption in the area of Oregon and the distributor D1 is down due to it, then the retailers R3, R5, and R15 have to select a different distributor facility. They will choose the distributors from D2 to D10 based on who has the best parameter values. Similarly, the distributor agents and manufacturer agents connect to the best available manufacturer agent and supplier agent respectively based on the parameters. In the meantime, the restoration of the disrupted facility is taking place using appropriate mitigation strategies. This is the basic working logic of the whole simulation model. The run time of the simulation for our model is 365 days and the three different scenarios are at distributor level, at manufacturer level, and at supplier level. Theses three scenarios are considered under normal working conditions, under disruption conditions, and under disruption conditions with contingency planning. Out of these three scenarios, we have considered the scenario for disruptions at the manufacturer level.

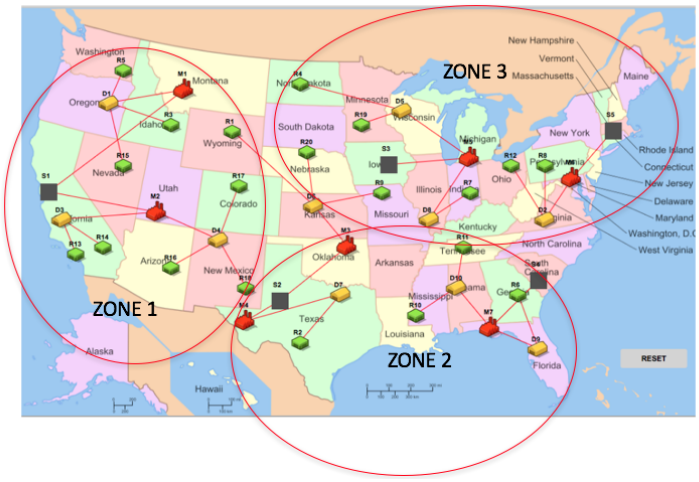


Figure 4.1: Base Model Agent Connections.

4.2 Modeling for disruptions at the Manufacturer Level

In this model, the connections of the supply chain are as shown in the Fig 4.1. There are three scenarios that can be observed for the behavior of supply chain at the manufacturer level. These scenarios are the supply chain under normal conditions, the supply chain under disruption condition, and the supply chain under disruption condition with contingency planning. The various sources of disruption are considered for these three scenarios. The total costs (lost) and the resiliency values corresponding to these scenarios are calculated.

4.2.1 Supply Chain Performance under Normal Conditions

In this scenario, the supply chain at manufacturer level is functioning under normal conditions. There exists losses in terms of cost due to the uncertainty of demands and unavailability of the inventory at certain facilities. These losses are due to the inventory holding costs and the backlog costs. The total costs incurred at the three different zones as shown in fig 4.1 are \$39,973.4, \$63,139.25, and \$15,842.02 for zones 1, 2, and 3 respectively. The next step is to find out these values under the conditions of disruption. The manufacturing facilities in the three different zones are disrupted at random and the performance of the supply chain is monitored.

4.2.2 Supply Chain Performance under Disruption Conditions

In this scenario, we have disrupted the different manufacturers which are located in the entire supply chain across the entire geographical United States of America. As these manufacturers are down, the effects of disruption spread throughout the supply chain through the facilities linked with them. This occurs due to the phenomenon known as ripple effect. As the manufacturers supply for the distributors, the distributors are unable to collect the finished goods and fulfill the demand for the retailers associated with them. As a result, the retailers are unable to fulfill the demands of the customers in their region. Thus, a backlog takes place both at the retailers and distributors. The suppliers linked to the manufacturers have to

hold the excess raw materials at their facility due to the uncertain duration of recovery of the disrupted facility. The connections before and after the disruption at one such manufacturer facility M2 are shown in the Fig 4.2 and Fig 4.3. The disruption causes the facilities R13, R14, R16, R17, R18, D3, and D4 to become inactive. The supplier S1 gets disconnected from the manufacturer M2.

The lost time and recovery time occurred during different scenarios has a different value. Apart from the loss of time, there are other ramifications such as the backlog cost, inventory holding cost and the loss of customer loyalty. The disruptions take place at the manufacturer level over the period of 365 days. In this period, there are 18 different disruptions which are caused due to the different sources of disruption which are mentioned in the methodology section. This causes a delay of 126 days in the supply chain. Out of these 126 days, the repair time (T_{N}) comprises of 54 days. The lost time (T_{L}) in this scenario is of 72 days. Thus, the recovery time of this scenario is calculated as follows.

$$T_R = T_N + T_L = 54 + 72 = 126 \tag{4.1}$$

The total cycle time (T_{C}) in this scenario is of 239 days. The total time of the system now becomes the sum of the total cycle time (T_{C}) and the recovery time (T_{R}). Thus, the resilience value for this scenario is calculated as follows.

$$R_S = \frac{T}{T_R} = \frac{365}{126} = 2.89 \tag{4.2}$$

The resilience value from the equation 4.2 is the existing resilience value (R_{existing}) of the supply chain. The total costs suffered due to the disruptions which comprise of the inventory holding cost and the backlog costs for zones 1, 2, and 3 are \$159,090.8, \$145,987.25, and \$184,948.28 respectively. These heavy losses are suffered due to the absence of mitigation and resilient strategies in the design of the supply chain.



