Tobias Bjørge Berntsen

On the Enabling Effect of Simulations for Decision-Making Support for Supply Chain Resilience

A Preliminary Investigation

Master's thesis in TPK4930, Production Management
Supervisor: Mirco Peron
June 2023

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

NTNU
Norwegian University of
Science and Technology

Tobias Bjørge Berntsen

On the Enabling Effect of Simulations for Decision-Making Support for Supply Chain Resilience

A Preliminary Investigation

Master’s thesis in TPK4930, Production Management
Supervisor: Mirco Peron
June 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

NTNU
Norwegian University of
Science and Technology

ACKNOWLEDGEMENTS

This thesis is the result of my master's degree. The research for the thesis was done at the Norwegian University of Science and Technology (NTNU), Department of Mechanical and Industrial Engineering (MTP), in Trondheim.

I would like to sincerely thank my supervisor at NTNU, Mirco Peron, for his advice, perseverance, and support. His expertise in the subject and perceptive criticism were very helpful in helping me to clarify my thoughts and choose the course of this thesis.

I also want to express my appreciation to the NTNU academic members and advisers, whose knowledge was very helpful in developing this thesis. In addition, I want to thank my friends and classmates for their encouragement and motivation as I wrote this thesis.

Finally, I want to thank my family from the bottom of my heart for their understanding and support during my academic career. Their support, conviction, and selflessness have served as a continual source of inspiration.

SUMMARY

The goal of the thesis is to present an analysis of proactive and reactive solutions discovered through a systematic literature review that were conducted to improve supply chain resilience and mitigate the negative effects of disruptions. Twelve strategies for enhancing SC resilience were identified through the literature review, comprising seven proactive and five reactive strategies.

The review indicated a consensus among researchers regarding the effectiveness of proactive strategies. Proactive strategies allow SC managers to prepare for potential disruptions and thus reduce their impacts. Among the strategies identified, backup inventory emerged as a key factor in enhancing SC resilience, with nine out of the twenty-one reviewed papers supporting the effectiveness of this strategy. The implementation of backup inventory involves conducting a risk assessment to determine the optimal backup inventory levels based on the probability of disruptions. This strategy proves attractive to SCs seeking to increase their resilience due to its relatively simple implementation process.

Similarly, adding backup capacity is regarded as an effective strategy when trying to increase the resilience of a SC. This strategy makes it possible to continue production even when experiencing disruptions. This strategy is also relatively easy to implement, but it does require proactive planning, in order to optimize when and where to implement the backup capacity.

Both backup capacity and inventory were used in simulations, in order to evaluate the strategies effectiveness as mitigation measures. The results indicated that the strategies are effective ways of enhancing SC resilience and reducing the negative effects of disruptions within the SC.

The main conclusion is that mitigation strategies, of any sort, should be implemented in order to increase the preparedness and resilience of a SC. Two effective ways of doing so is to implement backup capacity or inventory to the SC. This thesis contributes by giving a detailed insight into the challenges of SC disruption mitigation, where a number of mitigation strategies has been identified. SC managers could use this thesis as a guideline of which strategy to implement to their own SC.

SAMMENDRAG

Formålet med denne oppgaven er å gi en grundig analyse av proaktive og reaktive strategier identifisert gjennom ett systematisk litteraturstudie, utført for å øke robustheten til forsyningskjeder og redusere de negative effektene til forstyrelser i forsyningskjedene. Litteraturstudiet identifiserte tolv strategier, inkludert syv proaktive og fem reaktive, for å forbedre robustheten til forsyningskjedene.

Studiet indikerte enighet blant forskere om at proaktive strategier er en effektiv måte å styrke forsyningskjedene på. Proaktive strategier muliggjør forberedelse til potensielle forstyrelser, og dermed også redusere deres negative effekt. Bland de identifiserte strategiene viste reservelager som en viktig faktor for å øke robustheten til forsyningskjedene, der hele ni av de tjueen artiklene støttet effektiviteten av denne strategien. Implementeringen av reservelageret krever en risikovurdering for å bestemme optimale nivåer av varer på reservelageret, basert på sannsynligheten for en forstyrrelse i forsyningskjeden. Denne strategien er en attraktiv strategi, da den er relativt enkel å implementere i forsyningskjeden.

En annen strategi som ble betraktet som en effektiv strategi var reserve kapasitet. Denne strategien muliggjør det å opprettholde produksjonen til tross for forstyrrelser. Strategien er, i likhet med reservelager, relativt lett å implementere, men krever planlegging på forhånd for å optimalisere når og hvor kapasiteten skal implementeres.

Disse strategiene ble brukt i simuleringer for å vurdere deres effektivitet som strategier ment til å redusere virkningen av forstyrrelser. Resultatene indikerer at begge strategiene er med på å øke robusthet til forsyningskjeder og at de reduserer de negative effektene av forstyrrelser.

