Resilience in Upstream Supply Network

by

Gianmarco Alexander Merino Sandoval
Bachelor of Science in Industrial and System Engineering (Universidad de Piura, Peru)

and

Mostafa Khedr Mohamed Khedr Elzanfaly
Bachelor of Science in Industrial Engineering (Zagazig University, Egypt)

SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2023

Signature of Author: ____
Department of Supply Chain Management
May 12, 2023

Signature of Author: ____
Department of Supply Chain Management
May 12, 2023

Certified by: ____
Mr. James B. Rice, Jr.
Deputy Director, Center for Transportation and Logistics
Capstone Advisor

Certified by: ____
Dr. Jafar Namdar
MIT Postdoctoral Associate
Capstone Co-Advisor

Accepted by: ____
Prof. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

Resilience in Upstream Supply Network

by
Gianmarco Merino Sandoval
and
Mostafa Khedr Elzanfaly

Submitted to the Program in Supply Chain Management
on May 12, 2023, in Partial Fulfillment of the
Requirements for the Degree of Master of Applied Science in Supply Chain Management

ABSTRACT

After the Covid-19 pandemic, organizations re-evaluated their supply chain strategies and began a race to build resilience in their networks. However, quantifying the level of resilience of any supply chain is a complex task, given the uncertainties associated with disruptions and the dynamics of global markets. This paper proposes a novel framework for quantifying supply chain resilience, with a focus on the upstream side of the network. Using Social Network Analysis (SNA) indicators and Business Impact concepts, we developed a methodology that captures the impact and robustness within the different tiers of suppliers. The framework also proposes resilience score metrics for comparing different sourcing strategies and network designs. Using a synthetic network, the framework suggests that enhancing flexibility and redundancy could bolster the resilience of other nodes in the supply chain by up to 50%. However, these strategies may also impact overall resilience and introduce criticality to certain nodes, limiting the overall resilience enhancement to only 3%. These findings stem from an analysis based on specific assumptions and characteristics. Consequently, the results may vary when implemented in unique supply chain networks with distinct characteristics. The proposed framework provides a valuable starting point to practitioners for understanding and improving supply chain resilience.

Capstone Advisor: James B. Rice, Jr.
Title: Deputy Director, Center for Transportation and Logistics
Capstone Co-Advisor: Dr. Jafar Namdar
Title: MIT Postdoctoral Associate

ACKNOWLEDGMENTS

We hereby express our profound gratitude to our advisor, Mr. James Rice, for his invaluable support and wisdom throughout the development of this work. Further, we must sincerely thank Dr. Jafar Namdar for his enlightened contributions and strong guidance. Our writing advisor, Toby Gooley, deserves our infinite appreciation for her tireless efforts in enhancing this work written in a language that is not ours. This work would not have been possible without you three. We also extend our sincerest appreciation to Maria Jesús Saenz, Justin Snow, Leonard Morison, Josué Velázquez, and all the staff and faculty of the SCM program at the Massachusetts Institute of Technology for providing the best academic experience in the world. We are also grateful to the Nike team, whose insights and expertise have lent invaluable support to our project. Lastly, we must express our deepest gratitude to our dear colleagues, whose unconditional support has been a source of inspiration and comfort throughout this academic journey. Thank you!

Gianmarco M. and Mostafa K.

With profound gratitude, I acknowledge Allah's continuous blessings and guidance throughout my life. To my future wife, Hend, my beacon of inspiration, this accomplishment is a testament to our shared dreams and your unwavering support. It's all for you. We made it! My utmost thanks to my family, notably my late father, whose foresight ignited my passion for coding, and my mother, who shaped me into the version I am now. I deeply appreciate the Fulbright Committee in Egypt, and Amideast, especially Ms. Heather Yuzvenko, for believing in my potential and facilitating my journey to MIT. Lastly, I sincerely thank Dr. Mohamed Grida, who introduced me to the world of supply chain management.

Mostafa Khedr

Looking back, I feel that there is only one person I owe all to: my mother. Without her, I wouldn't be where I am today. I am also grateful for the unconditional support of my partner, sister, and large family. I also want to dedicate this work to my two nieces: Ana and Sofia, hoping this serves as inspiration. Finally, to my loved land: I remain optimistic that, someday not too very far, we will have overcome our main challenges.

Gianmarco Merino

TABLE OF CONTENT

LIST OF FIGURES 5

LIST OF TABLES 5

1. INTRODUCTION 6
   - 1.1. PROBLEM STATEMENT 7
   - 1.2. SCOPE 7

2. STATE OF THE ART 9
   - 2.1. SUPPLY CHAIN DISRUPTIONS: SOURCES AND IMPACTS 9
   - 2.2. MODES OF FAILURE 12
   - 2.3. SUPPLY CHAIN RISK MANAGEMENT VS. SUPPLY CHAIN RESILIENCE 12
   - 2.4. SUPPLY CHAIN RESILIENCE AND RISK MANAGEMENT STRATEGIES 14
   - 2.5. QUANTIFYING SCRM: VALUE-AT-RISK 17
   - 2.6. RESILIENCE FRAMEWORKS 18
   - 2.7. QUANTIFYING SUPPLY CHAIN RESILIENCE 19
   - 2.8. SOCIAL NETWORK APPROACH 20

3. DATA AND METHODOLOGY 23
   - 3.1. MAPPING THE SUPPLY NETWORK 24
   - 3.2. TIMING 25
   - 3.3. TWO APPROACHES 26
     - 3.3.1. Revenue impact 26
     - 3.3.2. Social Network Approach 26
     - 3.3.3. Degree Centrality 28
   - 3.4. THE IMPACT ROBUSTNESS RESILIENCE (IRR) FRAMEWORK 30
     - 3.4.1. Impact 30
     - 3.4.2. Robustness 31
     - 3.4.3. Resilience Score 33
   - 3.5. CREATING A SUPPLY NETWORK 35
     - 3.5.1. Product Composition 35
     - 3.5.2. Synthetic Network 36
   - 3.6. ASSUMPTIONS 37

4. RESULTS AND DISCUSSION 38
   - 4.1. FIRST RESULTS 38
   - 4.2. STRATEGY 1: ADDING FLEXIBILITY 41
   - 4.3. STRATEGY 2: ADDING REDUNDANCY 44
   - 4.4. SUMMARY OF FINDINGS 46

5. CONCLUSION 48
   - 5.1. LIMITATIONS 50
   - 5.2. FUTURE RESEARCH 50

REFERENCES 52

LIST OF FIGURES

Figure 1.1 *Project Flow Chart* 8
Figure 2.1 *Frequency of Disruptions* 10
Figure 2.2 *Impact and Likelihood of Supply Chain Disruptions* 11
Figure 2.3 *Risk Management, Disruptions and Resilience* 13
Figure 2.4 *Risk classification Matrix* 14
Figure 3.1 *Research Methodology* 23
Figure 3.2 *Finished Product P1* 24
Figure 3.3 *Supply Network of Product P1* 24
Figure 3.4 *Degree, Closeness and Betweenness* 27
Figure 3.5 *Simplified Degree Centrality Equations* 29
Figure 3.6 *P1 Composition* 35
Figure 3.7 *Synthetic Supply Network* 36
Figure 4.1 *Resilience Results - Initial Model* 40
Figure 4.2 *Network Resilience Results After Flexibility* 43
Figure 4.3 *Network Resilience Results After Redundancy* 45

LIST OF TABLES

Table 2.1 *Resilience Strategies* 15
Table 4.1 *Baseline result* 39
Table 4.2 *Network Resilience Results After Flexibility* 42
Table 4.3 *Network Resilience Results After Redundancy* 44

1. INTRODUCTION

The recent global disruptions have shown a clear example of the interconnectivity of supply chains. The global Covid-19 pandemic is among the most recent contributors to global disruptions; however, it will not be the last. Over the past two years, the world has faced a series of events that caused global disruptions, including, but not limited to, geopolitical conflicts such as the Russian invasion of Ukraine, natural disasters such as frequent floods and hurricanes, and the rising inflation rates in developing countries. Those events obstructed the fluidity of many logistics and supply chain operations and blocked other ones entirely (Gartner, 2022).

As a result, many industries are now emphasizing building a supply chain that can respond quickly and effectively to unforeseen disruptions (Cohen, et al., 2022). To achieve this, companies must invest in solutions to help them recover from disruptions and build a risk-aware culture. However, building a resilient supply chain can be costly. Companies must carefully balance the need for resilience with the associated costs and assets in short-term and long-term investments.

For Nike, a leading American multinational company in the footwear and apparel industry, pursuing resilience has become a top priority to ensure continued success in its supply chain. With over 450 finished-goods factories in 38 countries, Nike experienced challenges in the last two years caused by the Covid-19 pandemic, besides other global disruptions and shortages in the raw material supply (Nike, 2022). Therefore, they want to measure the level of resilience of their upstream supply chain consisting of Tier-1 and Tier-2 suppliers to better respond to disruptions.

1.1. Problem Statement

In the academic context, making a supply chain resilient means recreating the lost capacity after the disruption, which also means continuing to operate despite the disruption (Rice, 2021). After two years of dealing with the pandemic and its consequences, Nike wants to be well-prepared to face any potential trouble by incorporating supply chain resilience in their network design, particularly on the upstream side, which is the manufacturing side. To achieve this, Nike aims to include measures that help them discover the critical and weakest entities in their network in order to take action and be more resilient when disruptions occur.

In this context, the questions to be answered include the following:

1. How can we define resilience in Nike's upstream supply chain?
2. What are some metrics that could assist Nike in enhancing its upstream supply chain resilience?

1.2. Scope

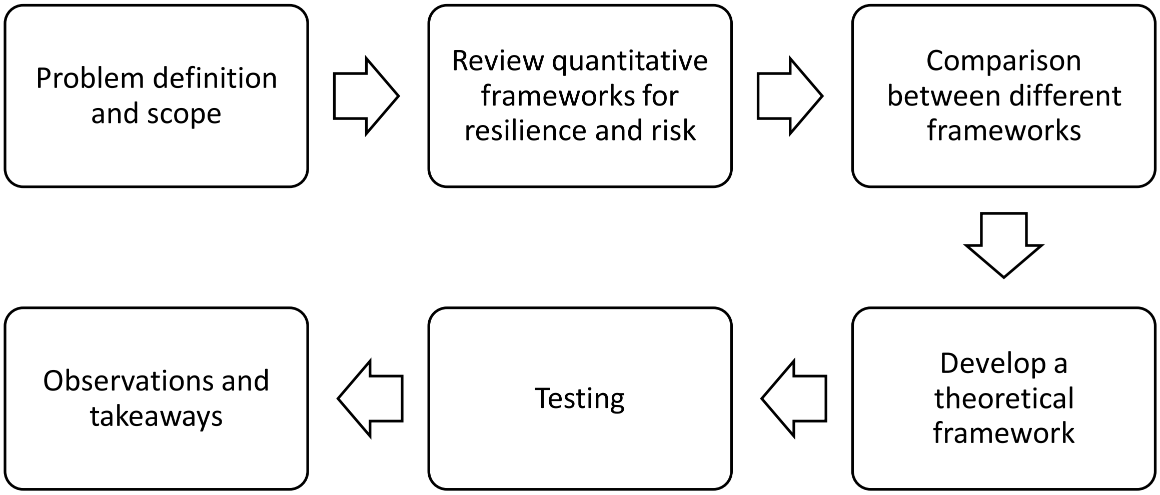
The project's overall goal was to work towards a theoretical framework that might quantify the resilience of an upstream supply chain. So, we explored some potential proxies that companies can use to assess upstream supply chain resilience. Having said that, we focused our efforts on developing:

1. Proxy metrics to quantify the upstream supply chain resilience.
2. A theoretical representation of these metrics in an upstream supply chain network.