Figure 4.2: Manufacturer Level Disruption (Before).

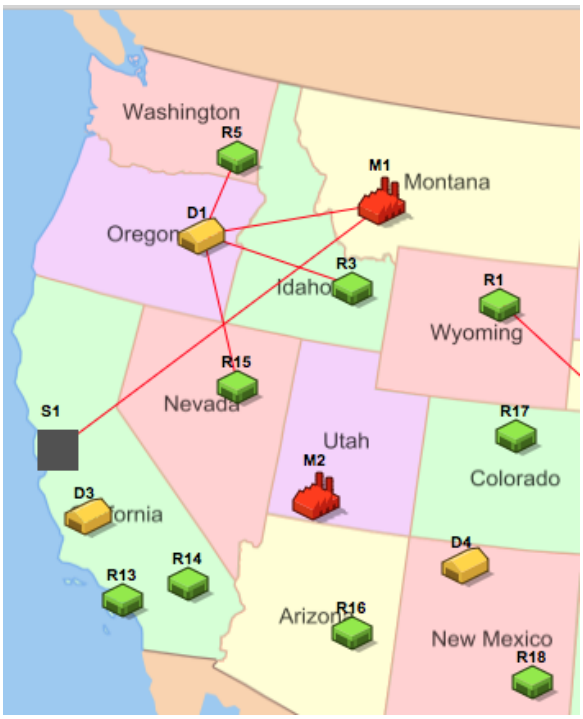


Figure 4.3: Manufacturer Level Disruption (After).

4.2.3 Supply Chain Performance under Disruption Conditions with Contingency Planning and Key Indicators Identification

In this scenario, we have implemented the key indicator identification and contingency planning components into our supply chain. Whenever a disruption takes place, the source of the disruption is identified and a team of management personnel look into the capabilities that need to be strengthened in order to reduce the recovery time. In the meantime, an alternate facility having the least distance, lowest costs, high fulfillment rate, and low response time is selected from the other available facilities. There is transportation cost that is incurred due to alternate facility location. But, this cost is just a small price to pay in order to avoid huge losses if we wait for the damaged facility to be repaired. The lost time is reduced by a drastic amount and thus the total delay caused by the disruption is reduced while keeping the supply chain working simultaneously. Thus, a resilient and robust supply chain is achieved.

In this period, there are 18 different disruptions which are caused due to the different sources of disruption which are mentioned in the methodology section. In this scenario due to the inclusion of resilience techniques such as contingency planning and key indicators identification, there is a delay of 72 days in the supply chain. Out of these 72 days, the repair time (T_{N}) comprises of 54 days. The lost time (T_{L}) in this scenario is of 18 days. Thus, the recovery time of this scenario is calculated as follows.

$$T_R = T_N + T_L = 54 + 18 = 72 \tag{4.3}$$

The total time of the system now becomes the sum of the total cycle time (T_{C}) and the recovery time (T_{R}) which is 365 days. Thus, the resilience value for this scenario is calculated as follows.

$$R_S = \frac{T}{T_R} = \frac{365}{72} = 5.0694 \tag{4.4}$$

The resilience value from the equation 4.4 is the existing resilience value (R_{new}) of the supply chain. The percentage change in the resilience value can now be calculated as follows.

$$\%changeinresilience = \frac{5.0694 - 2.89}{2.89} * 100 = 75.411\% \tag{4.5}$$

The equation 4.5 represents the improvement achieved in the resilience value after incorporating the resilience factors in the supply chain. The total costs suffered due to the disruptions which comprise of the inventory holding cost and the backlog costs for zones 1, 2, and 3 are \$63,606.4, \$82,938.00, and \$43,773.04 respectively.

