Strategic Approach for Assessing Supply Chain Resilience Investment Options

by

Rachael Grace Clark
Bachelor of Science in Finance and Supply Chain Management (Arizona State University)

and

Weiqian Pan
Bachelor of Arts in Economics and Statistics (University of California, Berkeley)

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Signature of Author: ______________________________
Department of Supply Chain Management
May 6, 2022

Signature of Author: ______________________________
Department of Supply Chain Management
May 6, 2022

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

Certified by: ______________________________
Kai Trepte
MIT Research Affiliate
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

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and
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ABSTRACT

In today's business world, supply chain resilience has been brought to the forefront of management topics due to the increasing number of both natural and manmade supply chain disruptions in the past decades. Without an effective method to identify the most impactful resilience actions to take and the amount of investment needed, companies face challenges in appropriately allocating resources to improve overall resilience of their supply chain networks. In collaboration with researchers from the MIT Center for Transportation and Logistics and with data from a sponsoring company, this project characterizes impactful resilience actions and necessary investments within a supply chain network to increase supply chain resilience for a firm. Furthermore, this project provides a roadmap assessing various disruption mitigation and resilience actions and provides a theoretical methodology to identify a firm's performance loss at risk as an indicator for the maximum amount of investment for a particular resilience action. This methodology serves to support supply chain managers in creating effective and actionable resilience strategies to prepare for and respond to unexpected disruptions and build sustainable operations.

Capstone Advisor: James B. Rice, Jr.
Title: Deputy Director, Center for Transportation and Logistics
Capstone Co-Advisor: Kai Trepte
Title: MIT Research Affiliate

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1. INTRODUCTION

Supply chain resilience has been a topic of interest to many researchers and industry professionals in the past decades because of various catastrophic events, such as the September 11 attack in 2001 and the Sendai earthquake in 2011 (Rice, 2011). Supply chain resilience can be defined as “the ability to bounce back from a disruption” (Sheffi & Rice, 2005). Many companies, such as Cisco and Ford Motor, have established Business Continuity Plans (BCP) and resilience strategies in their supply chain networks, which help the companies respond and recover from the disruptions faster than their competitors (Harrington & O'Connor, 2009). Most recently, this topic has been brought to the forefront of supply chain management concerns due to multi-faceted disruptions caused by the Covid-19 pandemic. As a result, having an effective and actionable supply chain strategy for companies to prepare for and respond to unexpected disruptions is crucial to building a sustainable and resilient supply chain.

1.1 Problem Statement

Despite efforts of large corporations to create a resilient supply chain over the last decades, there is no universally accepted method to identify the most appropriate resilience actions or measure the value of investments in resilience for a company within its supply chain networks. As a result of these limitations, it is unclear to the industry what specific resilience action to take, or the amount of upfront investment needed to build resilience. Resilience actions, as Rice and Caniato defined, are key actions that firms can take to enhance the resilience level of their supply chain (2003). It is especially difficult to communicate to stakeholders, given that investments in resilience do not have a defined positive impact on future cash flows like other capital investment options. In fact, a best case outcome of a resilience investment, in many cases, is simply business continuity; therefore, practitioners often do not get credit for preventing issues that may not ever happen (Rice & Caniato, 2003). While it may be commonplace for companies to identify risks and weaknesses in their supply chain and come up with plans to combat these risks, identifying action plans against every possible risk would prove difficult or impossible. Thus, risk management is fundamentally different from having resilience in one's supply chain. The ability to respond to disruption with specific resilience actions and procedures is essential for sustainable operations in the long run.

1.2 Motivation

The purpose of this project is to close the gap between the research that has created methodologies to understand the impact of disruption by mapping vulnerabilities in a supply chain (Simchi-Levi, et al.) and the lack of a standard methodology to determine and quantify the value of a particular resilience action could generate for a firm. This research project partnered with current researchers at MIT Center for Transportation and Logistics (CTL) to develop a framework for and craft initial steps of a model that visualizes the most impactful resilience actions on a resilience input variable of a supply chain node. This study was supported with data from a multinational pharmaceuticals and consumer packaged goods corporation ("ABC Corporation"). This research also aims to identify the maximum reasonable resilience investment amount needed to build a particular degree of resilience into the company's supply chain. This process includes collecting data around the performance impact of disruption for all nodes of a particular supply chain, understanding which elements of a supply chain are most benefited by an investment in increasing resilience, characterizing the types of resilience investments that could address these elements, understanding how disruptions impact loss of capacities within a supply chain, and understanding the impact to a range of possible outcomes with and without resilience investments to help determine investment levels.

2. LITERATURE REVIEW

Supply chain resilience has been a topic of interest to both industry professionals and academic researchers as a result of various disruptive events. From 1900 to early 2000, the world had experienced an exponential growth in the number of natural disasters with flooding being the most common natural disaster since 1990 (Institute for Economics & Peace, 2020). In recent years, 94% of Fortune 1000 companies cited seeing supply chain disruptions in their business due to the Covid-19 pandemic, with 75% of firms citing "negative or strongly native impacts on their business." (Accenture, n.d.). Evidence suggests that not only are disruptions becoming more common, but disruptions are also increasingly impacting the performance of large firms with global, cost-conscious supply chains (Simchi-Levi, et al, 2015). According to McKinsey & Company, companies can expect a disruption to impact their supply chain for four weeks or longer every 3.7 years (Risk, resilience, and rebalancing in global value chains, 2020). Research has shown that having an active disaster protocol has allowed companies to become more responsive and recover quicker compared to their competitors when dealing with supply chain disruptions (Greimel, 2012). Some disruptions are common and, in many cases, can be preemptively addressed through 'traditional' risk-mitigation exercises. However, other disruptions are infrequent and have the propensity to be highly impactful (Simchi-Levi, et al. 2014). The rare nature of these disruptions makes proactive investments in mitigation strategies more difficult. In addition, the data collection process on the impact of rare, impactful disruptions could be incomplete for two reasons. According to Macdonald et al. (2018), researchers can collect data only about disruptive events that happened in the past but have limited insight into future occurrence, and the data collection process itself may be incomplete due to confounding factors. Therefore, building methodologies to identify key elements that would yield the highest resilience level and the return on investment has been challenging. The purpose of this capstone project is to examine the existing research that identifies supply chain resilience vulnerabilities and expand on these methodologies to develop a framework for assessing and quantifying the value of specific resilience decisions in a supply chain network. This chapter will first define resilience and identify the reasons for the gaps in existing research. Second, it will discuss some of the factors that influence the level of supply chain resilience. Finally, it will discuss current quantitative methods of understanding disruption impact, and explore potential technical models that could be utilized to quantify investments necessary to mitigate disruption impacts in this capstone project.

2.1 - Defining Supply Chain Resilience Versus Risk

This review defines supply chain resilience as the "ability to bounce back from a disruption" (Sheffi & Rice, 2005). This generally includes the ability to prepare, respond and recover from a supply chain network. This definition on resilience was the earliest accurate definition we could find that is relevant to supply chain management and distinguishes the topic of resilience from risk management. The ideas of supply chain resilience and supply chain risk management are frequently used interchangeably, as they both involve identifying and eliminating the source of interruptions to maximum profit. However, resilience and risk management are different concepts as there could be thousands of risks in any given supply chain. Due to the large number, it is impossible to eliminate all risk factors. Therefore, companies tend to manage the most critical risks. In contrast, supply chain resilience focuses on building the capability to respond and recover from any disruptions regardless of the level of impact and the likelihood of occurrence (Rice, 2021a).

Despite the importance of building resilience into a supply chain, companies tend to focus more on risk management for two reasons. First, the value and importance of resilience is difficult to justify if disruptions happen infrequently. Second, universal and standardized methods to assess resilience investment types and quantify the investment needed to increase a particular level of resilience within a supply chain do not currently exist. In other words, a business case cannot be justified if we cannot illustrate the return on resilience investment. If this is the case, the firms may take actions based more on their historical experiences on disastrous events instead of fact-based decisions that derived from resilience assessment tools (Rice & Caniato, 2003). This could lead to misdirected company resources.

2.2 - Current Methodologies and Research Gaps

Since the probability of a major supply chain disruption is very low and difficult to characterize, many researchers have shifted from the approach of identifying the causes and probability of every supply chain disruption to a more consequence-driven methodology. Simchi-Levi et al. (2014) “quantifi[ed] the disruption exposure across all the nodes in the company's supply chain based on company-level performance impacts, [and]... identifi[ed] the specific nodes in a firm's operations and supply chain that would, if disrupted, result in the greatest damage to firm performance,” as an indicator to prioritize resilience actions.