Therefore, companies might use this framework to assess upstream supply chain design and resilience. To achieve the above points, this capstone project starts by studying the existing frameworks to quantify resilience and risk, focusing on quantitative methodologies. Then, we narrowed our focus based on a mixed model to deploy theoretical testing of an upstream supply network. Finally, we conducted an analysis based on different strategies to observe these metrics' behaviors in a synthetic network, as shown in Figure 1.1.

Figure 1.1

Project Flow Chart



This framework showed that robustness and impactful might be good proxies for assessing the resilience within a network. Moreover, under some specific scenarios, it provides an objective measure of resilience that companies can consider for assessing different sourcing or network design scenarios.

2. STATE OF THE ART

This chapter summarizes the current State of the Art of supply chain resilience that we have found relevant for our research. First, we describe the causes and impacts of disruptions in supply chains. Then, we offer a brief difference between risk management and resilience in a supply chain context, ending by commenting on the existing frameworks to assess resilience in a supply chain.

2.1. Supply Chain Disruptions: Sources and Impacts

Supply chain disruption is the unplanned incident that disrupts the normal flow of materials, products, or information from source to destination in supply chains (Svensson, 2000; K. Hendricks, 2005). Sheffi (2015) categorized supply chain disruptions into natural, negligent, and intentional disruptions. Natural disasters such as pandemics, floods, and hurricanes are hard to predict and prepare for. Moreover, their impact can be severe and affect whole industries.

In contrast, negligent disruption is mainly a result of violating the safety or quality procedures of the company. However, companies tend to minimize negligent disruptions by adopting zero-tolerance policies regarding the safety of people and materials and strict quality control procedures. The third type of disruption, intentional disruption, can be originated internally, inside the company, or externally from competitors. Furthermore, intentional disruptions are selective in terms of time and point of impact, increasing the loss for the company in a short time (Sheffi, 2015). For instance, cyber-attacks can potentially disrupt global supply chains (Rice, 2022; Sepúlveda & Khan, 2015).

Although disruptions are usually sudden and unpredictable, sometimes they happen regularly (Lund, 2020). A survey conducted by Lund et al. (2020) shows that many recent disruptions and catastrophes didn’t happen by chance. However, some variables affect the frequency of these disruptions, including, but not limited to, climate change, global economic changes, and geopolitical affairs. The survey classified the disruptions based on their shock magnitude and ability to anticipate them (see Figure 2.1). The figure shows that companies can face more than two months of disruption every five years, which reflects a serious threat for industries to prepare for.

Figure 2.1

Frequency of Disruptions

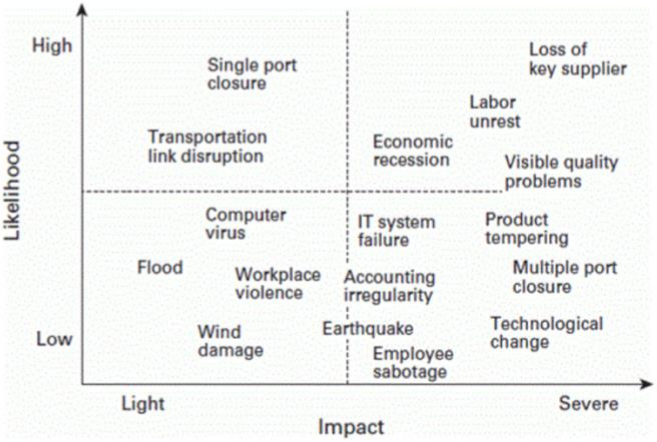
Note. From “Risk, resilience, and rebalancing in the global value chain” by S. Lund, J. Manyika, J.Woetzel, E. Barriball, M. Krishnan, K. Alicke, M. Birshan, K. George, S. Smit, D. Swan, K. Hutzler, 2020, Retrieved from Mckinsey Web Site.

The impact of supply chain disruptions is meaningful. In a survey conducted by Rice & Caniato (2003), one company estimated their cost impact for each day of their supply chain network disruption to be $50 - $100 million. On top of that, the current connectedness and spread of global supply chain networks for businesses not only escalates the impacts of disruptions (Simchi-Levi, et al., 2015) but also increases the complexity of the supply chain, which is considered a potential contributing factor to supply chain disruptions (Choi & Krause, 2006; Craighead et al., 2007; Sheffi, 2015).

In Figure 2.2, Sheffi (2015) classifies the supply chain potential disruptions based on their level of impact and the likelihood of happening based on risk experts' reports. The figure shows both natural and operational disasters within the firm. As shown in the figure, some operational disruptions can impact more than natural disasters.

Figure 2.2

Impact and Likelihood of Supply Chain Disruptions



Note. From *The Power of Resilience: How the Best Companies Manage the Unexpected* by Y. Sheffi, 2015, MIT Press.

The impact of disruptions on businesses is not periodic. Businesses can suffer from disruptions for long after the disruption period due to the resulting losses on their operations, customer satisfaction, and market share (Oke & Gopalakrishnan, 2009). Therefore, due to the uncertainty of disruptions, studying the impact of the disruption and the associated recovery plan is more essential for businesses than avoiding the source of this disruption.

2.2. Modes of Failure

To better prepare for and recover from disruptions, businesses need to identify the expected areas of losses that could be impacted. Rice (2021) defined seven core potential capacities that disruptions can affect: the required materials for production, the transport of materials, the communication capabilities, the manufacturing capacity, the labor, the financial flow, and the access to demand. Hence, businesses can assess how these capacities can be recovered during disruptions regardless of the reason for disruption.

Addressing the modes of failure can help map the variables that contribute to the point of strength and weaknesses inside the organizations (Craighead et al., 2007). Moreover, companies can use this analysis to prepare for future threats by identifying areas for improvement to mitigate expected risks or recover from any upcoming disruptions. In other words, companies can use this analysis to make their supply chain more resilient.

2.3. Supply Chain Risk Management vs. Supply Chain Resilience

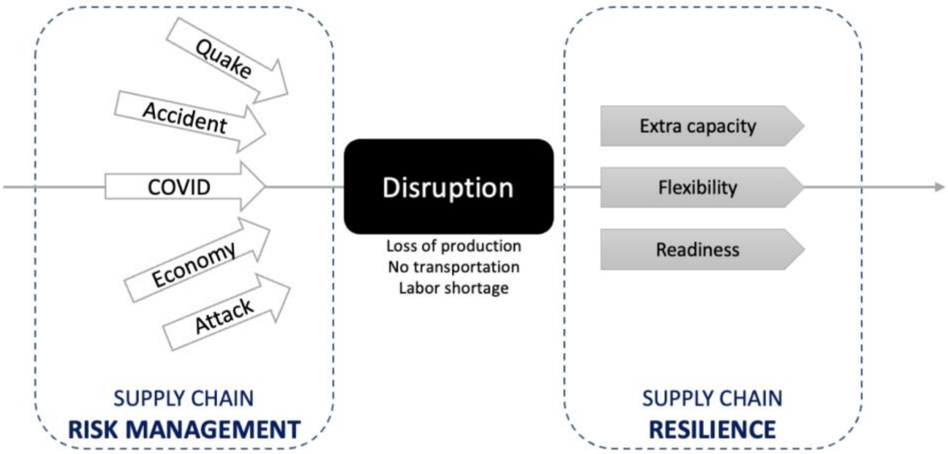
Companies often interchange the terms Supply Chain Risk Management (SCRM) and Supply Chain Resilience (SCR). However, these two terms differ in meaning. Whereas resilience is the capability to recreate lost capacity after an adverse event (disruption), risk management deal with avoiding or mitigating before the potential disruption occurs. Although they are related, they are not the same.

Supply Chain Risk Management refers to the collaborative process of identifying, assessing, and mitigating any unexpected external or internal risk which might adversely impact any part of a supply chain (Ho et al., 2015). Given the inherent vulnerability of supply chains to risks, managers can implement various strategies to deal with them effectively.

However, SCRM is a prior process to the disruption that focuses on the causes of disruptions, while SCR focuses on the capabilities after the disruption (Rice, 2022), as shown in Figure 2.3.

Figure 2.3

Risk Management, Disruptions and Resilience

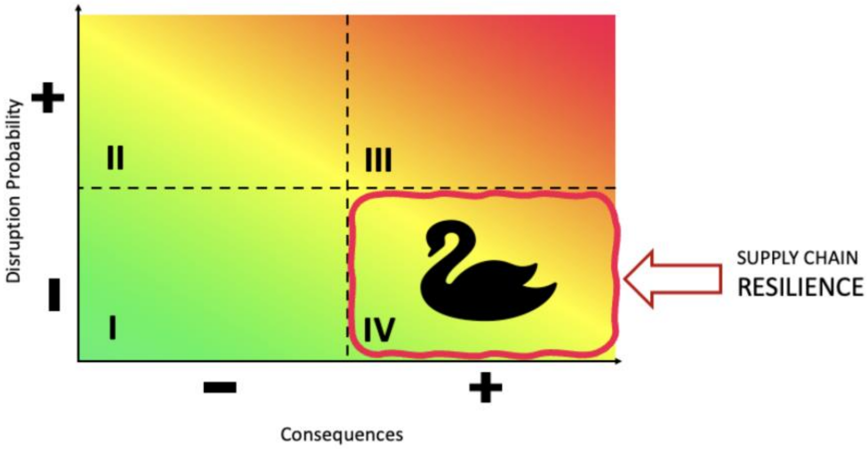


Another difference is that Resilience is about capabilities (extra capacity, flexibility, etc.), not merely an assessment of likelihood. So, each company must develop these capabilities through different initiatives in order to respond to any disruption. Hence, a supply chain might be more resilient than another despite having a similar SCRM process.

There is a third difference between Supply Chain Risk Management and Supply Chain Resilience. To assess risks, the classic method is to plot the probability of disruption and its consequences, as illustrated in Figure 2.4. With this distribution, and knowing that the number of potential causes of disruptions is too many, it is virtually impossible to mitigate all risks (Rice, 2022). This might explain why risk managers focused on Quadrant III (high probability, high consequences): it gives the highest expected values. However, high-probability events are predictable; hence the management teams can be prepared for them with some frequency. On the other hand, supply chain resilience tends to focus on Quadrant IV (high consequences, low probability) because unexpected disruptions are generally the most dangerous (a.k.a., “Black Swans”), such as pandemics, wars, and earthquakes. Therefore, building resilience in Quadrant IV can make the difference (Sheffi, 2015).

Figure 2.4

Risk Classification Matrix



Note: Adapted from Sheffi Y. (2015). *The Power of Resilience: How the Best Companies Manage the Unexpected*. MIT Press.