Due to the contingency planning, whenever a manufacturing facility is down due to disruption, an alternate manufacturing facility is provided without much loss in time. This enables for the demand of the distributor facilities associated with the disrupted facility to be satisfied so that the demand of the retailers associated with the distributors can be satisfied. If there is a disruption at the manufacturers in the zone 1, then the distribution facilities D1, D3, and D4 get affected as well. Thus, affecting the retailers R3, R5, R13, R14, R15, R16, R17 and R18. Through contingency planning, in times of disruption, the distribution facilities are allocated the manufacturing facility M4 for the fulfillment of their demands such that the supply chain does not come to a halt. The effect of disruption on the manufacturing facilities in the zone 1 is shown in the fig 4.4. The pictorial representation of the contingency planning for zone 1 is shown in the fig 4.5. Similarly, the effects of disruption on the manufacturing facilities of zone 2 and zone 3 can be seen in the figures 4.6 and 4.8. The contingency planning for zone 2 and 3 are shown in figures 4.7 and 4.9. Through the key indicators identification, the capabilities associated with the source of the disruption can be utilized for mitigating the effects of the disruption. The capabilities are highlighted in the simulation depending on the duration of the disruptions which identifies the source of disruption. This identification of the capabilities in the simulation software is as shown in figure 4.10, 4.11, 4.12, 4.13, and 4.14 for the disruption sources (vulnerabilities) as Turbulence, Supplier/Customer disruptions, Resource Limits, Connectivity, and Deliberate threats. This aids in reducing the recovery time of the supply chain from disruption and reducing the losses incurred.