Other methods proposed by researchers and industry experts are integrating resilience investment conversations into regular S&OP/IBP meetings (Trepte & Rice, 2018) or creating various resilience assessment tools to quantify the resilience level of a firm’s supply chain network. Pettit et al. (2010) developed the Supply Chain Resilience Framework that provided insight into a company’s strengths, weaknesses, and priorities in terms of strategies needed to improve its resilience. The researchers later created “a survey-based assessment tool – the Supply Chain

Resilience Assessment and Management (SCRAM)" – to further measure each vulnerability factor and subfactor identified by the assessment (Pettit et al. 2013). In addition to researchers in academia, companies have created their own resilience assessment tool that fits their specific needs. Cisco's Supply Chain Risk Management (SCRM) team created a supply chain risk assessment as part of their Business Continuity Plan (BCP). This assessment allowed Cisco to incorporate supply chain resilience measure into their supply chain network and eventually helped them to recover faster from the disastrous earthquake occured in China in 2008 compared to their competitors (Harrington & O'Connor, 2009).

Despite the effort to create new approaches to measure and improve resilience within an organization, there remains a gap in research providing a methodology to assess specific actions to take to improve resilience, and quantifying the necessary investments.

2.3 – Supply Chain Failure Modes

Identifying the types of failures a disruption can have on a supply chain is essential to determining and analyzing the key attributes associated with supply chain resilience. This impact of disruption, referred to as a failure mode, is a, "loss of the key functions and capabilities of the supply chain, loss of any such would reduce or remove the ability of the system to perform its mission [for an extended amount of time]" (Berle et al., 2011). According to Rice (2021b), these 'failure modes' can be characterized in seven ways, and they all lead to one shared outcome – loss of capacity.

Failure modes:

1. Loss of production material
2. Loss of transportation
3. Loss of communication

4. Loss of manufacturing capacity
5. Loss of personnel
6. Loss of financial resources
7. Loss of distribution to end customers

Understanding the ways the supply chain network could fail allows researchers to shift focus away from identifying mitigation strategies for a particular type of disruption to focusing on resilience actions that address one of seven specific losses of capacity.

2.4 – Key Resilience Metrics

To measure the resilience level of a supply chain network, Time-to-Recover (TTR) and Time-to-Survive (TTS) are two universally accepted metrics both in business and academia. The idea of TTR was first developed by Cisco Systems, Inc. as a key element in measuring the resilience in the company's BCP program assessment (Harrington & O'Connor, 2009). TTR measures the amount of time that the supply chain needs to restore its functionality to its pre-disruption level (Miklovic & Witty, 2010). In contrast, TTS measures the amount of time that the supply chain can continue to operate without an impact to the firm's performance metrics when affected by an unexpected disruption (Simchi-Levi, 2015). Companies could use both metrics, TTR and TTS, to determine the resilience level of a specific node.

For any of the seven types of lost capacity, if the time-to-recover (TTR) is shorter than time-to-survive (TTS), a firm will not experience performance interruptions because the supply chain will recover to its prior output level before a shortage occurs and performance is impacted. On the other hand, if the TTR is longer than TTS, the supply chain will experience a gap in product supply continuity; therefore, a performance gap will be created (Simchi-Levi, 2015).

With the identification of the types of supply chain disruptions and possible resilience measuring methods, researchers in various fields have conducted research to explore the key attributes of supply chain resilience. Macdonald et al. (2018) examined three major components that could impact the level of resilience in the global supply chain: characteristics of a disruption, the ecosystem, and upfront investments (2018). The interarrival time between disruptions is positively correlated to the gap between TTS and TTR. In other words, the longer the interarrival time between disruptions, the longer it takes for the supply chain to recover (Macdonald et al. 2018). However, interarrival time between disruptions is not the sole factor to consider when building resilience, the ecosystem a network operates in can either inherently reduce or exacerbate the impact of a disruption on a firm’s operation. Finally, the specific resilient investments made by firms themselves have an impact on the firm's overall ability to recover from disruptions (Macdonald et al., 2018). However, there is no standard method to value resilience investments needed to build a given level of resiliency.

2.5 – Quantifying Resilience Investments

In “Quantifying the Resilience of Community Structure in Network,” Ramirez-Marquez et al. (2018) advance research on resilience investments around the impact of disruptions and proposes a method to “quantify resilience and identify community structures in networks.” The researchers identify moments in time of a disruption, and name specific states of recovery for a network. In doing so, the researchers create measurable parameters to assess a network's ability to prepare, respond and recover when facing unexpected disruptions as previously defined. Drawing upon previous research on identifying vulnerabilities in networks (Rocco S. & Ramirez-Marquez, 2012), the researchers advance the methods in valuing the magnitude of impact of a disruption in the “time to complete restoration of the network”, or TTCR.

While research by Ramirez-Marquez et al. (2018) advances research on methods for quantifying the impact of disruptions themselves, our research project highlights gaps in literature that remain in assessing the value of particular resilience investments in a supply chain node. Drawing upon the Black-Scholes options pricing method established in 1973, current methods such as those used by Vinay Datar and Scott Mathews offer potential insights as to how researchers might consider the value of highly uncertain project investments (Datar & Mathews 2004). They investigate the underlying assumptions of options pricing in capital investments when facing uncertainty and provide a valuation technique familiar to investment decision-makers. Given the uncertain nature of disruption events, there is evidence to suggest such an approach may be appropriate for valuing resilience investments in a supply chain network. This 'real options approach' has gained momentum in firms such as Boeing. It provided the framework for an adjusted net present value (NPV) analysis that allows for uncertain projects to be considered by management that otherwise would likely be rejected using a traditional NPV approach. The method used dynamic discount rates and provided underlying intuition of options valuation for project evaluations (Mathews et al., 2007). Such an approach has also been proposed in the realm of integrating flexibility of engineering systems, and has been identified to provide an easily understood method for incorporating uncertainty into investment decision-making. (de Neufville et al., 2006). Current research on the topic of a real options approach to valuation of uncertain projects seems promising, and will be further explored for its potential to quantify resilience investments in this capstone project.

2.6 – Resilience Investment Options

Several common investment options are either empirically tested or universally accepted by the industries to address vulnerabilities when facing disruptions and increase the resilience level within a firm, which we call resilience options.

MacDonald et al. (2018) revealed that as companies hold more inventory, the severity of the disruption decreases. As a result, the supply chain would remain functional for a longer period of time after the disruption and thus, increase the overall resilience level of the supply chain network. The inventory mentioned in this context is referred to as risk mitigation inventory (RMI) when facing supply chain disruptions. It is different from operational safety stock that deals with periodic fluctuations of customer demand (Lucker et al., 2018). Lucker showed that when RMI holding cost is not too high, a mixed strategy, holding more inventory and having reserve capacity, would increase the supply chain's capability to cope with disruptions. However, when inventory holding cost is high, as seen in the automotive industry, having reserve capacity – free capacity that can be used when facing supply chain disruptions – is more favorable than a sole inventory holding strategy. Nonetheless, investing in either option would have a positive impact on TTS and thus, the overall resilience level of a firm.

In addition to increasing inventory and reserve capacity, establishing dual sourcing and supplier strategy will increase the resilience level within a company's supply chain network with a reasonable premium cost both in the commercial supply chains (Wang et al., 2019) and humanitarian supply chains (Iakovou et al., 2014). Iakovou et al. (2014) observed that with the dual supplier strategy, organizations could clear backorders considerably faster than having a single supplier when facing significant supply chain disruptions. In other words, TTR would decrease with a dual sourcing/supplier strategy.

Another finding made by MacDonald et al. (2018) is that when the nodes in a supply chain network are highly connected, the network would be more vulnerable to disruptions. The reason is that the impact of the shock would transmit through the supply chain network at a higher degree and result in a longer recovery time. Therefore, companies not only should implement dual supplier strategies, the suppliers should be heterogeneous and should not be localized within the same region that could be exposed to the same disruptions. In this case, even if one supplier is impacted by the disruption, the other one would still be able to function independently.

In the book, *The New (Ab)Normal,* Yossi Sheffi asserts that a firm's reaction time to disruption can be reduced through an "amount of forewarning." This suggests that, while transparency alone may not be sufficient in making a supply chain resilient, improving the visibility of a network allows for mitigation actions to be executed sooner, thus improving a firm's TTR. One way to increase visibility of a network is to promote collaboration between the nodes in the supply chain so information and knowledge could be shared in a timely manner. Scholten and Schilder (2015) supported the idea of improving supply chain resilience through increasing visibility. They found in their study that collaboration between mutually dependent organizations within a supply chain network leads to higher degree of information sharing which indirectly increases the overall supply chain resilience of the network.