Finally, investments in resilience strategies are hard to justify financially due to the unlikelihood of catastrophic events. This could explain why companies generally focus more on risk management (such as historical disruptions) than on building supply chain resilience (regardless of the causes). Hence, this also might be wasting the company's investments (Rice & Caniato, 2003).

2.4. Supply Chain Resilience and Risk Management Strategies

According to Sheffi (2015), there are three general ways to build resilience in the supply chain: Redundancy, Flexibility, and Preparedness. Redundancy means having extra. It might be extra inventory, extra suppliers, or extra capacity to use in case of emergencies. Next, Flexibility refers to interchangeability and postponement. This could be achieved by having similar plants that can produce the same products regardless of location, having standard products or parts that can be easily interchangeable, and having a flexible and cross-trained labor force. On the other hand, postponement refers to a switch toward a pull system.

Finally, operational plans/procedures should be established to implement these strategies. Sheffi (2015) refers to this as "Readiness" and outlines the operational actions to follow once a disruption occurs, such as who does what and who makes the decisions. These plans are also known as Business Continuity Plans (BCP), which are essential to ensure that an organization can quickly recover from disruptions and continue to operate effectively.

Meanwhile, other authors consider Risk Management as part of Resilience. For instance, Namdar et al. (2020) collected several strategies in the literature available on Resilience and Risk Management and classified them into four categories: Anticipation, Preparation, Robustness, and Recovery. Although other combinations of strategies could be used, these categories provide a useful summary. Table 2.1 presents the strategies classified under each of these categories.

Table 2.1

Resilience Strategies

Dimension	Supply Chain Resilience Strategies
Anticipation	Information sharing
	RFID
	Information Technology (IT)
	Enterprise Resource Planning (ERP) System
	TQM and Six Sigma
	Supply Chain intelligence
	Suppliers' risk awareness as a key criterion for selection
	Align procurement strategy with suppliers' relationship (deep relationship with key suppliers)
	Distributed power, empowered to take necessary action (need for situational awareness and initiative at levels closest to the event

	Conditioning for disruption
	Board-level responsibility and leadership
	Collaboration with partners (customers and suppliers) through e.g., CPFR system
Preparation	Establish supply chain continuity team
	Formal ‘P.E.S.T.’ type analysis (strategic level of supply chain knowledge)/ (Learning from experiences)
	Supply chain Risk Management, BCP, ERM
	Break down ‘functional silos’ to create multi-disciplinary, cross-functional process teams
	Continuous communication among employees/or partners
	E-based process rather than paper-based
	Interchangeable people (Cross Training)
	Standardize Process, part commonality
Robustness	Redundancy (via inventory prepositioning, backup suppliers, reserved extra capacity)
	Strategic stock and slack
	Multiple sourcing
	Single source for an item or service into each site
	Supplier contract flexibility (e.g., via quantity flexibility contracts)
	Diversification (supply chain re-engineering)
Recovery	Passion for work
	Standardize Process, part commonality
	Identical plant design/process and facility
	Interchangeable and generic parts
	Interchangeable people (Cross-training)
	Postponement and Product Flexibility
	Flexible Manufacturing System (FMS)
	Revenue management via Dynamic Pricing
	Assortment planning
	Silent product rollover recovery planning system
	Synchronization of schedules based on shared information
	E-based process rather than paper-based
	Process improvement 1. Reduced in-bound lead-times (lead-time reduction) 2. Added time reduction (idle time, inventory process time)
	Parallel process rather than in series
	Streamlined and simplified processes

Note. Adapted from “Business continuity-inspired resilient supply chain network design” by Namdar, J. et al, 2020, *International Journal of Production Research*, 59:5, 1331-1367.

2.5. Quantifying SCRM: Value-at-Risk

Now that we have described the differences and similarities between Risk Management and Resilience, we have delved into companies' different strategies to build strong and resilient supply chains; we described how companies might quantify the level of resilience they possess through different frameworks in SCRM and SCR.

Over time, several approaches have been developed to assess risks in supply chains, and according to Ho et al. (2015), one extensively used approach to SCMR is the common Value-at-Risk (VaR) metric. Initially used in the financial industry, this statistical metric estimates a company's potential financial losses due to unexpected events or disruptions. By using VaR, companies can identify and manage risks in the supply by attempting to reduce the maximum losses within a specific period (Ho et al., 2015).

Value-at-Risk relies on forecasts of the volatility of portfolio revenue or returns over a given period (Sanders & Manfredo, 2002). In a supply chain context, VaR expresses the business impact of a supply chain disruption. Equation 2.1. captures this, where z is the number of standard deviations corresponding to the desired confidence level, σ is the standard deviation of the losses incurred due to supply chain disruptions, and L is the expected loss due to a supply chain disruption. This could be estimated with the loss of revenue or profit (Sanders & Manfredo, 2002).

$$VaR = \mathrm{z} \times \sigma \times \mathrm{L} \tag{2.1}$$

Unfortunately, VaR also has certain limitations. One significant limitation is its assumption that risks follow a normal distribution, which may only sometimes be accurate. This can lead to underestimating risks, particularly extreme events such as “Black Swans” (Ho et al., 2015). In addition, gathering accurate data on the probabilities and impacts of risks can be tricky, leading to inaccurate risk assessments and flawed decision-making (Ho et al., 2015).

Ho et al. (2015) also remark that VaR only focuses on the downside risk and does not consider the upside potential or benefits of opportunities for growth that may arise from supply chain disruptions. Several modifications, such as Conditional Value-at-Risk (CVaR), have been developed to address all these limitations (Ho et al., 2015). In addition to its simplicity and usefulness, VaR is still widely used.

2.6. Resilience Frameworks

Although this topic has been discussed for around 20 years, Supply Chain Resilience became a high-relevance, almost mandatory topic just after the pandemic hit. However, despite all efforts, there has yet to be a universal agreement regarding what being resilient means in a supply chain context (Golan et al., 2020). Therefore, a universally accepted framework to depict and successfully measure the level of resilience within the supply chain has yet to be created (Rice et al, 2022; Golan et al., 2020).

Among the several frameworks out there, Golan et al. (2020) found that many papers focus on qualitative evaluation, primarily identifying best practices through surveys and case studies. On the other hand, some other studies also use quantitative approaches, but the measures used to quantify resilience are often only proxies that try to capture the resilience within the supply chain, such as service level or time to recover, which are useful when the concept of resilience is not clearly defined. Nonetheless, some metrics, such as Time-to-Recover (TTR) and Time-to-Survive (TTS), are good-enough approximations to estimate a supply chain's behavior in what-if scenarios (Simchi-Levi et al., 2015).

Golan et al. (2020) also highlights some quantitative frameworks that have effectively quantified the supply chain's resilience as a percentage between 0 and 1. However, these frameworks have not been universally accepted by the research community, indicating the need for further research to develop a standardized and widely accepted framework for effectively measuring supply chain resilience (Golan et al., 2020).

2.7. Quantifying Supply Chain Resilience

As we pointed out in 2.6., many studies rely on “proxies” as indicators of supply chain resilience. These proxies are often adapted from some core key performance indicators like service level or recovery rates, thus enabling the evaluation of supply chain performance in disruptions (Golan et al., 2020).

For instance, Paul et al. (2019) used two mathematical models to measure supply chain resilience in transportation using delivery delay and quantity loss as proxies for supply chain disruptions. This model formulated ideal and recovery plans after disruptions and used backlog and lost sales as indicators for the cost of disruptions. However, it did not consider safety stock or the integration and connectivity of supply chain functions, limiting its ability to simulate resilience accurately.

Another framework developed by Sabouhi et al. (2018) used the percentage of disrupted suppliers with a loss of capacity as a proxy. This two-stage model used mathematical programming and data envelopment analysis (DEA) to evaluate the efficiency of suppliers in the normal phase and the effects of partial or complete disruptions. However, the model did not consider transportation links or multi-tier supply chain networks, crucial factors affecting supply chain resilience.

In contrast, Chen et al. (2017) remark that only a few frameworks effectively address supply chain resilience quantification. Most existing methods fail to represent interdependencies between different supply chain nodes and do not allow for actionable decision-making to guide improvement strategies. Hence, Chen et al. (2017) proposed a framework that captures several degrees of risks involved in the supply and demand side, internal firm, and environmental factors, as well as pre-and post-disruption mitigation capabilities. This framework measures node-level resilience but expands it throughout the complete supply network, including buyer-supplier links. However, the data complexity required to formulate the optimization model could be challenging for most organizations.

Another comprehensive framework developed by Camacho et al. (2017), quantifies the level of resilience of Australian supply chains facing simulated climate disruptions. This framework calculates four supply chain indices (evenness, resilience, continuity of supply, and climate resilience), and it develops a performance metric that expresses the level of supply chain resilience as an overall percentage, allowing for sensitivity analyses among different strategies (Camacho et al., 2017).

2.8. Social Network Approach

The application of Social Network Analysis (SNA) to measure the complexity of supply networks has gained interest as an approach for understanding supply network dynamics. Hence, it has been used as a proxy to assess complexity and, thus, supply chain resilience.

SNA is a methodology based on graph theory that examines the patterns of ties in a network. In social networks, the nodes are individuals or organizations that possess agency, which means they can make decisions and take actions that affect the network's overall structure.

Traditionally, SNA has been employed to study the structure of communities, communication patterns, and the spread of diseases (Kim et al., 2011). Within the operations and supply management context, SNA has proven useful in examining the social structure of supply networks (Kim et al., 2011).

SNA metrics can be evaluated at two levels: node level and network level. Node-level metrics examine how an individual node is situated within the network from that node's perspective. These metrics focus on individual nodes' characteristics within a network (Kim et al., 2011). In contrast, network-level metrics assess the properties of the network as a whole. Node-level metrics include degree, closeness, and betweenness centrality, while network density, centralization, and complexity are examples of network-level metrics. Therefore, each metric provides unique insights into the network's structure and function (Kim et al., 2011).

For instance, in their paper, Kim et al. (2011) argue that a linear perspective is insufficient for understanding supply chain management and advocate for a network perspective, with SNA being a suitable approach for analyzing the structural characteristics of supply networks. The authors (2011) link SNA metrics at the firm level to specific roles in the supply network and use real-world data from published case studies of automotive supply networks to apply their framework. The results suggest that quantitative SNA findings complement qualitative research and provide a more nuanced understanding of supply networks.

Similarly, another study by Kazemian et al. (2021)use the SNA approach to assess networks. However, this time the authors go beyond and propose a resilience assessment model using SNA-inspired indicators in a multi-attribute decision-making (MADM) context to help decision-makers quantify the resilience of their supply chain networks. Kazemian et al. (2021) recognize SNA as an emerging methodological tool to map and quantify relationships between interdependent actors. Therefore, the main insight of this resilience model is to identify the significant aspects of a resilient supply chain network's structure and complexity.

Overall, using SNA in understanding supply chain complexity and resilience is a promising research approach that might provide valuable insights into assessing the structure of supply networks to identify vulnerabilities.