Hovedkonklusjonen av denne oppgaven er at strategier for å redusere effekten til forstyrrelser bør implementeres i en forsyningskjede, og at reserve kapasitet eller reservelager er to effektive måter å øke robusthet på. Det viktigste bidraget denne oppgaven gir er en detaljert innsikt i utfordringene tilknyttet til forstyrrelser i forsyningskjeder, og hvordan man kan redusere de negative effektene av disse. Det er identifisert flere strategier forsyningskjeder kan bruke, og denne oppgaven kan brukes som en retningslinje til hvilke strategier man kan velge mellom.

Table of contents

List of Tables

List of Figures

1 Introduction

The introduction of the master thesis will provide background information on the topic of supply chain disruptions, as well as a problem description, and the research questions used to resolve the problem of the thesis. An outline of the remainder of the thesis will be presented at the end of the introduction chapter.

1.1 Background and Motivation

Supply chain (SC) disruptions can cause severe impacts to businesses, such as reduced productivity, revenue loss, increased costs, and reputational damage. In the current complex and interconnected global market, supply chains (SCs) are increasingly vulnerable to various disruptions such as political instability, natural disasters, and cyber-attacks [1]. Therefore, effective strategies to mitigate SC disruptions and responding effectively to them are critical for the success of a SC.

The importance of researching and investigating possible proactive and reactive strategies for mitigating the negative effects of SC disruptions has increased in the past decades, due to lean management practices and the globalization of SCs [1]. The interest of researching the subject of SC disruptions has increased since the beginning of the 21st century, which is seen by a noticeable upsurge in the academic papers dedicated to this topic [2]. In 2005, Blackhurst et al. [3] forecasted that the frequency of SC disruptions would escalate due to global sourcing, the transition towards reduced inventory levels, enhanced responsiveness, and increased agility, which aligns with Snyder et al.'s [2] reasoning behind the increased interest in SC disruption theory.

The elevated risk of disruptions has been underscored by a series of major disruptions, including the COVID-19 pandemic, the 2021 Suez Canal blockage, and multiple natural disasters, such as wildfires, earthquakes, and tsunamis. As the risk of disruption increases, the importance of mitigating the negative disruptions becomes even more critical, which is what motivates towards research of this topic. Effective disruption management can help reduce the negative impacts on the operations and performance of firms.

The two main categories of mitigation strategies are reactive and proactive mitigation. Reactive mitigation involves acting at the time of disruption, such as increasing the workforce or information sharing. Proactive mitigation involves preparing for disruptions with the likes of backup inventory, backup capacity, and more. Through the implementation of these strategies as well as continuous monitoring and improvement of the resilience of the supply chain, the negative effects of supply chain disruptions can be minimized.

1.2 Objectives

This thesis aims to evaluate the effectiveness of SC disruption mitigation strategies through a systematic literature review and simulations. The Scopus database was used to conduct the search query for the systematic literature review. The software used for the simulations are anyLogistix. Multiple scenarios will be simulated, using two different mitigation strategies, explored in the systematic literature review, in order to investigate what the effectiveness of the two strategies are.

The main study areas of this thesis are:

- General supply chain disruption theory, with focus on mitigation and resilience.
- Reactive/proactive strategies discussed in literature.
- Simulation of SC disruptions

1.3 Problem Description

Disruptions can have significant negative impact on the resilience, operations, and overall performance of a SC. In order to mitigate these disruptions and improve the resilience of SCs, it is crucial to identify effective proactive and reactive mitigation strategies. Previous research has identified a range of strategies, however, there is a need for a comprehensive analysis and evaluation of the strategies. This research aims to address this gap by conducting a systematic literature review to identify proactive and reactive mitigation strategies.

To further investigate the effects of the strategies, simulations will be conducted under disruptive scenarios. The simulations will evaluate the impact of implementing backup capacity and backup inventory on the resilience of the SCs. The research will analyse the outcomes of these strategies.

By gaining a comprehensive understanding of the effects and implications of implementing these strategies, this research will contribute to the knowledge on SC disruption mitigation. The findings will provide valuable insights for SC managers seeking to enhance their preparedness and resilience in the event of disruptions.

1.4 Research Questions

Seeing an increase in frequency as well as risk of SC disruptions, investigation of how to best mitigate them is of high interest. Therefore, a systematic literature review on SC disruption mitigation strategies, and simulations of disruptions will be conducted in order to answer the following research questions:

- RQ1: What are the possible reactive and proactive strategies to mitigate the potential negative effects of supply chain disruptions?
- RQ2: What are the effects of implementing specific strategies, such as backup inventory and backup capacity, on the resilience of supply chains when simulated under disruptive scenarios?

This thesis aims to identify the most effective strategies for mitigating supply chain disruptions and provide a guideline for firms facing disruptions. The results of this study will contribute to the industry by providing a comprehensive analysis of different disruption mitigation strategies. The research questions will be resolved through a systematic literature review and simulations using the anyLogistix software.

1.5 Outline

The structure of the thesis is as follows. In chapter 2, the theoretical background will be presented. After that, in chapter 3, the research methodology of the thesis will be described in detail, followed by chapter 4 which contains the results of the thesis as well as a discussion of the results. In chapter 5, the thesis will be concluded followed by proposal for further research and limitations of the thesis.