In addition, investing in supply chain digital technology would increase demand responsiveness and capacity flexibility, which could improve both TTR and TTS of the supply chain network (Ivanov et al., 2019). Ivanov et al. (2019) identified several methods that digital technology could improve the resilience of a supply chain. For example, additive manufacturing could reduce the structural complexity of a supply chain and therefore shorten the overall lead times for production and empower greater efficiency in the inventory control process. To improve

TTS, investing in a smart manufacturing network that utilizes more adaptive and reconfiguative autonomous machineries would increase supply chain resilience by having the ability to continue supply chain operations when facing disruptions.

In addition to improving TTR and TTS of the supply chain, companies could protect their revenue by leveraging dynamic pricing and offering promotions to substitute products to satisfy customer demand during disruptions (Tang, 2019). Although reducing revenue loss is not directly related to increasing supply chain resilience, it is still crucial for businesses to have a strategy in place that would mitigate the sales exposure when facing supply chain disruptions.

2.7 – Conclusion

Supply chain resilience has been a topic of interest for researchers and practitioners for decades. While the need for firms to respond quickly to unexpected events is clear, assessing resilience investment options and valuing these investments remains a current gap in research and is the topic of this capstone research. Exploring three elements of resilience — disruption characteristics, the supply chain ecosystem, and resilience investments (Macdonald et al., 2018) — helps identify the key factors that impact resilience, and thus provides the foundation for quantifying the investment needed to build a more resilient supply chain.

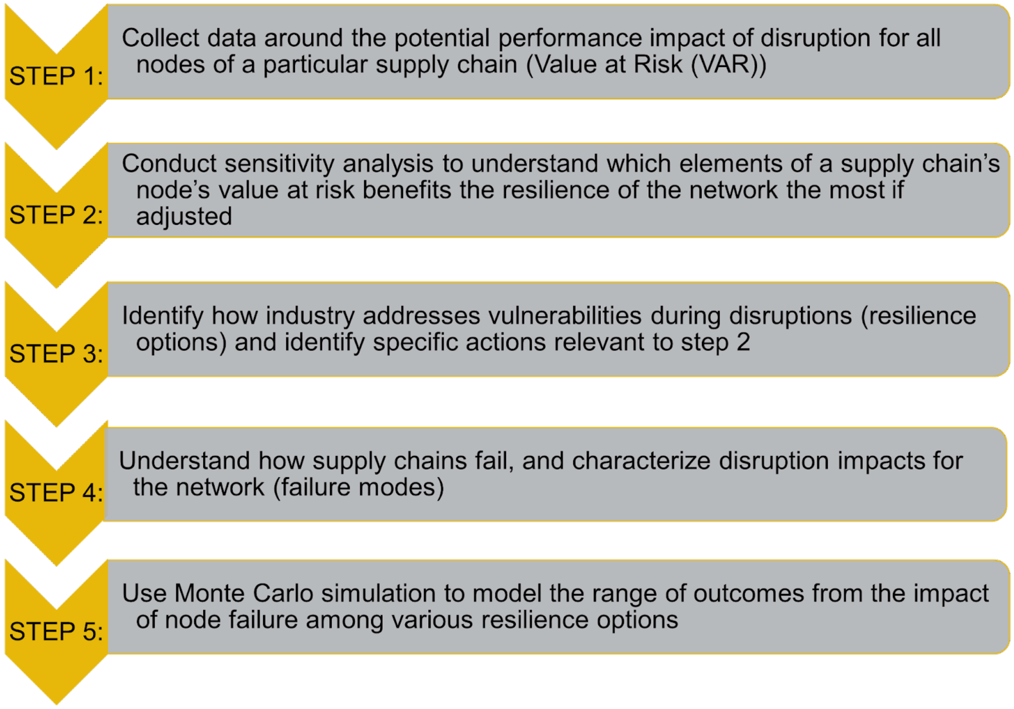
Research has made progress on creating methods around defining clear characteristics of resilience and subsequently identifying methods for quantifying the impact of disruptions themselves, but a gap still exists in defining the value of resilience investments. Given that investments in resilience do not have defined positive impacts on future cash flows like other capital investment options, utilizing traditional valuation techniques is a challenge. As a result, this capstone will explore identifying elements of a supply chain most sensitive to improving overall resilience, mapping possible resilience investment options to address these elements, and providing a framework for a ‘real options’ approach to value these highly uncertain investments.

3. DATA AND METHODOLOGY

This chapter provides an in-depth explanation of the datasets used, the methods considered, and the models used to perform analysis advancing the topic of valuing supply chain resilience investments. In order to begin to develop a framework to quantify the investment needed to achieve a particular level of resilience into a company’s supply chain, the research team identified the key research steps shown in Figure 1.

Figure 1

Methodology of the Research Team



STEP 1: Collect data around the potential performance impact of disruption for all nodes of a particular supply chain (Value at Risk (VAR))

STEP 2: Conduct sensitivity analysis to understand which elements of a supply chain’s node’s value at risk benefits the resilience of the network the most if adjusted

STEP 3: Identify how industry addresses vulnerabilities during disruptions (resilience options) and identify specific actions relevant to step 2

STEP 4: Understand how supply chains fail, and characterize disruption impacts for the network (failure modes)

STEP 5: Use Monte Carlo simulation to model the range of outcomes from the impact of node failure among various resilience options

The methodology in this chapter follows these identified research steps. While the scope of this research project will largely focus on steps one through three in the methodology above, we briefly explain a theoretical model for steps four and five to be empirically realized in further engagements with the research team's sponsor firm.

3.1 Collected Data and Definition of Variables

To quantify the upfront investment needed to build resilience into a company's supply chain, the data from ABC company provided pre-calculated data for all supply chain nodes of a particular product line. This data has been developed internally over the past two years following a similar methodology to that utilized by Simchi-Levi, et al. (2014), including the concepts of Time-to-Recover (TTR) and Time-to-Survive (TTS). The research team has provided us with an assessment of vulnerabilities in the company's supply chain of a particular product line. The developed metrics allowed us to begin to include financial lost value to the firm, first as a 'worst case' for node disruption across a product line. The below definitions describe variables considered in the firm's risk and resilience analysis of a particular product line.

3.1.1 Time-to-Recover (TTR) - TTR refers to the total amount of time for a node in the company's supply chain network to restore its full functionality after a disruption. An example of an action that a firm might take to improve the TTR is transitioning all node capabilities to a backup supplier.

3.1.2 Time-to-Survive (TTS) - TTS represents the maximum amount of time a node in the company's supply chain network can continue its full functionality after a disruption. An example of improving the TTS for a given node is increasing inventory levels to continue to meet customer demand when impacted by a disruption.

3.1.3 TTR-TTS Gap - TTR-TTS Gap refers to the difference between TTR and TTS of a node in the firm's supply chain network. If the TTR-TTS Gap is positive, the node will be impacted by the disruption and functionality or firm performance will suffer for a period of time. On the other hand, if the TTR-TTS Gap is negative or zero, a disruption will not generate a performance impact for the node.

3.1.4 Revenue impact - This represents the maximum potential loss of sales of a particular product line that a node could impact if disrupted.

3.1.5 Value at Risk (VAR) – As shown in Formula 1 below, VAR demonstrates the total revenue impact for a node, divided by 365 to get an estimated daily sales impact, and multiplied by the duration specified by the TTR-TTS Gap. Thus, VAR in this case, can be interpreted as a worst case scenario of total facility maximum performance disruption for that node.

Formula 1

Value at Risk (VAR) Calculation

$$\text{VAR} = \frac{\text{Revenue Impact}}{365} \times (\text{TTR} - \text{TTS Gap})$$

3.1.6 Environmental Factors (EF) - EF is a relative risk score of an external environment a node operates in. This score can be determined by a third-party risk analysis index such as the risk assessment categories used by British Standards Institution (BSI). The EF score is a measurement of external risk, and represents a maximum relative risk ranking from 0 to 1 of all risk categories presented in a particular node of a particular supply chain. Risk could include categories such as: geopolitics, economics, environmental, physical security, social accessibility, supplier, transparency, ethical, etc. (British Standards Institution, 2021a; British Standards Institution, 2021b).

Possible resilience actions that could change this EF by node could include site relocation or re-design of the supply chain network. Since such actions are more costly, taking the maximum risk value of all the risk categories allows us to calculate the plausible worst case losses of a node.