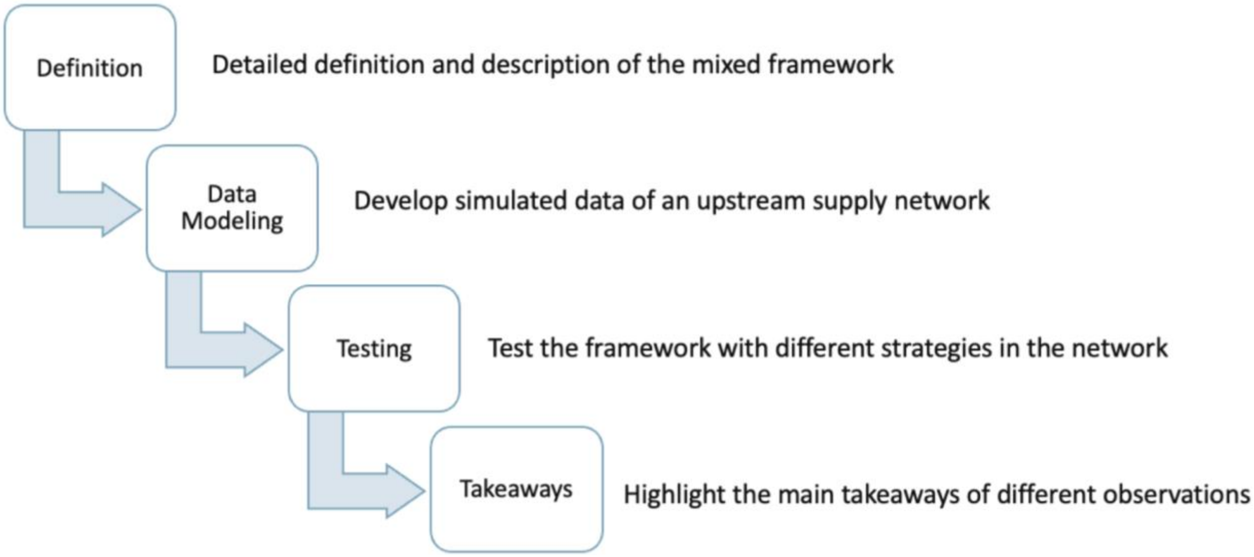
Therefore, given the priorities of this project to quantify the complexity and vulnerabilities of a supply chain for network design proposes, we decided to incorporate SNA-inspired indicators for developing our framework for measuring resilience.

3. DATA AND METHODOLOGY

As noted in section 2.8, we attempted to develop a theoretical framework to assess the complexity and hence the vulnerability of a supply network as a proxy of resilience. Therefore, this chapter explains the methodology and measures we employed as a proxy to assess the vulnerabilities on the upstream side of a supply network. To start, we have outlined the steps we followed in Figure 3.1 to provide a clear understanding of our approach to the research.

Figure 3.1

Research Methodology



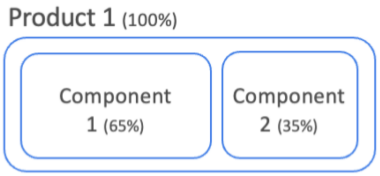
Initially, we focus on mapping the product and its supply network, then explain how to calculate each metric within the network. Finally, we describe the process of getting the data to test the framework.

3.1. Mapping The Supply Network

The framework is applied to a supply network at a product level. First, we chose only one finished good. Then, we mapped its Bill of Materials (BOM) to know all the components needed with their corresponding proportion, as shown in Figure 3.2.

Figure 3.2

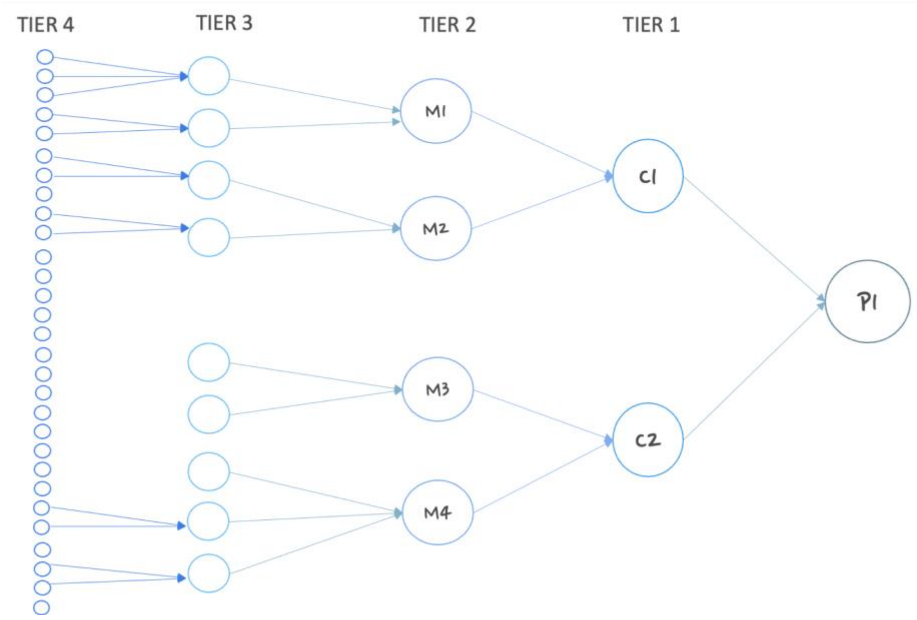
Finished Product P1



This framework only focuses on the raw material and components needed to produce the finished good. Therefore, the framework does not consider the services or processes that do not imply materials or components, such as labor and transportation, among other logistics activities.

Figure 3.3

Supply Network of Product P1



Once we have this composition of Figure 3.2, a similar approach is followed for each component and its corresponding supplier. The idea is to map all the supply chains needed to make one product. This approach is repeated at different levels or tiers as data becomes available. As illustrated in Figure 3.3, Product P1 is composed of two components (C1 and C2), while Component 1 is made up of two materials (M1 and M2) and so on. This shows a hierarchical structure in which each tier depends on the tier below. It is important to note that, for the sake of simplicity, we have assumed that only one supplier supplies each material or component. Therefore, if a single supplier provides two materials, we have represented each supplier-material combination as a separate node in the network.

3.2. Timing

One of the main challenges in risk management and resilience is dealing with disruptive events whose timing and impact are unknown. While conventional risk assessment methods rely on probability calculations to estimate the impact of the disruption, they fall short when the timing is uncertain (Rice, et al., 2022). In such situations, it may be necessary to consider the entire impact of the event.

Even though following this approach is more practical in some cases, it also has challenges. Investing in preventing such an impact when the timing is uncertain is difficult because the net present value (NPV) can vary significantly depending on when the disruption occurs, such as in year two versus year twenty (Rice, et al., 2022).

3.3. Two Approaches

The framework incorporates two fundamental approaches. The first one, Revenue Impact, is commonly used to estimate the financial impact of each node in the finished product sales. The second one employs an SNA-based approach to quantify the network's complexity using the centrality metrics.

Using these approaches, this framework aims to comprehensively understand the supply network's financial performance and complexity, which might help organizations to identify critical nodes in the network and improve the overall resilience of the upstream supply chain.

3.3.1. Revenue impact

Revenue Impact, sometimes called Business Impact, depicts the maximum potential loss of sales for a specific product line that a node could cause during a disruption. In other words, it quantifies the potential impact that a particular node's failure or disruption could have on the sales of a given product line. This metric answers the question: If this node becomes unavailable, how much revenue from the finished product could be lost? Naturally, this loss could be measured in any unit of time.

Additionally, we assumed that the loss of sales is proportional to the loss of production we cannot make. Therefore, for our purposes, we compute the Business Impact as the proportion of production of finished goods that would be impacted annually, which we explain in 3.6.

3.3.2. Social Network Approach

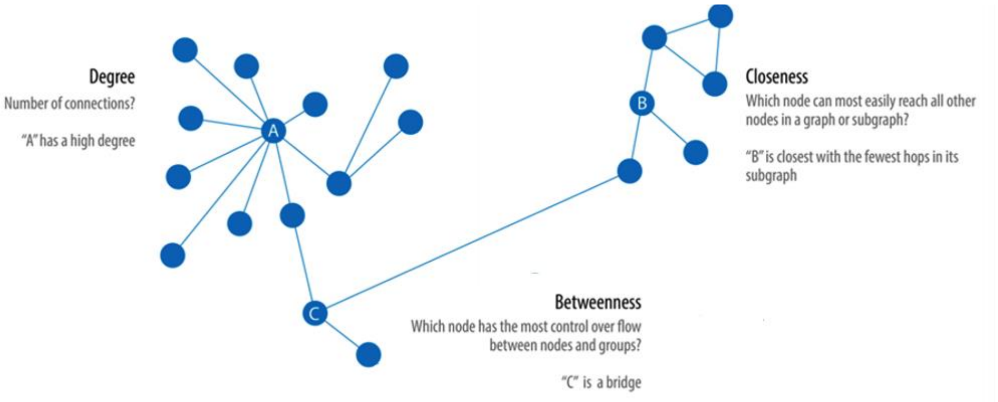
The SNA only considered whether the nodes were supplying each other. If there is a supply between two nodes, the indicator will be 1; otherwise, it will be 0. As shown in Figure

3.4., in-degree centrality quantifies the importance of a node based on the number of incoming edges, reflecting its influence or popularity within the network. Out-degree centrality, on the other hand, measures the reach of a node by counting the number of outgoing edges, thereby assessing the extent to which a node can exert influence on others. Degree centrality, a more general measure of connectivity, computes the number of edges connected to a node in an undirected graph or the sum of in-degree and out-degree centrality in a directed graph.

On the other hand, betweenness centrality evaluates a node's significance as a bridge or gateway in the network by examining its frequency on the shortest paths between other nodes. This measure is particularly useful for understanding information flow and control within the network.

Figure 3.4

Degree, Closeness and Betweenness



Note: Adapted from "Graph algorithms: practical examples in apache spark and neo4j" by Mark Needham and Amy E. Hodler, 2019, O'Reilly Media, Inc.

Lastly, closeness centrality estimates a node's proximity to all other nodes by calculating the inverse of the average shortest path length, thereby offering insights into the node's efficiency in disseminating information throughout the network. Collectively, these centrality measures provide valuable insights into the topology and dynamics of complex networks, enabling researchers to discern patterns, identify critical nodes, and predict network behavior.

3.3.3. Degree Centrality

As noted in 3.4, degree centrality measures the importance of a particular node within a network (Kim et al., 2011). It is calculated by considering the number of edges or links that touch a node; the more connections it has, the more important it is compared to the other nodes within the network. Hence, degree centrality $C_D(n_i)$ in a non-directional network for node $i(n_i)$ is defined as follows:

$$C_D(n_i) = \sum_j x_{ij} = \sum_j x_{ji} \tag{3.1}$$

Where x_{ij} is the binary variable equal to 1 if there is a connection between n_i and n_j, and equal to 0 otherwise (Kim et al., 2011). Now, in order to consider the weight of network size g, this metric is normalized as the proportion of nodes directly adjacent to n_i as follows:

$$C'_D(n_i) = \frac{C_D(n_i)}{g-1} \tag{3.2}$$

On the computations, a higher degree centrality score indicates “where the action is” within a network. On the other hand, nodes with a low degree centrality have fewer connections and are considered peripheral in the same network (Kim et al., 2011).

As our analysis is focused on a supply network, which is a directional network, it is important to note that degree centrality can also be measured with this in mind by calculating in-degree and out-degree centrality. In-degree centrality measures the number of incoming connections that point to a particular node (see Equation 3.3), while out-degree centrality indicates the number of outgoing edges that start from the node (see Equation 3.4).

