PERFORMANCE IMPROVEMENT THROUGH BETTER UNDERSTANDING OF SUPPLY CHAIN RESILIENCE

DISSERTATION

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Abstract

Businesses operate every day in a disruptive environment. Supply and demand uncertainty, natural disasters, global pandemics, and mishaps can all cause chaos to a supply chain's flow. It is impossible to predict every disruption a supply chain may encounter. The best an organization can do to protect network performance is to build resilience in the supply chain and life-blood of its operations. Ensuring that a supply chain has the proper built-in mechanisms to resist and recover from disruptions is referred to as Supply Chain Resilience (SCR). While it is generally agreed that SCR can be improved through the implementation of SCR strategies, the links between these strategies, performance improvement and resilience is understudied. This dissertation leans on resource based view and theory of constraints to categorize these SCR strategies, examine the links between the strategies and performance, and develop a metric to measure network resilience over time. First, a meta-analytical study identifies generalizable relationships between SCR strategies and firm performance measures. Then, the SCR redundancy strategies are applied to a model simulation to illustrate the resilience curve response to different SCR strategic decisions. Resilience outcomes are compared using a developed Resilience Capability Metric (RCM) utilizing Area under the Curve (AUC) to measure the cumulative performance level of the system from disruption to predetermined endpoint, representing how much of the system demand can be served by different network resilience designs. Finally, SCR flexibility strategies are analyzed to see how constraints imposed on a supply chain's response time could impact the resilience of the supply chain. This dissertation highlights the positive impact on performance and resilience that can be

realized when organizations take the time to implement the proper SCR strategies, while providing managers with RCM to measure and compare the impact of different strategies within their organization.

To my children… knowledge will give you the confidence to lead, the humility to follow and the power to stand up for what you believe in. Learn something new every day and your opportunities will be limitless.

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PERFORMANCE IMPROVEMENT THROUGH BETTER UNDERSTANDING OF SUPPLY CHAIN RESILIENCE

I. Introduction

Organizations operate every day in disruptive environments. Far-reaching global logistics operations stretching across oceans and continents have created massive supply chains vulnerable to disruptions and uncertainty. Since many of these disruptions are impossible to predict, organizations must strategize ways to protect their vital supply chains. Ensuring that a supply chain has the proper built-in mechanisms to resist and recover from disruptions is referred to as Supply Chain Resilience (SCR).

SCR can be improved through the implementation of SCR strategies. Strategy selection can be complicated, often influenced by geographic location, holding and shipping costs, storage capability, product shelf life and predictability of disruption occurrence. Cookie-cutter resilience strategy recommendations do little to assist with so many scenarios to consider. Organizations require a way to compare resilience impact in order to select the best strategies to mitigate risk to their supply chain.

1.1 General Issue

Organizational supply chains exist in resource constrained environments. While it is widely accepted that Supply Chain Resilience (SCR) is important to the performance of an organization, decision makers may struggle with the details of how to operationalize SCR. Many different SCR strategies are used to counteract disruptions, but the ability to compare strategies is not well understood. A more streamlined categorization of these strategies can help decision-makers better grasp the options available in their resilience tool-kit.

Frequently, relationships between SCR strategies and network resilience are not well established, and selecting the right SCR strategy to implement can be unclear without a proper mechanism to compare resilience outcomes. Organizations and supply chains are unique to their own purpose and goals. Therefore, the strategies that are ideal for one organization are not necessarily a good choice for another. Existing research relies heavily on measuring loss in resilience models to determine the best strategies to implement. Building on existing resilience research, the development of a more comparable, performance based metric can change the way organizations determine investment strategies. Using this method, organizations can select personalized SCR strategies to develop stronger, more resilient supply chains.

1.2 Research Objective

The objective of this research is to analyze the triggers which can be leveraged to improve the resilience of a supply chain. Specifically, this research seeks to 1) establish the associations between different Supply Chain Resilience (SCR) strategies and performance outcomes; 2) develop a resilience metric to allow decision makers to compare SCR strategy investments; 3) examine the impact of different SCR strategies on performance and overall network resilience.

1.3 Research Contributions

This dissertation provides the following contributions:

1. *Establishes generalizable associations between different Supply Chain Resilience (SCR) strategies and performance outcomes*. One reason for maintaining a resilient supply chain is the ability to sustain a firm's performance in the presence of a disruption. Accepting that these disruptions will occur, the purpose of this study is to review the connections already identified in previous studies between SCR strategies and firm performance in order to support the theory that the competitive advantage created by a more resilient firm is associated with a better performing firm. Additionally, to aid in strategy selection, two main SCR strategy categories have been identified in the literature as redundancy and flexibility.

This dissertation aims to help decision makers in reducing the impact of a disruption on performance of a firm by confirming that investing in SCR is strongly correlated to increased performance and identifying which SCR strategies have the strongest correlation to that performance increase. This knowledge can assist in better informed, more targeted SCR investments, increase a firm's competitive advantage, and provide the best performance outcome for the organizational success.

2. *Develops a resilience metric to allow decision makers to compare SCR strategy investments.* To better quantify supply chain resilience, this dissertation develops the Resilience Capability Metric (RCM). RCM uses an Area under the Curve (AUC) of supply chain performance following a disruption to quantify cumulative system performance over time after disruption. The study proposes that SCR can be measured relative to the supply chain's requirements by the ratio of the AUC to the system's total demand over time. The development of RCM allows for SCR to be measured as system performance over time with AUC.

Ultimately, the goal of quantifying SCR is to determine the best SCR investment strategy to improve system resilience. Predicting how different supply chain designs will respond to a disruption enables rigorous comparison and selection of investment tradeoffs in anticipation of a disruption occurrence. This research aims to provide managers with a SCR metric that will allow for informed capital allocation decisions when designing and assessing supply chains.

3. *Examines the impact of different SCR Strategies on performance and overall network resilience.* This study examines the impact of SCR redundancy strategies and SCR flexibility strategies on the resilience through the use of inventory, production capacity and response time. For redundancy strategies, this study identifies the impact of added inventory and added production capacity. The SCR strategy of investing in inventory was shown to create a buffer against disruption, showing that inventory level pre-disruption is the driver of how low performance declines after disruption. The addition of inventory allows for not only a higher performance level during the pre-disruption steady state, but also buffers the impact of the disruption, resulting in a higher minimum performance level. A redundant inventory strategy also directly impacts the length of time the system is able to resist the disruption. In one example, as the amount of redundant inventory increase, the amount of time to reach minimum performance level post-disruption increases, buying organizations more time as the drop in performance is slowed.

The SCR strategy of added redundant capacity also impacts minimum performance levels, showing a significant increase in performance level when utilizing redundant production capacity after disruption. Furthermore, as the amount of added production capacity incrementally increases, the system experiences diminishing returns, illustrating a lack of linearity. This finding highlights the fact that SCR strategies must be strategically balanced based on an organization's desired outcome.

For SCR flexibility strategies, this study identifies the impact that recovery response has on supply chain resilience. The time it takes an organization to implement a recovery response to a disruption has a critical impact on the network's performance and overall resilience. Based on what is known about SCR flexibility strategies, it is predicted that a more flexible supply chain, with a decreased response time to disruptions means an increased performance rate. Imposing organizational policy changes to decrease response time and increase agility may not only reduce customer backorders, but also increase performance rates. This will ultimately create a more resilient network able to better respond to disruptions. The study provides evidence that resilience can be improved by both SCR flexibility and redundancy strategies.

1.4 Preview

The remainder of this dissertation follows a scholarly article format. Chapters II, III, and IV are independent research articles on supply chain resilience. Each chapter is self-contained in that it contains its own introduction, literature review, methodology, results and analysis, and discussion sections. Additionally, each chapter contains its own future research recommendations.

Chapter II provides generalized relationships between supply chain resilience (SCR) strategies and an organization's performance. The study in this chapter examines SCR strategies and firm performance measures in three different models: a general model, a SCR strategy model, and a performance model. Using a resource-based view of the firm and Structural Equation Modeling (SEM)-based meta-analysis, SCR strategies were identified as resource-based capabilities that could provide competitive advantage and a positive relationship to firm performance outcomes. This study supports not only a general positive relationship between SCR strategies and performance measures, but also the distinctive categorization of SCR strategies into redundancy and flexibility lanes. SCR redundancy strategies include excess capacity that may or may not be used in response to a disruption, and SCR flexibility strategies include existing capacity that has been restructured prior to or in anticipation of being needed. This study provides evidence to support that firms can improve their performance by putting forth an effort to increase the resilience of their supply chains. This knowledge can assist in better informed, more targeted SCR investments, increase a firm's competitive advantage, and provide the best performance outcome for the organization as a whole.

Chapter III identifies the need for resilience metric development and steps the reader through the creation of the Resilience Capability Metric (RCM) that utilizes Area under the Curve (AUC) to measure the resilience of a supply chain when confronted with a disruption. This study offers an example of how to test and measure the effect of specific SCR strategy investments. To illustrate how to use the RCM proposed in this paper, a simulation model based on a United States Air Force (USAF) aircraft engine repair network is presented. The example explores two different SCR redundancy strategies; increased inventory (i.e., spare parts) and redundant production capacity (i.e., number of repair servers) to improve the network's response to a disruption. While the example chosen is a military repair network, the decision between SCR strategy investments is fundamental. Managers can build their own simulations and use RCM to analyze the resilience of their supply chains against different disruptions, as well as test the resilience impact of added SCR strategy investments such as added inventory and redundant capacity.

The RCM allows a means by which to properly compare these SCR strategy investment scenarios. There is evidence to suggest that strategies can work together to provide the best results. This study highlights that organizations must have a deep understanding of costs associated with each SCR strategy to determine the best combination to use, and that the length of time it takes to provide a SCR strategy response is critical to the system's resilience. Since a quicker response may be more expensive, when evaluating the feasibility of a shortened response time the organization should examine whether the associated costs of a recovery speed are worth the added resilience.

Chapter IV provides evidence to support the theory of constraints by highlighting ways organizations can impose constraints to network performance and supply chain resilience through policy oversight. This research suggests that organizations can utilize supply chain resilience (SCR) flexibility strategies, like decreased disruption response time, to improve their organization's performance. Specifically, more deliberate lateral echelon part sourcing, and faster shipping mode selection can be utilized to break down response time constraints in an organization to improve SCR. Managers can influence the resilience of their supply chain by lifting the constraints on inventory transportation to allow for the quickest modes and more deliberate placement of spare parts for more lateral resupply option

The final chapter discusses any overarching concluding commentary and reiterates the contributions that each academic paper makes followed by suggestions for future research efforts.

II. The Relationship between Supply Chain Resilience Strategies and Firm Performance: A Structural Equation Modeling-Based Meta-Analysis

2.1 Introduction

A company's supply chain is its lifeline and connection to the outside world. Even the smallest disruption in a supply chain can lead to damages and loss of potential profits that can reach into the billions of dollars (Clemons, 2016). Natural disasters, current political or military climates, global pandemics, shipping delays, and mechanical malfunctions are all examples of real-world disruptions that impact the ability of a supply chain to operate. Disruptions can also destroy public trust by plummeting stock values and increasing equity risk (Hendricks and Singhal, 2005). Without the tools to recover in a timely manner after a disruption, many companies could experience a drastic decrease in their performance. Companies that invest in the resilience of their supply chains build their competitive advantage over those that do not by enabling them with the ability to respond quickly and to recover faster from disruptions (Ponomarov and Holcomb, 2009).

Resilience in the most common sense is the ability for something to recover when disturbed. Supply chain resilience (SCR) is the ability of a supply chain to reduce probability of disruptions, to resist impact from disruptions, and to respond and recover from the disruptions (Ponomarov and Holcomb, 2009). The resilience of a supply chain can be bolstered through the support of different types of SCR strategies. In the last twenty years, the definition of SCR and the different types of strategies that support resilience within a supply chain have continued to evolve throughout the literature

(Shashi et al., 2020). Recent publications support SCR strategies as being either redundant or flexible (Kamalahamdi and Parast, 2016; Kochan and Nowicki, 2018).

One of the most important rationales for maintaining a resilient supply chain is the ability to sustain a firm's performance in the presence of a disruption. Accepting that these disruptions will occur, the purpose of this study is to review the connections already identified in previous studies between SCR strategies and firm performance in order to support the theory that the competitive advantage created by a more resilient firm is associated with a better performing firm. Investment both in redundancy and flexibility SCR strategies has been extensively studied, often proving to have a significant impact the performance of a firm (Shashi et al., 2020). This study gathers all research efforts published between the years of 2000 and 2020 that identify a correlation between SCR strategies and performance, coding all SCR strategies as either flexible or redundant. This study attempts to answer the questions: *(RQ1) Is there a positive correlation between investment in supply chain resilience (SCR) and firm performance? (RQ2) Which SCR strategies have a greater correlation to firm performance? (RQ3) What is the relationship between these SCR strategies and different types of firm performance measures?*

This study aims to aid decision makers in reducing the impact of a disruption on performance of a firm by confirming that investing in SCR is strongly correlated to increased performance and identifying which SCR strategies have the strongest correlation to that performance increase. This knowledge can assist in better informed, more targeted SCR investments, increase a firm's competitive advantage, and provide the best performance outcome for the organization as a whole. The rest of this study consists of literature review, methodology, and results followed by discussion and conclusion.

2.2 Literature Review

In accordance with the resource-based view (RBV), this study analyses SCR strategies as resource-based capabilities firms can employ to gain competitive advantage and improve performance of the firm. SCR strategies have been the focus of many supply chain management research efforts in the last twenty years, often being categorized into two lanes: flexibility strategies and redundancy strategies (Kamalahmadi and Parast, 2016). Often, primary studies focus on the impact these strategies have on different performance measures to see how investment in resilience can benefit the firm.

2.2.1 Theoretical Background

Resource Based View (RBV) is a view, which depicts resources as key to superior firm performance, and relies on companies employing these resources to exploit external opportunities (Lavie, 2006). RBV explains how companies can use what makes them unique as a way to get a leg up on their external competition (Lavie, 2006). According to RBV, firms that exploit their resource endowments are efficient and effective, leading to higher levels of firm performance (Barney, 1991). A firm that has resources that are valuable, rare, and difficult to duplicate and substitute can achieve competitive advantage when managers are able to identify the performance potential of a firm's resource endowments and properly employ those resources (Barney, 1991). A firm's performance can be improved based on its ability to maintain a competitive advantage. If a company can identify vulnerabilities in its supply chain and act more efficient and effective by employing its specific resource endowments, then the firm may be able to maintain production, minimize downtime and recover quicker in the event of a disruption to its supply chain.

RBV is a popular logistics management view discussed extensively in supply chain literature to explain how strategic supply chain efforts lead to increased performance and sustainable competitive advantage for a firm (Olavarrieta and Ellinger, 1997; Daugherty et al., 1998; Lynch et al., 2000; Esper et al., 2007; Gligor, et al., 2019). The ability to be more "resilient" is a competitive advantage that will allow the firm to sustain or improve performance. The RBV concept of resources creating competitive advantage supports the argument that if a company were to invest in supply chain resilience (SCR) strategies, it would experience a positive association to its performance measures.

2.2.2 Supply Chain Resilience (SCR)

As the world continues to advance technologically and globalization trends upwards, supply chains are getting longer, more complicated, and more vulnerable to disruption. The more complicated supply chains become, the more important supply chain management is for increasing a firm's performance (Gunasekaran, et al., 2001). The ability for an organization to properly manage the risk to disruptions imposed on its supply chain can have a great impact on the performance of the organization (Pettit et al., 2010). To this end, supply chain resilience (SCR) strategies have been developed to help reduce the risk of disruption to an organization (Melnyk et al., 2010). The study of SCR has gained momentum since the year 2000, with more than three hundred studies on the topic published between 2000 and 2017 (Kochan and Nowicki, 2018). Implementing

SCR allows companies to resist the impact of disturbances, and to recover from them. The definition of SCR has continued to evolve in the literature. For clarification, this paper will focus on SCR defined by Ponomoarov and Holcomb (2009) as, *"the adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations"*.

Research in the last two decades has approached the phenomenon of SCR in different ways. Quantifiable research has focused on SCR metric development, analyzing the absorptive, adaptive, and restorative capacity of a firm's supply chain to determine resiliency and qualitative SCR research has focused on identifying the conceptual drivers or strategies of SCR. These studies have comprehensively established a basis for the importance of SCR to both researchers and practitioners (Macdonald et al., 2018). SCR research supports a definitive relationship between supply chain disruptions and the performance of the system that supply chain resides in, providing evidence that this relationship is heavily influenced by a firm's decision to build the resilience of the supply chain (Macdonald et al., 2018). Research is pressing forward with the task of better defining these relationships, modeling network behavior in regards to disruption and resilience, and moving towards theory development related to disruption and resilience (Macdonald et al., 2018).

Leuschner et al. (2013) & Mackelprang et al. (2014) conducted studies using meta-analysis which found a positive relationship between strategic supply chain integration and performance and reached similar results. These studies both identified a significant and positive relationship between supply chain integration and performance of a firm. Leuschner, et al. (2013) broke supply chain integration into three sub categories (Information Integration, Operational Integration, Relational Integration), finding positive correlations between each of the sub-categories and firm performance. Mackelprang, et al. (2014) found that the integration-performance relationship was too complex to state that there was a strong positive relationship between the two, but suggested a correlation existed and recommended further research be done to determine exactly what connections can be made. Supply chain integration, a range of mechanisms including information sharing, joint decision making, synchronization, and collaboration between supply chain partners, has been shown throughout the literature to enhance supply chain capabilities and organizational performance (Huang et al., 2014; Chaudhuri et al., 2018; Rajaguru, 2019). However, while supply chain integration could be used to improve SCR, it is just one strategy of many. A meta-analysis analyzing cumulative evidence on the relationship between a broader grouping of SCR strategies and firm performance is difficult to find at the time of this study.

Most recently, Shashi et al.'s (2020) conducted a systematic literature review of 125 SCR studies and provided a comprehensive and holistic view of metrics used to measure SCR performance, strategies to support SCR, and barriers to developing SCR in a firm. This study hopes to expand these research efforts by taking a broader look at the supply chain resilience research to find a more robust connection between the SCR strategies and firm performance. Therefore, the first hypothesis tested in this study is based on the general relationship between SCR strategies and firm performance.

I hypothesize:

(H1) *Implementing supply chain resilience (SCR) strategies is positively associated with firm performance.*

2.2.3. Supply Chain Resilience (SCR) Strategies

Supply chain literature has identified a great deal of inconsistency with the terms used to describe the strategies of SCR with many terms used interchangeably to define similar concepts (Kochan and Nowicki, 2018). Part of the SCR community supports an argument for only two truly different categories of resilience strategies: flexibility and redundancy (Kamalahamdi and Parast, 2016; Kochan and Nowicki, 2018). Case studies support the claim that companies may be able to influence uncertainty through their strategic investments in flexibility and redundancy (Pagell et al., 2000).