3.1.7 Plausible Worst Case (PlWC) - PlWC represents the potential financial loss of a node impacted by a disruption. This metric was developed by Mr. Kai Trepte, Prof. Walid Klibi, and Mr. James Rice, researchers associated with the MIT Center for Transportation and Logistics (CTL) as a part of ongoing research. This is calculated by taking the VAR times the EF and represents the VAR maximum performance loss 'tapered' to the relative risk measure of EF as shown in Formula 2. This gives a more realistic measure of a worst case scenario, weighted by an external risk weighting.

Formula 2

Plausible Worse Case (PlWC) Calculation

$$\text{PlWC} = \frac{\text{Revenue Impact}}{365} \times (\text{TTR} - \text{TTS Gap}) \times \text{EF}$$

3.1.8 Central Tendency – As shown in Formula 3 below, Central Tendency is the sales weighted average of PlWC outcomes for each node. This metric was also developed by Mr. Kai Trepte, Prof. Walid Klibi, and Mr. James Rice, researchers associate with the MIT Center for Transportation and Logistics (CTL) as a part of ongoing research.

Formula 3

Central Tendency Calculation

$$\text{Central Tendency} = \frac{\text{Sum Product of Revenue Impact by Node} \times \text{PlWC}}{\Sigma\ \text{Revenue Impact of All Nodes}}$$

3.2 Sensitivity Analysis

Aligning with the methodology identified in Figure 1, the research team first needed to identify which elements of a supply chain's nodes' resilience measures would benefit the overall resilience of a supply chain the most if adjusted. This was recognized as a key step in order to understand what types of investments a firm should focus on to most quickly improve resilience of a supply chain. The research team conducted a sensitivity analysis on the different input variables by supply chain node for a particular product's supply chain. By looking at the contribution margin of each variable to the network's measure of central tendency, our analysis highlights which elements of a supply chain's node's value at risk improves the resilience of the network the most if adjusted.

A sensitivity analysis was conducted on the input variables of TTR, TTS, Sales Impacted, and EF for the Plausible Worst Case scenarios for all nodes of a supply chain at ABC firm. For our analysis, we took the supply chain network of six different products. These supply chains ranged from having 17 to 63 different nodes in the network. Given that each node had four different input variables: TTR, TTS, EF, and Revenue Impact, we altered each input variable until that node's PlWC output equaled zero (where the DailyRevenue x (TTR-TTS) x EF = 0 and the node was hence considered 'resilient'). We captured the necessary unit change in each input independently needed to achieve this resilience output for its corresponding node, then noted the resulting change in the network's central tendency.

Finally, after repeating this process for all nodes of each of the six products independently, we developed a ratio, which we call the 'resilience impact ratio', for all node inputs of the unit change in input over the resulting unit change in Central Tendency. This is represented by Formula 4 below:

Formula 4

Resilience Impact Ratio Calculation

$$\text{Resilience Impact Ratio} = \frac{\%\Delta \text{ in Central Tendency}}{\%\Delta \text{ in Node Input}}, \ \text{ where Node Revenue} \times (\text{TTR} - \text{TTS}) \times \text{EF} = 0$$

This analysis highlights which inputs, if adjusted through a resilience investment on a per percent change basis, would impact that supply chain's measure of central tendency on a percent change basis the most.

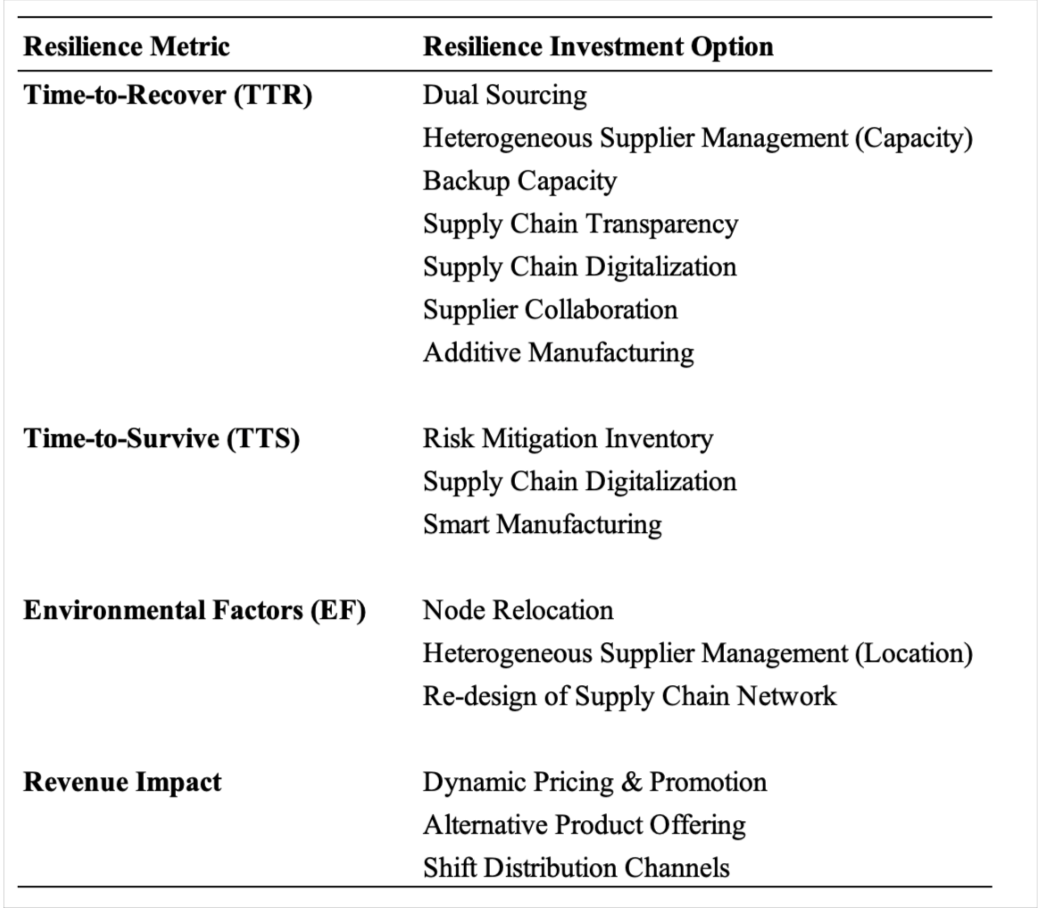
3.3 Recommendation of Potential Options for Resilience Investment Modeling

After identifying inputs that generate the largest impact to resilience central tendency improvement per percentage modified, we illustrate how the industry addresses vulnerabilities during disruptions, which we call resilience options. Then, we tie these resilience options to specific resilience metrics and summarize these options in Figure 2.

Figure 2. identifies key resilience metrics that are being used to calculate the resilience level of a company’s supply chain network in this capstone project. For each metric, a list of possible resilience investment options has been generated based on the literature review on existing resilience actions in Section 2.6. A company may choose one or more actions to improve the corresponding resilience metric as they deem appropriate and thus, increase the overall resilience level in a supply chain network. This chart does not aim to provide an exhaustive list of all possible resilience actions a firm can take, but instead serves as context for our research methodology.

Figure 2

Resilience Investment Options to Improve Particular Resilience Metrics



Resilience Metric	**Resilience Investment Option**
Time-to-Recover (TTR)	Dual Sourcing
	Heterogeneous Supplier Management (Capacity)
	Backup Capacity
	Supply Chain Transparency
	Supply Chain Digitalization
	Supplier Collaboration
	Additive Manufacturing
Time-to-Survive (TTS)	Risk Mitigation Inventory
	Supply Chain Digitalization
	Smart Manufacturing
Environmental Factors (EF)	Node Relocation
	Heterogeneous Supplier Management (Location)
	Re-design of Supply Chain Network
Revenue Impact	Dynamic Pricing & Promotion
	Alternative Product Offering
	Shift Distribution Channels

Based on this understanding of resilience options to address supply chain vulnerability during disruption and our findings of dominating inputs to changes in a supply chain's resilience central tendency, we recommend specific action types relevant to our findings.

3.4 Theoretical Framework for Monte Carlo Simulation

After defining resilience options relevant to impactful inputs of a supply chain for investment consideration, we propose a theoretical model for tying these findings to resilience impact from monetary investment. We outline this framework for the research team to consider in their continuing research with the sponsor firm.

The team used the 'real options' methodology, as defined by Datar-Mathews (2004) and demonstrated by de Neufville (2006), to simulate the theoretical impact of a disruption with or without a resilience ‘option’ measured by impact to a firm’s financial flows associated with the time-to-recover (TTR), time-to-survive (TTS) and resulting Plausible Worst Case (PlWC) of a particular supply chain. Comparing simulated means of PlWC scenarios for all nodes associated with failure mode distributions (base case), and these scenarios with a resilience investment option (alternative case) gives way to understanding an upper bound for the potential investment amount for that option. To demonstrate this framework before the research team implements this methodology with the sponsor company, we propose first understanding a distribution to apply to the current Plausible Worst Case data points for Monte Carlo simulation.