Figure 4.4: Zone 1 during disruption



Figure 4.5: Zone 1 after disruption with contingency planning



Figure 4.6: Zone 2 during disruption



Figure 4.7: Zone 2 after disruption with contingency planning



Figure 4.8: Zone 3 during disruption



Figure 4.9: Zone 3 after disruption with contingency planning

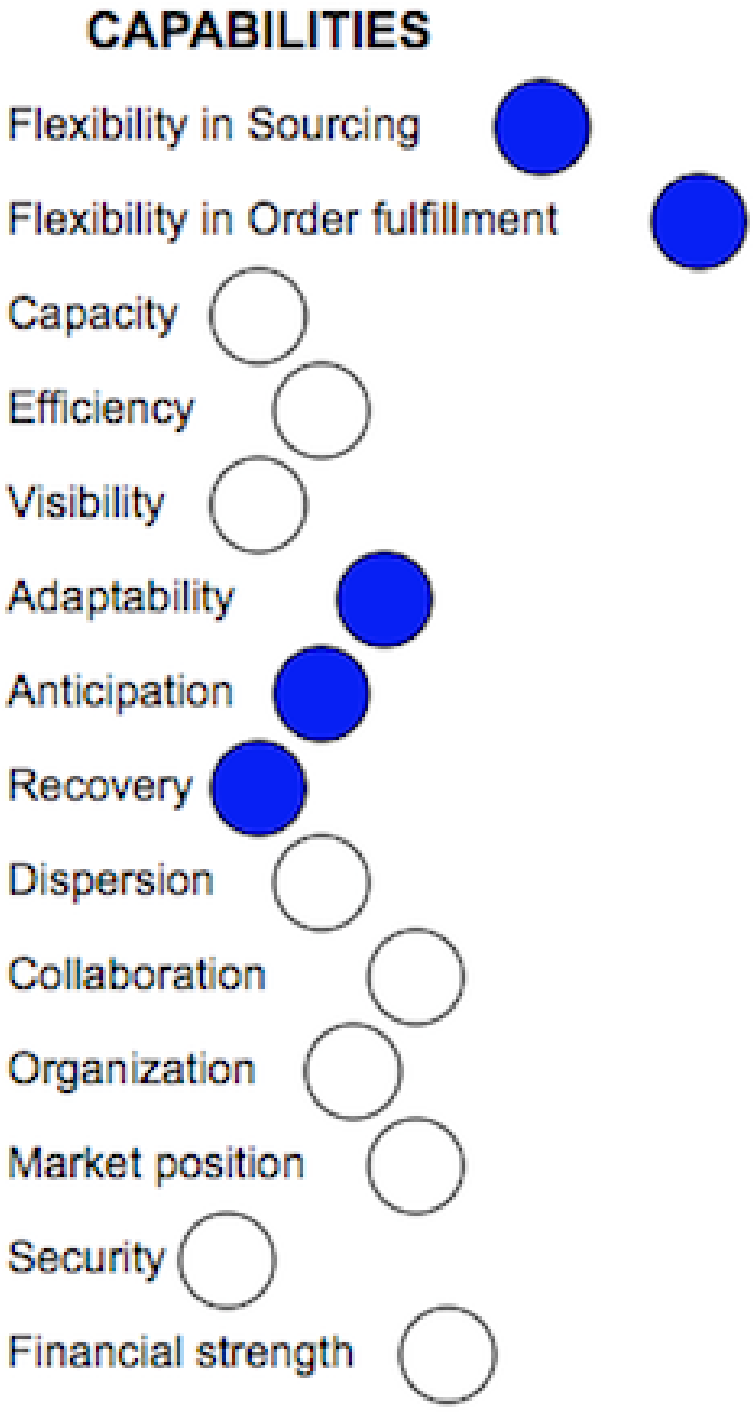


Figure 4.10: Capabilities for Vulnerabilities due to Turbulence

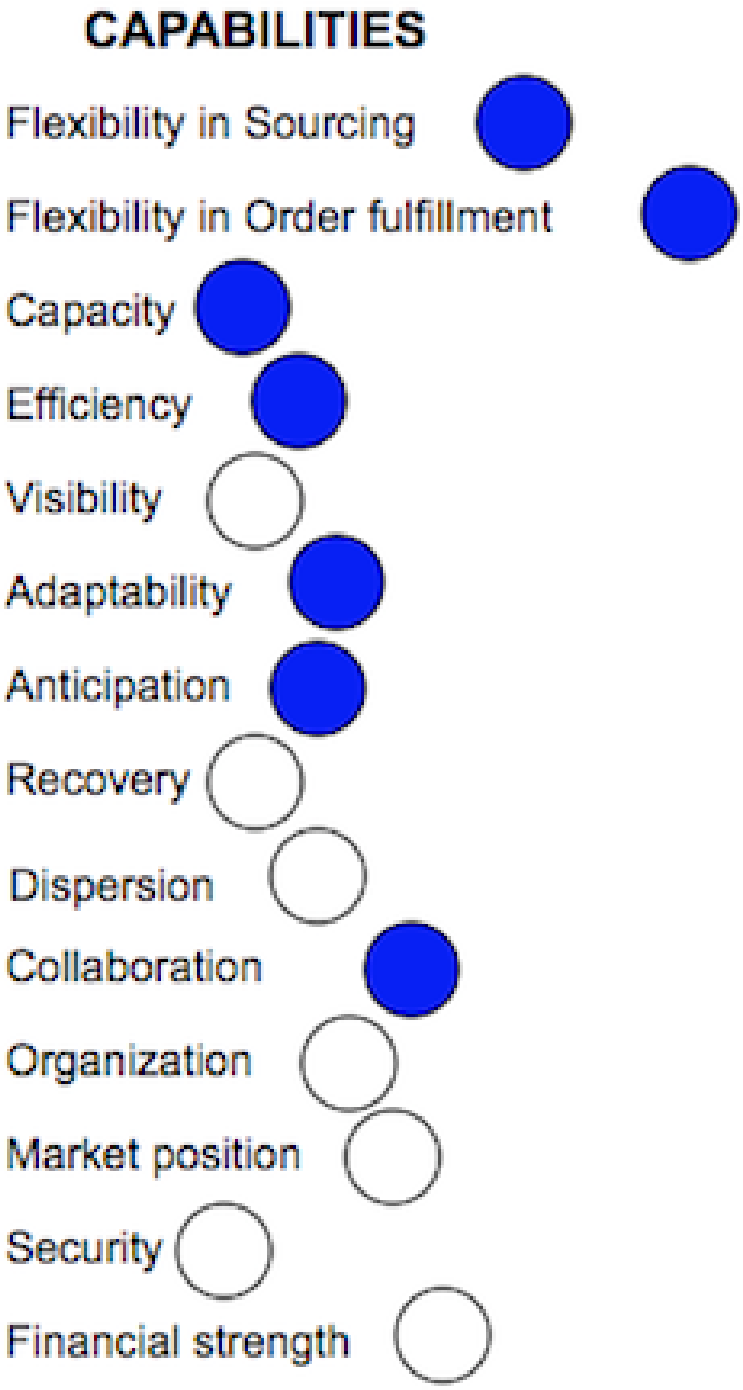


Figure 4.11: Capabilities for Vulnerabilities due to Supplier/Customer disruptions