2 Theory

The theory chapter will provide an overview of SC disruptions, resilience, vulnerability, and modelling. Firstly, an introduction of the concept of SC disruption will be presented, followed by some negative impacts' disruptions can have on a SC. Additionally, the importance of SC resilience will be highlighted. The theory chapter will also cover several factors contributing to increased vulnerability in a SC. Lastly, an insight into modelling of SCs and disruptions within the SC will be provided.

2.1 Supply Chain Disruptions

The disruptions in a SC can occur in different types and intensities and can be either global or local. According to Wagner and Bode [4], SC disruptions refer to an unintended and undesirable situation that poses a supply chain risk. These situations are typically caused by one or more triggering events that can be broadly classified into three categories: accidents, natural disasters, and terrorist attacks [5]. The following subsections will present three examples of significant disruptions from each of the triggering event categories.

2.1.1 Accidents

In March 2021, Ever Given, a 400-meter-long freight ship carrying 20,000 containers, ran aground, which resulted in the blockage of the Suez Canal, which serves as a vital trade route with 12% of global shipping passing through it annually [6]. This incident is an example of an accident leading to a major SC disruption. The narrow and restricted waterway's potential cost of disruptions was highlighted by this event, as the blockage led to major financial losses. The blockage caused a daily loss of approximately 10.9 million pounds for the canal and an estimated seven billion pounds in trade per day [7]. To mitigate the disruption, some ships were rerouted around the Cape of Good Hope, which included an additional five to twelve days of transit, where armed guards was necessary in order to ensure safe passage [8].

2.1.2 Natural Disasters

Natural disasters can occur in many varieties, one of which is the COVID-19 pandemic that has had a colossal impact on global SC. The Duke Global Health Institute warns that SC needs to be more aware of global pandemics, as the probability of pandemics with similar consequences to COVID-19 is on the rise each passing year [9]. The pandemic caused substantial disruptions in global SC, causing increased cost for companies, delays, and shortages. Approximately 78-95% of SC networks have been affected [10]. The disruption caused by the pandemic has raised a debate on whether the globalization of SC should come to an end, due to the vulnerability to pandemic-related disruptions, such as lockdowns and the closing of national borders, which create difficulties in shipping and transportation [11]. The impacts of the pandemic were particularly evident in personal protective equipment, such as gloves, facemasks etcetera, which are mainly produced in low-cost production areas in eastern Asia, such as China. This highlights the potential difficulties that arise by having far-away production facilities, especially under a pandemic-related disruption, but also during other types of disruptions causing transportation difficulties [12].

2.1.3 Terrorist Attacks

SC disruptions originating from terrorist attacks, causing significant disruptions in the SC, has happened at an increased frequency since the beginning of the 21st century. An example of this is the terrorist attack on September 9 in 2001, when the World Trade Center was destroyed. Schmitt and Sing [13] discovered that localized disruptions could have global consequences, as was evident after the attacks. The attack directly impacted the companies located in and around the World Trade Center, furthermore, the closure of US airspace and borders resulted in substantial disruptions of companies outside the US as well. For instance, the Ford Motor Company had to close multiple plants due to a shortage of parts from their Canadian suppliers, resulting in a 13% decline in production during that quarter [14], showing that local disruptions can cause problems for SCs around the globe.

2.1.4 Summary of Supply Chain Disruptions

Mitigation of SC disruptions is of high importance, as seen by the consequences of the above examples of significant disruptions. Large-scale SC disruptions can have a significant impact on a business in terms of economy, lead time to customers, production time and other aspects. However, it is essential to note that SC disruptions is not limited to large-scale events only. Smaller disruptions such as slow shipment, machine failures and custom delays are more frequent, but easier to anticipate. Nonetheless, it is crucial to consider and develop mitigative strategies to reduce the negative effects of the smaller disruptions as they occur more frequently [15].

2.2 Negative Impacts of Supply Chain Disruptions

Since the focus of this master thesis is regarding mitigating the negative impacts of SC disruptions, this section will provide an overview of some of the typical consequences of such disruptions. SC disruptions can cause a wide range of negative effects, from disruptions in individual SCs, to ripple effects that can impact entire industries. Common negatives include reduced profits, downtime in production, increased lead time to customers, delays in shipment and price increases [16]. Furthermore, firms that lack effective mitigation strategies may face the risk of losing market shares to competitors, as well as negative customer experience [1]. To summarize, the main negative impacts of SC disruptions are:

- Reduced profits
- Production downtime
- Shipment delays
- Price inflation
- Reputational damage
- Loss of market share
- Increased lead time to customers

2.3 Supply Chain Resilience

The term supply chain resilience refers to the ability of a SC to effectively prepare and respond to various types of disruptions, with the goal of returning to its previous state [17]. The resilience of a SC is a measure that evaluates the adaptability of a SC when faced with disruptions [18]. This section will highlight some factors which can help enhance the resilience of a SC.