3.4.1 Failure Mode Distributions

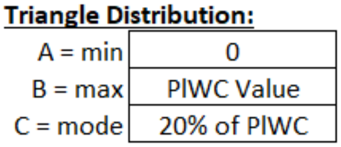
To generate possible distributions of performance impact up to Plausible Worst Case scenarios for each node, we must understand how these nodes are likely to fail, and characterize the distribution of disruption impacts for all nodes in the network.

Given the unlikely nature of a Plausible Worst Case loss of capacity occurring at every node currently used in the calculation, we postulate that this is an unrealistic upper bound to illustrate the impact of disruption events for the purpose of making capital investments. Thus, by relying solely on the value at risk associated with PlWC scenarios, over-investments in resilience actions could occur. To generate a realistic view of the financial impact of disruption on a supply chain, next steps for the research team will include understanding the distribution for loss of capacity for each node when faced with disruption as described in Section 2.2. While a precise methodology to determine these distributions is still under development with ongoing work by MIT CTL research affiliates, we anticipate this team utilizing various proxies for each loss of capacity frequency and characterizing each node to a specific loss of capacity. Monte Carlo simulation of these specific distributions to each node can then be used to capture a realistic range of future possibilities of value the supply chain stands to lose from losses of capacity by node should it incur a disruption.

For the purpose of our theoretical model, we assume all PlWC values loss of capacity distributions for all nodes will follow a single triangle distribution with the parameters shown in Figure 3 below:

Figure 3

Example distribution used for theoretical model



Triangle Distribution:

A = min	0
B = max	PlWC Value
C = mode	20% of PlWC

The distribution in Figure 3 states that in a best-case scenario, a supply chain will face no value at risk. Most frequently, a supply chain sees a performance impact of 20% of the current Plausible Worst Case scenario by node, and in the worst case, the supply chain faces the actual Plausible Worst Case (PlWC) scenario. Using 20% of the PlWC scenario for each node as the mode is arbitrary, but skews the results towards the occurrence of a PlWC scenario being unlikely.

3.4.2 Conducting A Monte Carlo Simulation and Comparing Investment Options

After understanding which elements of a supply chain are most benefited by an investment in increasing resilience, characterizing the types of resilience investments that could address these elements, and determining distribution(s) for node failure modes, we aim to understand the range of possible performance impact outcomes both with and without resilience investments.

In comparing the means of these performance outcomes, we provide a framework to determine a maximum monetary investment for a particular resilience option. To do this, our methodology calls for Monte Carlo simulation.

For the purpose of illustrating the comparison, we used the simple triangle distribution mentioned in Figure 3 for all nodes to represent failure mode distributions of each node. We simulated each node 2000 times and created a resulting single distribution of all PlWC iterations of all nodes.

After iterating a range of possible future outcomes given the distributions of lost capacity by node, we then duplicate this simulation on one of the resilience metrics assuming by implementing one of the resilience investment options in Figure 2, it would improve the performance of the corresponding resilience metric. In our theoretical illustration, we look at Product A for ABC company and identify an input with the highest resilience impact ratio - TTR for node 1. We assume an investment can be made to make this node resilient, by finding a backup supplier that reduces the TTR from 540 days to 132 days. This reduces the PlWC of this node to zero. After simulating the same distribution of the updated PlWC values of all nodes, we then compare the means of the distribution without the option and with the option. If the option simulated distribution mean is less than the simulated node's PlWC distributions without a resilience option, then the difference suggests a maximum amount the firm may be willing to invest in that resilience option.

4. RESULTS AND DISCUSSION

This chapter presents and discusses the implications of executing the above methodology and the implications to valuing supply chain resilience investments through characterizing impactful node types to overall resilience, defining particular resilience actions to take to address vulnerabilities, and proposing next steps for researchers to determine particular investment levels based on a theoretical example.

4.1 Sensitivity Analysis Results

The results of the sensitivity analysis highlight the ranking of inputs that, if adjusted through a resilience investment on a per percentage change basis, would impact that supply chain's measure of central tendency on a per percentage change basis. This analysis found that in all six product supply chains, inputs of TTR dominated by percent change in input to percent benefit to central tendency, followed by EF, then either TTS or Sales Impact. Figure 4 and Figure 5 demonstrate the distribution of all nodes' resilience impact ratios by these four inputs for products A and B. Key findings of these rankings are illustrated by input type in the sections below.

Figure 4

Resilience Impact Ratios for a Supply Chain Network of Product A

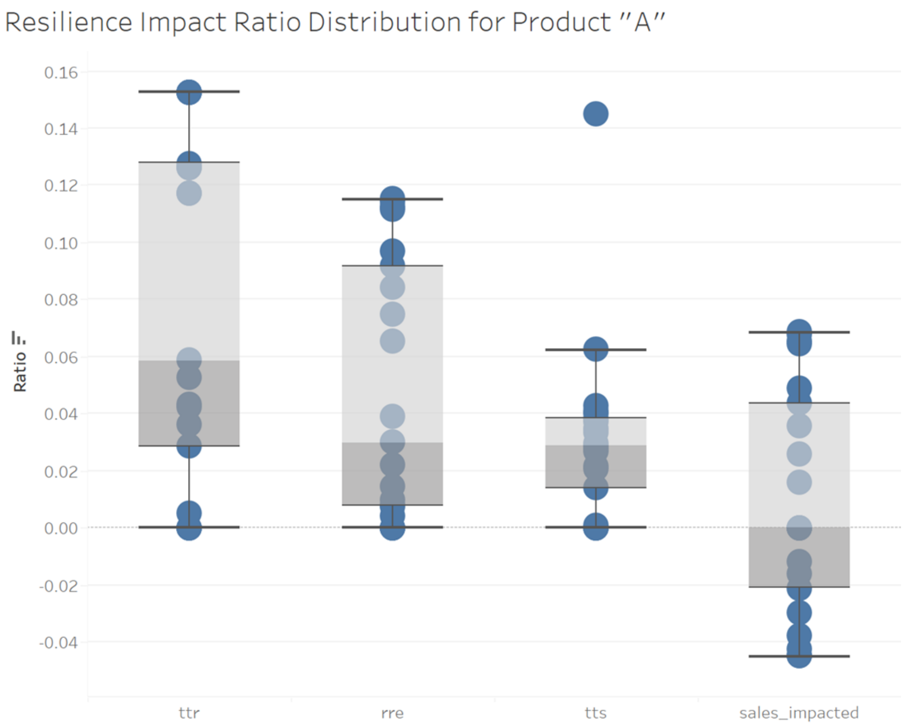
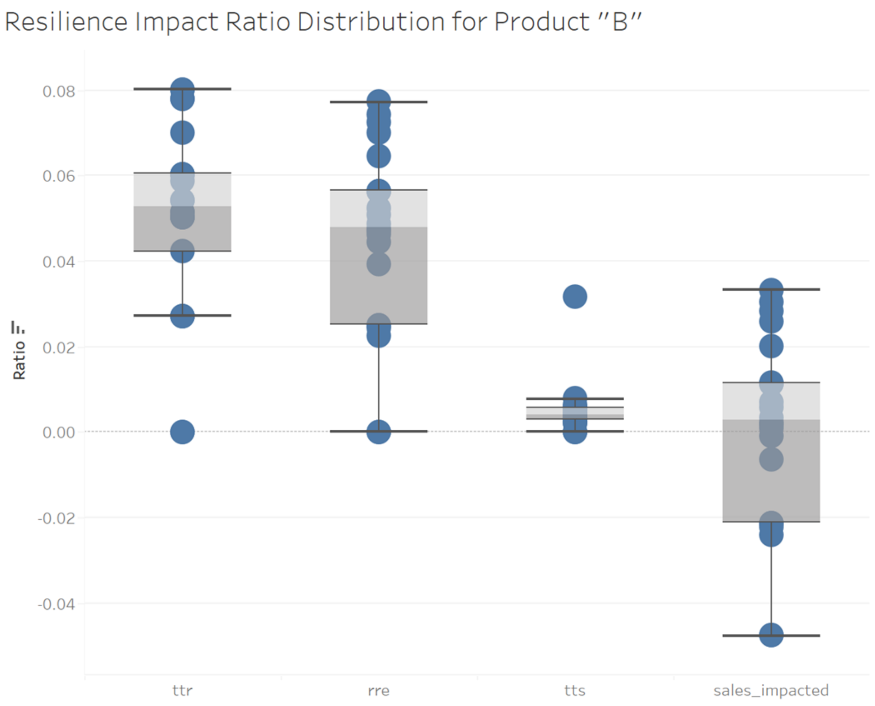


Figure 5

Resilience Impact Ratios for a Supply Chain Network of product B



4.1.1 Time-to-Survive (TTS) Findings

As seen in Figures 4 and Figure 5 for products A and B and ABC firm, percent changes in TTS seem to have the least impact on overall central tendency change compared to the other three inputs measured. Referencing Figure 2, inventory is a common investment option considered when aiming to improve a firm's time to survive. However, this analysis suggests that, based on trends for six supply chains of ABC company, common practices such as investing in inventory to be more resilient are actually the least likely to impact overall product resilience. While 'lean' inventory strategies, such as Just-in-Time, have been cited to decrease resilience of firms and cause shortages for companies during the COVID-19 disruption (Sheffi, 2021), our data supports the argument that these strategies are not the biggest contributor to blame. In fact, some researchers argue that such strategies actually, "create resilience - not fragility," due to their ability to allow for flexibility (Sheffi, 2021).