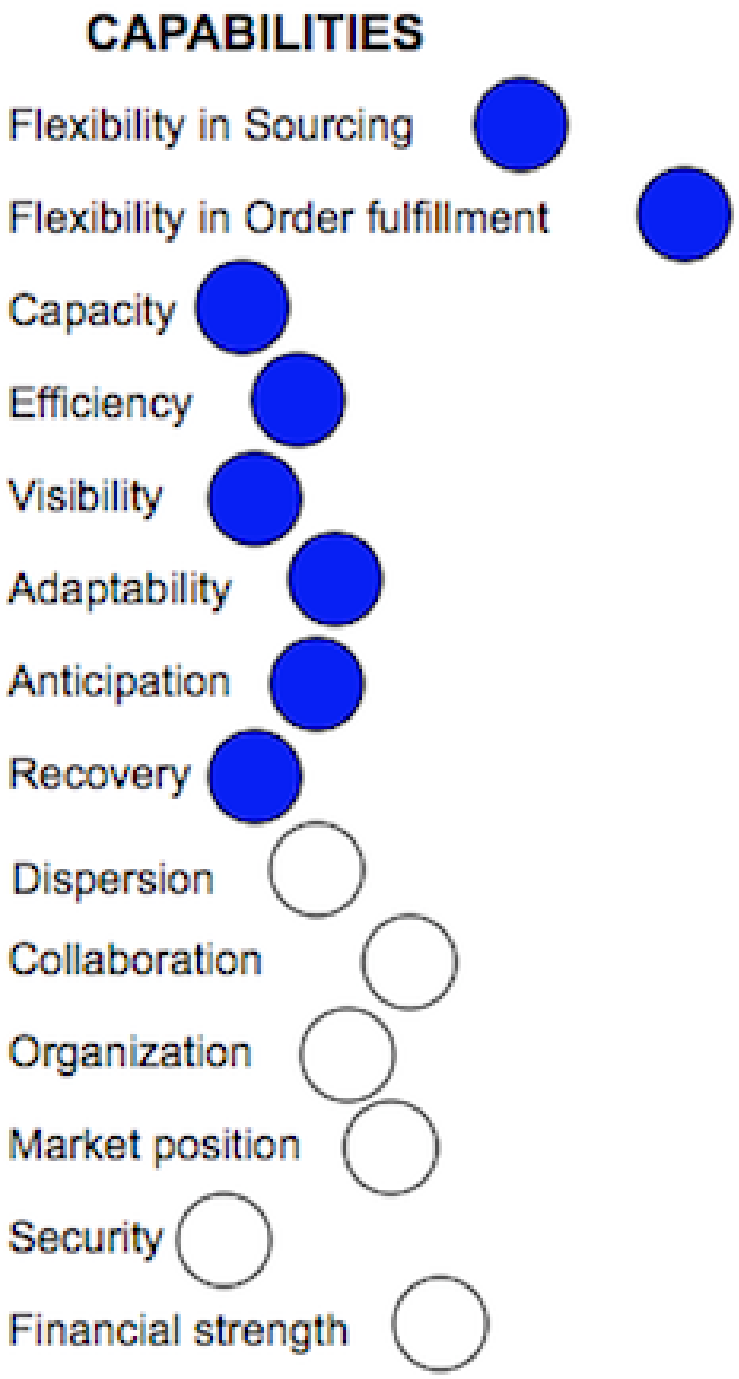


Figure 4.12: Capabilities for Vulnerabilities due to Resource Limits

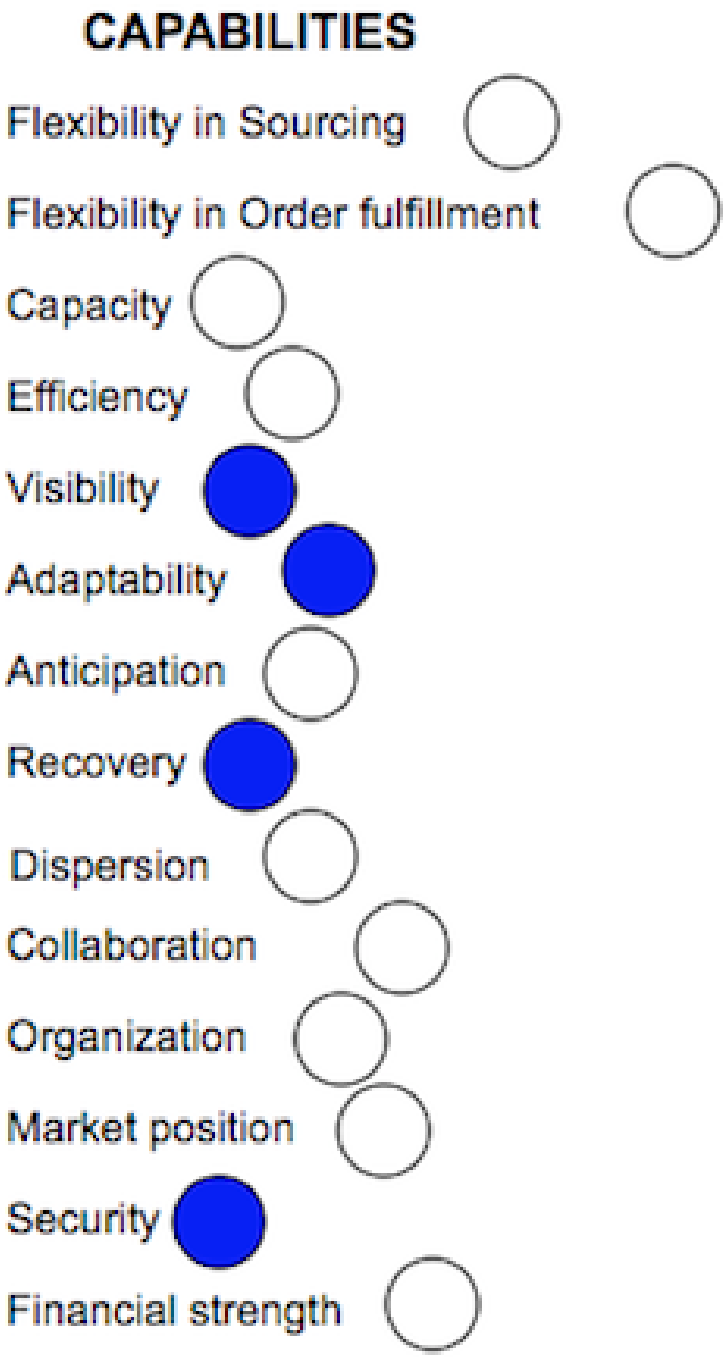


Figure 4.13: Capabilities for Vulnerabilities due to Connectivity

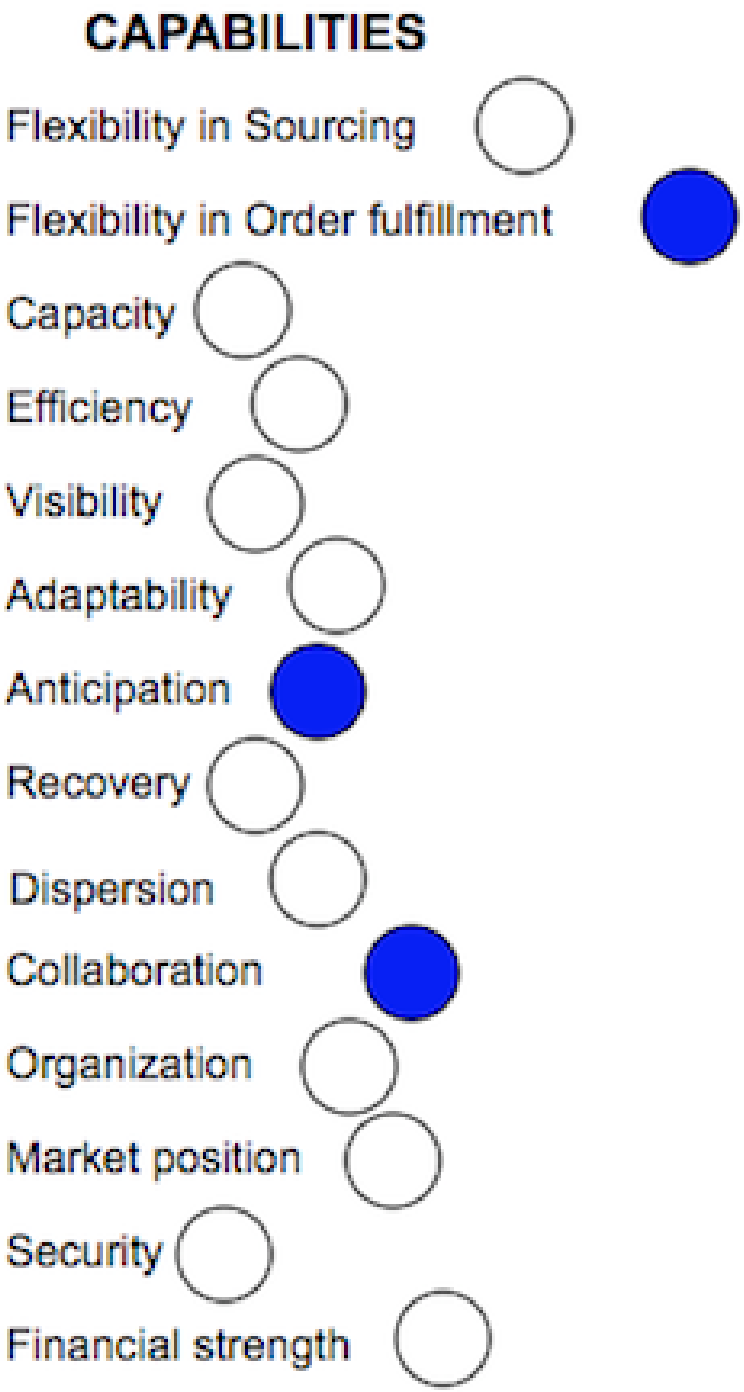


Figure 4.14: Capabilities for Vulnerabilities due to Deliberate Threats

Among the two, the manufacturer level under disruption with contingency planning and key indicators identification scenario seems to have a better resilience value and less loss in terms of money due to the short recovery time and alternate sourcing. These values are calculated so that the importance of implementing resilience and robustness in the supply chain can be quantified. There can be a huge variation in these values depending on the source of disruption. Thus the resilience values for the disruptions at other levels of the supply chain can be found out as well. It is clearly evident that there is an improvement in the resilience after the inclusion on resilience and robustness components in the design of the supply chain. The total costs incurred at all three scenarios for all three zones of the supply chain model are compared for exhibiting the significance of incorporating the resilience components of contingency planning and key indicators identification. In addition to this, another key observation that can be made through this study is the relationship between the resilience value and the total costs. This relation can be observed in the graph in the fig 4.16. It can be inferred from this graph that higher the resilience value, lesser are the total costs suffered.