2.3.1 Emergency Stock, Diversification and Collaboration

To improve SC resilience, one strategy is to keep safety and emergency stock levels, which can assist the supply chain in preparing for potential disruptions [18]. Another approach to enhance SC resilience is to diversify suppliers and transportation routes. This can help mitigate the impact of disruptions by providing alternatives to disrupted sources or routes of transportation [19]. These strategies can also reduce dependency in the SC, reducing the likelihood of complete disruptions within the SC [20]. Collaboration is another factor which can help improve the resilience of a SC. Collaboration in form of information sharing and collaborative communication is found to help increase the transparency of the SC, thus making the SC able to better detect and respond to disruptions both upstream and downstream [21].

2.3.2 The Future of Supply Chain Resilience

In the context of building more resilient SC, various new technologies have emerged with Industry 4.0 and advanced new technology. These technologies include, but are not limited to, additive manufacturing, big data analytics, and digital twins. According to Ivanov and Dolgui [22], the use of digital twins in SC management can help learn from real disruptions and identify patterns of disruptions, thereby helping to manage SC disruptions. Furthermore, Khajavi, Partanen and Holmström [23] explored the potential of additive manufacturing as a means of producing spare parts within a SC, contributing to a more sustainable and resilient SC. This shows that the emerging technologies could strengthen the current SCs ability to prepare for disruptions, and increase the SCs resilience.

2.3.3 Summary of Supply Chain Resilience

Enhancing SC resilience can potentially lead to benefits including increased market share, profits, and overall SC capabilities in addition to reducing the negative effects of disruptions. Furthermore, a resilient SC has a competitive advantage over its competitors because it can respond quickly and efficiently to disruptions [24]. Overall, improving SC resilience requires addressing various aspects of the SC, including supply chain design, risk management, and stakeholder collaboration. By adopting these strategies, companies can improve their ability to adapt and respond to disruptions, ultimately increasing their competitiveness and ability to meet customer needs.

2.4 Supply Chain Vulnerability

In today's global economy, SC vulnerability has become a critical concern for companies across all industries. Disruptions to the SC can have huge impacts on the SC as explained in section 2.1 and 2.2. It is therefore important for companies to identify and reduce vulnerabilities within their SC. This section will explore some of the causes that increases SC Vulnerability.

2.4.1 Lean Manufacturing and Globalization

According to Christopher and Lee, lean manufacturing has led to an increase in the vulnerability of SCs [25]. This observation is supported by various sources, such as [2], [4] and [13]. Lean manufacturing philosophy drives down inventory levels and adopts just-in-time manufacturing, thereby making SCs vulnerable to disruptions. Globalization of the SC is another factor that contributes to its vulnerability, as longer transportation routes increase the likelihood of unforeseen disruptions [24]. Furthermore, globalization can lead to local disasters having global consequences, as disruptions in one region or facility can impact SCs worldwide [4].

2.4.2 Single Sourcing

Single sourcing is another factor that increases the vulnerability of the supply chain. Although it may reduce administrative and purchasing costs, it leaves the supply chain dependant on a single supplier's ability to maintain lead times [26]. Dependency on either customers or suppliers can also be a contributing factor of making the SC vulnerable [20].

2.4.3 Climate Change

The impact of climate change on the vulnerability of SCs is significant, leading to unpredictable weather patterns, natural disasters, and changes in the environment. These effects can disrupt transportations, manufacturing, and distribution networks [27]. Additionally, climate change can case supply chain disruptions through the scarcity of raw materials, such as water or energy, which can lead to increased prices and production delays [28].

2.4.4 *Political Instability*

Political instability is another factor that can lead to vulnerability within a SC. It can result in increased tariffs, trade barriers, and restrictions on imports and exports, leading to a disruption in the flow of goods and services [29]. Political instability can also lead to an increase in labour strikes, protests, and civil unrest, which can affect manufacturing, transportation, and distribution activities. Such disruptions can cause delays, stockouts, and production losses, impacting SC performance leading to reduced customer satisfaction and loss of market share [29].

2.4.5 *Summary of Supply Chain Vulnerability*

In conclusion, supply chain vulnerability is a critical issue that needs to be addressed by both global and local SCs. Disruptions in the supply chain can have significant impacts on business performance, customer satisfaction, and market share. Factors such as lean manufacturing, globalization, single sourcing, climate change, and political instability all contribute to the vulnerability of the supply chain. It is therefore crucial for companies to develop resilient strategies to mitigate these vulnerabilities and prepare for disruptions.

2.5 Modelling supply chain disruptions

In their study on modelling of disruptions in SCs, Schmitt and Snyder [15] highlighted the importance of incorporating multiple time periods while managing disruptions, as the disruptions can have substantial impact on future time periods. Furthermore, the two authors emphasised the importance of considering the appropriate SC model type to apply the disruptions on, whether single-echelon, double-echelon, or multi-echelon. Schmitt et. al. [30] suggested that a comprehensive SC model should comprise four echelons with an assembly plant. The study further highlighted the importance of including backorders and lost sales as forms of shortages, disruptions at various stages of the SC, expedite capabilities at all levels and bullwhip effects in the model to reflect the actual functioning of SCs.