4.1.2 The TTR/TTS Boundary

We observed one exception to the rule of percent changes in TTS having the least impact on overall resilience central tendency. As seen in the outlier nodes for product A and B's TTS resilience impact ratios in Figures 4 and 5, there are certain conditions that create high impact for overall central tendency per percent change in TTS. Our analysis suggests that this occurs on what we call the "TTR/TTS Boundary." Illustrated in Formula 5, this is when the days of TTR-TTS divided by TTR as a means of standardization are at a low percent relative to other TTS nodes for that product.

Formula 5

TTR/TTS Boundary Calculation

$$\text{TTR/TTS Boundary} = \frac{\text{TTR} - \text{TTS}}{\text{TTR}}$$

In these cases for these nodes, resilience impact ratios can be as high as other inputs, such as EF or TTR, as reflected in Figure 4. It is important that firms identify these nodes, as investments in the TTS for nodes at the TTR/TTS Boundary could yield more resilience value of decrease in central tendency per dollar invested than investing in other inputs, such as EF or TTR. We aim to provide a methodology to answer this question in Section 4.2.

4.1.3 Time-to-Recover (TTR) Findings

Time-to-Recover for all six supply chains proved to be the dominant input in terms of distribution of resilience impact ratios. These distributions can be seen in Figures 4 and 5. This insight suggests that investments in time-to-recover, in general, drive overall resilience for the six products analyzed at ABC company. Referencing Figure 2, high resilience impact ratios for TTR demonstrate that investments in options such as dual sourcing, especially when utilized to split capacity, are dominant strategies to improve supply chain resilience. However, these decisions should be considered on a node-by-node basis, especially for supply chains with broader ranges of TTR resilience impact ratios.

4.1.4 Environmental Factors (EF) Findings

As seen in Figures 4 and 5, EF in all six supply chain networks was the second most impactful metric on a percent change basis to overall percent change in resilience central tendency. This was the case for all six supply chains analyzed.

As defined in Figure 2, possible resilience investment options for nodes with high EF resilience impact ratios could include node relocation or split capacity in different geographies (heterogeneous supplier management). It is important to note that, given the distribution of EF impact ratios are similar to that of TTR ratios, our analysis suggests that EF should be considered when making investments in TTR. For example, when considering a dual source as mentioned in Section 4.1.2, supply chain professionals would be wise to consider the EF resilience impact ratios for that node. If these ratios prove significant to resilience, then dual sourcing or splitting capacity in the same geography, or a geography with the same EF, would not be as advantageous to the firm. Finally, it is important to note that options that impact EF, such as node relocation, are characteristically large changes to a firm's operations and, while generally have high resilience impact ratios, could be disruptive or expensive.

4.1.5 Sales Impact Findings

Sales Impact, as seen in our analysis, typically has a lower impact on the overall resilience central tendency of a supply chain per percentage change. While a few nodes have the ability to have higher resilience impact ratios such as in products A and E, Sales Impact is also the only input seen to actually have a negative impact to overall resilience when increased in some nodes. This observation illustrates an underlying rule that when the company decreases the sales of nodes that are on average more resilient, it decreases the overall central tendency of the node. The key insight from this analysis suggests that, all else being equal, supply chain resilience can be improved through increasing sales exposure of already more resilient nodes or decreasing a product's potential sales exposure through nodes with higher PlWC values (or rather 'lower than average resilience') nodes. One example of this, referencing Figure 2, could be firms modifying distribution channels of products to maintain or increase sales. In doing this, firms could adjust sales exposure to certain nodes, such as shifting distribution volume from one impacted warehouse to a more resilient one, in order to minimize overall performance impact.

Finally, while not always the driving force for overall central tendency, focusing on improving resilience for nodes with higher sales volume would be advantageous to reducing the impact of a loss of performance in the supply chain.

4.1.6 Discussion of Resilient Nodes

For all inputs, a trend in numerous nodes with plausible worst case values of zero can be seen. This represents nodes that are already considered ‘resilient’. For example, in supply chain network A, Nodes 18 to 21 currently have TTS values that exceed TTR values, and are insensitive to changes. In Node 20, for example, the TTS value is 118 days, while the TTR value is only 21 days. Thus, the TTR could be increased as much as 462% before the node would have any performance impact exposure (or where the PlWC is greater than zero). Because these nodes are insensitive to changes in these inputs, this suggests resources could be divested from resilience measures in these nodes and distributed to more vulnerable nodes. For example, if the firm has invested in risk mitigation inventory to fulfill the current TTS value of 118 days, this inventory could be significantly reduced without any impact on the current resilience level.

4.1.7 Sensitivity Analysis Conclusion

Overall, by performing the sensitivity analysis, the research team was able to better understand trends in resilience input types as well as specific node inputs that would be most impactful to improving the overall resilience of a particular supply chain. This analysis did not, however, consider the change in resilience per dollar invested in resilience options. We demonstrate a theoretical framework to explore this in the next section.

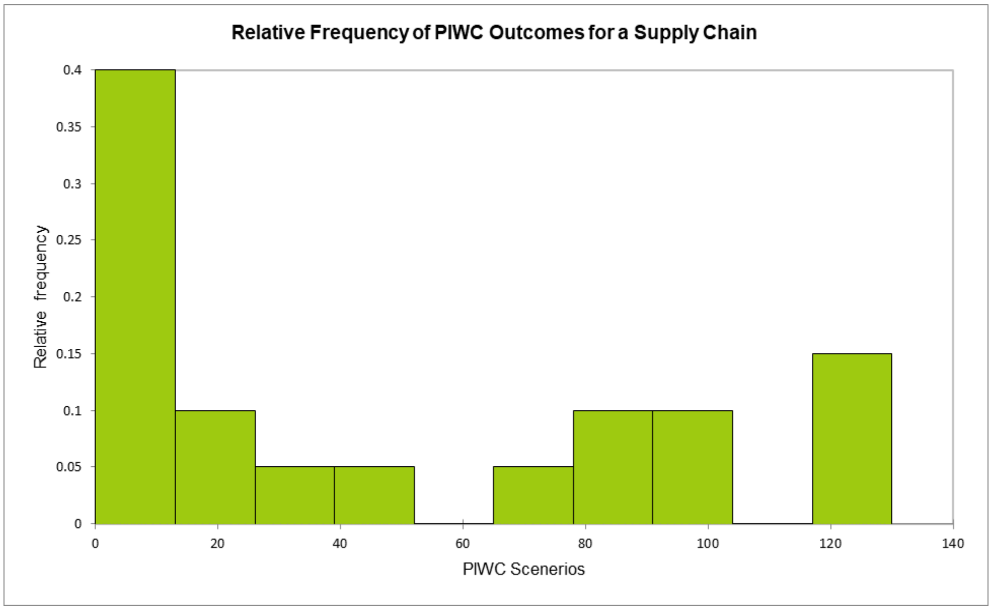
4.2 Resilience Investment Framework

The analysis performed in Section 4.1 considered resilience impact not by monetary investment but instead by percent change in the input value itself (for example, in days of TTR or TTS) to the overall percent change in central tendency (in revenue value at risk for ABC firm). In this section, we couple the above findings with a theoretical framework to better understand valuing a particular resilience investment in terms of monetary investment.

Without considering the impact of any resilience investments, the current frequency of Plausible Worst Case (PlWC) scenarios for all nodes for Product A are shown in Figure 6. This demonstrates a distribution of performance vulnerability in Plausible Worst Case scenarios for Product A.