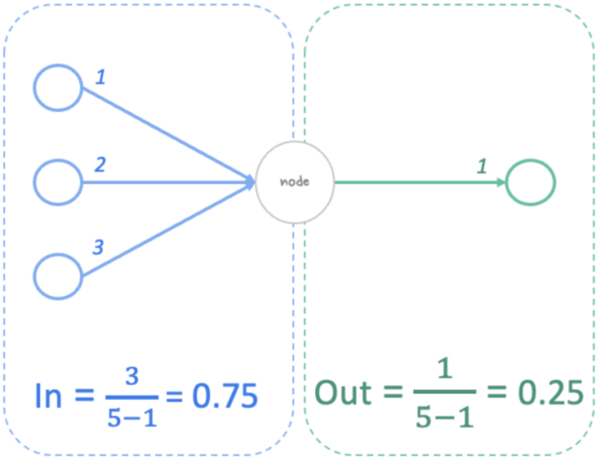
$$C'_D(n_i) = \frac{x_{j+}}{g-1} \quad \text{[in-flow links]} \tag{3.3}$$

$$C'_D(n_i) = \frac{x_{i+}}{g-1} \quad \text{[out-flow links]} \tag{3.4}$$

Figure 3.5 shows graphically how in-degree, and out-degree centrality calculation works. For instance, if we would want to calculate the in and out-degree centrality of the node in the middle ("node"), we can see that it has three links in and one out. So, the in-degree centrality is measured by adding the three links and dividing them by the number of nodes minus one, which will result in 0.75. This approach is similar to computing the out-degree centrality, which will be one link over four, resulting in 0.25.

Figure 3.5

Simplified Degree Centrality Equations



Therefore, in a supply chain context, a node with high in-degree centrality will likely be a key supplier connected to many downstream nodes. In contrast, a node with high out-degree centrality may be a key customer or distributor linked to many upstream nodes. Hence, considering both centrality measures, we can understand the size of the adjacent upstream and downstream tiers within a supply network and the different roles that nodes play in it. This information can be valuable for identifying potential critical or vulnerable nodes in the supply chain.

3.4. The Impact Robustness Resilience (IRR) Framework

The IRR framework uses two primary metrics to assess the network's resilience level. The weighted impact measures the business impact of each node, while Robustness measures the level of adjusted connectedness of each node on the upstream side.

3.4.1. Impact

We consider this metric to measure the weighted impact of each node in the whole network. So, used the revenue impact explained in 3.3.1 to get the final impact of the unavailability of each network. However, this metric itself seemed incomplete in ranking different types of nodes. This is why we incorporated two more metrics: out-degree centrality and product composition.

First, out-degree centrality captures the level of outbound connectedness. And this is important because the revenue impact is also a metric that captures the outbound impact toward the downstream supply. So, the more connections a particular node has, the more impactful it is. Secondly, in order to capture the importance of the specific component in the BOM, we also incorporate the product composition of each material. Likewise, the more important the material, the more impactful the node is.

Therefore, the weighted impact metric quantifies the business impact of each node in the network based on connections and importance. The calculation is shown in Equation 3.5.

$$\boldsymbol{I_i} = RI_i * D_{out_i} * C_i \tag{3.5}$$

Where:

- $\boldsymbol{I}_i$ represents the weighted impact for node *i*.
- $\boldsymbol{RI_i}$ represents the revenue impact on the network if node *i* goes down.
- $\boldsymbol{D}_{out_i}$ represents the out-degree centrality of node *i*.
- $\boldsymbol{C}_i$ represents the product composition in a percentage of node *i*.

Now, we need to normalize the impact of each node in order to capture the different behavior of tiers. Because in a supply chain network, each tier has a different function within the network. For instance, Tier-1 is for factories, Tier-2 is for components suppliers, and Tier-3 is for raw material suppliers. We normalize the tier impact simply by taking a proportion of each impact within the different, making that all the impacts in a tier sum up to 100%. We called this the Adjusted Impact, which is shown in Equation 3.6.

$$\boldsymbol{I}_{ji}^{a} = \frac{RI_i * D_{out_i} * C_i}{\Sigma_j I} \tag{3.6}$$

Where:

- $\boldsymbol{I}_{ji}^{a}$ represents the adjusted impact for node *i* by tier *j*.
- $\boldsymbol{RI_i}$ represents the revenue impact on the network if node *i* goes down.
- $\boldsymbol{D}_{out_i}$ represents the out-degree centrality of node *i*.
- $\boldsymbol{C}_i$ represents the percent of product composition of node *i*.
- $\Sigma_j \boldsymbol{I}$ represents the summation of all Impacts *i* within tier *j*.

Noticed that we are measuring the Impact in the tiers but not in the final market nodes. If these nodes are calculated, the Impact will be zero because the out-degree will also be zero.

3.4.2. Robustness

A second metric, Robustness (Ro), examines the flexibility of each node concerning its sourcing strategy. A node's robustness is positively correlated with its number of suppliers, enhancing its flexibility and adaptability in the face of potential disruptions. The in-degree centrality is used to measure the robustness as it only considers the supply to each node, as shown in Formula 3.7.

$$Ro_i = \sum_i D_{in} \tag{3.7}$$

Where:

- $\boldsymbol{Ro}_i$ represents the Robustness of node *i*.
- $\boldsymbol{D}_{in}$ represents the in-degree centrality of node *i*.
- $\sum$ denotes the summation of in-degree centralities for the precedent nodes, which is the cumulative in-degree centrality.

Once we have the Robustness at the node level, we incorporate the supply availability of the specific component or commodity in the market. Therefore, we adjusted the robustness by incorporating the Herfindahl-Hirschman index (HHI) (Namdar et al., 2023). HHI is a commonly used index for estimating market concentration, indicating whether or not a few companies dominate an industry. We standardized the HHI to a range from 0 to 1, with higher values representing a more concentrated market (Namdar et al., 2023). We also followed a similar approach to the Impact and normalized it within the tiers. The resulting Adjusted Robustness metric is calculated in Equation 3.8.

$$Ro_i^a = \frac{Ro}{(1+HHI_{std}) * \Sigma_j Ro} \tag{3.8}$$

Where:

- $\boldsymbol{Ro}_i^a$represents the Adjusted Robustness of node *i*.
- $\boldsymbol{HHI}_{std}$ represents the standardized Herfindahl-Hirschman Index
- $\Sigma_j \boldsymbol{Ro}$ represents the summation of all Robustness *i* within tier *j*.

Noticed that we are measuring the Robustness in the tiers but not in the final market nodes. However, the last tier will have zero robustness because the in-degree centrality will be zero. As a result, the level of analysis depends on the number of tiers we evaluate. For instance, if we want to evaluate four tiers, we'll need data for at least five. Similarly, if we want to evaluate five tiers, we'll need data for six tiers, and so on.

3.4.3. Resilience Score

The Resilience score represents the ratio between the Adjusted Robustness by a proportion of Robustness and Adjusted Impact. Firstly, we calculated the resilience score at the node level by considering the proportion of the summation of the Robustness and Adjusted Impact multiplied by a penalization factor α, as shown in Equation 3.9. We chose to penalize the Impact by assuming that Impact is harder to control than Robustness. This penalization factor α is an arbitrary number the company chooses based on its peculiarities.

$$R_i = \frac{Ro_i^a}{Ro_i^a + \alpha I_i^a} \tag{3.9}$$

Where:

- $\boldsymbol{R_i}$ represents the resilience score of node *i*.
- $\boldsymbol{Ro_i^a}$ represents the Adjusted Robustness of node *i*.
- $\boldsymbol{I_i^a}$ represents the adjusted impact for node *i*.
- $\boldsymbol{\alpha}$ represents the penalization factor of the Adjusted Robustness.

To better determine the overall resilience of the network, we considered that each tier has distinct characteristics, similar to the methodology used in the Adjusted Impact approach. However, we prioritized tiers based on their proximity to the downstream to account for this behavior. Specifically, we assumed that Tier-1 is prioritized over Tier-2; and Tier-2 over Tier-3, as we move towards the downstream. Equation 3.10 shows this calculation.

$$R = \frac{\sum_j w_j (\sum_i R_i)}{\sum_j w} \tag{3.10}$$

Where:

- $\boldsymbol{R}$ represents the resilience score of the network.
- $\boldsymbol{R_i}$ represents the resilience score of node *i*.
- $\boldsymbol{w_j}$ represents the weight of each tier *j*.

Similarly, with Impact and Robustness, the resilience score of the last tier and the market nodes will not be considered in calculations since there is insufficient data. As mentioned in 3.4.2, the level of analysis depends on the number of tiers we evaluate.

However, since this score is a weighted average, it has low-sensitive. Therefore, we also considered one more resilience metric: the network's minimum resilience score, as shown in Equation 3.11. This is because we believe that the weakest point of the network is a complementary indicator of the whole resilience of the network.

$$R_{min} = \min_i (R_i) \tag{3.11}$$

Where:

- $\boldsymbol{R_{min}}$ represents the minimum resilience score of the network.
- $\boldsymbol{R_i}$ represents the resilience score of node *i*.

By employing these metrics, the methodology tries to shed light on the resilience and stability of the network under examination, thereby offering valuable insights to quantify the complexity and vulnerabilities.

3.5. Creating a Supply Network

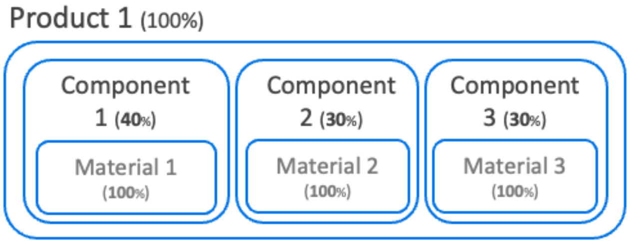
Gathering real data for a research project can be challenging for several reasons, such as confidentiality and limited time. In this part, we describe the data generation process for our research. Our approach involved creating a network with a structure similar to the sponsor company, which consists of three tiers.

3.5.1. Product Composition

First and foremost, we understood that the company outsources all the finished goods manufacturing to its suppliers around the globe. Therefore, our network was structured as follows: Tier 1 as suppliers manufacturing finished goods, these are the factories; Tier 2 as suppliers providing materials listed on the Bill of Materials (BOM) to Tier 1 suppliers. Finally, Tier 3 as the suppliers providing raw materials and commodities to the Tier 2 suppliers.