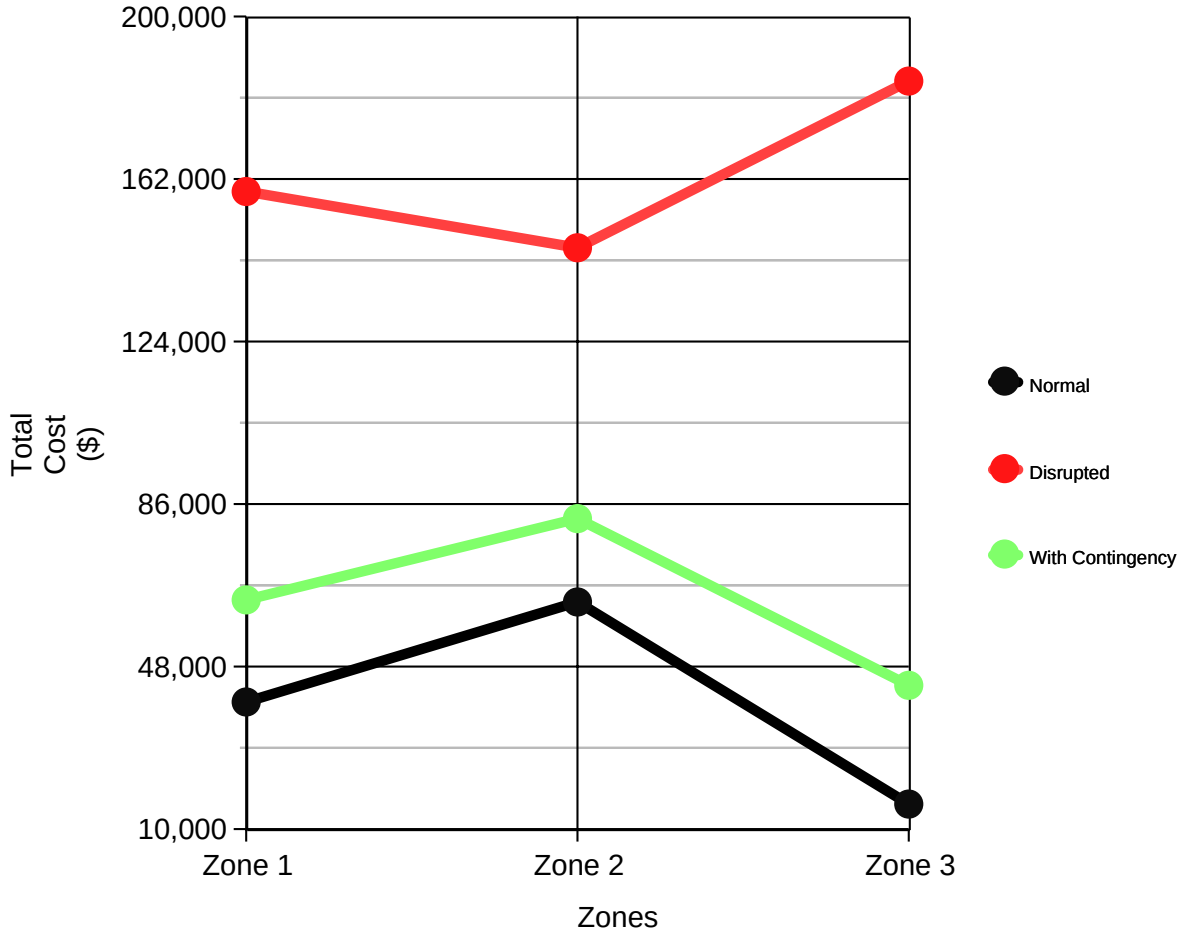


Figure 4.15: Graph for the total costs for all the three scenarios at the different zones of the Supply Chain Model