This study will utilize flexibility and redundancy as the two main SCR strategies, allowing any other sub-strategy to fall into those two categories for data comparison. All strategies listed in the primary studies incorporated into this study are identified as either a redundancy strategy (excess capacity that may or may not be used in response to a disruption) or a flexibility strategy (existing capacity that has been restructured prior to or in anticipation of being needed). Table 1 provides the defined SCR sub-strategies, identifying them as either flexibility or redundancy.

Table 1. SCR Strategies and Definitions

Supply Chain Resilience Strategies		Definitions	References
Flexibility Strategies	**Agility**	The ability of a supply chain to rapidly adapt its initial stable configuration to respond to disruption or change.	Wieland and Wallenburg (2012)
	Collaboration	The process of joint decision making among key stakeholders of a problem domain about the future of that domain, commonly used to describe organizations working together towards a mutuality of benefit.	Barratt (2004)
	Contingency Planning	Activities designed to plan, prepare and train for supply chain risks before they occur.	Svensson (2004)
	Information Sharing	The deliberate exchange of critical and/or proprietary information with supply chain partners to increase transparency.	Li et al. (2005)
	Innovation	The capability of the firm to develop and introduce new products or processes.	Dmanpour and Gopalakrishnan (2001)
	Visibility	Enabling identity, location and status of entities transiting the supply chain to be captured in timely messages.	Francis (2008)
Redundancy Strategies	**Excess Capacity**	Deliberately maintaining low capacity utilization rates to absorb the impact of supply chain disruptions.	Sheffi and Rice Jr (2005)
	Excess Inventory	Maintaining redundant inventory stockpiles to absorb the impact of supply chain disruptions.	Inman and Blumenfeld (2014)
	Redundant Suppliers	Maintaining contracts with more than one supplier or having backup suppliers to be utilized in the event that the primary supplier cannot meet demand requirements.	Chopra and Sodhi (2004)
	Robustness	The ability of systems to withstand stress or demand without suffering degradation or loss of function.	Brandon-Jones, et al. (2014)

The consideration regarding the ability for flexibility and redundancy strategies to bleed into each other is thought provoking. However, this study assumes firms exploit each SCR strategy as either redundant or flexible. While there are some conflicting definitions for the different sub-strategy resilience efforts, strategies included in this study have been carefully defined to limit confusion.

A redundant SCR strategy is defined as an investment in capital and capacity in order to maintain the ability to respond to disruptions (Tang and Tomlin, 2008). Generally, redundancy is a passive protection from disruptions, while flexibility is an active restructuring of the organization so it is capable of adapting to the new circumstances caused by a disruption (Mackay et al., 2020). Investment in redundancy can be seen as an insurance policy to be used if a disruption occurs and may or may not ever be used in response to a disruption (Rice and Caniato, 2003). Key redundancy strategies include excess capacity, excess inventory stockpiles, robust infrastructure, and multiple supply sources (Shashi et al., 2020). Some researchers consider the excess inventory by means of strategic inventory stock and prepositioning excess capacity to mitigate disruption impact to be some of the most important ways to build SCR (Carvalho et al., 2012; Shashi et al., 2020). Acquiring emergency backup is a powerful tool for firms to build SCR and many researchers believe that redundancy strategies lead towards a higher value of supply chain resilience than flexibility strategies (Ratick et al., 2008; Liu et al., 2016).

A flexibility strategy is defined as an investment in infrastructure and resources in anticipation of a disruption (Tang and Tomlin, 2008). Key flexibility strategies include agility, collaboration, integration, information sharing, innovation, visibility and contingency planning (Dmanpour and Gopalakrishnan, 2001; Barratt, 2004; Svensson, 2004; Li et al., 2005; Francis, 2008; Wieland and Wallenburg, 2012). Flexibility strategies involve restructuring a previously existing system, and therefore are implemented and utilized immediately, altering a firm's operations prior to disruption to better survive and recover when one does occur. Therefore, flexible SCR strategies help firms with more than just disruptions, but improve day to day operations as well (Sheffi, 2005). Thus, I hypothesize:

(H2-1) *Implementing SCR flexibility strategies is positively associated with firm performance.*

(H2-2) *Implementing SCR redundancy strategies is positively associated with firm performance.*

While the literature provides a good deal of support for each of these strategic categories, not all publications agree on which strategy produces the best overall results for the firm. Some researchers propose that while both strategies are critical for organizations to be resilient, there are circumstances where flexible strategies are more beneficial and can be implemented at lower cost (Zsidisin and Wagner, 2010; Carvalho et al., 2012). SCR flexibility strategies have been lauded for their deeper impacts on mitigating organizational risk, which often proves more useful for supply chain risk management than their redundant counterparts (Tang and Tomlin, 2008). Based on these findings, and since this study is incorporating financial performance as a performance measure, it is assumed that the cost prohibitive nature of carrying redundant capacity and resources will lead to a weaker correlation between redundancy strategies and performance. Therefore I hypothesize:

(H2-3) *Implementing SCR flexibility strategies has a stronger positive association to firm performance than investment in SCR redundancy strategies.*

2.2.4 Performance Measures

While there are other factors to consider, a firm's ability to harbor a resilient supply chain has a good deal of influence on its success (Ivanov and Sokolov, 2013). The overall performance of a firm is measured through financial and non-financial (operational) indicators (Gosselin, 2005). Financial performance measures allow organizations to see true operating efficiency and profitability (Teeratansirikool et al., 2013). Most manufacturing organizations rely heavily on financial performance measurements to gain a better understanding of the company's strengths and weaknesses (Gosselin, 2005). Studies support the positive impact of SCR on financial performance measures by enabling firms to face disruptions while also fostering competiveness (Sheffi, 2005; Liu et al., 2017). The ability to respond and recover quicker than competitors is a key component in increasing a firm's profitability and market shares (Liu et al., 2017). Therefore, effective SCR strategies can protect from costly turbulence which leads to a decrease in financial performance (Ivanov & Sokolov, 2013).

A firm's financial performance can be measured using both profitability and return on assets or revenue such as sales and market shares (Leuschner et al., 2013). The primary studies in this study look at financial performance in terms of return on sales, return on investment, market share, sales, profitability, earnings, gross margin, and market value. While some non-financial performance indicators are not very reliable, including these operational measures is critical to see the full picture of how a firm is doing in the short-term and long-term (Chatterji and Levine, 2006). Adding operational performance indicators creates a balanced scorecard, which allows for all processes of the supply chain to be considered and measured and provides good feedback for the company's operations (Kaplan and Norton, 1992; Holmberg, 2000). Supply chain management researchers have utilized quality, flexibility, customer service, and delivery performance as indicators for operational performance (Kauppi et al., 2016). Other indicators in the field include fill rate, lead time, inventory turnover, and on-time delivery (Chae, 2009). The primary studies in this meta-analysis look at operational performance related to customer service, quality of performance, delivery speed/accuracy, product capability, and product performance.

Looking at these two common performance measures in the SCR literature – firm financial performance and firm operational performance, I hypothesize the relationship between the use of SCR strategies and these separate performance measures as:

(H3-1) *Implementing SCR strategies is positively associated with firm financial performance.*

(H3-2) *Implementing SCR strategies is positively associated with firm operational performance.*

Finally, while the supply chain literature agrees that a broad range of performance measures were needed to see the full picture of firm performance, research seems to stress a stronger connection between SCR and firm financial performance (Anand and Grover, 2015). Because decisions regarding an organization's supply chain are critically linked to financial components of the firm, decision makers should understand the financial impact these supply chain actions will have (Elgazzar et al., 2012). Therefore, when considering the strength of association between the aggregated SCR strategies and the different performance measures, I hypothesize:

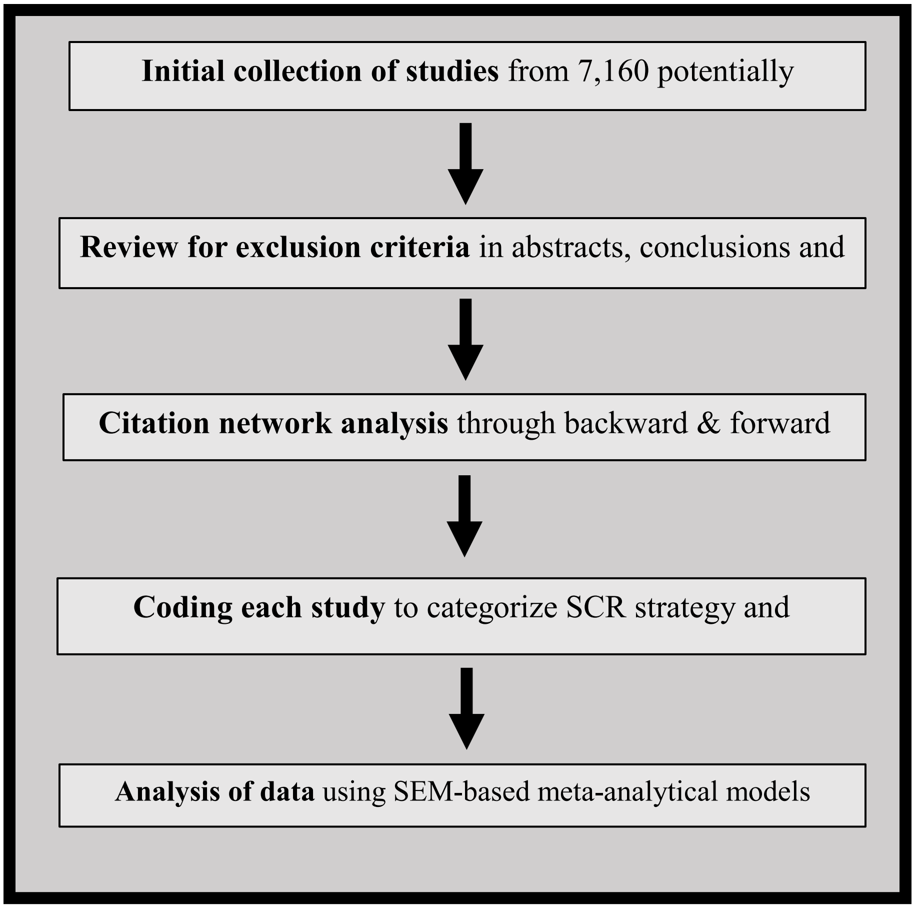
(H3-3) *Implementing SCR strategies has a stronger positive association to financial performance than to operational performance.*

2.3 Methodology

A thorough literature review was conducted to locate the sample of studies for this meta-analysis. The potentially relevant articles discovered in the online databases were narrowed down using key terms and inclusion and exclusion criteria. In addition, forward and backward searches were utilized for finding all relevant studies. Finally, email solicitation was sent to the authors of the studies missing correlation matrices, but no responses were received. Effect sizes from the studies were then coded and prepared for analysis.

Structural equation modeling (SEM)-based meta-analytic models are used in this study to test the hypotheses. Initially, a random-effects model explores the general relationship between SCR strategies and performance. Next, a mixed-effects model tests the relationship between the separate SCR strategies such as redundancy and flexibility and overall performance. Finally, a second mixed-effects model tests the relationship between the two performance measures such as financial and operational and overall SCR strategies. A random-effects model is selected over fixed-effects due to the limited generalizability of results. Figure 1 shows the methodological process flow of this study.

Figure 1. Meta-Analysis Process Flow Diagram



2.3.1 Analysis Method

Effect sizes or correlations, which have already been operationalized and measured in the sample studies, are analyzed for finding cumulative evidence using SEM-based meta-analysis. While some of the variables in the pooled studies may be operationalized differently, ensuring the conceptual definitions are the same allows for the meta-analysis to still gather patterns of correlation among variables of interest (Mackelprang et al., 2014).

The first step to testing the correlation between supply chain resilience (SCR) strategy and firm performance was to record the effect sizes between each set of variables from each primary study. Some researchers choose to utilize primary study Cronbach's alpha or reliability measures in an attempt to correct for attenuation. However, this practice is controversial, and corrected values are sometimes greater than one that is not allowed for correlation values (Cheung, 2015: 243). In fact, a 2011 review of published meta-analyses provided evidence that these statistical corrections did not have much impact on the studies' conclusions (Michel et al., 2011). Therefore, correlation coefficients (*r*) in this study were not corrected to the de-attenuated *r* value (r_c). Pearson correlation coefficients (*r*) were, however, transformed with Fisher's transformation method to correct for differences in primary study sample sizes (Cheung, 2015: 55).

While each effect size gathered will indicate the correlation between the two variables, the -1 to +1 bound of the correlation makes the sample distribution for correlated variables highly skewed and therefore challenging to estimate confidence intervals or to run hypothesis tests (Fouladi and Steiger, 2008). To remedy this, the Fisher's transformation of r (also known as the Fisher z-transformation) is used to convert the skewed distribution of the sample correlation (*r*) into an approximately normal distribution, working as a variance stabilizer (Cheung, 2015: 55). A transformed effect size (y_i) and its variance (v_i) are expressed like the following equations (Cheung, 2015: 55):

$$y_i = 0.5 \log\left(\frac{1+\mathrm{r}}{1-\mathrm{r}}\right) \tag{1}$$

$$v_i = \frac{1}{(n-3)} \tag{2}$$

SEM-based meta-analysis is an approach utilizing structural equation modeling (SEM) to model the correlations between variables (Card, 2012: 289). This approach is beneficial in cases where some studies being used fail to include all variables being analyzed (Card, 2012: 289). This approach also allows researchers to study and address effect size heterogeneity; an important component of any meta-analysis (Higgins and Thompson, 2002). SEM-based meta-analysis makes it possible to compare various studies that utilize a number of sample sizes, conditions and measurements (Cheung, 2015: 55).

A methodological shortcoming in meta-analysis is a dependence on primary studies which may pose concerns in terms of quantity available and quality of the studies collected (Card, 2012: 257-260). To counteract this deficiency, this study utilized multiple databases, an extensive search criteria and an adequate sample size of primary studies. Publication bias has been accounted for by use of the failsafe number (Card, 2012: 268). The failsafe number is the number of studies that would have to be included in a meta-analysis to lower the average effect size to a non-significant level (Orwin, 1983). In this study, the value of the fail-safe N was high enough (60,198) to quell any publication bias concerns (Card, 2012: 270). While SEM-based meta-analysis is an important tool for meta-analysis, it is not without limitations. Specifically, since this method is incorporating summary statistic data, analysis of raw data is not often possible, and any issues with raw data are difficult to correct (Cheung, 2015: 217).

There are three univariate SEM-based meta-analysis models, including fixed-effects models, also known as the common effect model, random-effects models and mixed-effects models (Hedges and Vevea, 1998). The use of the SEM-based meta-analysis fixed-effects model is appropriate when the effects sizes of the sample studies are homogenous and the researcher is looking to synthesize well-controlled studies (Cheung, 2015: 86, 93). Random-effects models are designed to incorporate studies with heterogeneous effect sizes, making them a better fit for pooling studies with different samples, measures or quality (Cheung, 2015: 87). Researchers can use random-effects models to estimate the average effect from all studies as well as the variability in the effect sizes (Cheung, 2015: 87). Random-effects models can be extended by looking at study characteristics as moderators through the use of mixed-effects models (Cheung, 2015: 96). Due to the limited generalizability of the fixed-effects model, this study uses the random-effects and mixed-effects models.

For simplification, the mathematical explanation of the random-effects model was based on the equations expressed in Cheung (2015: 87). Let the true population effect size, β_R, be the mean population effect size in the random-effects model, u_i, be the heterogeneity variance to be estimated, and ε_i be the error terms for the ith observation. Then, the observed effect size, y_i, can be expressed as the following:

$$y_i = f_i + \varepsilon_i \tag{3}$$

$$f_i = \beta_R + u_i \tag{4}$$

where u_i is distributed with the mean, zero, and the variance of the true effect size, τ^2, is theoretically not influenced by the sampling error. We can merge the equations (3) and (4) to get equation (5):

$$y_i = \beta_R + u_i + \varepsilon_i \tag{5}$$

With v_i as error variance, equation (5) can be used to express the distribution for y_i as:

$$y_i \sim \mathrm{N}\,(\beta_R, \tau^2 + v_i) \qquad (6)$$

The univariate random-effects meta-analytic model becomes a one-factor confirmatory factor analysis model with one indicator (Cheung, 2015:137). Figure 2 is a graphical representation of the equation (6). The constant one is shown as the triangle, and the observed variable is represented using the rectangle.

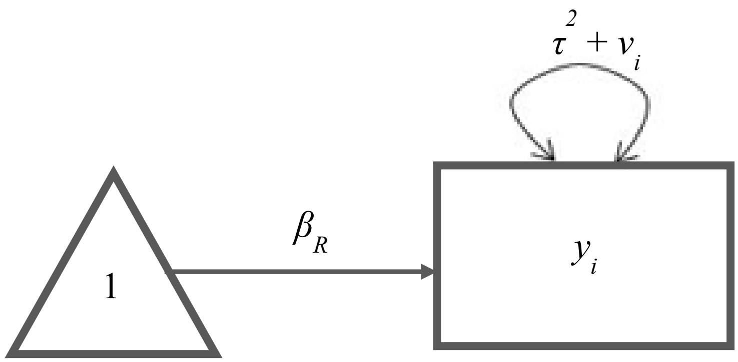


Figure 2. Meta-Analysis Random-Effects Model (Cheung, 2015: 82)

The following equation (7) implies moments are fitted for executing the univariate random-effects meta-analysis, where β_R and τ^2 are estimated simultaneously:

$$\mu_i\,(\theta) = \beta_R \text{ and } \textstyle\sum_i (\theta) = \tau^2 + v_i \qquad (7)$$

As discussed, random-effects models can be extended by looking at study characteristics as moderators through the use of mixed-effects models (Cheung, 2015: 138). A mixed-effects model that treats moderators as variables is reviewed in this study. The following mathematical equation represents the mixed-effects model. The equation for the observed effect size is the same as in equation (5), and the true population effect size is defined as the following in equation (8):

$$f_i = \beta_0 + \beta_1 x_i + u_i \qquad (8)$$

Figure 3 shows the graphical representation of the equation (8) mixed-effects model that treats the moderators as the variables.