3 Methodology

The methodology chapter outlines the systematic literature review and simulation methodology that were employed to investigate the research questions. In order to answer RQ1 a systematic literature review was conducted to identify the existing research on supply chain disruption mitigation, and thereby explore the possible reactive and proactive mitigation strategies. RQ2 was answered through conducting simulations, which was used to evaluate the effectiveness of two different mitigation strategies in response to disruptions. In the following section the two different methods will be explained in detail. In Figure 1 the process of this thesis is described through a flowchart.

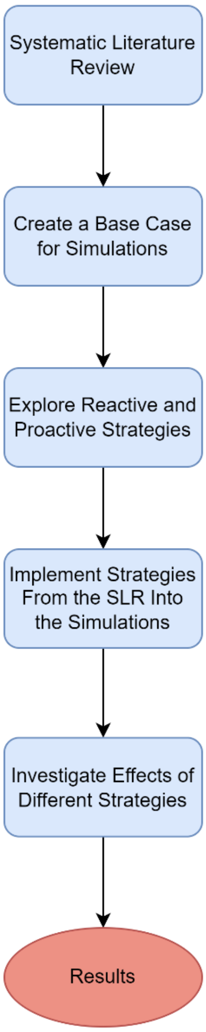

Figure 1: Flowchart of the Process

3.1 Systematic literature review

In order to obtain the necessary knowledge to answer research question 1: *What are the possible reactive and proactive strategies to mitigate the potential negative effects of supply chain disruptions?,* a systematic literature review was conducted. Conducting a systematic literature review contributes to structuring and organizing the literature on the topic of SC disruption mitigation [30]. The guidelines presented in [31] were followed in order to ensure a systematic and transparent search process. The systematic literature review was conducted in order to investigate the possible mitigation strategies, both reactive and proactive, which could be applied to SCs, and which strategies best suited for the simulation analysis in this thesis.

The Scopus database, which is among the largest databases containing scientific literature [32], was used to conduct the search. Firstly, two groups of keywords were defined. The first group contained two keywords: “supply chain*” and “supply network*”. The second group of keywords were: “resilienc*”, “disruption*”, “proactiv*”, and “reactiv*”. The AND operator combined the two groups, whereas the keywords in the same group were combined with the OR operator. In

Table 1, the two groups of keywords are shown.

Group 1	Group 2
"supply chain*" "supply network*"	"resilienc*" "disruption*" "proactiv*" "reactiv*"

Table 1: Keywords

The asterisk (*) and the quotation marks (“”) are included with the keywords in order to broaden the search. Quotation marks are used to search for loose phrases, while the asterisk allows for variations of a keyword with the word preceding the asterisk at its base. For instance, searching for “resilienc*” would include both resilience and resiliency. Following the keyword definition, inclusion criteria were implemented in order to restrict the query to the following subject areas:

- Business and Management and Accounting
- Engineering
- Economics, Econometrics and Finance
- Decision Sciences

Finally, document types other than “Article” and “Review”, as well as articles not written in English, were excluded. The final structure of the query is presented below:

(TITLE-ABS-KEY ("supply chain*") OR TITLE-ABS-KEY ("supply network*") AND TITLE-ABS-KEY ("resilienc*") OR TITLE-ABS-KEY ("disruption*") OR TITLE-ABS-KEY ("proactiv*") OR TITLE-ABS-KEY ("reactiv*")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "DECI") OR LIMIT-TO (SUBJAREA , "ECON")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")).

The search led to 4400 results in February 2023, which was reduced throughout multiple steps. Firstly, the papers with less than 0.5 in SJR ranking was excluded by exporting the Scopus results and SJR ranking from Scimago Journal and Country Rank [32] to excel where the “VLOOKUP” function was utilized to match the SJR rank with the results from Scopus. After the excluding the papers with less than 0.5 SJR ranking the results were narrowed down to 2826. After this, the papers which were not published in the top seventy journals on operations management and supply chain, as well as papers with less than 1.0 in SJR ranking, were excluded from the search. The top seventy journals can be seen in Appendix A. The results were then narrowed down to 1441 papers, the titles and keywords where then manually screened, and narrowed down to 244 papers. The abstracts of the remaining papers were read in order to manually narrow the results down to sixty-seven papers. The full text of the remaining sixty-seven articles and reviews were read, which led to a final sample of nineteen papers. The final two papers included by doing a snowball search of the original nineteen papers, therefore twenty-one articles and reviews was included in the systematic literature review. The process can be seen in Figure 2.