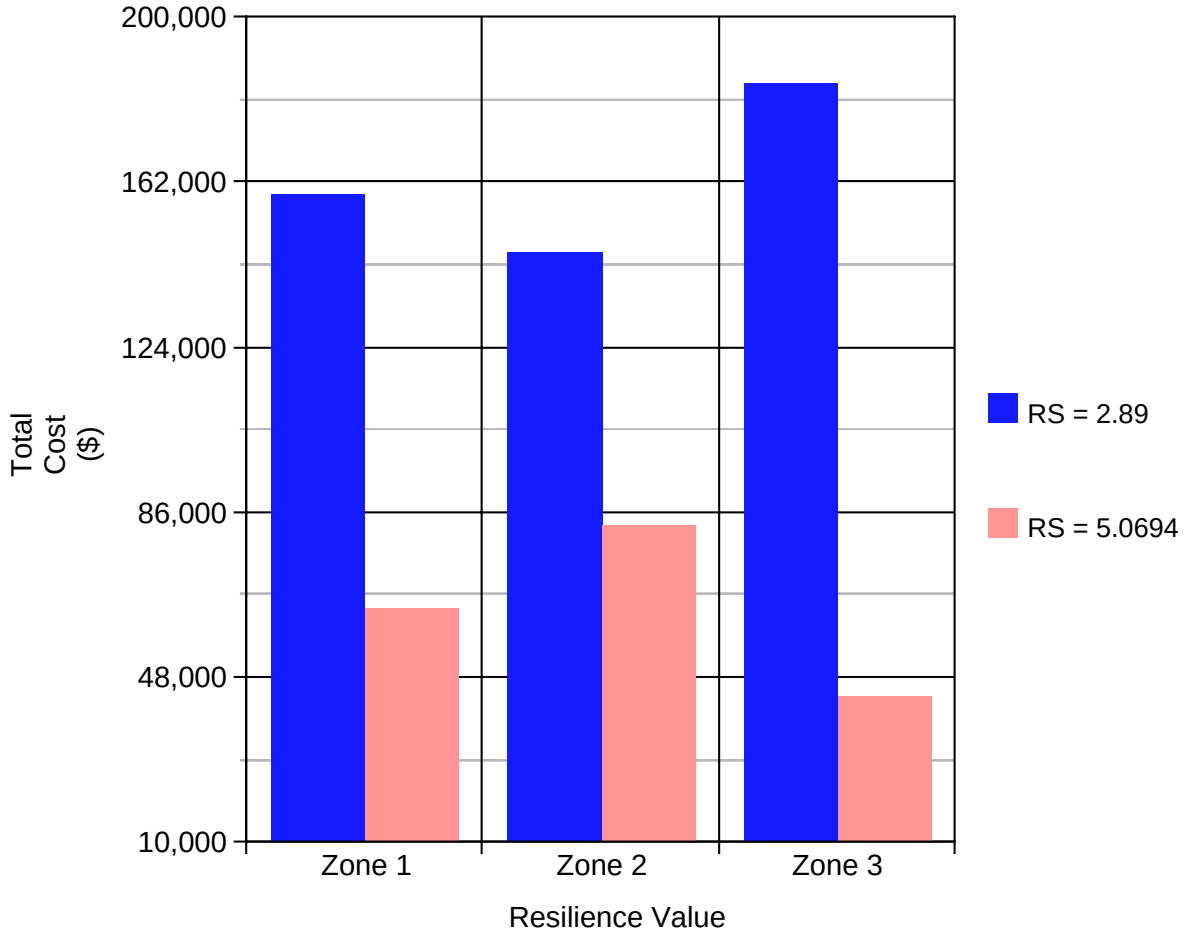


Figure 4.16: Resilience value VS Total Costs for different zones of the Supply Chain Model

Chapter 5

Conclusions

The complexity of the modern era supply chain makes it vulnerable to all kinds of disruption. The network structure of supply chain becomes disadvantageous during a disruption as the effects of the disruption can spread through the phenomenon of ripple effect. The disruptions can come from a various number of sources. The comprehension of these sources can help in finding out what capabilities of the supply chain it will most likely target. Once the most vulnerable capabilities are identified, it can help in devising the mitigation strategies. If there is no information about the vulnerable capabilities, a lot of time is wasted in the assessment of the damage and searching for the area for improvement that would aid in recovery of the disrupted facility of the supply chain. The contingency planning allocates a different facility from the available list based on the parameters. These parameters can be altered as per different types of supply chains. The base model created is a very generic model which can be modified as per the need of the company. The number of agents depends on the number of facilities present in the supply chain. This model can be applied to real and complex supply chains and the best results can be obtained in just a short span of time.

It is important to design the supply chain keeping in mind these disruptions. The inclusion of the resilience and robustness components as mentioned in this research will make the supply chain able to recover from the damages of these disruptions in as less duration of time as possible. The results obtained from the methodology justifies the importance of these components from the supply chain design perspective. The resilience percentage of the supply chain is increased by minimum 10 %. The time lost in the identification of the

capabilities during a disruption is brought down by a considerable amount. This in turn reduces the time difference between the time to initiate the recovery process and and the time to recovery. The resilience triangle mentioned earlier in the study, is shortened by this process. The future scope of the study would be to implement the logistics capability into the model. The study quantifies the need for implementation of resiliency and robustness into the supply chain for having a competitive advantage in the market and also makes the supply chain more responsive.

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Vita

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