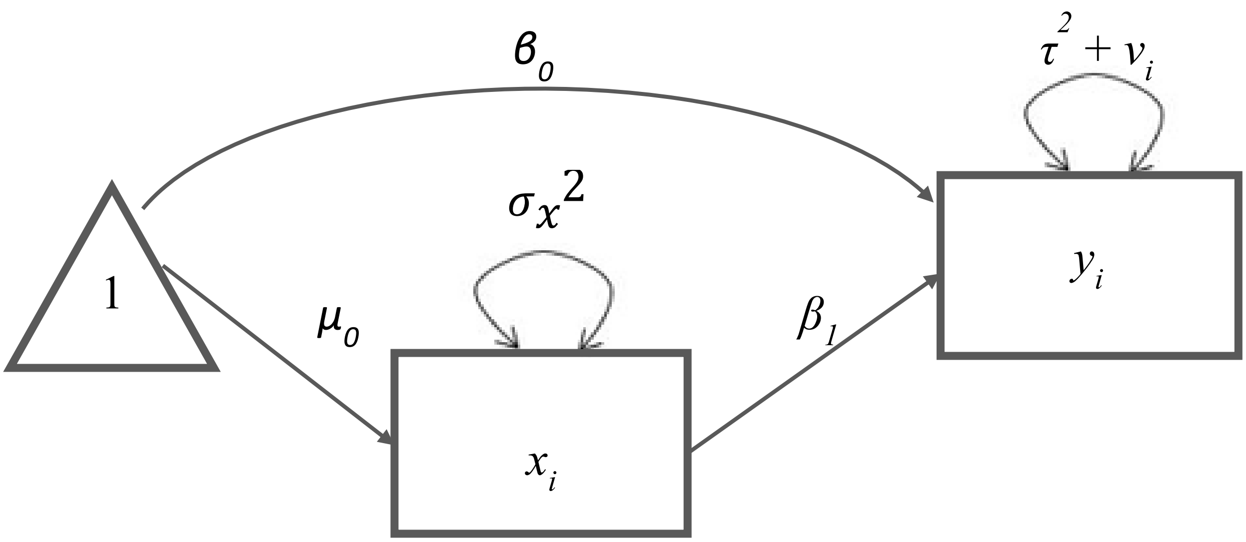


Figure 3. Meta-Analysis Mixed-Effects Model (Cheung, 2015: 103)

Similar to the equation (7), the following two moments are fitted in equation (9):

$$\mu_i\ (\theta|x_i) = \mathrm{x}^{\mathrm{T}}\beta \text{ and } \textstyle\sum_i\ (\theta|x_i) = \tau^2 + v_i \qquad (9)$$

To conduct the data analysis, I utilized the metaSEM package in R (R Core Team, 2018).

2.3.2 Data Collection

For this study, a systematic literature search was conducted for keywords including supply chain resilience and firm performance, using the sets of terms: [supply chain resilience or supply chain resiliency], [performance or operational performance or financial performance] and [correlation, meta-analysis, or SEM] in the full text, abstract or key words listing of publications between the year 2000 and 2020. Databases searched to discover the required studies included EBSCOhost and Google Scholar. In September 2020, this initial search returned approximately 643 articles. The studies were not limited by theory or type of firm, but were limited by method. Including only empirical studies with effect size data narrowed the results to a total of 174 articles. Finally, the articles were reviewed for inclusion of hypothesized relationships between a supply chain resilience strategy and the performance of a firm. A review of the initial collection of studies for this additional exclusion criteria resulted in 21 useful articles. Table 2 outlines the material search keywords used to search in the EBSCOhost and Google Scholar databases.

Table 2. Material Search

Databases searched	**EBSCOhost AND Google Scholar**
Keywords Used	**["supply chain resilience" OR "supply chain resiliency"] AND ["performance" OR "financial performance" OR "operational performance"] AND [correlation OR meta-analysis OR SEM]**
Date range	**2000-2020**
Total hits from keywords	**643**
Articles meeting data structure requirement	**174**
Articles meeting hypothesis / content review	**21**

Finally, backward and forward searches through citation network analysis were conducted, and email requests were sent to the authors of articles found with no usable correlation matrices. These efforts presented no other useful articles. In total, 21 articles were identified in the overall search.

2.3.3 Sample Characteristics

The relationship between supply chain resilience and performance has been studied with increasing interest over the last twenty years (Shashi et al., 2020). The sample collected for this meta-analysis represents a diverse range of empirical studies published between 2013 and 2020 from seventeen different journals. Table 3 provides a summary of the sample studies used in the meta-analysis.

While most journals represented only one of the articles used in this meta-analysis, the *International Journal of Production Research* and the *International Journal of Production Economics* are the two journals responsible for the highest number of studies at three each. The majority of the twenty-one samples used (57%) were studies conducted in the manufacturing industry. At 29% of the sample studies used, supply chain management organizations were the next most common industry, followed by the retail and the marketing industries, each representing 0.5% of the sample size.

The primary studies used in this meta-analysis referenced firms most often operating in the Asia and Pacific regions of the world (52%), but also included several studies conducted on firms operating in Europe and Africa (19%) and the Americas (14%). There were also two studies that gathered data from firms internationally and one studied that did not specify a location for their firms.

Table 3. Meta-Analysis Sample Summary

Location	Total n (%)	*Industry*	Total n (%)
Asia and the Pacific	11(52%)	Manufacturing	12(57%)
Europe and Africa	4(19%)	Supply Chain Management	7(33%)
Americas	3(14%)	Marketing	1(~5%)
International	2(10%)	Retail	1(~5%)
Unspecified	1(~5%)	*Year of Publication*	
		Range	2013-2020
		Median	2018
		Mode	2019, 7(33%)

Journal	Total n (%)
International Journal of Production Research	3(14%)
International Journal of Production Economics	3(14%)
Business: Theory & Practice	1(~5%)
Decision Sciences	1(~5%)
European Management Journal	1(~5%)
Industrial Marketing Management	1(~5%)
International Journal of Disaster Resilience in the Built Environment	1(~5%)
International Journal of Physical Distribution & Logistics Management.	1(~5%)
Journal of Business Logistics	1(~5%)
Journal of Industrial Engineering and Management	1(~5%)
Journal of Manufacturing Technology Management	1(~5%)
Journal of Transport and Supply Chain Management	1(~5%)
Supply Chain Management: An International Journal	1(~5%)
Other	4(19%)

2.3.4 Variables

This study looks at supply chain resilience (SCR) strategies as both a single and multi-dimensional measure. As a single measure, all SCR strategies used by firms in the primary studies were grouped together. For a multi-dimensional look, the strategies utilized in the primary studies were classified into one of two categories such as redundancy or flexibility. Flexibility strategies allow the firm to better respond to disruptions through rapidly adapting operations (Lee, 2004). Redundancy strategies create back up buffers to resist the impact of a disruption (Sheffi, 2005). As previously discussed in Table 1, flexibility strategies include agility, collaboration, contingency planning, information sharing, innovation and visibility. Redundancy strategies include excess capacity, excess inventory, redundant suppliers and robustness. The majority of the studies tested the correlation of flexibility SCR strategies on performance (95%) where fewer studies incorporated redundancy based strategies (33%). Six of the studies (29%) tested both flexibility and redundancy SCR strategies.

In this study, firm performance is categorized as either financial performance or operational performance. In the primary studies, different constructs and measures were used to represent performance. For financial performance, primary studies measured return on sales, return on investment, market share, sales, profitability, earnings, gross margin, and market value. For operational performance, studies most often cited performance outcomes related to customer service, quality of performance, delivery speed/accuracy, product capability, and product performance. In total, 67% of primary studies utilized operational performance measures, 52% utilized financial performance measures, and 19% cited both types of performance measures in their studies.

2.4 Results and Discussion

To analyse aggregated correlation effects sizes of the models, estimated effects sizes of 0.5 were considered strong, estimated effects sizes of 0.3 were considered moderate and estimated effects sizes of 0.1 were considered weak correlations (Cohen, 1992).

2.4.1 General Model

The first hypothesis was tested through SEM-based meta-analysis random-effects modelling. The model was fitted for an overall effect size between two aggregated constructs (SCR strategies & firm performance). The estimated population effect size (β_R) was found to be 0.414064, which was positive and significant at $\alpha = 0.01$. This finding provides evidence that SCR strategies are moderately associated with firm performance and supports the relationship proposed in the first hypothesis. The variance of the true effect sizes (τ^2) of 0.089756 is significant at $\alpha = 0.01$. The results are presented in Table 4.

Table 4. Meta-Analysis of General Model

Meta-Analysis Overall SCR Strategies on Overall Performance Model Results						
	Estimate	Standard Error	Lower Bound	Upper Bound	z-value	Significance
SCR Strategies	0.414064	0.037739	0.340097	0.488031	10.9718	0.000***
Tau (τ^2)	0.089756	0.01642	0.057573	0.121939	5.4662	0.000***
Significance: '***' <0.001 '**' <0.01 '*' <0.05						

Determining the heterogeneity of effects sizes is conducted using the Q-statistic and the I^2 value that show the percentage of variability among effect sizes that exists between studies relative to the total variability among effects sizes. Heterogeneity of effect sizes was supported by a significantly high Q-statistic, 1,645.47, given the degrees of freedom, 64. Furthermore, the I^2 value supports a high magnitude of heterogeneity at

96.6 percent (Card, 2012: 330). These findings in the general model support moving forward to test hypotheses 2 and 3 to predict the between-study differences in effect size (Card, 2012: 232).

2.4.2 SCR Strategy Model

Hypothesis two was tested by dividing SCR strategies into two categories such as flexibility strategies and redundancy strategies and by analyzing the effects size between each category and aggregated firm performance. Dummy variables were used in the mixed-effects model to indicate the SCR strategy of interest. Results for this analysis are shown in Table 5.

Table 5. Meta-Analysis of SCR Strategy Model

Meta-Analysis SCR Strategy Model Results						
	Estimate	Standard Error	Lower Bound	Upper Bound	z-value	Significance
Flexibility	0.470275	0.038998	0.39384	0.546711	12.0589	0.000***
Redundancy	0.180246	0.079368	0.024688	0.335805	2.271	0.02315*
Tau (τ^2)	0.076629	0.01411	0.048973	0.104284	5.4307	0.000***
Significance: '***' <0.001 '**' <0.01 '*' <0.05						

Results from the mixed-effects SCR strategy model show that while the effects sizes for both flexibility and redundancy strategies are positive, flexibility provides a much stronger correlation (0.470275) to performance than redundancy (0.180246). To test that these strategies are truly significantly different, the SCR Strategy model is compared with the general model using analysis of variance (ANOVA). The analysis returned a likelihood ratio statistic of 9.977 with one degree of freedom difference, which is significant at $\alpha = 0.01$. Therefore, the null hypothesis is rejected, concluding that there is a difference between the two models and that classifying SCR Strategies into these two categories is worthwhile for understanding the relationship between SCR strategies and firm performance.

2.4.3 Performance Model

Hypothesis three was tested by dividing firm performance into two categories such as financial performance and operational performance and analyzing the effects size between each category and aggregated SCR strategies. Dummy variables were used in the mixed-effects model to indicate the performance measure of interest. Results for this analysis are shown in Table 6.

Table 6. Meta-Analysis of Performance Model

Meta-Analysis Performance Model Results						
	Estimate	Standard Error	Lower Bound	Upper Bound	z-value	Significance
Financial Performance (FP)	0.448439	0.053163	0.344242	0.552636	8.4352	0.000***
Operational Performance (OP)	0.380024	0.052879	0.276383	0.483665	7.1866	0.000***
Tau (τ^2)	0.088529	0.016217	0.056744	0.120313	5.4591	0.000***
Significance: '***' <0.001 '**' <0.01 '*' <0.05						

Results from the SEM-based meta-analysis mixed-effects performance model show that the effects sizes for both financial performance (0.448439) and operational performance (0.380024) are positive and represent moderate correlations to the aggregated SCR strategies. The overlapping confidence intervals by the two performance measures suggest that the two categories are not statistically different, and differences in the two categories may be explained by sampling variance.

To test if these performance categories are statistically different, the performance model is compared with the general model using ANOVA. The analysis returned a likelihood ratio statistic of 0.827 with one degree of freedom difference, which is insignificant at $\alpha = 0.01$. Therefore, the null hypothesis fails to reject, concluding that there is a no significant difference between the two categories. Based on this data, classifying firm performance into these two categories is not helpful in understanding the relationship between SCR strategies and different firm performance.

2.4.4 Discussion

The general model resulted in a significant and moderate effect. Therefore, the hypothesis (H1), SCR strategies are positively associated with firm performance, was supported. Support for this hypothesis and the general model suggests that a broad range of SCR strategies can be used to benefit firm performance. Support for the general model demonstrates how SCR strategies can improve a firm's ability to maintain a competitive advantage. If a company can identify vulnerabilities in its supply chain and fill the gap, it will be able to maintain production, minimize downtime, and recover quicker in the event of a disruption to its supply chain.

To test the second set of hypotheses, involving the individual categories of SCR strategies and pooled firm performance, a mixed-effects model was employed. In the SCR strategy model, two categories of SCR strategies (flexibility and redundancy) were tested. Both SCR strategies showed significant and positive associations with firm performance, with a stronger positive association between flexibility strategies and performance identified. Neither confidence intervals overlaps, which suggest that the two strategy categories truly have distinct effects on firm performance. Thus, H2-1, H2-2, and H2-3 were supported. In addition, the ANOVA test supports this finding that classifying SCR strategies into two categories is meaningful.

To test the third set of hypotheses involving the pooled SCR strategies and individual performance categories (financial and operational performance), another mixed-effects model was employed. While both performance categories used in the performance model were significantly and positively associated with the aggregated SCR strategies, the individual effects of financial performance and operational performance were not distinctive as indicated by overlapped confidence intervals. Accordingly, H3-1 and H3-2 are supported. However, H3-3 is not. In addition, the insignificant ANOVA result for comparing the performance model to the general model indicates that classifying performance measures into different categories by aggregating the SCR strategies is not meaningful.

2.4.5 Recommendations for Practitioners

The results of this study provide a couple important recommendations for practitioners:

(1) Supply chain resilience (SCR) strategies are required to ensure your organization is prepared for disruptions to your supply chain. It is recommended, when looking to invest in strategies that are right for your organization, to focus on flexibility strategies that support a more transparent, collaborative, and responsive environment. Strategies to build flexibility involve efforts made to aid the firm in sensing threats to the supply chain and responding more rapidly (Sheffi and Rice, 2005). While redundancy strategies centered on excess capacity, inventory, and robust infrastructure will most likely have a positive impact on the performance of your firm when faced with disruption, this study

provides evidence to support that the greater return on investment can be realized through an emphasis on flexibility.

(2) It is recommended that relying on a diverse set of performance measures to determine the impact of investments in SCR strategies on your firm. Relying on only financial performance measures or only operational performance measures will not enable a firm to see the true impact of the SCR strategy efforts. Set your performance measures based on the goals and priorities of your firm by including both financial and operational outcomes.

2.5 Conclusion

Supply chain resilience is a rapidly expanding research topic of interest. Over the last twenty years, great strides have been made in regards to the way researchers and practitioners look at the supply chain, and how it can best be organized and managed. Where firms once take very isolationist views on running their operations, they now accept the impact that the whole supply chain has on the success of its parts. Now, more than ever, lean, transparent, and agile systems are seen as solutions to stay ahead of rapidly changing global markets. Keeping supply chains resilient when faced with so many uncertainties across these vastly connected networks can seem overwhelming.

This study examined the relationship between different SCR strategies and firm performance measures in three different models: a general model, a SCR strategy model, and a performance model. Using a resource-based view of the firm and SEM-based meta-analysis, SCR strategies were identified as resource-based capabilities that could provide competitive advantage and a positive relationship to firm performance outcomes.

2.5.1 Theoretical Implications

Evidence provided by this study supports SCR strategies as resource-based capabilities, which dispense a competitive advantage to the firm. This study supports not only a general positive relationship between SCR strategies and performance measures but also the distinctive categorization of SCR strategies into flexibility and redundancy lanes. Classifying performance measures into two separate categories was not meaningful. In addition, this study is a novel application of SEM-based meta-analysis for examining cumulative findings on the relationship between SCR strategies and firm performance outcomes, which is rare in the supply chain management area.

2.5.2 Managerial Implications

This study provides evidence to support that firms can improve their performance by putting forth an effort to increase the resilience of their supply chains. This evidence can inform decision makers on how to best invest the money their firm has set aside for supply chain resilience and help persuade firms to invest in resilience if they were on the fence about the importance of that investment. This knowledge can assist in better informed, more targeted SCR investments, increase a firm's competitive advantage, and provide the best performance outcome for the organization as a whole. A strong positive association between SCR flexibility strategies and performance should encourage managers to prioritize flexibility investments to maintain performance and gain competitive advantage.

2.5.3 Limitations and Future Research

This research effort is focused on the relationship between specific categories of SCR strategies and firm performance outcomes. While it supports the idea that SCR is important to the performance of a firm, it is limited in its ability to analyze the relationship between aggregated variables. Part of this issue is due to the limited primary studies concerning SCR strategies and performance measures. In addition, while this study shows a positive association between performance and SCR strategies, it does not address how a failure to implement SCR strategies is associated with firm performance.

Notably, one of the main limitations of this study is the use of primary studies that analyze qualitative survey data. Since survey responses tend to record a respondents' perception on the questions or topics asked by researchers, it is difficult to understand motivation and perspective behind each respondents answer. Therefore, consistency of measures and reliability of the effect sizes may be questionable.

Current literature has identified the need for comparing different SCR strategies used to improve performance, but is lacking in studies on the interactions between strategies (Shashi et al., 2020). The question stands, does the use of flexibility strategies have an impact on the correlation between the use of redundant SCR strategies and performance? Published research provides evidence to support that the incorporation of flexibility strategies can improve efficient use of redundant resources (Hopp and Xu, 2008). Other research suggests that there is a tradeoff between investment in flexibility and redundancy resilience strategies (Deflem and Van Nieuwenhuyse, 2011). Organizations must determine the optimal level of investment in either strategy based on their budget and unique operating environment when making SCR investment decisions. The more an organization chooses to invest in one, the less they are able to invest in the other. Taking these ideas a step further, future research may consider looking closer at the interactions between the two categories of SCR strategies. Does investment in redundancy degrade strategies to improve flexibility? Is there a moderating impact of one strategy on the other?

Future research could also analyze the cost of investing in each type of resilience strategy. While flexibility strategies may have a greater impact on performance, are these strategies cost-prohibitive in the long run? Furthermore, what is the cost to an organization of not investing in that resilience strategy? If investing in one strategy carries a sticker shock, and does not yield high levels of increased performance, managers may steer away from it. However, would managers make the same choice if they knew the cost of not investing in that strategy? Perhaps the cost to a firm's performance by not investing is undermining efforts elsewhere to boost SCR, degrading the impact of other SCR strategy investments. All of these topics would be worthwhile future research efforts to pursue.