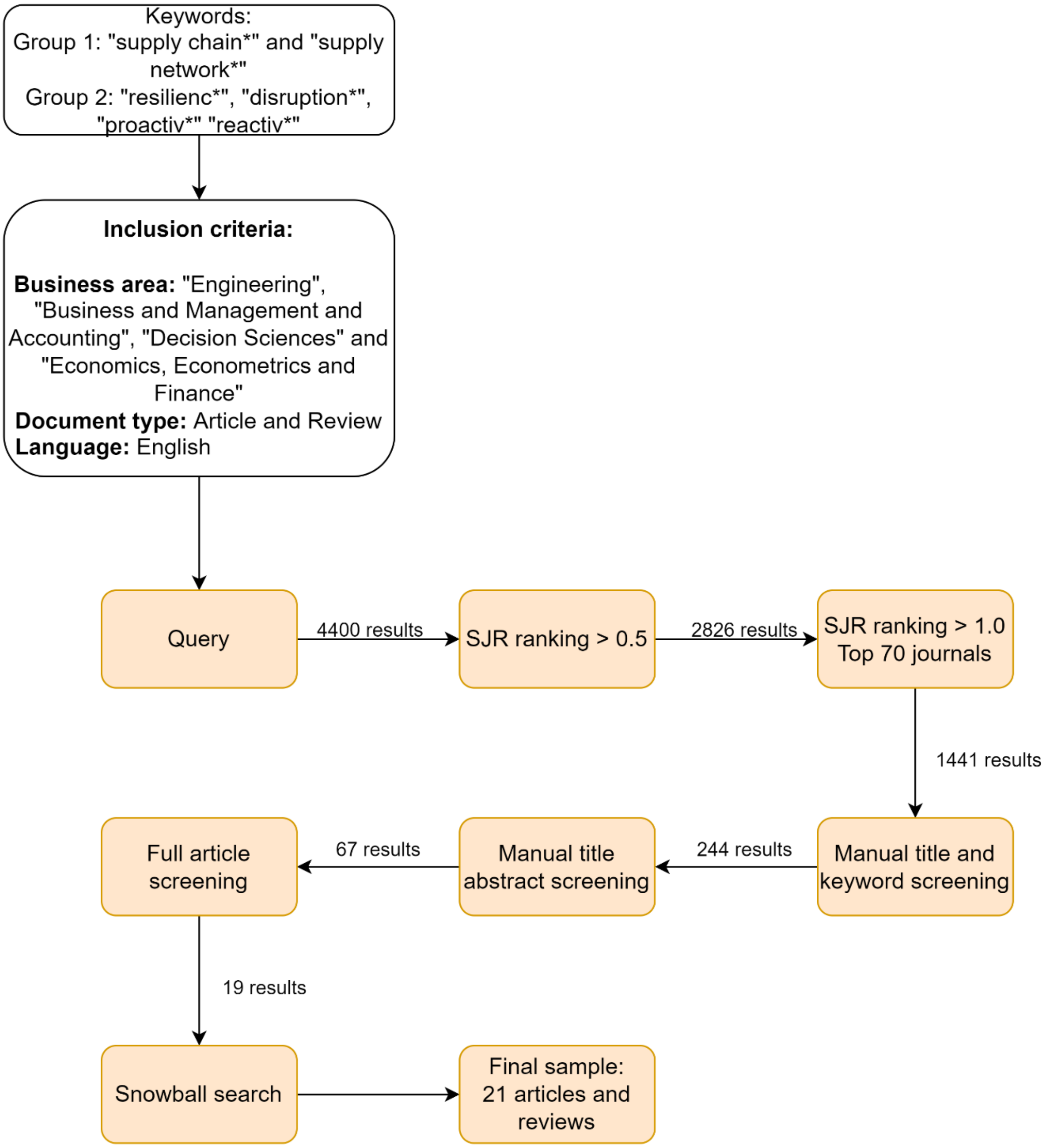

Figure 2: Flowchart of the creation of the sample

Table 2 presents a compilation of papers obtained from the systematic literature review. The table includes the authors' names, paper titles, publication years, and journals.