Figure 6

Static distribution of Plausible Worst Case scenarios for nodes of Product A's supply chain (in millions of dollars at risk)



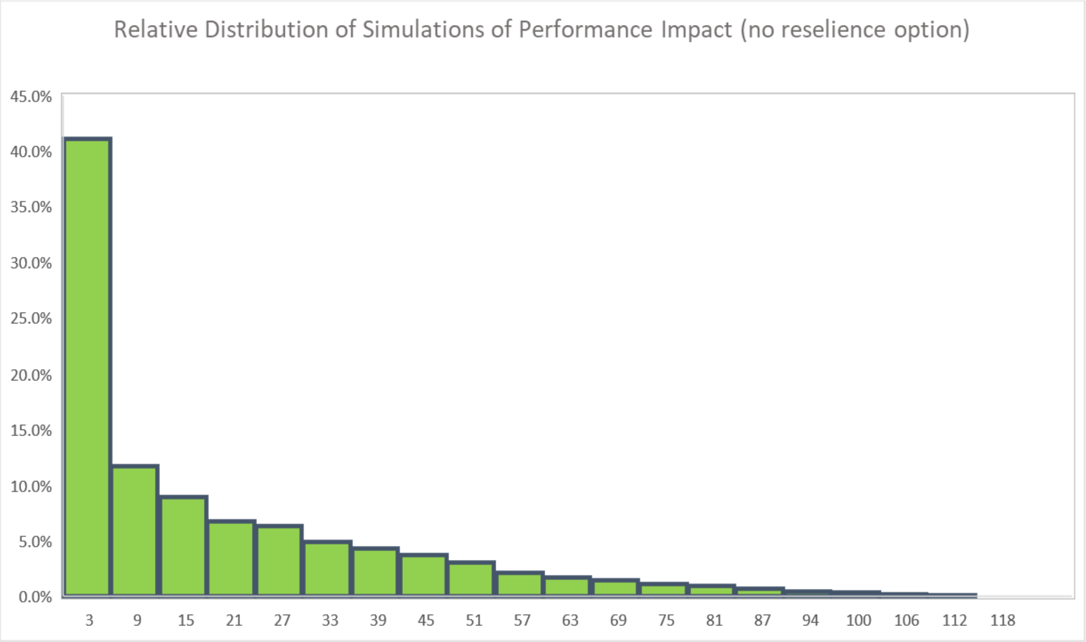
Currently, while the most frequent outcome of nodes has relatively low Plausible Worst Case outcomes, about 67% of nodes have worst case scenarios that impact performance greater than $10M in sales.

4.2.1 Monte Carlo Simulation

For the purpose of illustrating how a particular change in a node's resilience input (TTR, TTS, EF, or Sales Impact) may change this distribution of a firm's range of potential outcomes when facing disruption, we used the simple triangle distribution mentioned in Figure 3 for all nodes to represent failure mode distributions of each node. We simulated each node 2000 times and created a resulting single distribution of all PlWC iterations of all nodes of Product A. This resulting distribution is seen in Figure 7. This distribution represents a more realistic distribution of performance impact given a disruption, as outlined in section 3.4.1.

Figure 7

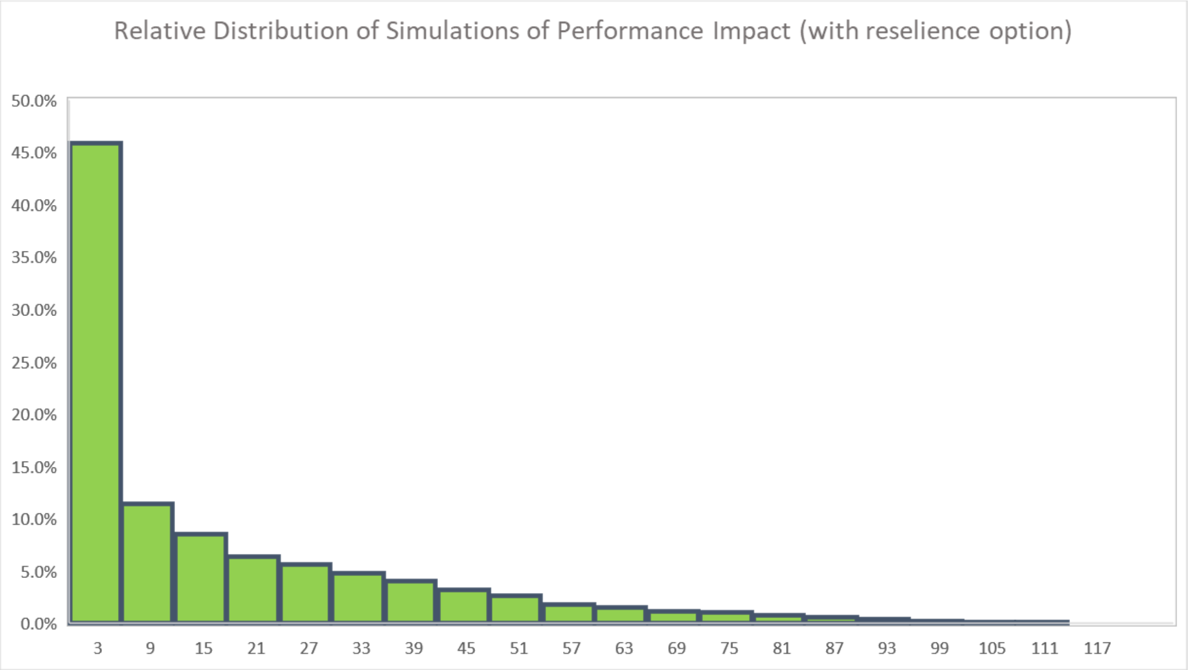
Value at Risk Probability Density Function (PDF) for simulated nodes of Product A supply chain, no resilience investment



Next, we identify an input with the highest resilience impact ratio - TTR for node 1 as mentioned in Section 3.4.2. We assume an investment can be made to make this node resilient, by finding a backup supplier that reduces the TTR from 540 days to 132 days. This reduces the PlWC of this node to zero. Updating the data for this node and re-running the same simulation all else equal yields the probability distribution in Figure 8.

Figure 8

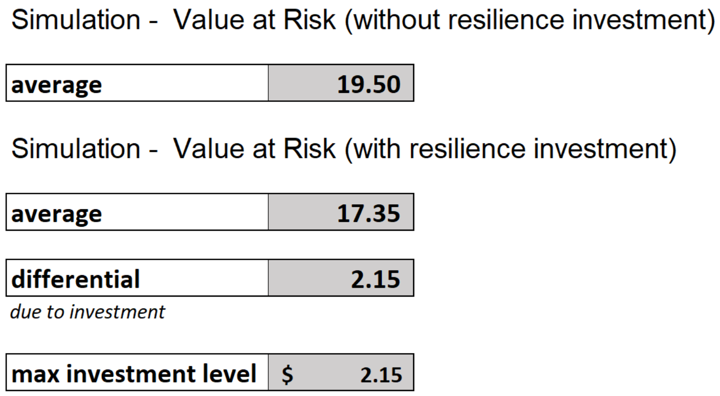
Value at Risk Probability Density Function (PDF) for simulated nodes of Product A supply chain, ***with*** *resilience investment*



While the graphs appear nearly identical to the simulation outputs without the resilience investment visually, in comparing the means for these distributions, we see there are significant differences in means. This is outlined in Figure 9.

Figure 9

Change in distribution means for simulated nodes of Product A supply chain, with and without a resilience investment (in millions of dollars)



Simulation - Value at Risk (without resilience investment)

average	**19.50**

Simulation - Value at Risk (with resilience investment)

average	**17.35**
differential	**2.15**

due to investment

max investment level	**$ 2.15**

The above illustration demonstrates how an investment in increasing Node 1's TTR by 408 days yields a difference in simulated means of roughly $2M. The result of comparing these means serves to understand a maximum investment level practitioners would consider for this particular investment. This maximum assumes no cost to implement the option. Practitioners could then consider the cost of implementing such an investment, and determine if the decrease in value at risk exceeds the cost to implement. If this is the case, this analysis would suggest they "execute", or invest in, this resilience option.

Using this simulation approach allows for a realistic analysis of potential resilience investment options, as typical NPV investment analysis would seldom favor investing in resilience measures due to the uncertain nature of disruptions. Therefore, a firm may otherwise ignore this risk when evaluating investments based on static projections. Thus, the real options approach allows the firm to understand the value they stand to lose should disruption occur, and in this case, in terms of daily sales, this method identifies how much a firm might be willing to invest to generate a more advantageous performance outcome when faced with disruption.