III. Measuring Supply Chain Resilience for Informed Resilience Strategy Investment

3.1 Introduction

At the height of the COVID-19 pandemic, supply chains throughout the world were disrupted in epic proportions. Global supply chains supporting industries responsible for producing and distributing food, healthcare products, paper products and cleaning supplies were having trouble meeting growing demands (Singh et al., 2020). While product demand spiked, forced lockdowns incapacitated workforces which slowed production, increased supplier backorders, and limited transportation options (Ivanov and Das, 2020). While some industries showcased their flexibility by transforming their production operations to meet pandemic needs, others relied on redundant stockpiles of raw materials or capacity to increase operations to meet customer demand (Singh et al., 2020; Iswara, 2020). As countries around the world reacted to the pandemic, organizations lacking resilient supply chains were forced to shut down or throttle back, with a cascading effect of an estimated forty million jobs lost worldwide (Singh et al., 2020).

The importance of logistics and supply chains has long been recognized as critical to both commercial and military operations. The modern economy has enhanced supply chain importance by connecting global governments, militaries and private companies to an unprecedented extent. Whether from pandemic, natural disaster, war, or purposeful disruption by an adversary, there are inherent risks in any supply chain. These risks lead to disruptions which impact network performance and damage profit.

How supply chains respond to these disruptions can have consequences that shape the competitive landscape and future of entire industries (Sheffi, 2005). Thus, it is important to understand how to measure a supply chain's resilience to these disruptions so that organizations invest in the best strategies for more resilient systems. Properly defining and measuring the resilience of a supply chain is an important step to improving risk management and organizational performance.

The ability to respond to and recover from disruptions is a critical component of supply chain resilience (SCR). SCR involves building capabilities within a supply chain which can work to counteract vulnerabilities the supply chain might face (Pettit et al., 2010). With limited organizational budgets, investments in SCR must be carefully considered. In order to better inform those investments, decision makers require an accurate assessment of available options.

One way to assess SCR is by reviewing an organization's performance over time in phases following a disruption event (Barroso et al., 2015). These phases make up a resilience triangle (or curve) depicting a characteristic drop in performance after a disruption event and a recovery period for the performance to return to pre-disruption levels (Barroso et al., 2015). A good way of seeing it is through the concept of resistance and recovery capacity (Melynk et al., 2014). Resistance capacity as the ability of a system to minimize the impact of a disruption by evading it entirely or by minimizing the time between disruption onset and the start of recovery from the disruption, and recovery capacity as the ability of a system to return to functionality once a disruption has occurred (Melynk et al., 2014). While resilience literature provides a range of metrics to measure SCR at different phases of the resilience curve, current research provides limited guidance on measuring SCR as a cumulative whole from disruption to recovery (Simchi-Levi et al., 2018; Gao et al., 2019; Behzadi et al., 2020). The SCR measurement strategies that do consider the whole resilience curve tend to focus on measuring the loss of performance after a disruption event making it difficult to compare systems with different pre-disruption performance levels (Bruneau et al., 2003; Melnyk et al., 2014; Zobel and Khansa, 2014; Todman et al., 2016; MacDonald et al., 2018).

To better quantify supply chain resilience, this research developed the Resilience Capability Metric (RCM). RCM uses an Area under the curve (AUC) of supply chain performance following a disruption to quantify cumulative system performance over time after disruption. It is proposed that SCR can be measured relative to the supply chain's requirements by the ratio of the AUC to the system's total demand over time. The different SCR investment options are operationalized through the use of inventory, capacity and time to demonstrate the use of the RCM in a simulation model based on the United States Air Force (USAF) repair network supply chain for aircraft engines.

The contributions of this paper are: (1) the development of RCM which allows for SCR to be measured as system performance over time with AUC, (2) comparing the resilience of various unrelated systems with different pre-disruption steady states and recovery capacity, (3) demonstrating how to use the RCM to explore the trade-offs between investing in spare parts and system repair capacity with respect to supply chain resistance, recovery, and overall resilience, and finally, (4) through this model the importance that recovery response time plays in resilience is highlighted.

Ultimately, the goal of quantifying SCR is to determine the best SCR investment strategy to improve system resilience. Predicting how different supply chain designs will respond to a disruption enables rigorous comparison and selection of investment tradeoffs in anticipation of a disruption occurrence. This research aims to provide managers with a SCR metric that will allow for informed capital allocation decisions when designing and assessing supply chains.

3.2 Literature Review

Resilience has been studied across many domains. Most supply chain resilience research has focused on examining recent historical events and categorizing how different practices led to different outcomes. When faced with a disruption, a more resilient supply chain enables better network performance, but determining which investments to make to increase resiliency is still the major question. These investment decisions must consider all phases of network performance, from initial steady state to disruption and to recovery to determine what resilience levers should be pulled. Understanding the way disruptions impact the network and how different resilience strategies cause the network to respond is critical to the network's long term resilience. Ultimately, having a good metric to quantify resilience is important to realize the impact of and to justify each resilience strategy investment. The relevant streams of literature to answer this question are (1) supply chain resilience frameworks, (2) flexibility and redundancy, (3) investment in resilience and (4) resilience performance metrics.

3.2.1 Supply Chain Resilience (SCR)

Supply chain Resilience (SCR) is the ability for a supply chain to reduce the probability of disruption, reduce the spread of a disruption's impact, and recover the supply chain back to functioning operations (Ponomarov and Holcomb, 2009). In the last twenty years, over sixty empirical research studies have been published contributing to the establishment of a systemic framework for SCR, better defining SCR properties and understanding the strategies that are used to operationalize SCR (Shashi et al., 2020).

Throughout the last two decades, research in the field of SCR has grown from a risk management concept that sustainable supply chains are important to the health of an organization, to the understanding that proper SCR strategies can be leveraged to protect organizations from disastrous disruptions (Kochan and Nowicki, 2018). With the understanding that companies are often driven by financial performance, the idea of sustainable supply chain management (SSCM) was established to improve an organization's supply chain sustainability for long-term economic success (Carter and Rogers, 2008). As more research was conducted on SSCM, SCR frameworks were developed to highlight the importance of balancing an organization's investment in its supply chain capabilities to improve resilience, and counteract supply chain vulnerabilities that had been identified (Pettit et al., 2010). Achieving the best possible outcome for the resilience of an organization's supply chain means understanding this balance between vulnerabilities and resilience investments (Pettit et al., 2010).

There is a keen understanding in the SCR literature that a resilient supply chain can impact the success or failure of an organization. Researchers have developed metrics to measure and predict supply chain response to disruption in order to measure a supply chain's resilience (Behzadi et al., 2020). Recording an organization's performance over time in phases in a resilience triangle (or resilience curve) has been useful for illustrating a supply chain's response to a disruption event (Barroso et al., 2015). These phases, sometimes referred to as the resistance phase and recovery phase, depict a characteristic drop in performance after a disruption event and a recovery period for the performance to return to pre-disruption levels (Melynk et al., 2014; Barroso et al., 2015).

Throughout years of research, the SCR literature continues to support the idea that organizations must embrace supply chain risk management culture in order to become more resilient (Christopher and Peck, 2004; Sheffi, 2005; Chowdhury and Quaddus, 2016). Numerous research efforts have been published on the topic of investment in SCR strategies to improve the performance of the supply chain and the overall performance of an organization (Shashi et al., 2020). The research shows that targeted investments in redundant, robust, resistant supply chains, and investments in flexible, agile, responsive supply chains are both important strategies to increase supply chain resilience when anticipating disruptions (Christopher and Peck, 2004; Hasani and Khosrojerdi, 2016; Shashi et al, 2020). Building flexibility and redundancy into an organization’s supply chain can increase SCR and better protect organization performance (Christopher and Peck, 2004; Sheffi and Rice, 2005).

3.2.2 Flexibility & Redundancy

One way to classify organizational strategies to build SCR is as either redundancy or flexibility-focused (Sheffi and Rice, 2005; Zsidisin and Wagner, 2010; Kamalahamdi and Parast, 2016; Kochan and Nowicki, 2018). Flexibility strategies deal with investing in infrastructure and resources in anticipation of a disruption to enable a quick response (Sheffi and Rice, 2005). Redundancy strategies deal with investing in capital and capacity as a security buffer to disruption impacts (Tang and Tomlin, 2008). Resources are kept in reserve by means of safety stock, establishing redundant supplier options or operating with low capacity utilization rates (Zsidisin and Wagner, 2010). A redundancy investment may or may not ever be used in response to a disruption, but flexibility strategies involve immediate restructuring of previously existing organizational capabilities (Rice and Caniato, 2003; Kochan and Nowicki, 2018). Generally, redundancy is a more passive protection from disruptions, while flexibility is an active restructuring of the organization and supply chain so it is capable of rapidly responding to challenges created by a disruption (Mackay et al., 2020).

Case studies documented in the literature support the claim that companies may be able to influence uncertainty through strategic flexibility (Pagell et al., 2000). These flexibility strategies can be especially critical to rapid recovery of supply chains that have seen catastrophic damage due to natural disaster. Implementing processes that leverage conversion flexibility, such as interchangeable people and equipment, can allow organizations to easily relocate operations in the event of a disruption (Sheffi and Rice, 2005). The literature provides a great deal of evidence to support increased resilience in times of disruption through supply chain flexibility (Sheffi and Rice, 2005).

Utilizing supply chain redundancy strategies to ensure resilience and stability is also well documented in supply chain resilience literature (Dong, 2006; Tang, 2006; Zsidisin and Wagner, 2010). Redundancy strategies can provide cost savings for the firm by mitigating disruptions that threaten to reduce capacity and cause an inability to meet demand (Ambulkar et al., 2015). Employing these strategies can assist in the supply chain’s resistance capacity immediately following a disruption to the chain, creating a buffer while allowing the organization to recover from the disruption (Zsidisin and

Wagner, 2010). For example, investing in multiple, decentralized systems or backup power generation systems that can withstand natural disasters can allow an organization to continue to meet customer demand and hold off performance level dips after disruption (Forbes and Wilson, 2018).

Another way that a SCR redundancy strategy can be implemented is through the addition of stockpiled inventory and added production capacity to the network (Sheffi and Rice, 2005). These two redundancy strategies are utilized in this model, operationalizing the concept of excess inventory and production capacity through an organizational investment in increased numbers of spare parts inventory and added excess capacity to repair the parts that break. While both investment in inventory and capacity are considered a redundancy strategy, each has a different impact on the network's performance. Without a way to measure the cumulative impact of their investment, firms cannot be sure in which type of capacity should be prioritized. This research utilizes the developed RCM to demonstrate the trade-off between both types of redundancy investment with respect to supply chain resistance, recovery, and overall resilience.

3.2.3 Investment in Resilience Strategies

Once a firm accepts that vulnerabilities exist in their supply chain, it must determine how to mitigate the impacts of a disruption and limit the risk to the firm's performance. In any organization, the budget available for resilience investments will not be unlimited. A company must determine where the best area of investment would be for its specific vulnerabilities (Melnyk et al., 2014). Under conditions of uncertain risk the best investment approach may be to invest in the ability to recover from a broad range of disruptions, but a company with more predictable risks may want to be more targeted with its SCR strategy investments (Melnyk et al., 2014). It is important to analyze a network's unique ability for resistance and recovery, as well as which areas are most vulnerable to disruption and pose the greatest risk to the network's performance. Furthermore, organizations must identify which resilience strategies carry the highest investment costs, and which strategies will have the greatest impact on improving the firm's resilience.

This research looks at the SCR redundancy strategies of investment in inventory and investment in production capacity to improve resilience. Although these are both redundancy strategies, excess inventory investments (often referred to as reserve mitigation inventory or RMI) and excess capacity investments (reserve capacity) impact the organization differently (Lücker et al., 2019). Each type of redundancy investment comes with an added expense to the organization. RMI is extra inventory built up to ensure customer demands are met in the event of a supply chain disruption, which is different from safety stock used to address demand uncertainty (Lücker et al., 2019). Investment in RMI will mean an initial bulk purchase cost and higher holding costs for the excess inventory (Lücker et al., 2019). Reserve capacity is the act of reserving capacity which can be used for production if there is a disruption event which impacts the supply chain (Lücker and Seifert, 2016). Choosing a reserve capacity strategy will mean a large upfront investment and low capacity utilization rates (Zsidisin and Wagner, 2010).

Literature in this area makes the argument for selecting risk mitigation redundancy investments which best align with the type of industry supported by the supply chain (Lücker et al., 2019). Models have already been developed to evaluate the way investments in RMI and reserve capacity are used to manage the impact of disruptions to determine the optimal strategy for a certain type of organizations and the level of investment required (Lücker et al., 2019; Tomlin, 2006). These models found that the optimal amount of reserve capacity will always increase as variation for normally distributed demand increases, but that the optimal amount of RMI can increase or decrease with demand variation based on holding costs (Lücker et al., 2019). Optimal RMI levels will decrease in an organization that has high holding costs as demand uncertainty increase, and RMI levels will increase as demand uncertainty increases if holding costs are low. Therefore, determining how much reserve inventory and capacity an organization holds will be specific to that organization and the costs associated with their inventory. Keeping in mind that the optimal levels of inventory and capacity will be organization dependent due to holding costs, this research went a step further to see the different impacts that the two redundancy strategies can have on supply chain resilience (SCR). If cost was not in the equation, which strategy would have the greatest impact on resilience?

3.2.4 Resilience Performance Metrics

There are multiple metrics used to analyze the resilience of supply chains. Behzadi et al. (2020) establishes three main classifications of metrics that have been used in SCR, including those that measure recovery time (Time to Recover or TTR), recovery level (RL), and loss of performance during recovery (LPR). These classifications can be modified or combined depending on different performance measures available or goals of the researcher. Another metric that has been commonly used with supply chain resilience is time to survive (TTS) (Simchi-Levi et al., 2018).

TTR metrics tend to take on time-based performance measures such as Out-of-service time, Lead-time ratio, and On-time delivery (Losada et al., 2012; Carvalho et al., 2012; Schmitt and Singh, 2012). TTRs can define resilience as lead-time ratio between promised and actual lead-times, or as speed of recovery by multiplying the ratio of disrupted performance over baseline performance by the ratio of steady recovered performance over the baseline performance (Carvalho et al., 2012; Francis and Bekera, 2014). TTR metrics are focused on time-based performance measures, which are great for organizations that are focused on returning to normal operations post disruption and need to optimize the time it takes to make that transition happen. However, in some supply chain networks, speed of recovery may not be the most important component to resilience.

For some organizations, meeting or maintaining a specific demand or service level is a greater concern than speed. Time to Survive (TTS) is the metric that indicates how long an organization can continue matching demand if faced with a disruption (Simchi-Levi et al., 2018). Calculating TTS helps identify challenges within the supply chain and allows the entire supply chain to be mapped out to identify the needs of each node (Simchi-Levi et al., 2018). Organizations can test their resilience by observing how long performance demands can be met post-disruption (without reactive recovery efforts) after a simulated disruption.

A metric that measures recovery levels (RLs) focus on modeling service levels and supply chain responsiveness through unfulfilled demand rate (Behzadi et al., 2020).

Normally this metric is defined as the fraction of baseline performance that is able to be recovered after a disruption and can be measured by utilizing customer service levels, fill rates, backorder rate, or unfulfilled demand percentages (Behzadi et al., 2020). The main focus of the RL metric are the long-term performance goals of the system (Behzadi et al., 2020). While RLs help to paint a picture of how recovered a supply chain is at a point in time after a disruption occurred, they do not do a great job of painting the whole picture of SCR since they are focused on only half of the resilience picture. Determining the amount of baseline performance recovered post disruption is helpful for analyzing the recovery capacity of a system, but the metric neglects some key measurements regarding the system's capacity to resist the impact of a disruption (Melynk et al., 2014).

Another metric with a narrow focus on the recovery capacity of the supply chain is the Loss of Performance during Recovery (LPR) metric. LPRs utilize performance measures that focus on what is being lost (profit or performance) during the recovery period after a disruption (Behzadi et al., 2020). This metric also fails to identify key resilience capabilities or vulnerabilities in the resistance capacity of the supply chain system, and therefore the cumulative resilience of the supply chain. Of all these commonly used metrics, existing SCR literature mainly focuses on the TTR metric to measure a network's resilience (Simchi-Levi et al., 2014, 2015; Gao et al., 2019). TTS, TTR, RL and LPR are all resilience performance metrics that focus on only one aspect of resilience. TTS determines how long an organization can meet demand, TTR determines the time it takes to recover, RL considers long-term performance and LPR is intent on short-term performance (Simchi-Levi et al., 2018; Behzadi et al., 2020).

Since first published by Bruneau et al. (2003), Area under the Curve (AUC) has been used to analyze an organization's resilience after a disruption (Melnyk et al., 2014; Todman et al., 2016; MacDonald et al., 2018; Murdock, 2018). Using AUC, researchers can measure relative amount of performance lost in the supply chain after disruption in order to quantify that supply chain's resilience (Melnyk et al., 2014; Zobel and Khansa, 2014; Todman et al., 2016; MacDonald et al., 2018). The use of AUC allows both the resistance and recovery phases of the resilience curve to be considered in the overall SCR measurement. AUC is also used in the field of ecological resilience, which looks at the ability for a system to tolerate disturbance without changing to an alternative configuration (Holling, 1973: Todman et al., 2016). In this situation, AUC is utilized to realize the cumulative magnitude of a system's performance before a new state is reached (Todman et al., 2016).

The use of AUC in this paper differs from the existing literature by measuring the resilience of the supply chain through the maintained and recovered performance capability after disruption, rather than performance lost. (Zobel and Khansa, 2014; Melnyk et al., 2014). Also, rather than being focused on individual sections of the resilience curve, this research uses AUC to analyze cumulative performance throughout the entire period of focus. It utilizes a cumulative AUC measurement to analyze the performance of a network from disruption event through recovery, highlighting resilience as a performance capability against a given demand.