List of included articles from the systematic literature review

Authors	Title	Year	Journal
S. Sarkar, S. Kumar	A behavioral experiment on inventory management with supply chain disruption	2015	International Journal of Production Economics
H. Y. Huang, Y. C. Chou, S. Chang	A dynamic system model for proactive control of dynamic events in full-load states of manufacturing chains	2019	International Journal of Production Research
Y. Li, M. R. Kramer, A. J. M. Beulens, J. G. A. J. van der Vorst	A framework for early warning and proactive control systems in food supply chain networks	2010	Computers in Industry
T. G. Schmitt, S. Kumar, K. E. Stecke, F. W. Glover, M. A. Ehlen	Mitigating disruptions in a multi-echelon supply chain using adaptive ordering	2017	Omega
Z. Liu, M. Li, Y. Lei, X. Zhai	A joint strategy based on ordering and insurance for mitigating the effects of supply chain disruption on risk-averse firms	2022	International Journal of Production Economics
E. Esmaeili-Najafabadi, M. S. Fallah Nezhad, H. Pourmohammadi, M. Honarvar, M. A. Vahdatzad	A joint supplier selection and order allocation model with disruption risks in centralized supply chain	2019	Computers and Industrial Engineering
A. J. Schmitt, L. V. Snyder	Infinite-horizon models for inventory control under yield uncertainty and disruptions	2012	Computers & Operations Research
A. J. Schmitt, M. Singh	A quantitative analysis of disruption risk in a multi-echelon supply chain	2012	International Journal of Production Economics
M. R. G. Samani, S.-M. Hosseini-Motlagh, S. Homaei	A reactive phase against disruptions for designing a proactive platelet supply network	2020	Transportation Research, Part E: Logistics and Transportation Review
Hirofumi Matsuo	Implications of the Tohoku earthquake for Toyota's coordination mechanism: Supply chain disruption of automotive semiconductors	2015	International Journal of Production Economics
E. Sanci, M. S. Daskin, Y.-C. Hong, S. Roesch, D. Zhang	Mitigation strategies against supply disruption risk: a case study at the Ford Motor Company	2021	International Journal of Production Research
T. Chakraborty, S. S. Chauhan, M. Ouhimmou	Mitigating supply disruption with a backup supplier under uncertain demand: competition vs. Cooperation	2020	International Journal of Production Research
T G. Schmitt, S. Kumar, K. E. Stecke, F W. Glover, M. A. Ehlen	Mitigating disruptions in a multi-echelon supply chain using adaptive ordering	2017	Omega
A. Azadegan , S. Modi, L. Lucianetti	Surprising supply chain disruptions: Mitigation effects of operational slack and supply redundancy	2021	International Journal of Production Economics
J.Y. Son, R. K. Orchard	Effectiveness of policies for mitigating supply disruptions	2013	International Journal of Physical Distribution & Logistics Management
Lucker, Florian; Chopra, Sunil; Seifert, Ralf W.	Mitigating Product Shortage Due to Disruptions in Multi-Stage Supply Chains	2021	Production and Operations Management
S. Xi, X. Siqin, C. Zhang	Mitigating supply disruption risks by diversifying competing suppliers and using sales effort	2023	International Journal of Production Economics
K. Govindan, H. Mina, B. Alavi	A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19)	2020	Transportation Research, Part E: Logistics and Transportation Review
M. M. Hughes, Z. Zhou, W. Zinn, A. M. Knemeyer	Plastic response to disruptions: Significant redesign of supply chains	2023	Journal of Business Logistics
F. Lücker, R. W. Seifert, I. Biçer	Roles of inventory and reserve capacity in mitigating supply chain disruption risk	2019	International Journal of Production Research
G. Li, M. Liu, H. Zheng	Subsidization or Diversification? Mitigating Supply Disruption with Manufacturer Information Sharing	2022	Omega

Table 2: Papers included from the Systematic Literature Review

3.2 Distribution of papers by journal and year

In the following section, the distribution of papers, among years and journals, will be presented through the figures below. The distribution of journals, as seen in Figure 3, visualizes that some journals are higher represented in the papers included from the systematic literature review. The International Journal of Production Research and Omega are represented by four and three papers, while the journal with the highest representation, International Journal of Production Research, has seven included papers. The remaining six journals are represented by one paper each in this study.