It is important to note for future researchers that the resulting maximum investment level recommendation for a particular resilience option will depend on the chosen distribution utilized in simulation. Thus, the above results are intended to illustrate a framework to be further explored by researchers.

5. CONCLUSION

This capstone advances the current research in valuing supply chain resilience investments. Our sensitivity analysis provides the insight that the Time-to-Recover and Environmental Factors inputs generally have the greatest impact on a percent change basis to supply chain resilience.

Combined with resilience actions identified through our literature review, the team created a roadmap for potential resilience investment options for each input variable under different scenarios. However, this initial analysis does not indicate the amount of financial investment needed to achieve a particular level of resilience. To address this question, we propose conducting Monte Carlo simulation on a supply chain node's value at risk and comparing the mean of the range of the outcomes to yield the maximum reasonable resilience investment amount for a particular investment option. The limitation faced for performing this analysis is defining the underlying distribution of the supply chain disruptions for each node.

5.1 Observations

This research suggests that investments in Time-to-Recover elicit the greatest impact to overall resilience of a product's supply chain network. This observation suggests that investing in options such as dual sourcing, heterogeneous supplier capacity, supply chain transparency, supplier collaboration, and supply chain digitization could best improve the average resilience of a supply chain. Additionally, our research suggests that there could be trends in supply chain nodes on the "TTR/TTS Boundary" that could generate high impact to overall resilience when investing in TTS. This finding suggests that there are certain criteria when investing in TTS options, such as additional inventory, is a dominating strategy. Given that TTS investments could be less expensive compared to other resilience options, these specific nodes may be particularly attractive to supply chain managers. Firms should consider identifying these nodes and further explore implications of marginal investments in TTS improvements to achieve the highest return on the investments.

It is important to note other elements of this research that stakeholders may also consider. First, firms may consider due-diligence to determine the cost for such investment options. Costs will play a large role in whether various resilience options have the possibility to be 'executed.' Additionally, research should be conducted if this generalization for Time-to-Recover impact applies to other products and other industries. The analysis and results in this capstone project may provide a roadmap to identifying the most high-yield resilience variables in a company's supply chain network and potential resilience investment options for each variable. To do this, industry experts and researchers might consider:

1. Utilizing previous research on identifying resilience metrics for a particular supply chain to map current-state vulnerabilities,
2. Expanding on this framework to identify node inputs most sensitive to resilience investments,
3. Identifying potential investment option types which could best address improving resilience, and
4. Creating a framework to conduct Monte Carlo simulation with realistic underlying distributions to determine the value of investing in a particular resilience option.

5.2 Next Steps for Future Research

As the next step for future research, the team suggests expanding on the current framework and gaining more in-depth understanding on the precise distributions of failure modes for PlWC simulations. Another suggestion is to characterize costs of resilience option types and integrate them into the methodology. Furthermore, the Monte Carlo analysis illustrated does not consider future cash flows nor the time value of money; however, future researchers or practitioners could consider incorporating this methodology into a net present value calculation. Future research may also provide a framework on how firms can estimate the resilience option costs in a more efficient and practical way. Most importantly, it would be useful to test the framework for valuing supply chain resilience options and generalized for a variety of other products and firms outside of the scope of the data used for this research to understand if the emerging observations continue to hold true.

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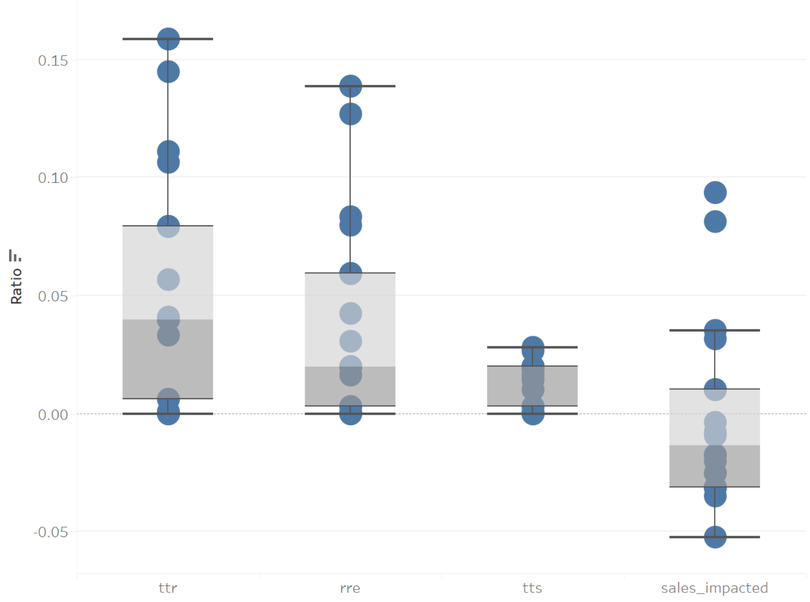
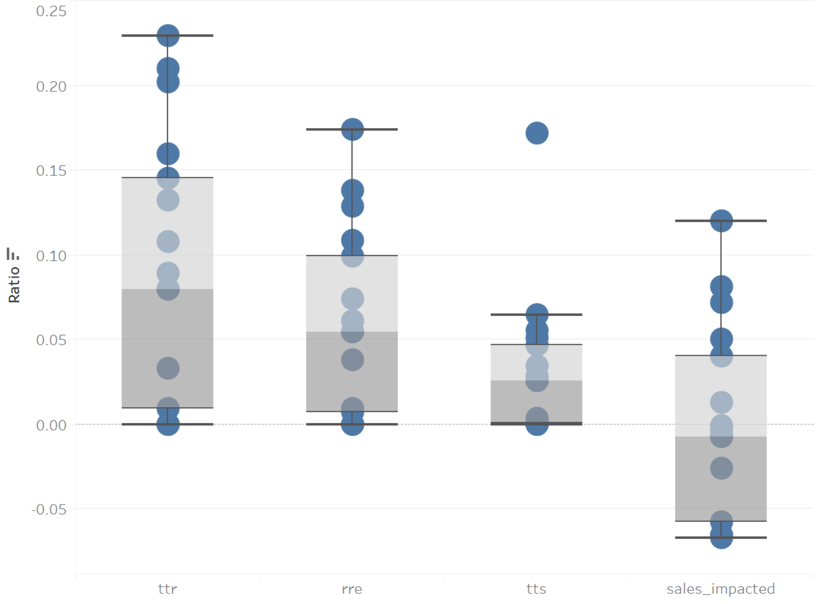
APPENDIX

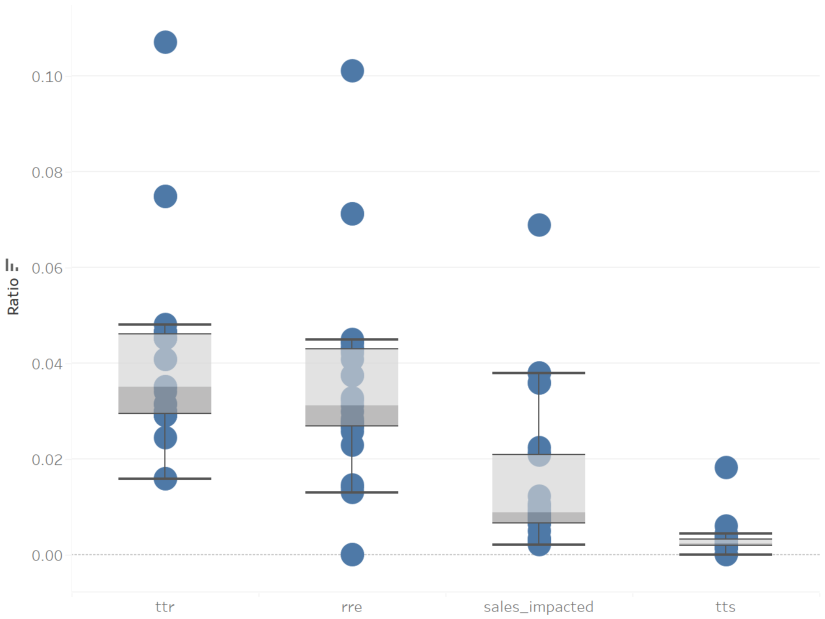
The below graphs provide additional visualizations for other Products tested on the methodology outlined by this capstone. These graphs illustrate consistency in findings reported in the Results section of this report.

Resilience Impact Ratio Distribution for Product "C"



Resilience Impact Ratio Distribution for Product "D"





Resilience Impact Ratio Distribution for Product "E"