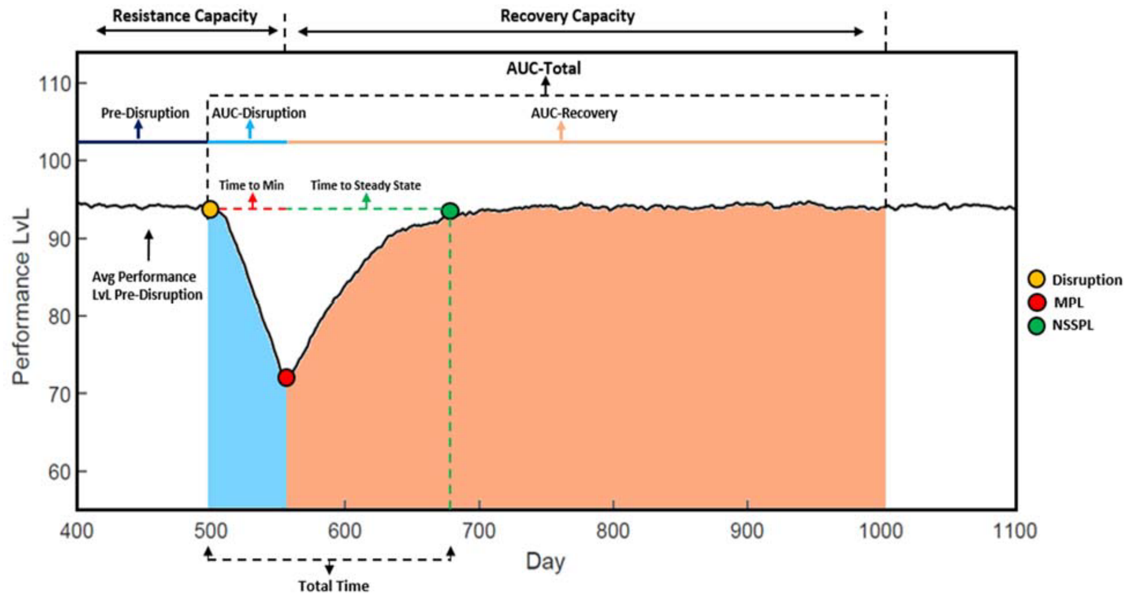
3.2.5 Literature Conclusion

This research draws on four supply chain management and resilience literature streams: (1) supply chain resilience frameworks, (2) flexibility and redundancy, (3) investment in resilience and (4) resilience performance metrics. Many studies have been conducted to analyze best practices in the way that companies have responded to disruptions in their supply chains. These studies serve as excellent pillars from which to build upon but are mostly focused on targeted resilience metrics, and do not allow for much discussion on predicting best overall resilience from disruption to new steady state recovery. There is a good deal of literature that focuses on measuring a supply chain's time to recover from a disruption, the short-term performance implications after disruption, or the long-term performance implications post disruption. However, there still remains a gap in the broader picture of cumulative performance from disruption through recovery in SCR research. Addressing this gap can help firms determine the right SCR strategy to create the most resilient network at the lowest possible cost.

3.3 Measuring Resilience

SCR strategies, such as the redundancy strategies of procuring excess inventory and capacity, are supply chain management decisions that must be made before a disruption occurs. The ability to more accurately measure and predict SCR can aid in these often expensive strategy choices. The resilience curve in Figure 4 represents a typical disruption response. There is a pre-disruption state which exhibits stable performance with normal variability, followed by a decrease in performance after a disruption event until the organization intervenes with recovery efforts. Following the intervention, system performance improves until a new steady state is reached. Drawing from queueing theory, much of the focus in network design is on steady state performance (Graves, 1982).

Figure 4. Performance Metrics and Area Under the Curve (AUC)



However, when assessing the response to a disruption, the system's resilience is best measured by its performance during the transient states (Melynk et al., 2014). Therefore, there are three periods of focus for resilience measurement: pre-disruption, post-disruption during the system's decline, and recovery. Within each of these periods, it is critical to assess both the system's average and minimum performance in the period, the amount of time it takes to transition to the next period, and the total capability of the system during that period using AUC.

3.3.1 Resilience Metrics

The system's overall resilience is defined by its resistance capacity and recovery capacity. Performance is a critical metric for any system and represents the availability of assets to do work, conduct operations, and provide service to customers. In the military repair network example used in Section 3.4, system performance is represented by the number of aircraft that are available to conduct operational missions at any one time.

Aircraft availability depends directly on the spare parts inventory and engine repair capacity. The three direct performance characteristics shown by the solid black line in Figure 4 are:

Average Performance Level Pre-Disruption*: The average daily performance level from day 0 through the disruption***.**
Minimum Performance Level (MPL)*: The minimum point on the post-disruption decline curve.*
New Steady State Performance Level (NSSPL)*: The average new steady state performance level after recovery*.

Of similar importance to the performance level is the length of time the system spends in the disruption phases outlined in Figure 1. The length of time is critical to understanding how different investment decisions impact how long the system's performance is degraded and how long it takes to reach a new steady state.

Therefore, time is captured by the following metrics:

Time to Minimum*: The amount of time to reach the minimum performance level.*
Time to Steady State*: Following the minimum, the time to reach the new steady state.*
Total Time*: The sum of Time to Min and Time to Steady State.*

3.3.2 Area under the Curve (AUC) & Resilience Capability Metric (RCM)

The final set of performance measurements, Area under the Curve: Decline (D), Recovery (R), and Total (T), represent the main contribution for how to measure resilience. The Area under the Curve measures the cumulative performance level from disruption through a predetermined endpoint. The highlighted areas in Figure 1 show the different periods of focus for the Area under the Curve and are defined as:

Area under Curve - Decline (AUC-D)*: The cumulative performance over time under the decline curve.*
Area under Curve – Recovery (AUC-R)*: The cumulative performance over time under the recovery curve.*
Area under Curve – Total (AUC–T)*: The cumulative performance under the decline and recovery curves.*

Integrating from disruption day through a pre-defined endpoint allows for comparison of different SCR strategy performance outcomes in terms of ability to meet demand over time, as opposed to average performance. This is a critical distinction because it indicates performance over time across different decisions. Previous research has similarly used integration to measure resilience but has done so by measuring lost performance—the area between the no-disruption performance curve and the disruption performance curve (Bruneau et al., 2003; Melnyk et al., 2014; Zobel and Khansa, 2014; Todman et al., 2016; MacDonald et al., 2018).

SCR strategy investment and supply chain design decisions must be considered holistically. Focusing the AUC on cumulative performance over time provides a more accurate sense of performance in the face of disruption since it allows for consideration of the system's initial performance starting point. Given the complexity of real-world networks, there are an extremely large number of possible, acceptable system designs. Often, what matters most in the event of a disruption is the ability to meet some required performance level, and the system's steady state pre-disruption performance level directly impacts this ability. The AUC provides a measurement for what capacity the system actually has in terms of Resistance: AUC – D, Recovery: AUC – R, and overall Resilience: AUC – T.

The ratio of the AUC to the total demand over the time period of focus also a generalizable resilience capability metric (RCM) to compare network designs.

$$Resilience\ Capability\ Metric = \frac{AUC_t}{D_t} \qquad (10)$$

The Resilience Capability Metric (RCM) depicted in equation (10) is defined as the AUC over a specified period of time divided by the demand over the same time period. This metric can be generated for the disruption, recovery or any total time period. The RCM was developed using AUC, performance and time measurements to quantify the cumulative performance level of the system from disruption to a predetermined endpoint. RCM takes performance level pre-disruption, minimum performance level (MPL) and New Steady State Performance Level (NSSPL), identifies the time it takes for the system to reach a MPL post-disruption, the time it takes the system to recover to a NSSPL, and the total sum of time from disruption to NSSPL in order to determine the resilience level of the system. By measuring the cumulative performance over the total event, the RCM provides managers with the ability to truly compare different SCR strategies to see which has the greatest impact on overall network resilience. Regardless of the organization, there will be some total demand over the period, and the disruption will impact the capability to meet that demand. The RCM quantifies the system's resilience.

3.3.3 Analyzing System Performance during Disruption

Performance data for system analysis is time-series data collected in regular intervals. The data is aggregated, via weight averaging, to the appropriate *time unit of analysis*, e.g., daily, weekly, etc. Measures are obtained via a curve fitting method to estimate the expected performance level versus time.

Referring to Figure 4, three phases were considered during the disruption event: (1) Pre-disruption, for $t \in (-\infty, t_1)$, (2) Disruption, for $t \in (t_1, t_2)$, and (3) Recovery, for $t \in (t_2, \infty)$. The respective functions estimating their expected values over time are denoted by $f_{\text{pre}}, f_{\text{dis}}, f_{\text{rec}}$. The *lsqcurvefit* function in Matlab was used for curve fitting.

Pre-disruption: It is assumed that the phase immediately preceding the disruption follows a stationary process with mean λ_{pre}.

Let

$$f_{\text{pre}}(t, \lambda_{\text{pre}}) = \lambda_{\text{pre}} \; for \; t \in (-\infty, t_1) \qquad (11)$$

be the function describing the expected performance level of the pre-disruption phase. Note that λ_{pre} can be estimated by simply taking the average of the performance data immediately preceding t_1.

Disruption: To model the performance during the disruption phase of the system, a scaled and translated complementary Weibull cumulative distribution function is suggested:

$$f_{dis}(t, \lambda_{pre}, \lambda_{dis}, k_{dis}, c_{dis}, t_1) = (\lambda_{pre} - \lambda_{dis})\left(e^{\left(\frac{t-t_1}{k_{dis}}\right)^{c_{dis}}}\right) + \lambda_{dis} \; for \; t \in [t_1, t_2) \qquad (12)$$

where λ_{dis} is the new steady state performance level that results after the disruption, t_1 is the time of the disruption, t_2 is the time the recovery begins, and k_{dis} and c_{dis} are shape parameters. Note that λ_{pre}, is obtained when fitting f_{pre}. When estimating the parameters of f_{dis}, it may be necessary to assume the value λ_{dis}, which can be done via queuing theory or other means (e.g., in Section 3.4, a simulation model is used to observe it directly).

Recovery: To model the performance during the recovery phase of the system, a scaled and translated Weibull cumulative distribution function is suggested:

$$f(t, \lambda_{rec}, m, k_{rec}, c_{rec}, t_2) = (\lambda_{rec} - m)\left(1 - e^{\left(\frac{t-t_1}{k_{rec}}\right)^{c_{rec}}}\right) + m \ for\ t \in [t_2, \infty) \quad (13)$$

where λ_{rec} is the new steady state performance level that results after the recovery actions have been taken, t_2 is the time the recovery begins, m is value of f_{dis} at t_2, and k_{dis}, and c_{dis} are shape parameters.

3.4 Illustrating Example – USAF Repair Network

A United States Air Force (USAF) repair supply chain is used to illustrate how SCR strategy decisions and their resilience impacts can be quantified. A military repair network was chosen because the cost of capability loss is extremely high, and the network has a high reliability requirement. Performance is operationalized as the availability of mission capable assets, or aircraft, available to perform missions. SCR strategy decisions are operationalized as 1) production capacity, i.e., the ability to conduct repairs, and 2) inventory, i.e., spare engines that can be placed on an aircraft.

A discrete event simulation model is utilized, which is well suited for the design and emulation of complex, multi-layered problem sets that require the use of many experimental designs. SIMIO software is used to build a model of four operating locations and two centralized repair facilities (CRFs) where engines are the item of focus. This simulation models broken engines as the sole entity being generated by a parameterized Poisson process reflecting historical engine break rates per assigned operational use rates. A simulation model enables the changing of multiple SCR strategy investment decisions simultaneously, while capturing and exporting the results. Thousands of experimental designs were tested, and 88 scenarios were ultimately included in the analysis.

3.4.1 High Level Model Design

The simulation captures repair operations of a notional USAF sustainment network by modelling the repair of broken engines by centralized repair facilities. Flying operations generate a demand for repair through a parameterized Poisson process that is determined by a specified break rate based on hours flown. The break rate is expressed in terms of incidences per flying hour. Mean time between failures (MTBF) is used as the inter-arrival time of broken engines. As broken engines emerge, the model assigns a break severity to the engine. Figure 5 depicts the flow of broken engines. As the broken entity is created, it leaves the asset pool. Depending upon the severity, if the engine cannot be repaired at the location where the break occurred, it will be routed to the centralized repair facility (CRF), as depicted in Figure 5. The engine will be repaired in accordance with the time associated with the specified severity. Once the repair has been completed, the engine is routed back to the asset pool where it is placed back on an aircraft awaiting a repaired engine.

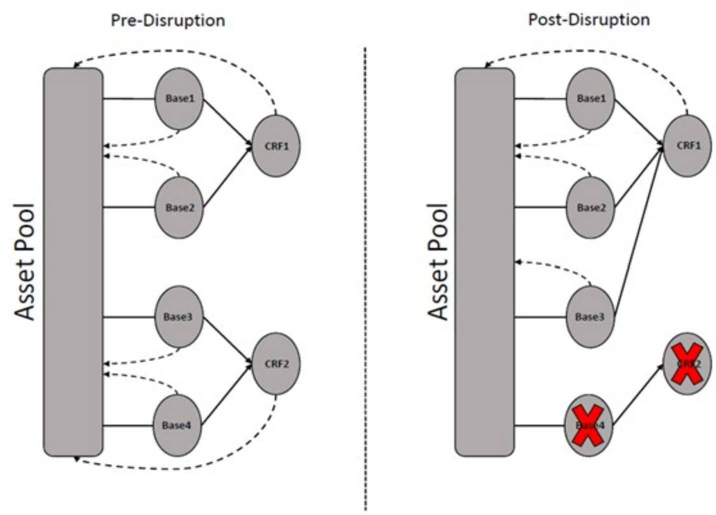


Figure 5. High Level Design

The number of mission capable aircraft located at each base is a function of the number of breaks that occur at each base. Each base starts with 25 mission capable aircraft, or 100 for the network, and all aircraft begin with one functional engine. Hence, at time 0, the network starts with 100 engines.

After a specified time period, a predetermined disruption occurs which terminates operations at Base4 and CRF2, which are co-located. This ceases all flying operations at Base4 whose operational requirements and assets are shifted to Base3. This is done so that total system demand remains the same. Broken engines are now only created at Bases 1-3. Furthermore, the disruption prevents any broken engine from being routed to CRF2 for repair. This eliminates 50% of the network's available repair capacity. While operations at Bases 1-3 remain unscathed, all intermediate level repairs generated at Base3 will now be routed to CRF1 rather than CRF2.

3.4.2 Scenario Development

While based on a real-world scenario, the model in this example utilized notional data with realistic demand. The model was used to assess how different spare and capacity investments impact the system's ability to respond to a disruption. The goal is to understand the role that the SCR redundancy strategies of added spares and added production capacity play in resistance to and recovery from a disruption event. An assumption is that some level of SCR strategy investment is required to be implemented pre-disruption to ensure that the remaining repair facility could be expanded in a reasonable time period. Production capacity pre-disruption at both CRFs is assumed to be the same.

Baseline scenarios were first developed to verify and validate the model and to understand the underlying system steady states. The baseline scenarios were run with zero added SCR strategy investment: one without a disruption and one with a disruption occurring at day 500. Consistent with both scenarios, each simulation begins at time 0 with 2 initial spares and 3 initial servers at each CRF. Therefore, the network has the capacity to repair 6 engines simultaneously. In the disruption-free scenario, the four bases and two repair facilities remain operational throughout the entire 1,000-day duration.

Two sets of system design parameters were considered. The first set of system design parameters were (1) initial spare parts at each base in the system; and (2) capacity added at the remaining CRF, in the form of number of servers, for system recovery. All even combinations of 0 - 12 initial spare parts per Base and 0, 1, 2, and 3 servers added at the CRF for recovery were tested. Each combination of added server and spare was run using a 1,000-day simulation with the predetermined disruption occurring at day 500. Each set of 88 scenarios were run with a 50-day delay in response time and also with a 25-day delay to measure the effect of the speed of the response. The response delay time is the amount of time the added servers take to become operational at the remaining repair facility. All scenarios were run for 100 iterations.

Table 7. Scenario Combinations Run

Scenarios			
Servers	**Spares**	**Servers**	**Spares**
0	0	2	0
	2		2
	4		4
	6		6
	8		8
	10		10
	12		12
1	0	3	0
	2		2
	4		4
	6		6
	8		8
	10		10
	12		12

3.5 Results & Analysis

The USAF repair scenario is used to explore the resilience of a network when utilizing the SCR redundancy strategies of increasing production capacity and inventory. The performance level in this scenario represents the ability to conduct flying missions and is operationalized as the number of aircraft available. Since the model is run with 100 aircraft in the system it can be read as an actual number available or a percentage. Results are collected for three distinct periods: 1) Pre-disruption, 2) Post-disruption during the system's decline, and 3) Recovery phase.

Performance level, length of time to each phase transition, and AUC are captured for each of the three phases. The AUC measures the mission capable days for each scenario from disruption day through day 1000. The length of time to assess the AUC can be modified, and 1000 days was chosen for this system to provide enough time for all scenarios to return to steady state. Table 8 shows the consolidated outputs from the 50-day response set of scenarios for all capacity and inventory combinations. The disruption occurs at day 500 and terminates operations at Base4 and CRF2, thereby eliminating 50% of the network's production capability. The pre-disruption steady state performance level steadily increases as the number of initial spares increase. Scenarios run with zero added spares experience the lowest starting point for the pre-disruption steady state performance levels.

Table 8. Scenario Data Table, 50-Day Response

Scenarios		Pre-Disruption	Post-Disruption [Decline]			Post-Disruption [Recovery]					
Servers	Spares	APL	MPL	Time to MPL (Days)	AUC-D	NSSPL	Time to NSSPL (Days)	AUC-R	AUC-T	Total Time	RCM
0	0	84.13	53.80	438	29196	54.20	N/A	0	29196	438	0.694
	2	89.78	55.68	474	30322	55.69	N/A	0	30322	474	0.721
	4	94.18	54.84	558	30649	55.88	N/A	0	30649	558	0.729
	6	97.08	54.30	594	31458	55.91	N/A	0	31458	594	0.748
	8	98.43	54.22	578	32148	55.66	N/A	0	32148	578	0.764
	10	98.8	54.69	559	32679	55.79	N/A	0	32679	559	0.777
	12	99.01	54.49	622	33283	56.53	N/A	0	33283	622	0.791
1	0	84.13	62.15	56	3756	72.73	172	31755	35511	228	0.844
	2	89.78	67.33	62	4049	72.86	245	32385	36434	307	0.866
	4	94.18	71.06	60	4287	73.06	N/A	32692	36980	60	0.879
	6	97.08	74.65	191	4514	72.83	N/A	33290	37804	191	0.899
	8	98.43	72.81	269	4637	73.23	N/A	33814	38451	269	0.914
	10	98.8	73.49	448	4735	73.09	N/A	34134	38869	448	0.924
	12	99.01	73.34	425	4829	73.09	N/A	34682	39512	425	0.939
2	0	84.13	62.52	56	3756	82.74	322	35909	39666	378	0.943
	2	89.78	67.34	56	4049	86.72	344	37551	41600	400	0.989
	4	94.18	71.57	59	4287	89.15	233	38636	42923	292	1.020
	6	97.08	76.30	58	4514	90.46	340	39152	43666	398	1.038
	8	98.43	80.53	59	4637	90.84	330	39934	44571	389	1.060
	10	98.8	83.75	57	4735	91.59	277	40476	45211	334	1.075
	12	99.01	88.02	56	4829	91.31	71	40753	45582	127	1.084
3	0	84.13	62.69	54	3756	84.06	87	37011	40767	141	0.969
	2	89.78	67.83	58	4049	89.66	123	39358	43407	181	1.032
	4	94.18	72.01	57	4287	94.06	121	41129	45416	178	1.080
	6	97.08	76.44	58	4514	96.34	125	42228	46742	183	1.111
	8	98.43	80.43	58	4637	97.1	161	42709	47346	219	1.126
	10	98.8	83.87	53	4735	97.36	148	43096	47831	201	1.137
	12	99.01	88.15	59	4829	97.48	100	43382	48211	159	1.146

APL: Average Performance Level, MPL: Minimum Performance Level, AUC-D: Area under the Curve – Decline, NSSPL: New Steady State Performance Level, AUC-R: Area under the Curve – Recovery, AUC-T: Area under the Curve Total, RCM: Resilience Capability Metric

3.5.1 Measuring Impact after Disruption

As Table 8 illustrates, the SCR strategy of investing in added spare parts inventory creates a buffer against disruption. Table 8 shows inventory level pre-disruption is the driver of how low performance declines after disruption. This strategy allows for not only a higher performance level during the pre-disruption steady state, but also buffers the impact of the disruption, resulting in a higher minimum performance level (MPL). In addition to impacting the initial performance level (APL) and the MPL, inventory also directly impacts the length of time the system is able to resist the disruption. This is depicted by the increase in time to MPL corresponding with the increase in initial spares added to the system. As the number of spares are increased, the amount of time to reach MPL post-disruption increases. It should be noted that in Table 8, this relationship holds at 0 and 1 added servers only. At 2 and 3 added servers, recovery is expedited due to the increase in production capacity, which partially mitigates the effects of increased initial spares on the time it takes to reach the MPL. This is consistent with what Lücker et al. (2019) found as to the effect of reserve mitigation inventory (RMI).