Figure 3.6

P1 Composition



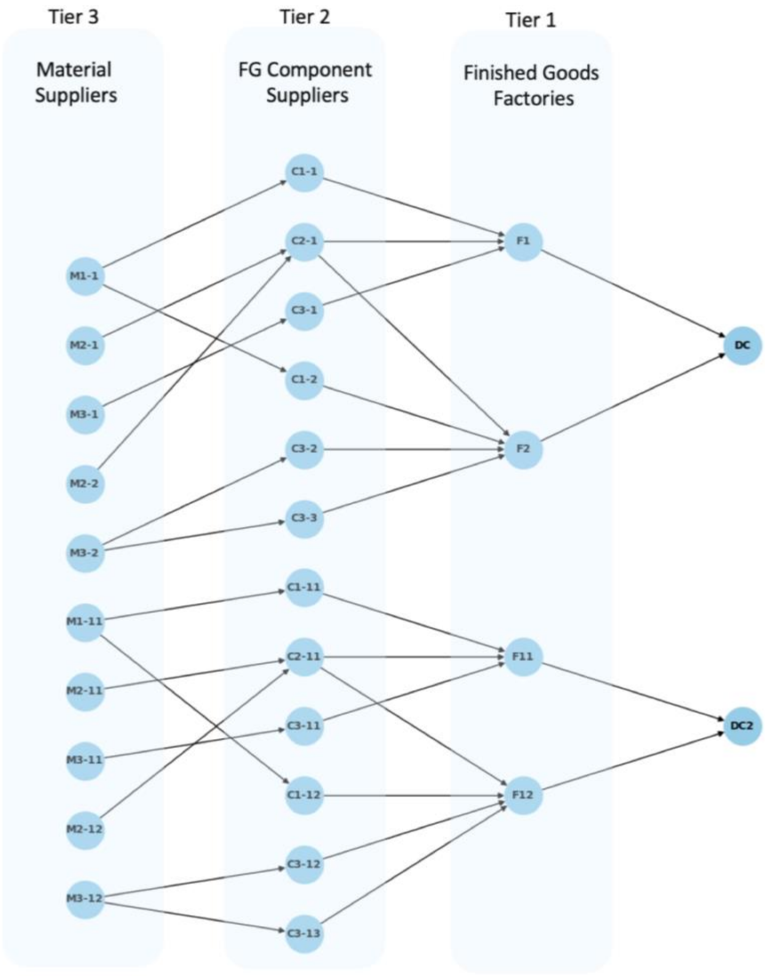
As illustrated in Figure 3.6, Product 1 was constructed using 40% of Component C1, 30% of Component C2, and 30% of Component C3. Similarly, Component 1 consists entirely of Material M1 and so forth.

3.5.2. Synthetic Network

Once we had the product composition, we could recreate a synthetic network. We followed what we mentioned in 3.5.1, and we developed three tiers. Tier-1 corresponds to the supplier's manufacturing finished goods; Tier-2 corresponds supplier’s providing materials listed on the BOM to Tier-1 suppliers; and Tier-3 corresponds supplier’s providing raw materials to Tier-2 suppliers. Then, we established the network of each component-supplier combination, as shown in Figure 3.7.

Figure 3.7

Synthetic Supply Network



3.6. Assumptions

Our framework is designed with some assumptions to simplify calculations, which are listed as follows:

- Production and impact of each node are calculated in proportion to a given period, being the maximum proportion of 100% of a final product.
- Node Impact is calculated based on the complete unavailability of that given node.
- Supplier capacity is considered unlimited. The suppliers supply the exact amount that is ordered.
- Labor, Transportation, and other factors are considered reliable and not considered constraints.
- Networks, composition, proportions, and all data are created only for research purposes.
- Timing is not considered.

4. RESULTS AND DISCUSSION

In this chapter, we discuss the results of our framework in which we applied Social Network Analysis (SNA) to measure the resilience of a synthetic upstream supply chain network presented in Figure 3.7. As explained in section 3.5, we focused on a single product with three components, each with one material. The level of resilience for each supplier was measured by looking at the impact and the robustness within the network.

In the following sections, we explore the process of calculating impact and robustness were calculated for a representative, and we demonstrate how these proxies contribute to the overall measurement of resilience for each supplier. Furthermore, we described how the Weighted Average and Minimum Resilience of the network might be potential indicators that provide a holistic understanding of the overall network resilience and shed light on the most vulnerable nodes.

NetworkX, a specialized Python library for SNA, is used to compute the in-degree and out-degree centrality, key elements of the impact and robustness metrics.

4.1. First results

In this section, we conducted a Social Network Analysis (SNA) on the synthetic network depicted in Figure 3.7. We calculated the Adjusted Impact, Adjusted Robustness, and Resilience score of each node using Equations 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, and 3.11. For simplicity of presenting results, we refer to Adjusted Impact only as Impact and as Robustness to Adjusted Robustness. Furthermore, as outlined in 3.4, we calculated the metrics for the first two tiers of suppliers using data for the three tiers available. The calculations for each node are presented in Table 4.1.

Table 4.1

Baseline Result

NODE	Impact	Robustness	Resilience
F1	0.20	0.22	0.35
F2	0.30	0.28	0.32
F11	0.20	0.22	0.35
F12	0.30	0.28	0.32
C1-1	0.07	0.07	0.33
C2-1	0.11	0.14	0.40
C3-1	0.05	0.07	0.40
C1-2	0.11	0.07	0.25
C3-2	0.04	0.07	0.47
C3-3	0.04	0.07	0.47
C1-11	0.07	0.07	0.33
C2-11	0.27	0.14	0.21
C3-11	0.05	0.07	0.40
C1-12	0.11	0.07	0.25
C3-12	0.04	0.07	0.47
C3-13	0.04	0.07	0.47

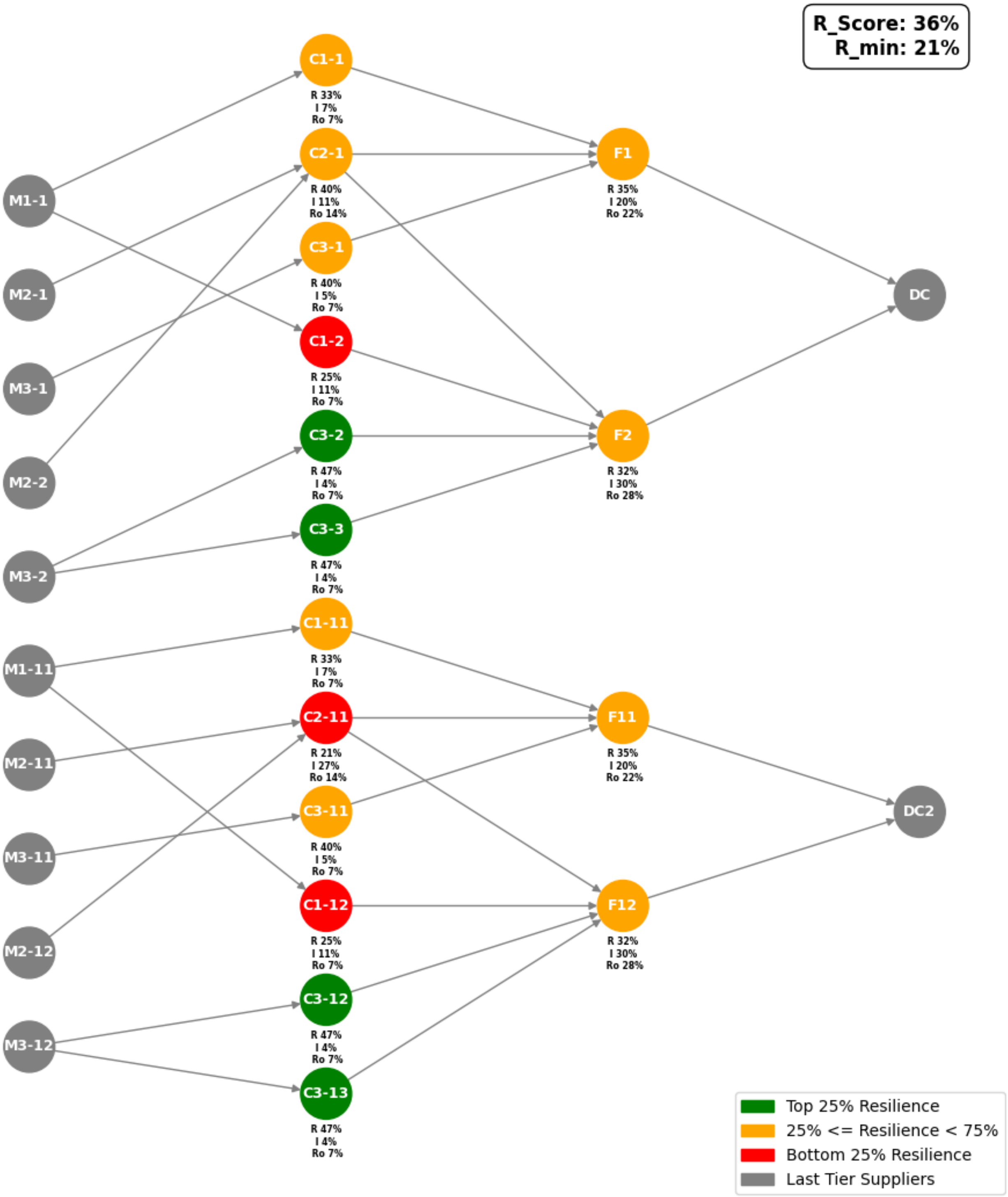
The Impact was calculated following Equation 3.5. For instance, we computed the impact of node F1 as follows. F1 has a revenue impact (RI_i) of 0.2, an out-degree centrality (D_{out_i}) of 0.037 and a production composition (C_i) of 1 (since it is the final product). Then we normalized it by Tier-1 using Equation 3.6, resulting in 0.20.

Likewise, the Robustness was computed using Equation 3.7. Similarly, we computed the Robustness of F1 as follows. F1 has cumulative degree centrality ($\sum_i D_{in}$) of 0.259, an HHI of 0.8. Then, we normalized it by tier using Equation 3.8, resulting in 0.22.

Based on our assumptions, we weighted the impact more heavily than robustness, resulting in an alpha value of 2, resulting in the graph in Figure 4.1.

Figure 4.1

Resilience Results - Initial Model



For better presentation, we assigned a specific color to each supplier based on their resilience level within the network. The top 25% of suppliers, considered most resilient, were assigned a green color, while the bottom 25%, considered least resilient, were colored red. The remaining suppliers in between were marked yellow. This color-coding system assists in visualizing the strongest and weakest areas within the network.

For the resilience score by node, we used Equation 3.9. Again, we computed the score of F1 as follows. F1 has an Impact of 0.2, a Robustness of 22, and, given the alpha of 2, the resilience score resulted in 0.35. Then to calculate the overall resilience score of the network, we used Equation 3.10. Assuming Tier-2 has a weight of 2 and Tier-2 has a weight of 1, we ended up with a resilience score of 0.36 of 36%. Finally, the minimum resilience resulted in 21%, meaning the network's lowest resilience is node C2-11, with a 21% of resilience score.

4.2. Strategy 1: Adding Flexibility

Our first strategy to enhance the network's resilience involved increasing its flexibility by adding more connections from Tier 1 suppliers to distribution centers (F11 to DC). As illustrated in Figure 4.2, this simple adjustment raised the network's resilience score from 36% to 39%.

Furthermore, Table 4.2 shows that this modification in Tier 1 indirectly benefited Tier 2 suppliers by decreasing their potential impact points. For instance, the resilience of node C1-2 improved from 25% to 37%, while that of C3-11 jumped from 21% to 34%. However, it's important to note that while additional flexibility generally enhances network resilience, it can also negatively affect certain nodes depending on where connections are added. For example, node F11 became a critical point upon its connection to node DC, bolstering the resilience of node C2-11, as it is the sole supplier for component 2 for F11. Furthermore, given that Tier 1 suppliers contribute more significantly to the network resilience score than Tier 2 suppliers, this weighted distribution helps clarify why the resilience score did not increase significantly. The introduction of the additional connection amplified the impact on F11 in Tier 1, and the overall effect on the resilience score was relatively restrained.