Minimum performance level (MPL) is also impacted by the SCR strategy of added capacity. Figure 6 highlights how a significant improvement in MPL is achieved by adding servers after disruption. While MPL is increased with each server addition, at 3 added servers, a negligible improvement is realized. Furthermore, as the number of added servers incrementally increases, the system's MPL experiences diminishing returns. Figure 6 illustrates this lack of linearity. This finding highlights the fact that increasing MPL is not just a matter of choosing a strategy of either spares or capacity, but instead that SCR strategies must be strategically balanced based on the organizations desired outcome. It is worth noting, that even with high levels of added spares in the system, without added capacity, the system is not able to recover and the MPL can become the new steady-state performance level (NSSPL) (see Table 8).

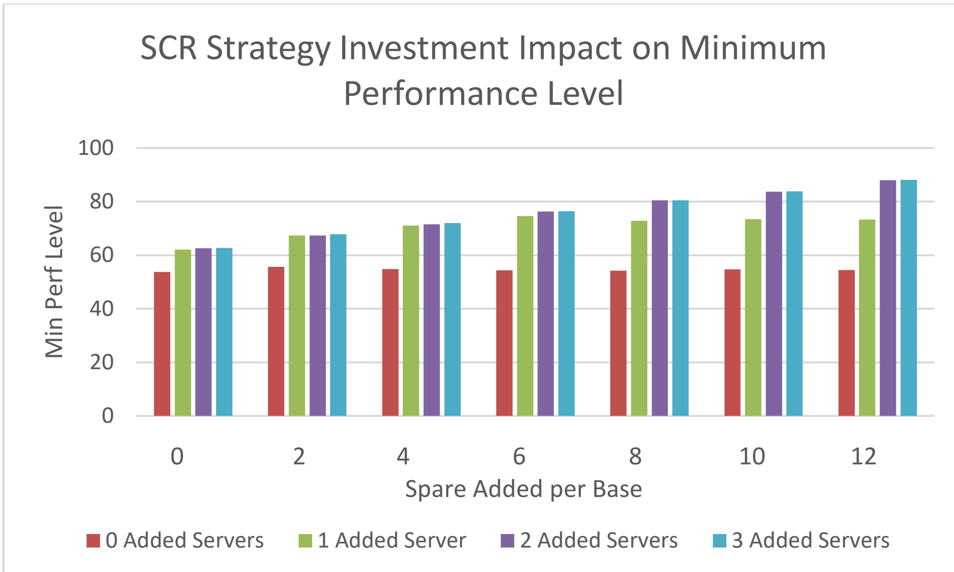


Figure 6. SCR Strategy Investment Impact on Minimum Performance Level

3.5.2 Applying RCM

The Total Area under the Curve (AUC-T), represents the cumulative performance under the decline and recovery curves in a specified time period. The higher the AUC-T, the better the network performed post-disruption. This is the total capability of the system over time. By comparing AUC-T to the system's total demand over the same time period, managers now have the Resilience Capability Metric (RCM) to assess different system designs. By combining the disruption and recovery areas, a snapshot of the best resilience investment combinations for overall network performance from disruption to recovery emerges.

Table 9 shows RCM for a 50-Day delayed recovery period. To analyze the RCM of the scenarios, the baseline scenario, which included no SCR strategy investment, was used to model the total demand over time based on the average performance level prior to disruption. This gave a model baseline average performance level of 84.13. That number was then multiplied by 500 which is the same time period as the AUC-T was measured (500 days starting from disruption at day 500 to simulation end at day 1000). This gave us a D_t of 42,065. Using equation (1), taking the AUC-T for each scenario and dividing by the D_t gave us each RCM.

The results highlight the tradeoffs between the addition of servers and spares. For example, two additional spares positioned at each base from day zero along with two additional servers after disruption provides a better overall network performance than zero spares positioned at each base from day zero and three additional servers after disruption.

Table 9. RCM, 50-Day Recovery Delay Heat Map

	Added Servers			
Spares	**0**	**1**	**2**	**3**
0	**0.694**	**0.844**	**0.943**	**0.969**
2	**0.721**	**0.866**	**0.989**	**1.032**
4	**0.729**	**0.879**	**1.020**	**1.080**
6	**0.748**	**0.899**	**1.038**	**1.111**
8	**0.764**	**0.914**	**1.060**	**1.126**
10	**0.777**	**0.924**	**1.075**	**1.137**
12	**0.791**	**0.939**	**1.084**	**1.146**

3.5.3 Impact of Recovery Response Time

The time it takes an organization to implement a recovery response to a disruption has a critical impact on the network's performance and overall resilience. In the case of this aircraft repair network, recovery response time is tied directly to the speed at which production capacity is added to the network after the disruption has occurred.

Specifically, recovery response time is the amount of time that it takes to add repair servers to CRF1 after a disruption has occurred. To analyze the resilience difference in regards to response time, all scenarios were run with both a 25 and 50-day recovery response. As one example of the difference between 25 and 50-day recovery responses, Figure 7 illustrates the impact of expediting the recovery response time in the 4 added spares, 3 added servers scenario.

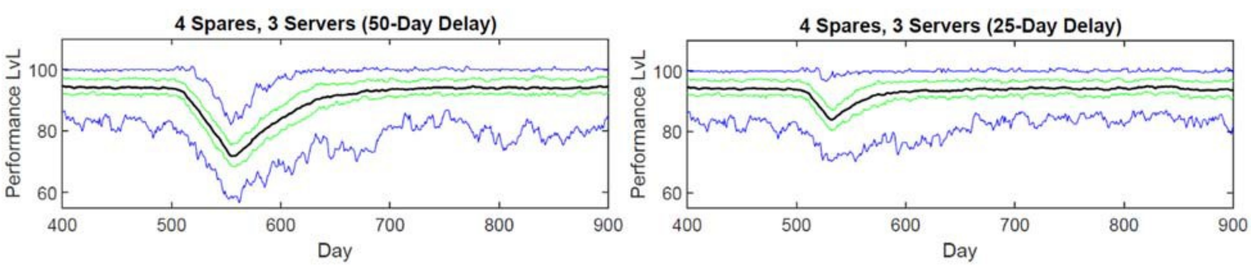


Figure 7. Impact of Recovery Response Time on Performance

Table 10 quantifies the difference between the two response times. Three key behaviors are highlighted. First, the time to MPL is drastically reduced when the recovery response time is shortened. Second, the MPL is greater when the recovery response time is shortened. Finally, although both systems ultimately recover to the same performance level, the time to the

NSSPL is drastically reduced when the recovery response time is shortened. Therefore, AUC-T is higher, and the RCM is greater when the response is quicker.

Table 10. Resilience Metric Differentiations

Response Time (Days)			Post-Disruption - Decline			Post-Disruption - Recovery					
	Servers	Spares	MPL	Time to MPL (Days)	AUC- D	NSSPL	Time to NSSPL (Days)	AUC- R	AUC-T	Total Time	RCM
25	3	4	83.92	32	2281	94.04	84	44324	46,605	116	1.108
50	3	4	72.01	57	4287	94.06	121	41129	45,416	178	1.080

The results in Table 10 highlight the value of speed when responding to a supply chain disruption. Figure 8 shows the difference in RCM made to each scenario by speeding up the response time by 25 days. When added servers and added spares were kept constant, every scenario saw an increase in RCM due to a faster response time.

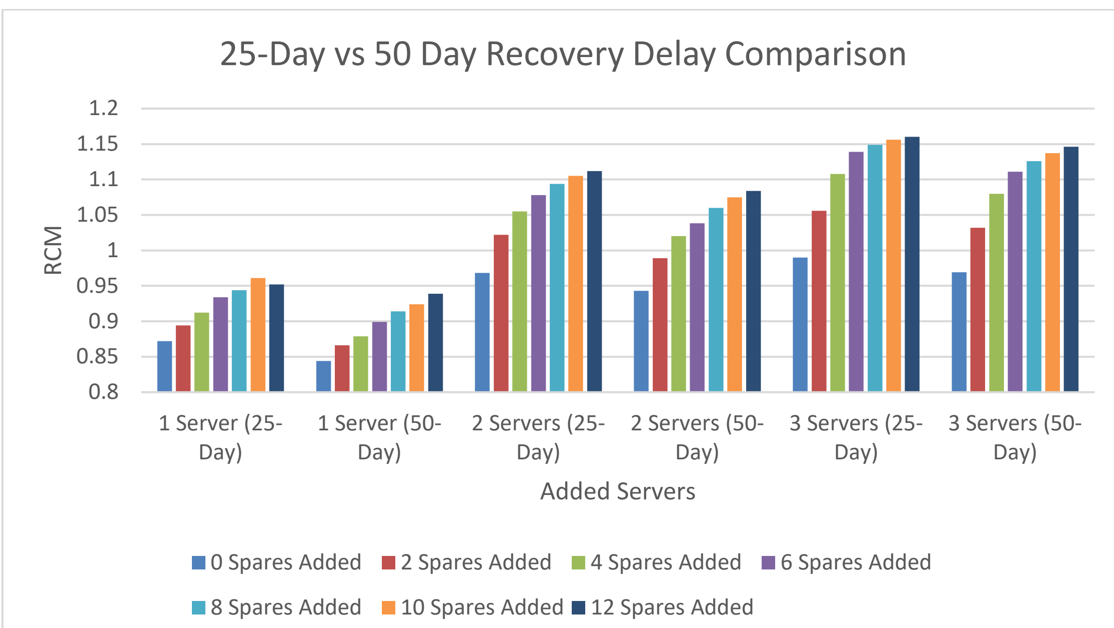


Figure 8. RCM, 25-Day vs 50-Day Recovery Delay Comparison

3.6 Contributions & Discussions

In order to reduce the probability and impact of disruptions, and put mechanisms in place for a supply chain to recover post-disruption, many organizations choose to invest in SCR strategies (Ponomarov and Holcomb, 2009). Understanding the balance between these SCR strategy investments and the vulnerabilities of an organization’s supply chain can assist an organization in maintaining or improving performance levels and overall financial success. (Pettit et al., 2010). Proper selection of SCR strategies to support a resilient network response to disruption requires rigorous comparison of strategy tradeoffs. The goal of quantifying supply chain resilience (SCR) is to enable more accurate comparison and improved system designs. This research has contributed to the SCR conversations regarding (1) how to measure supply chain resilience, (2) the use of SCR redundancy strategies to improve resilience, (3) how to apply a quantitative approach to design resilient supply chains with the best SCR strategies for the organization, and (4) the importance that response time plays in SCR.

3.6.1 Method

The results of the simulation provide several useful insights. The scenarios show improved resilience with the addition of spare parts prior to the disruption, allowing for an improved initial steady state average performance level (APL) as well as an improved minimum performance level (MPL). Increased inventory pre-disruption also prolongs the ability to maintain performance after a disruption. However, in the scenarios with a strict inventory strategy and no added capacity, performance levels were never able to recover from the MPL they dropped to, effectively transforming the MPL into the new steady state performance level (NSSPL). Examining the minimum is critical in many industries that require a specific minimum performance level to be maintained at all times. Understanding the organization's lowest minimum performance level (MPL) allowable can help managers highlight the absolute minimum supply chain resilience (SCR) strategy investment necessary to meet that threshold.

3.6.2 Inventory versus Capacity

An increase in production capacity after disruption allowed for recovery to occur in the network. As expected, the more repair servers added, the faster the network recovers. This had its limits though, and additional capacity requires higher inventory levels to capture the full benefits of the increased capacity. In terms of impact on resilience, there is greater improvement in resilience realized from adding capacity to the system versus adding inventory. While adding one server to the system post disruption raised the RCM by 22% from baseline, adding 12 spare engines to each base (a total of 48 engines across four bases) only raised the RCM by 14% from baseline. This finding leads us to believe that a redundant capacity strategy investment may provide a greater resilience return than an increased inventory strategy investment.

3.6.3 Response Time

Another important finding from the simulation is the importance of response time to the resilience of the system. The MPL is improved and the time to MPL is drastically reduced when the recovery response time is shortened. Also, the time to the NSSPL is drastically reduced when the recovery response time is shortened. Therefore, AUC-T is higher, and the RCM is greater when the response is quicker. The more time it takes to start recovery efforts, the lower performance can drop, and the longer it may take the system to reach a new recovered steady-state. It is worth mentioning that increasing response speed of recovery efforts will most likely come at an increased cost which organizations should take into account when determining their resilience strategy. Since a quicker response may be more expensive, the organization should examine whether the associated costs of a recovery speed are worth the added resilience.

3.6.4 Discussion

The main contribution of this research was the development of the resilience capability metric (RCM), proposing a better way to measure and compare system resilience. Similar to Melynk et al. (2014), this research views system performance over a disruption as being characterized by a resistance phase and recovery phase, with total system resilience being a combined result of these phases. This research proposes finding the AUC of the system performance metric of interest for each of these phases as a measure of the system's cumulative performance. The total of the AUCs for each phase represents the maximum demand that the supply chain can serve over the disruption event. Thus, unlike methods that only measure loss in system performance, AUC can be used to compare various system designs, most likely having different pre-disruption steady state average performance levels (APLs), in terms of their ability to serve customers. The use of performance over time also allows the comparison of actual capability to cost, given inventory and production capacity will have different upfront and ongoing costs. As an overall measure of system resilience, RCM is proposed as the ratio of the AUC for different SCR strategy investments against the system's total demand over time (see Equation 10).

3.7 Conclusion & Future Research

This research also offers an example of how to test and measure the effect of specific SCR strategy investments. To illustrate how to use the RCM proposed in this paper, a simulation model based on a USAF aircraft engine repair network is presented. The example illustrates how to explore two different SCR redundancy strategies; increased inventory (i.e., spare parts) and redundant production capacity (i.e., number of repair servers) to improve the network's response to a disruption. While the example chosen is a military repair network, the decision between SCR strategy investments is fundamental.

Managers can build their own simulations and use RCM to analyze the resilience of their supply chains against different disruptions, as well as test the resilience impact of added SCR strategy investments such as added inventory and redundant capacity. The RCM proposed in this paper allows a means by which to properly compare these SCR strategy investment scenarios. The simulation illustrates that the two SCR strategies modeled actually work in unison rather than in isolation. These results highlight two critical points for managers interested in utilizing these strategies: (1) Organizations must have a deep understanding of costs associated with each SCR strategy to determine the best combination to use, and (2) the length of time it takes to provide a SCR strategy response is critical to the system's resilience. Since a quicker response may be more expensive, when evaluating the feasibility of a shortened response time, the organization should examine whether the associated costs of a recovery speed are worth the added resilience.

While this paper provides a useful method of measuring SCR through the RCM, there are some very promising avenues of further inquiry in (1) understanding system behavior during disruption, (2) designing resilient systems, and (3) using other design decisions to improve resilience. For instance, methods of fitting functions to the system performance versus time during various phases of the disruption event are proposed. However, the application of queuing theory may reveal the underlying relationships between the system parameters and system behavior that generate the observed functional forms. A better understanding of the system behavior can then be used in optimization models to identify good design principles.

Furthermore, many real-life considerations such as working capital investment, space, holding and management costs of inventory, and employee incentives, among others, could be taken into account. Finally, many other SCR strategies exist besides increasing inventory and production capacity, and it would be interesting to apply RCM using other resilience strategies to determine the best SCR strategy combination for an organization.

IV. Improving Supply Chain Resilience with Flexibility: A Focus on Response Time

4.1 Introduction

Risk to supply chains is unavoidable. No matter how carefully planned or protected, an organization's supply chain will remain vulnerable to the chance of disruption. Organizations that invest in the resilience of their supply chains enable them with the ability to respond quicker and recover faster from predictable and unpredictable disruptions (Ponomarov and Holcomb, 2009). Fortunately, there are many strategies that can be leveraged by organizations to mitigate these risks and protect performance. Supply chain resilience (SCR) is the ability of a supply chain to reduce probability of disruptions, to resist impact from disruptions, and to respond and recover from the disruptions (Ponomarov and Holcomb, 2009). In the last twenty years, the definition of SCR and the different types of strategies that support resilience within a supply chain have continued to evolve throughout the literature (Shashi et al., 2020). Research conducted on improving the resilience of a supply chains supports two types of SCR strategies; redundancy and flexibility (Kamalahamdi and Parast, 2016; Kochan and Nowicki, 2018).

A redundant SCR strategy is defined as an investment in capital and capacity in order to maintain the ability to respond to disruptions (Tang and Tomlin, 2008). Key redundancy strategies include excess capacity, excess inventory stockpiles, robust infrastructure, and multiple supply sources (Shashi et al., 2020). A flexibility SCR strategy is defined as an investment in infrastructure and resources in anticipation of a disruption (Tang and Tomlin, 2008). Key flexibility strategies include agility, collaboration, integration, information sharing, innovation, visibility and contingency planning (Dmanpour and Gopalakrishnan, 2001; Barratt, 2004; Svensson, 2004; Li et al., 2005; Francis, 2008; Wieland and Wallenburg, 2012). Flexibility strategies involve restructuring a previously existing system, and therefore, are implemented and utilized immediately, helping firms improve day to day operations as well (Sheffi, 2005). Supply chain resilience (SCR) flexibility strategies require the investment in infrastructure and resources before they are actually needed, restructuring existing capacity in anticipation of a disruption (Kochan and Nowicki, 2018). Investment both in redundancy and flexibility SCR strategies has been extensively studied, often proving to have a significant impact the performance of a firm (Shashi et al., 2020).

In the supply chain literature, a disruption is defined as an unplanned and unanticipated occurrence which disrupts the normal flow of materials in a supply chain, or an event which causes delays in production or logistics process, and mismatches in supply and demand (Craighead et al., 2007; Hendricks and Singhal, 2014). These disruptions, regardless of size of impact, are seen to be negative occurrences that interrupt the network on some scale. Unanticipated demand spikes are an example of disruption events that can result in service failures and affect operational performance (Macdonald et al., 2018).

In a supply chain network, placement of inventory is key to ensuring that the network maintains adequate performance levels and minimizes customer backorders. Organizations put a great deal of effort into maintaining repair systems with limited budgets and spare parts inventory. In organizations where spare parts are not collocated, source of supply selected to resolve backorders and shipping mode source to the get the part to the customer can have a drastic impact on backorder response time and organization performance levels. Restructuring the movement and allocation of an organization’s existing spares inventory to have more fluid movement of spares from one location to another is an example of operationalizing the SCR flexibility strategy. Utilizing flexibility strategies to maintain a better balance and movement of inventory can help minimize the impact of any disruption that may occur.

Proper placement and movement of limited spare parts inventory has been the focus of many research efforts and metric system developments for the United States Air Force (USAF). Current systems work with unit requirements and budget restraints to allocate spare aircraft parts with the goal of minimizing backorders and weapon system down time, and maintaining an acceptable performance level; measured by Mission Capability (MC) rate. When looking at the inventory of spare parts in a USAF repair network, one of the greatest focus areas is that of spare parts identified with a MICAP (Mission Impaired Capability Awaiting Parts) code. This is a code that signifies a backordered part is causing a weapon system, such as an aircraft, to be unable to perform its full required mission.

This paper examines the impact of SCR flexibility strategies on the resilience of the USAF aircraft supply chain. Specifically, the focus of this research is the impact that recovery response for MICAP coded parts has on supply chain resilience through increased performance levels. It looks at USAF F16 mission capability rate data, as well as F16 MICAP resolution source and transportation mode code data provided by analysts at the 635th Supply Chain Operations Wing (SCOW).

Based on what is known about SCR flexibility strategies, it is predicted that a more flexible supply chain, with a decreased response time for obtaining parts (from a closer lateral resupply or a quicker shipping mode) will lead to an increased performance rate. Imposing policy changes to decrease MICAP response time through increased lateral resupply and faster shipping modes may not only reduce customer backorders, but increase aircraft availability and mission capability rates. This will ultimately create a more resilient repair network able to better respond to disruptions. This paper provides evidence that resilience in this network can be improved by allowing for more flexibility and less constraints in spare part movement between storage locations.

The main contribution of this paper is to show the impact that shipping mode and location of MICAP supply source can have on the resilience of a supply chain, highlighting that increasing response time leads to a lower performance level, decreasing the resilience of the network. The research provides evidence to inform spare part source of supply and shipping mode policy to allow for these faster part re-allocations to take place, creating a quicker recovery response time, and better performance levels to create a more resilient system. While this research was conducted through the lens of the United States Air Force (USAF) repair network, it is relatable to private sector commercial industries. Moving parts faster between end user locations is a relatively low-cost option that can lead to big returns in any organization

4.2 Literature Review

4.2.1 Theoretical Background

The Theory of Constraints (TOC) helps organizations to understand the processes and actions required to drive production timelines (Goldratt, 2014). TOC was first published by Goldratt and Cox (1984), and has continued to be mentioned throughout academic journals over one thousand times since its inception (McCleskey, 2020). The concept of a constraint in this theory is a factor that limits the performance of a system, which has the potential to be utilized more efficiently (Cox et al., 2012). The philosophy of TOC initially defines the five steps of focusing as identifying the constraints in the system, deciding how to exploit them, subordinating everything to the exploitation of the constraints in the system, elevating the constraints in the system and repeating steps one through four in a continuous process improvement loop (Goldratt, 1990).

Through the last forty years of TOC evolution, many organizations have realized that often times the most crucial constraint to a system is managerial policy and not physical bottlenecks (McCleskey, 2020). If an agile, swift response time to an organizational performance disruption is seen as a supply chain resilience (SCR) flexibility strategy, then it would behoove decision makers in those organizations to determine where the constraints exist that may slow down response time and decrease performance. This paper challenges some transportation policy constraints to the USAF repair network to identify the impact these constraints may be having on weapon system performance and resilience. Using TOC as a guide, combining deliberateness, speed, and the reduction of variability allows for better resource staging and maintenance execution (Goldratt, 2014).

4.2.2 Supply Chain Resilience (SCR) Strategies

Supply chain resilience (SCR) is the ability of a supply chain to reduce probability of disruptions, to resist impact from disruptions, and to respond and recover from the disruptions (Ponomarov and Holcomb, 2009). SCR can be visualized through an organization's performance over time in phases following a disruption event (Barroso et al., 2015). These phases make up a resilience triangle (or curve) depicting a characteristic drop in performance after a disruption event and a recovery period for the performance to return to pre-disruption levels (Barroso et al., 2015). Melynk et al. (2014) developed a concept of resistance and recovery capacity, defining resistance capacity as the ability of a system to minimize the impact of a disruption by evading it entirely or by minimizing the time between disruption onset and the start of recovery from the disruption, and recovery capacity as the ability of a system to return to functionality once a disruption has occurred.

One of the most important rationales for maintaining a resilient supply chain is the ability to sustain a firm's performance in the presence of a disruption. Chapter II provides evidence to support that a more resilient firm is associated with a better performing firm. Research conducted on improving the resilience of a supply chains supports two types of SCR strategies; redundancy and flexibility (Kamalahamdi and Parast, 2016; Kochan and Nowicki, 2018). Investment in both redundancy and flexibility SCR strategies has been extensively studied, often proving to have a significant impact to the performance of a firm (Shashi et al., 2020). Flexibility strategies deal with investing in infrastructure and resources in anticipation of a disruption to enable a quick response (Sheffi and Rice, 2005). This research effort will focus on the flexibility strategy of an agile, quick recovery response to disruption.

4.2.3 Impacts of Inventory on Resilience

Often, demand uncertainty is mitigated by increasing inventory (a SCR redundancy strategy), but inventory buffering comes at a cost. Inventory investment represents potential costs related to storing and maintaining the inventory (Silver et al., 1998). These costs can also include capital cost (opportunity cost of the money invested in inventory instead of other areas of the business), storage space costs (warehouse fees), inventory service costs (including insurance for the inventory, software to manage the inventory, and physical labor needed to manage inventory), and inventory risk costs (the risk of the items losing their value or having perishability before being sold) (Silver et al., 1998). Inventory investment can be minimized by prioritizing investment in high velocity items and high inventory turn items so that holding costs are lower (Silver et al., 1998).

Increasing inventory may seem like the solution to maintaining high performance when faced with demand spikes, but Braglia et al. (2004) identifies that while shortage cost incurred by the lack of a spare part is dramatic, the USAF spare parts inventory is already excessive and could be reduced significantly. If there are plenty of spare parts already in the inventory, how do decision makers get them in the right place at the right time? Since adding more inventory will increase the holding costs, an alternative to meeting unpredictable demand when locations of demand are geographically separated could lie in a transportation solution. In a futuristic world, perhaps inventory would be able to instantaneously arrive at its required location from wherever it was located previously. While instantaneous transport is not yet possible, the ability to move goods around the world fairly quickly does exist. Could a network's performance be improved by swifter relocation?

4.2.4 Impacts of Transportation Mode on Performance

The focus of this research is to highlight SCR flexibility strategies which lead to quicker recovery response times to network disruption, and how organizations can identify constraints to response times in order to improve their SCR. In any scenario where parts of the supply chain are geographically separated, transportation plays a key role in responding to problems that may threaten the performance of the organization. When identifying constraints to recovery response for MICAP codes, spare part transportation modes seem to be an obvious area to explore.

Efficient and effective transportation is important to seamless supply chain operations. Organizations with ample inventory levels can still find themselves with performance issues if they are not able to adequately deliver the inventory where it needs to go (Fox, 1992). Flexible supply chains can utilize a strategy of diversified transportation modes to provide options in case of disruption (Tang, 2006). However, utilization of low-speed surface transportation modes can create costly time buffers in the supply chain (Stank and Goldsby, 2000). Because of this, the transportation mode that is selected to move inventory can greatly impact the performance of the network.

When an organization like the USAF is faced with limited inventory levels and mission-critical backorders, the supply chain requires on-time and reliable transportation to avoid drastic decreases in performance. Since performance level drops can be very costly to an organization, decision makers may choose speedier transportation modes, such as air freight services, to ensure inventory moves quickly (Goel, 2010). Transporting inventory by sea, rail, or truck can be cost effective for larger bulk shipments, however if response time is the main decision requirement, the fastest mode of transport is by air (Goel, 2010). Applying this concept to the USAF repair network, it is easy to identify how important transportation mode selection is for timely MICAP resolutions.

Utilizing F16 MICAP transportation mode code data and the Theory of Constraints (TOC), this paper analyzed MICAP transportation modes to see if there was a constraint created by an increase in surface mode transported MICAP parts. The assumption was that allowing MICAPs to be transported by surface mode, and not by the faster air mode, was a managerial policy-induced constraint that may have a negative impact on the F16 fleet's performance. If this is true, then policy changes can be made to more effectively utilize this MICAP transportation mode constraint to improve performance and resilience. It was predicted that the number of MICAPs shipped through surface modes would be negatively correlated to improved MC Rate performance. Therefore I hypothesize:

(H1) An increased number of MICAP spare parts utilizing surface transportation modes is correlated with a decrease in network performance.

4.2.5 Impacts of Lateral Resupply on Performance

In the retail industry, expedited shipments and lateral resupply are both utilized to maintain customer service levels (Avci, 2019). Lateral resupply transshipments are inventory movements between stocking points at the same echelon (Avci, 2019). While companies can experience a monetary cost with each lost sale, they may also see a customer service level decline when backorders are increased. In the USAF repair network, the goal is readiness rather than profit, so performance levels tend to be tracked to support this goal. Where company shareholders are focused on profits, military leadership is focused on the capability of the aircraft to accomplish the mission. Responding to MICAP part requirement normally requires the part to be shipped from a separate source of supply location to the end user. The way that part is shipped can have a major impact on how quickly that aircraft is returned to a fully mission capable status.

The literature identifies two common types of lateral transshipments referred to as reactive transshipments and proactive transshipments (Paterson et al., 2011). Reactive transshipments are those that are allowed to take place at any time to respond to a stock-out or potential stock-out, and proactive transshipments are those that are designated to ship at specified times before a demand is identified (Paterson et al., 2011).

When measuring resilience of a supply chain, response time after a disruption is crucial. Therefore, it is critical to identify the constraints in the system that slow down this response and negatively impact performance recovery. These lateral transshipments can be an agile, quick recovery response strategy. Previous studies have been conducted to analyze the effect that increased lateral transshipments have on supply chain performance in the presence of disruptions, providing evidence that they are an efficient stock-out risk mitigation strategy (Avci, 2019).

In the USAF, proper placement and movement of limited spare parts inventory is a driver for many metrics and research efforts in an attempt to support a more resilient, sustainable aircraft fleet. One of the greatest focus areas in the USAF repair network is the ability to recover from MICAP (Mission Impaired Capability Awaiting Parts) codes. These codes signify that a backordered part(s) is causing an aircraft to be unable to perform its full mission. The ability for the supply chain to get MICAP coded parts efficiently to the customer location is critical to getting the aircraft awaiting the part back to full mission capability.

Understanding that the location of the spare parts can impact response time, and knowing that research suggests that lateral resupply transshipments from same echelon locations is efficient for stock-out risk mitigation, this paper took a step further to question if responding to a MICAP through lateral resupply would have an impact of network performance. Utilizing F16 MICAP delete code data and the Theory of Constraints (TOC), this paper analyzed the sources of MICAP resolutions to see if there was a constraint created by an increase in non-laterally sourced MICAP parts. The assumption was that resolving MICAPs with parts pulled from non-lateral sources was a managerial policy-induced constraint that may be have a negative impact on the F16 fleet's performance. If this is true, then policy changes can be made to more effectively utilize this MICAP resolution constraint to improve performance and resilience. It was predicted that the number of MICAPs resolved through non-lateral suppliers would be negatively correlated to performance. Therefore I hypothesize:

(H2) An increased number of MICAP spare parts sourced through non-lateral suppliers is correlated with a decrease in network performance.

4.3 Methodology

The goal of mathematical models is to provide managers with information necessary for good decision making (Ragsdale, 2003). Regression is a powerful tool for predicting numerical values. Linear models are used to determine the interactions between variables when all independent and dependent variables are discrete (Larose, 2015). Statistical analysis through the testing of regression modeling can be used to estimate these variable relationships.

4.3.1 Analysis Method

In this study, multiple linear regression is used to approximate the relationship between a continuous dependent variable and the set of predictor variables. Multiple regression modeling provides a way for researchers to describe the relationship between a target variable and two or more predictor variables (Larose, 2015). The model attempts to describe this relationship by fitting a linear equation to the data (Larose, 2015). Multiple regression allows researchers to understand associations between dependent and independent predictor variables, helping to assess the strength of the relationship between the variables and the importance of each of the independent variables to this relationship (Petchko, 2018).

Every value of the independent variables x is associated with a value of the dependent variable y. The equation for multiple linear regression, given n observations, is:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots \beta_n x_{in} + \varepsilon_i \text{ for } i = 1, 2, \ldots n \qquad (14)$$

where β_0 is the intercept of the regression equation, β_1, β_2…, β_n are the regression coefficients and ϵ is the residual error term of the model. The simplest multiple regression model for two predictor variables, and the equation used in this research is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \qquad (15)$$

To fit the regression models for this data analysis, the lm package in R Studio Software was utilized (R Core Team, 2020).

4.3.2 Variables

This study predicts that increased selection of surface shipping modes for MICAP parts is correlated with a decrease in network performance, and that increased sourcing of MICAP parts through non-lateral suppliers is correlated with a decrease in network performance. To test these relationships one dependent variable and two independent variables were selected for analysis.

Supply chain resilience (SCR) literature supports the idea that a resilient supply chain can impact the success or failure of an organization (Behzadi et al., 2020). Recording an organization's performance over time in a resilience triangle has been useful for illustrating a supply chain's response to a disruption event (Barroso et al., 2015). These phases depict a characteristic drop in performance after a disruption event and a recovery period for the performance to return to pre-disruption levels (Melynk et al., 2014; Barroso et al., 2015). To operationalize the resilience of USAF F16 repair network, this study selected the performance metric of monthly USAF F16 Mission Capability (MC) rate. This variable was selected because it is directly impacted when a disruption occurs to the repair network which impacts the availability of an aircraft to perform required missions. The study utilized total monthly surface mode shipped USAF F16 MICAPs and total monthly non-laterally resolved MICAPs as its two independent variables. The objective in testing these variables is to determine whether an increase in recovery response time through slower MICAP shipping mode and non-laterally resolved MICAPs decreases the performance of the USAF repair network.

4.3.3 Data Collection

This research was focused on USAF F16 aircraft historical mission capability (MC) rate data as the dependent variable. MC rate data was pulled by calendar month from January 2017 to December 2019 for the aircraft fleet through the USAF Logistics Installations and Mission Support Enterprise View (LIMS-EV) Supply Chain Management View data management system. The independent variables used in this study focused on transportation shipping mode code and MICAP delete codes for all USAF F16 MICAPs recorded between January 2017 and December 2019. This MICAP data was provided by the analysts at the 635th Supply Chain Operations Wing (SCOW).

Hypothesis one is tested by looking at all USAF F16 monthly MICAPs rectified through the surface shipment of the MICAP part (utilizing Shipping Mode Codes including any ground or sea shipments). Since hypothesis one predicts that utilizing slower shipping modes to resolve MICAPs will have a negative impact on performance, the “Surface Shipments” category was utilized for the model. Hypothesis two is tested by looking at all USAF F16 monthly MICAPs that were resolved non-laterally (utilizing "MICAP Delete Codes 1, 2 and 5"). Since hypothesis two predicts that resolving MICAPs from a non-local supplier will have a negative impact on performance, the "Non-laterally Resolved MICAPs" category was utilized for the model.

To determine surface-mode shipment totals, shipment mode codes were sorted for all MICAPs to identify any non-air mode codes utilized to move MICAPs to end user locations. Once the surface-shipped MICAPs were identified, they were sorted by date and the total number of MICAPs utilizing a surface mode code per calendar month was calculated. To determine non-lateral shipment totals, MICAP delete codes were sorted for all MICAPs to identify any MICAPs that were non-laterally resolved. Once the non-laterally resolved MICAPs were identified, they were sorted by date and the total number of MICAPs resolved non-laterally per calendar month was calculated.

4.4 Results and Analysis

4.4.1 Impact of MICAP Response Strategies

This research was focused on USAF F16 aircraft historical mission capability (MC) rate data as the dependent variable. MC rate data was pulled by calendar month from January 2017 to December 2019 for the aircraft fleet through the USAF Logistics Installations and Mission Support Enterprise View (LIMS-EV) Supply Chain Management View data management system. The independent variables used in this study focused on transportation shipping mode code and MICAP delete codes for all USAF F16 MICAPs recorded between January 2017 and December 2019. This MICAP data was provided by the analysts at the 635th Supply Chain Operations Wing (SCOW).

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Table 11. Impact of MICAP Response on MC Rate

The Impact of MICAP Response on MC Rate				
	Estimate	Standard Error	t-value	Significance
Intercept	0.7783204	0.0209499	37.151	0.000 ***
Total MICAPs Shipped Surface Mode	-0.0004678	0.0002451	-1.908	0.0651 .
Total Non-Lateral MICAP Resolutions	-0.0003048	0.0001238	-2.461	0.0193 *
Significance: '***' <0.001 '**' <0.01 '*' <0.05 '.' <0.1				

Results from the model show that the estimated effect size for Total MICAPs Shipped through a Surface Mode Code (-0.0004678) is negative and significant at alpha level (α) = 0.1. This finding provides evidence that the total number of surface mode shipped F16 MICAPs is associated negatively with F16 MC Rate and therefore supports the relationship proposed in the first hypothesis. The model results also show an estimated effect size for Total Non-lateral MICAP Resolutions (-0.0003048) is negative and significant at alpha level (α) = 0.1. This finding provides evidence that the total number of non-laterally resolved F16 MICAPs is associated negatively with F16 MC Rate and therefore supports the relationship proposed in the second hypothesis. Residuals were tested for normal distribution, independence, and constant variance, with test outcomes supporting that they are normally distributed, independent and have constant variance.