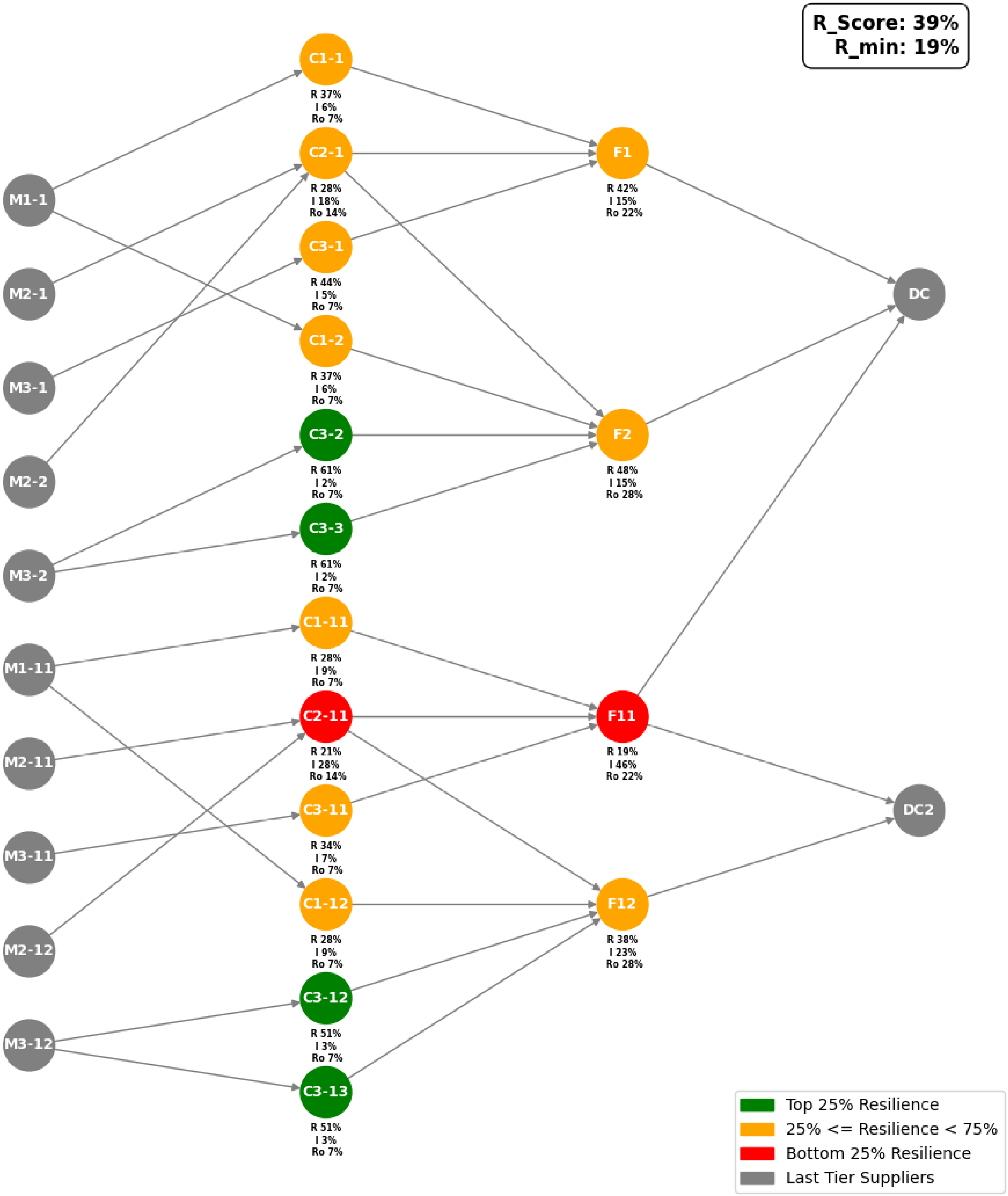
Table 4.2

Network Resilience Results After Flexibility

Node	Impact	Robustness	Resilience
F1	0.15	0.22	0.42
F2	0.15	0.28	0.48
F11	0.46	0.22	0.19
F12	0.23	0.28	0.38
C1-1	0.06	0.07	0.37
C2-1	0.18	0.14	0.28
C3-1	0.05	0.07	0.44
C1-2	0.06	0.07	0.37
C3-2	0.02	0.07	0.61
C3-3	0.02	0.07	0.61
C1-11	0.09	0.07	0.28
C2-11	0.28	0.14	0.21
C3-11	0.07	0.07	0.34
C1-12	0.09	0.07	0.28
C3-12	0.03	0.07	0.51
C3-13	0.03	0.07	0.51

Figure 4.2

Network Resilience Results After Flexibility



4.3. Strategy 2: Adding Redundancy

Our next approach for boosting network resilience involves adding more suppliers, thereby increasing redundancy. We theorize that new suppliers can reduce the impact of existing ones in the same tier while enhancing the robustness of those in the receiving tier. As illustrated in Figure 4.3, this strategy improved the network's resilience score from 36% to 39% and raised the lowest resilience from 21% to 22%.

Table 4.3

Network Resilience Results After Redundancy

Node	Impact	Robustness	Resilience
F1	0.14	0.16	0.35
F2	0.14	0.20	0.41
F13	0.29	0.28	0.33
F11	0.29	0.16	0.22
F12	0.14	0.20	0.41
C1-1	0.04	0.07	0.47
C2-1	0.23	0.14	0.24
C3-1	0.03	0.07	0.54
C1-2	0.12	0.07	0.23
C3-2	0.06	0.07	0.37
C3-3	0.06	0.07	0.37
C1-11	0.12	0.07	0.23
C2-11	0.23	0.14	0.24
C3-11	0.03	0.07	0.54
C1-12	0.04	0.07	0.47
C3-12	0.02	0.07	0.70
C3-13	0.02	0.07	0.70

Figure 4.3

Network Resilience Results After Redundancy

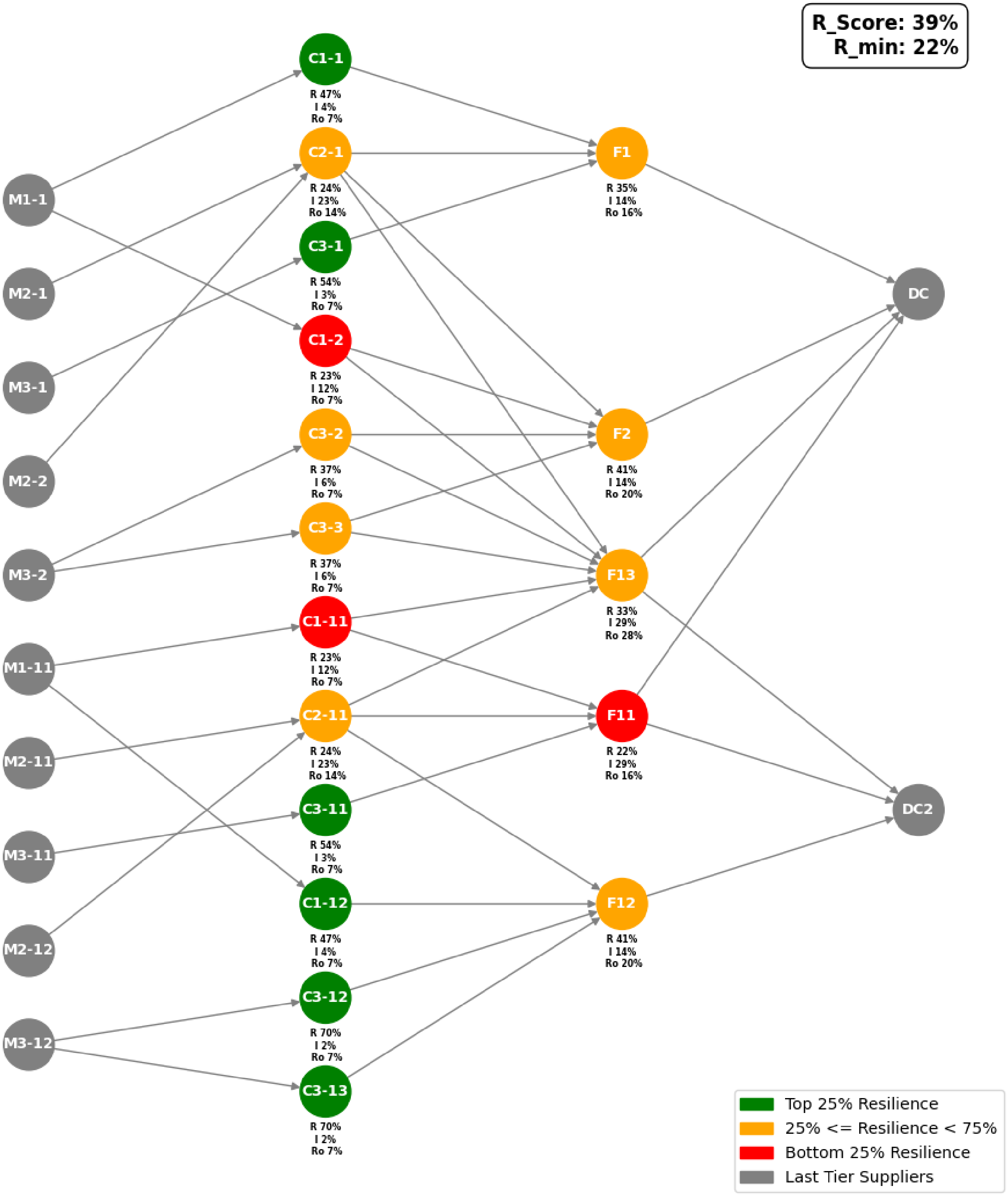


Table 4.3 indicates that adding a new node, F13 significantly decreases the impact on all other nodes in its tier. Although F13 and F11 have similar impacts, F13 shows a higher resilience score due to its broader connectivity with more nodes than F11.

While adding more suppliers can enhance the resilience of many nodes in the network, the overall effect on the final network resilience score is minimal, though it does provide some improvement. The network resilience score calculation takes a weighted average of all nodes' resilience. Therefore, an increase in suppliers tends to moderate the uplift in resilience.

4.4. Summary of Findings

This chapter employs Social Network Analysis (SNA) to measure the resilience of a synthetic upstream supply chain network, specifically for a single product with three components. Utilizing NetworkX, a Python library for SNA, the resilience for each supplier is calculated based on their impact and robustness within the network.

In the initial results, the resilience of each node was determined using Adjusted Impact and Adjusted Robustness equations. A color-coding system was introduced to identify the network's most and least resilient suppliers easily. The overall network resilience score was 36%, with the least resilient node, C2-11, scoring 21%.

Two strategies to enhance network resilience were explored: flexibility and redundancy. The first strategy involved adding more connections from Tier 1 suppliers to distribution centers, which increased the network's resilience score to 39%. However, the impact on the resilience score was relatively restrained due to the weighted contribution of Tier 1 suppliers.

The second strategy aimed at increasing redundancy by adding more suppliers to the network, again boosting the resilience score to 39% and raising the minimum resilience to 22%.