Based on the model results, there is enough evidence to suggest a statistically significant negative association between both an increased number of surface mode-shipped MICAPs and an increased number of non-laterally resolved MICAPs and the decrease of USAF F16 MC Rates. Specifically, for every 1% increase in F16 MICAPs resolved through a surface mode code shipment, F16 MC Rates drop by 0.05% on average, and for every 1% increase in F16 MICAPs resolved through a non-lateral supplier, F16 MC Rates drop by 0.03% on average.

4.4.2 Discussion

Based on the available research, it was predicted that the results from the model would support (1) more surface mode shipped MICAPs and (2) more non-lateral MICAP resolutions would decrease network performance and supply chain resilience. Results estimated that testing total number of MICAPs shipped by surface mode in the model resulted in a significant negative effect. Therefore, the hypothesis (H1), increasing surface mode MICAP shipments is correlated to decreased performance, was supported. Likewise, testing the total number of MICAPs resolved at by non-lateral suppliers had a significant negative effect. Therefore hypothesis (H2), increasing MICAPs resolved by non-lateral suppliers is correlated to decreased performance, was also supported. Support for these hypotheses suggests resilience can be improved by limiting the number of MICAPs being shipped through surface mode and the number of MICAPs being resolved from non-lateral sources of supply. Decision makers can potentially improve resilience by implementing procedures that would decrease response time for MICAP response.

The current operational threshold requirement for response and closure of a MICAP once it is sourced is set by the 635th Supply Chain Operations Wing (SCOW) at 164 hours (7 days), with the average MICAP closure in Fiscal Year 2019 reflecting 5.5 days (Litchfield, 2020). Since the MICAPs are not considered late until they fail to arrive within the seven day window, base supply personnel have a seven day goal to meet and may not receive further motivation to move the MICAP part any faster. Data provided by the 635th SCOW also indicates that the USAF has the proper levels of spare parts in its inventory based on 86 percent of its reported MICAPs being closed within the seven day threshold window (Litchfield, 2020). This data suggests that the parts are on base shelves, and increasing inventory of spare parts is not required. However, it does suggest that a potential constraint exists to which influences the way the USAF shares the parts already in the system.

Expediting the shipping process is one potential way to improve spare part placement and respond faster to a MICAP request. The R-squared result of 0.36 suggests that these F16 MICAP response variables tested account for 36% of our total variance in the model (the F16 MC Rate). This evidence supports the claim that the way which F16 MICAPs are resolved in the repair system has a significant impact on the MC Rate of the F16 aircraft. It is worth noting that even the most miniscule percent increase in MC Rate has a great impacts on the availability of USAF aircraft capacity and the ability of the USAF to meet mission requirements.

Furthermore, this research is in line with current efforts sponsored by the top logisticians of the USAF Headquarters. Simulations and proof of process experiments run for a MICAP Prime Tesseract initiative suggest that not only is faster shipping of MICAPs better for aircraft mission capability, but the cost is negligible (Litchfield, 2020). Every capacity hour produced by faster MICAP resolution response for the USAF F16 aircraft costs less than twenty cents, and returning an F16 aircraft to mission capable status 24 hours sooner through Express Next Day expedited shipping costs the USAF less than five dollars (Litchfield, 2020). On a much smaller scale, this model supports the MICAP Prime proposal findings by showing the significant impact that shipping mode and echelon of supplier can have on F16C MC Rate.

4.5 Conclusion

The model tested in this paper supports how utilizing non-lateral suppliers and slower surface shipping modes for MICAP parts can decrease resilience through decreased performance. Support for this MICAP response model demonstrates how SCR flexibility strategies, such as decreased recovery response time, can improve an organization’s ability to maintain and recover performance after disruption. If an organization can identify simple adjustments to speed up the response time to MICAP-like backorder disruptions in their production or repair network, it will be able to maintain performance, minimize downtime of assets, and ensure a quicker performance recovery in the event of a disruption to its supply chain.

While both SCR flexibility and redundancy strategies increase the resilience of the repair network, utilizing a SCR flexibility strategy of quicker shipping modes and lateral suppliers of backordered spare parts is a relatively simple, cost effective way to increase access to spare parts inventory across all end use locations.

4.5.1 Theoretical Implications

Theory of constraints (TOC) studies suggest that deliberateness and speed allows for better resource staging and maintenance execution (Goldratt, 2014). By allowing MICAPs to be shipped by slower shipping modes, the USAF repair system is creating a constraint this is a relatively low cost fix for big reward. Likewise, the organization is creating another constraint in MICAP response by not being as deliberate about spare part placement and sourcing parts from non-lateral echelons. Evidence provided by this study supports TOC by highlighting two types of MICAP resolution response options that have significant negative correlations to network performance and can be seen as critical constraints to supply chain resilience.

4.5.2 Managerial Implications

This research provides evidence that organizations can utilize SCR flexibility strategies, like decreased disruption response time, to improve their organization's performance. Specifically, more deliberate lateral echelon part sourcing, and faster shipping mode selection can be utilized to break down response time constraints in an organization to improve supply chain resilience (SCR). For the USAF, results support the Tesseract MICAP PRIME initiative looking at removing the constraint time wasted through shipping mode selection. This effort provides evidence to support the MICAP PRIME recommendation to send all MICAP parts as quickly as possible. Managers can influence the resilience of their supply chain by lifting the constraints on backorder shipment options to allow for the quickest modes and more deliberate placement of spare parts for more lateral resupply options.

4.5.3 Limitations

This research effort is focused on the relationship between MICAP resolution response strategies and MC rate. While it supports the idea that certain response strategies can be seen as unnecessary constraints in supply chain, it is limited in its ability to test all variables involved in MICAP resolution decisions. One predicator variable that was initially proposed was the number of days it took for the MICAP to travel from source of supply to the customer. However, the USAF data repository does not include reliable data for this variable. Data analysts at the SCOW recommended that the dates and times entered into the transportation tracker for MICAP shipments were not always accurate or consistent. To mimic the concept of shipping speed, analysts offered two other codes that they knew were accurately recorded in the data for F16 MICAPs, Shipping Mode Codes and MICAP Delete Codes, since air shipments tend to be faster than ground and sea shipments and MICAPs resolved laterally tend to be resolved quicker than MICAPs resolved non-laterally. Despite not being able to use the initial shipping days to show speed, both suggestions from the analysts were adequate to identify potential MICAP response constraints in the system.

Another limitation of the data is that MC rate is not impacted by MICAP parts alone. Many other factors can cause aircraft to be unable to perform at full mission capability. While results from this model suggest that MICAP shipments have an impact on performance, it is not the full story of why MC rates fluctuate as they do.

4.5.4 Future Research

Supply Chain Resilience (SCR) flexibility strategies are focused around the idea of being collaborative, innovative and agile (Barrat, 2004; Dmanpour and Gopalakrishnan, 2001; Wieland and Wallenburg, 2012). Future research in this area should allow for the study of historic metrics, but also think outside the box for innovative ways to remove the constraints to harboring supply chains ready for disruption. How can the USAF innovate its processes to shorten MICAP response time? Does the constraint exist in the inability to accurately predict MICAP part failure? Is there a constraint in the ability to apply additive manufacturing for these critical parts? Do inventory staging policies need another look? Future research efforts could take these ideas individually and identify the cost tradeoff required to remove these constraints to MICAP resolution response time.

V. Conclusion

It is impossible to predict every disruption a supply chain may encounter. The best an organization can do to protect network performance is to build resilience in the supply chain and life-blood of its operations. The research presented in this dissertation focuses on how organizations can select, measure and employ supply chain resilience (SCR) strategies. This dissertation established a mechanism for decision makers to posture their organizations for long-term success regardless of the uncertainty of the environments in which they operate. While a more thorough synopsis can be found in previous chapters, this conclusion establishes a summary of the original contributions from each of the dissertation research efforts, as well as suggestion for future research.

5.1 Original Contributions

Chapter II served as support for the positive relationship between supply chain resilience (SCR) strategies and firm performance. It also provided evidence for the identification of two solid resilience strategy categories – redundancy SCR strategies and flexibility SCR strategies. Chapter II identified that these two categories were both individually significant in relation to performance outcomes in an organization

Chapter III served to better quantify supply chain resilience through the development of the Resilience Capability Metric (RCM). The study proposes that SCR can be measured relative to the supply chain's requirements by the ratio of the AUC to the system's total demand over time. The SCR redundancy strategies tested in this study provide evidence that both redundant capacity and redundant inventory have a positive impact on performance levels.

For SCR flexibility strategies, this study identifies the impact that recovery response speed has on supply chain resilience. The time it takes an organization to implement a recovery response to a disruption has a critical impact on the network's performance and overall resilience. Based on what is known about SCR flexibility strategies, it is predicted that a more flexible supply chain, with a decreased response time to disruptions means an increased performance rate. The study not only provides evidence that resilience can be improved by both SCR flexibility and redundancy strategies, but suggests that employing multiple different strategies in the same organization can have a positive interactive impact on overall resilience.

Chapter IV demonstrates how barriers to SCR flexibility strategies can negatively impact an organization's ability to maintain and recover performance after disruption. Findings support that an organization can maintain performance, minimize downtime, and ensure a quicker performance recovery, if it can identify simple adjustments to speed up the response time to disruptions in its supply chain.

5.2 Implications for Managers

The original contributions of this research have practical implications for organization managers worldwide. This dissertation provides evidence to support that firms can improve their performance by putting forth an effort to increase the resilience of their supply chains. This evidence can inform decision makers on how to best invest the money their firm has set aside for supply chain resilience and help persuade firms to invest in resilience if they were on the fence about the importance of that investment. Categorizing Supply Chain Resilience (SCR) strategies into redundancy and flexibility groupings can help managers identify the SCR options available to their organization.

The research suggests that managers must consider the costs associated with each SCR strategy to determine the best type and combination to use, as well as the length of time it takes to provide a SCR strategy response. Since a quicker response may be more expensive, when evaluating the feasibility of a shortened response time, managers should examine whether the associated costs of recovery speed are worth the added resilience.

While redundancy strategies centered on excess capacity, inventory, and robust infrastructure will most likely have a positive impact on the performance of your firm when faced with disruption, this research provides evidence to support that the greater return on investment can be realized through an emphasis on flexibility. Utilizing a SCR flexibility strategy of quicker response times, such as faster shipping modes and sourcing from lateral suppliers can be a relatively simple, cost effective way to increase performance. Since the literature supports a stronger positive association between Supply Chain Resilience (SCR) flexibility strategies and performance should encourage managers to prioritize flexibility investments in organizations where this makes the most financial sense. Therefore, managers should focus on flexibility strategies that support a more transparent, collaborative, and responsive environment.

This research also provides managers with a resilience metric that allows for informed capital allocation decisions when designing and assessing their supply chains. It offers a simulated example of how to test and measure the impact SCR strategy investments. The Resilience Capability Metric (RCM) proposed in this paper allows a means by which to properly compare these SCR strategy investment scenarios. Managers can build their own simulations and use the RCM to analyze the resilience of their supply chains against different disruptions, as well as test the resilience impact of each strategy. Furthermore, many real-life considerations such as working capital investment, space, holding and management costs of inventory, and employee incentives, among others, could be taken into account. Ultimately, this study provides managers with the knowledge for making better informed, more targeted SCR investments to increase a firm's competitive advantage, reduce system constraints, and provide the best performance outcome for the organizational success.

5.3 Implications for United States Air Force Leaders

Along with the original contributions and managerial implications listed above, this research also has important implications for leadership in the United States Air Force (USAF). Supply chain resilience (SCR) is critically important to the ability of the USAF to support multiple weapons systems all over the world. Performance of these war-fighting capabilities is tracked constantly, and failure to maintain readiness of vital warfighting assets is unacceptable. Many times the readiness and performance of these assets is at the mercy of limited budgets, slow response times and complicated supply chains. The ability for USAF leadership to better utilize limited budget to get the most resilient supply chains is vital to the sustainment of aging fleets.

The new resilience capability metric (RCM) developed in this dissertations can be utilized by military logistics leaders and decision makers to quantify and compare the amount of resilience built into their supply chains for each investment, aiding in more informed resilience strategy investments. Military leaders can utilize this metric when making SCR investments in order to target specific requirements and desired outcomes.

Results of this dissertation also support the USAF Tesseract MICAP PRIME initiative to improve the speed at which mission critical parts in the USAF supply chain move. USAF leadership can influence the resilience of their supply chain by lifting policy constraints on backorder shipment options to allow for the quickest modes and more deliberate placement of spare parts for more lateral resupply options.

5.4 Suggested Future Research

Further studies should examine other ways in which organizations can improve their supply chain resilience (SCR). Current literature has identified the need for comparing different SCR strategies used to improve performance individually, but is lacking in studies on the interactions between strategies. Future research may consider looking closer at the interactions and tradeoffs between the two categories of SCR strategies identified in this dissertation. Understanding whether investment in one strategy has a moderating impact on the other would be useful for organizations interested in utilizing multiple strategies.

While this paper provides a useful method of measuring SCR through the RCM, there are some very promising avenues of further inquiry in understanding system behavior during disruption. The application of queuing theory may reveal the underlying relationships between the system parameters and system behavior that generate the observed functional forms. A better understanding of individual system behavior can then be used in optimization models to identify good design principles.

Furthermore, many real-life considerations such as working capital investment, space, holding and management costs of inventory, and employee incentives, among others, could be taken into account in following studies. Future research can also tackle innovation in Supply Chain Resilience (SCR) flexibility strategies by analyzing constraints found in supply chains in an attempt to remove these barriers to resilience. How can processes be innovated to improve disruption response time? Constraints that slow innovation, collaboration and agility must be better explored to truly harness the power of SCR flexibility strategies in creating more resilient supply chains. Finally, many other SCR strategies exist besides those observed in this dissertation, and it would be interesting to apply RCM using other resilience strategies to determine the best SCR strategy combination for an organization.

Appendix

A.1 Meta-Analysis Study Classification Sample

Study	SCR Strategy		n	r	yi	vi	Dep Var	Performance
Akgun, Ali E., Keskin, Halit (2014)	Product Innovativeness	Flexibility	224	0.70	0.867301	0.004525	Firm Performance	Financial Performance (FP)
	Original/unscripted agility	Flexibility	224	0.31	0.320545	0.004525	Firm Performance	Financial Performance (FP)
	Behavioral preparedness	Flexibility	224	0.32	0.331647	0.004525	Firm Performance	Financial Performance (FP)
	Broad resource networks	Redundancy	224	0.10	0.100335	0.004525	Firm Performance	Financial Performance (FP)
Brandon-Jones, E., Squire, B., Van Rossenberg, Y.G.T. (2015)	Extra Production Capacity	Redundancy	264	0.190	0.192337	0.003831	Plant Performance	Operational Performance (OP)
	Saftey Stock at Suppliers	Redundancy	264	0.080	0.080171	0.003831	Plant Performance	Operational Performance (OP)
	Safety Stock at Plant	Redundancy	264	-0.090	-0.09024	0.003831	Plant Performance	Operational Performance (OP)
	Visibility	Flexibility	264	0.240	0.244774	0.003831	Plant Performance	Operational Performance (OP)
Huo, B., Gu, M. & Wang, Z. (2018)	Supplier Flexibility	Flexibility	216	0.460	0.497311	0.004695	Operational Performance	Operational Performance (OP)
	Internal Flexibility	Flexibility	216	0.550	0.618381	0.004695	Operational Performance	Operational Performance (OP)
	Customer flexibility	Flexibility	216	0.530	0.590145	0.004695	Operational Performance	Operational Performance (OP)
	Supplier Flexibility	Flexibility	216	0.350	0.365444	0.004695	Financial Performance	Financial Performance (FP)
	Internal Flexibility	Flexibility	216	0.370	0.388423	0.004695	Financial Performance	Financial Performance (FP)
	Customer flexibility	Flexibility	216	0.420	0.447692	0.004695	Financial Performance	Financial Performance (FP)
Kach, A., Busse, C., Azadegan, A. & Wagner, S.M. (2016)	Process Innovativeness	Flexibility	148	0.250	0.255413	0.006897	Firm Performance	Financial Performance (FP)
	Product Innovativeness	Flexibility	148	0.160	0.161387	0.006897	Firm performance	Financial Performance (FP)

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Vita

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Major, United States Air Force

Major Amanda L. Femano has been serving as a Logistics Readiness Officer in the United States Air Force (USAF) for the last thirteen years. She received her commission through the Reserve Officer Training Corp (ROTC) from the University of Delaware in 2008 where she earned a Bachelor of Arts in Biological Sciences. She continued her formal education at Our Lady of the Lake University in San Antonio, Texas graduating in 2012 with a Master's in Business Administration. Amanda spent a year in Afghanistan serving as a logistics air advisor to the Afghan Air Force and Aide-de-Camp to the Commanding General of NATO Air Training Command-Afghanistan during Operation Enduring Freedom. She later led two onsite bilateral logistics subject matter expert exchanges with the Royal Singapore Air Force and the Bangladesh Air Force. Major Femano has leadership experience in refueling operations, deployment operations, logistics contingency planning, vehicle operations and management, air terminal operations, cargo movement and material management. Her logistics experience has sparked her desire to study supply chain resilience to aid in the establishment of more resilient military supply chains and improved USAF mission capability.

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14. ABSTRACT
Businesses operate every day in a disruptive environment. Supply and demand uncertainty, natural disasters, global pandemics, and mishaps can all cause chaos to a supply chain's flow. It is impossible to predict every disruption a supply chain may encounter. The best an organization can do to protect network performance is to build resilience in the supply chain and life-blood of its operations. Ensuring that a supply chain has the proper built-in mechanisms to resist and recover from disruptions is referred to as Supply Chain Resilience (SCR). While it is generally agreed that SCR can be improved through the implementation of SCR strategies, the links between these strategies, performance improvement and resilience is understudied. This dissertation leans on resource based view and theory of constraints to categorize these SCR strategies, examine the links between the strategies and performance, and develop a metric to measure network resilience over time. First, a meta-analytical study identifies generalizable relationships between SCR strategies and firm performance measures. Then, the SCR redundancy strategies are applied to a model simulation to illustrate the resilience curve response to different SCR strategic decisions. Resilience outcomes are compared using a developed Resilience Capability Metric (RCM) utilizing Area under the Curve (AUC) to measure the cumulative performance level of the system from disruption to predetermined endpoint, representing how much of the system demand can be served by different network resilience designs. Finally, SCR flexibility strategies are analyzed to see how constraints imposed on a supply chain's response time could impact the resilience of the supply chain. This dissertation highlights the positive impact on performance and resilience that can be realized when organizations take the time to implement the proper SCR strategies, while providing managers with RCM to measure and compare the impact of different strategies within their organization.

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