Introducing a new node, F13, decreased the impact on all other nodes within its tier and showed a higher resilience score due to its wider connectivity. However, while increasing redundancy generally enhances network resilience, the effect on the final network resilience score remained relatively modest.

5. CONCLUSION

This capstone project aimed to develop a theoretical framework as a proxy to quantify upstream supply chain resilience. To do this, we first reviewed the relevant literature on risk mitigation and resilience, then combined two approaches to building a novel framework. We used Social Network Analysis and Business Impact concepts to develop the Impact Robustness Resilience Framework (IRR). We took great care in defining it step by step, and then we created a synthetic network to test its effectiveness in capturing resilience within a network.

Throughout the project, the concepts of impact and robustness were used as proxies to quantify resilience. Under certain conditions, the combined use of these measures provided valuable insights into the criticality of specific nodes in a company's supply chain. By identifying these critical nodes, companies can strategically invest in increasing their flexibility and mitigating the impact of potential disruptions.

Additionally, it is essential to acknowledge that other models, as previously described, can also serve as proxies for measuring the resilience level of a supply chain. However, the complexity and availability of the required data will vary, depending on each organization's definition of resilience and its strategic approach to addressing it. Consequently, it is essential for businesses to carefully consider which model or combination of models is best suited to their operations and supply chain characteristics.

By selecting the most appropriate models, organizations can comprehensively understand their supply chain resilience, allowing them to identify vulnerabilities and implement targeted improvements. As resilience is critical to a company's overall supply chain strategy, adopting the most suitable models to measure and enhance it will ultimately contribute to its long-term success and sustainability in a dynamic and competitive global marketplace.

Based on certain assumptions, our study showed the usefulness of applying SNA as a proxy to capture the impact and robustness of the upstream supply chain and remarks on the importance of considering flexibility in designing resilient supply networks. Therefore, two strategies for enhancing network resilience were explored: adding flexibility via more connections and improving redundancy by introducing additional suppliers. Both strategies resulted in modest improvements in resilience scores. Yet, the effectiveness of these strategies can be influenced by the distribution of impacts and the network's structure. For instance, tier-based weight distribution in resilience calculations could offset the impact of increasing redundancy.

The complexity of measuring supply chain resilience is evident in these findings, underscoring the importance of a sophisticated understanding of network structures and inter-node interactions for successful resilience enhancement strategies. The analysis is based on assumptions discussed with practitioners and our sponsoring company, offering an approach that might provide valuable insights for decision-makers.

However, this study is a starting point, not a conclusion. The methods and strategies presented here are hypotheses that need testing and potential refinement. They could serve as a basis for mapping resilience networks and are subject to the dynamics of each company's supply chain and the accessibility of data for their suppliers. Consequently, the applicability of this model should be considered with caution, bearing in mind the specific circumstances of each supply chain under consideration.

5.1. Limitations

Several limitations of this capstone project should be recognized. Firstly, the time constraint posed a significant challenge, as quantifying resilience remains a relatively vague topic in academia and industry. If a company lacks a clear definition of its resilience strategy, it can be time-consuming to identify an approach relevant to its strategic objectives and practical regarding data availability and resource allocation.

Another limitation comes from the data itself. The sponsor company outsources all production, making obtaining data and achieving visibility across multiple supplier levels difficult. Furthermore, since the topic of resilience was relatively new to the company, they had yet to previously collect relevant data from past disruptions that could have been used to estimate the real effects in their network. This limitation influenced the decision not to consider more sophisticated approaches due to the unavailability of data, which could make the final model impractical.

The proposed framework did not include risk metrics for nodes, which could have accounted for external risk factors based on geographical location or other variables. By incorporating such information, the company might identify geographical risks within its supply chain and further enhance the robustness model.

While the current approach has innate limitations, future research and development could address these limitations by incorporating additional risk metrics and sophisticated formulation.

5.2. Future research

Future research can further enhance the proposed framework by considering the following points. Firstly, to enable companies to test the methodology in their supply network, the framework requires mapping the real supply chain as far as tiers as possible that they wish to assess, including data on suppliers' in and outflows, production capacities, and BOM. Secondly, the framework should incorporate additional factors such as labor and transportation and consider the probabilities of service levels by the suppliers by tier.

Furthermore, the framework could include more Social Network Analysis (SNA)-inspired indicators such as betweenness, page rank, and other relevant measures to capture the complexity of the network more accurately. Finally, to incorporate probabilities for disruptions, the model could adopt probability distributions or leverage tools such as Resilinc or others specifically designed for this purpose. By incorporating these enhancements, the framework can better assess supply chain resilience and support effective decision-making in practice.

REFERENCES

Chen, X., Xi, Z., & Pengyuan, J. (2017). A Unified Framework for Evaluating Supply Chain Reliability and Resilience. *IEEE TRANSACTIONS ON RELIABILITY, VOL. 66*, 1144-1156.

Choi, T. Y., & Krause, D. R. (2006). The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation. *Journal of Operations Management, 24*, 637-652.

Cohen, M., Cui, S., Doetsch, S., Ernst, R., Huchzermeier, A., Kouvelis, P., . . . Tsay, A. A. (2022). Bespoke supply-chain resilience: The gap between theory and practice. *Journal of Operations Management*, 515-531.

Craighead, C. W., Blackhurst, J., Rungtusanatham, M. J., & Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, 131-156.

Gartner. (2022). *Supply Chain Disruption - Build agility and resilience in the end-to-end supply chain*. Retrieved from https://www.gartner.com/en/supply-chain/insights/supply-chain-disruption

Golan, M. S., Jernegan, L. H., & Linkov, I. (2020). Trends and applications of resilience analytics in supply chain modeling: systematic literature review in the context of the COVID-19 pandemic. *Envorimental Systems Decisions 40*, 222-243.

Ho, W., Zheng, T., Yildiz, H., & Talluri, S. (2015). Supply chain risk management: a literature review. *International Journal of Production Research*, 5031-5069.

Ho, W., Zheng, T., Yildiz, H., & Talluri, S. (2015). Supply chain risk management: a literature review. *International Journal of Production Research 53:16*, 5031-5069.

K. Hendricks, V. S. (2005). An empirical analysis of the effect of supply chain disruptions on long run stock price performance and equity risk of the firm. *Production and Operations Management, 14*(1), 35-52.

Kazemian, I., Torabi, S. A., Zobel, C. W., Li, Y., & Baghersad, M. (2021). A multi-attribute supply chain network resilience assessment framework based on SNA-inspired indicators . *Operation Research 22*, 1853-1883.

Kim, Y., Choi, T. Y., Yan, T., & Dooley, K. (2011). Structural investigation of supply networks: A social network analysis approach. *Journal of Operations Management*, 194-211.

Kim, Y., Choi, T. Y., Yan, T., & Dooley, K. (n.d.). Structural investigation of supply networks: A social network analysis approach.

Lim-Camacho, L., Plagányi, É. E., Crimp, S., Hodgkinson, J. H., Hobday, A. J., Howden, S. M., & Loechel, B. (2017). Complex resource supply chains display higher resilience to simulated climate shocks. *Global Environmental Change 46*, 126-138.

Lund, S., Manyika, J., Woetzel, J., Barriball, E., Krishnan, M., Alicke, K., . . . Hutzler, K. (2020, August 6). *Risk, resilience, and rebalancing in global value chains*. Retrieved from Mckinsey: https://www.mckinsey.com/capabilities/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains

Maureen S. Golan, L. H. (2020). Trends and applications of resilience analytics in supply chain modeling: systematic literature review in the context of the COVID-19 pandemic. *Environment Systems and Decisions volume, 40*, 222-243.

Namdar, J., Pant, G., & Blackhurst, J. (2023). Impact of Industrial and Geographical Concentrations of Upstream Industries on Firm Performance during COVID-19. *SSRN*.

Nike. (2022). *Nike Manufacturing Map*. Retrieved from Nike Manufacturing Map: https://manufacturingmap.nikeinc.com/

Oke, A., & Gopalakrishnan, M. (2009). Managing disruptions in supply chains: A case study of a retail supply chain. *Int. J. Production Economics, 118*, 168-174.

Paul, S. K., Asian, S., Goh, M., & Torabi, S. A. (2019). Managing sudden transportation disruptions in supply chains under delivery delay and quantity loss. *Ann Oper Res, 273*, 783-814.

Rice, J. (2021, August 5). *The Seven Core Capacities of Supply Chain Resilience*. Retrieved from Supply Chain Management Review: https://www.scmr.com/article/the_seven_core_capacities_of_supply_chain_resilience

Rice, J. B. (2021, August 5). *The 7 Core Capacities of Supply Chain Resilience*. Retrieved from Medium: https://medium.com/mitsupplychain/the-7-core-capacities-of-supply-chain-resilience-dde24c96908b

Rice, J. B., & Caniato, F. (2003, October 1). Building a secure and resilient supply network. *Supply Chain Management Review*, pp. 22-30.

Rice, J. B., Klibi, J. W., & Trepte, K. (2022, November 01). *Overcoming the Financial Barriers to Building Resilient Supply Chains.* Retrieved from Harvard Business Review: https://hbr.org/2022/11/overcoming-the-financial-barriers-to-building-resilient-supply-chains

Rice, J., & Caniato, F. (2003, Sep). *Building a secure and resilient supply network.* Retrieved from Supply Chain Management Review; Framington Vol. 7, Iss. 5: 22-30.: https://www.proquest.com/docview/221137244?accountid=12492&forcedol=true

Sabouhi, F., Pishvaee, M. S., & Mohammad Saeed, J. (2018). Resilient supply chain design under operational and disruption risks considering quantity discount: A case study of pharmaceutical supply chain. *Computers & Industrial Engineering, 126*, 657-672.

Sanders, D., & Manfredo, M. (2002). The Role of Value-at-Risk in Purchasing: An Application to the Foodservice Industry. *Journal of Supply Chain Management, 38*, 38-45.

Sepúlveda Estay, D. A., & Khan, O. (2015). Extending supply chain risk and resilience frameworks to manage cyber risk. *22nd EurOMA Conference.* Neuchâtel: Technical University of Denmark.

Sheffi, Y. (2015). *The Power of Resilience: How the Best Companies Manage the Unexpected.* Cambridge: MIT Press.

Simchi-Levi, D., Schmidt, W., Wei, Y., Zhang, P. Y., Combs, K., Ge, Y., . . . Zhang, D. (2015). Identifying Risks and Mitigating Disruptions in the Automotive Supply Chain. *Interfaces, 45*(5), 375-390.

Sultan, T. (2022, 01 14). *5 ways the COVID-19 pandemic has changed the supply chain*. Retrieved from World Economic Forum: https://www.weforum.org/agenda/2022/01/5-ways-the-covid-19-pandemic-has-changed-the-supply-chain/

Susan Lund, K. G. (2020, November 16). *https://fortune.com/2020/11/16/supply-chain-shock-risk-resilience-covid-mckinsey/*. Retrieved from Fortune: https://fortune.com/2020/11/16/supply-chain-shock-risk-resilience-covid-mckinsey/

Svensson, G. (2000). A conceptual framework for the analysis of vulnerability in supply chains. *International Journal of Physical Distribution & Logistics Management, 30*, 731-749.