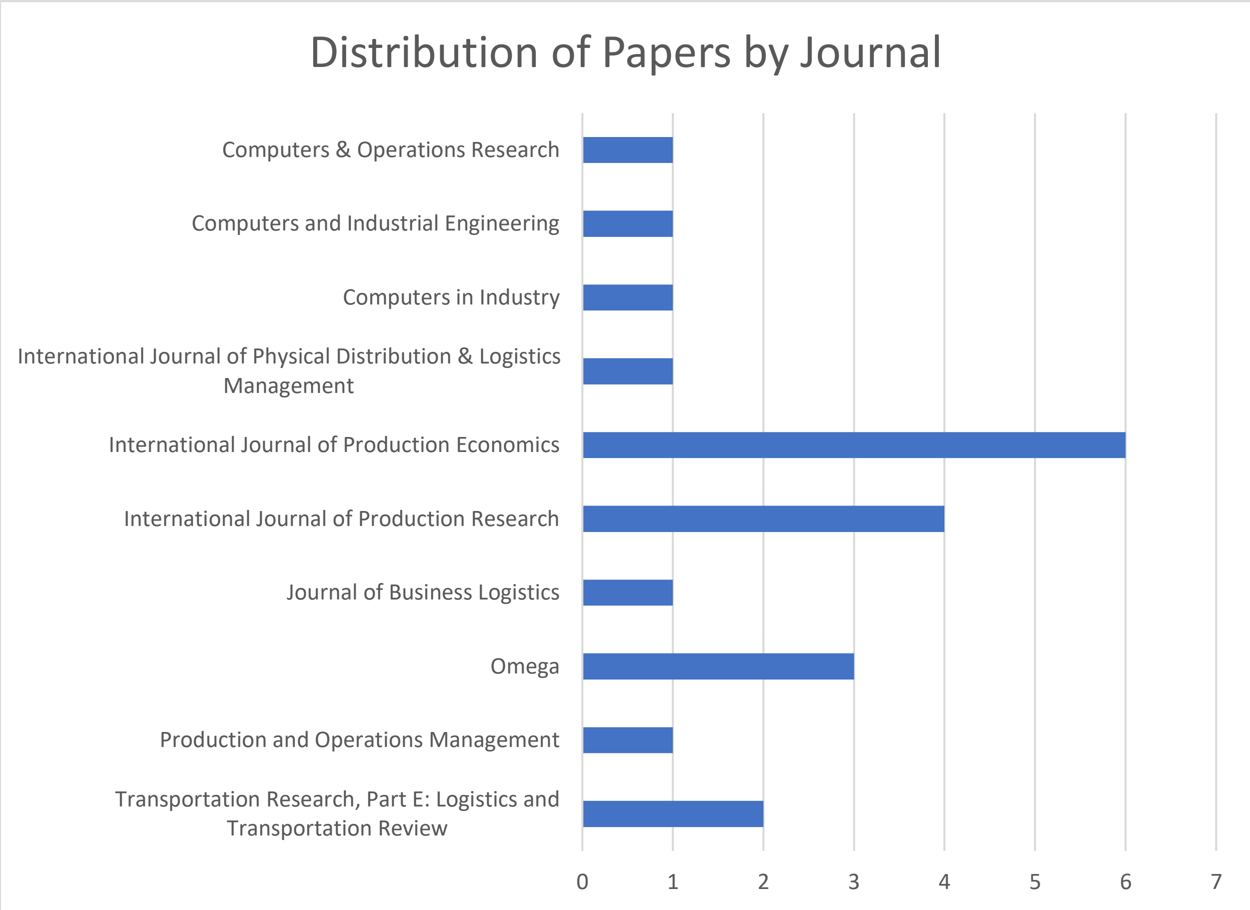

Figure 3: Distribution of papers per journal

The distribution among year of publication is visualized in Figure 4, the majority of papers are published within the recent eight years, with four papers published before 2015 and the remaining 17 articles published between 2015 to 2023. This supports Snyder et al.'s [2] observation of an increase interest on the topic of SC disruptions.

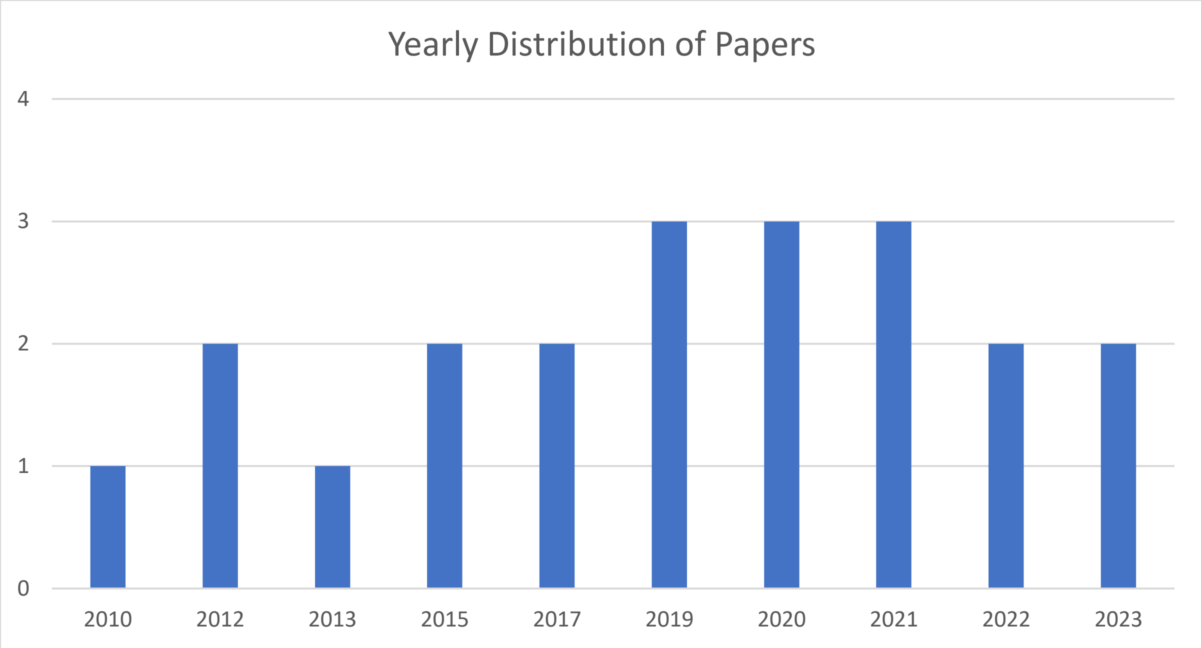

Figure 4: Yearly distribution of papers

3.3 Supply Chain Simulation

In order to answer research question 2: *What are the effects of implementing specific strategies, such as backup inventory and backup capacity, on the resilience of supply chains when simulated under disruptive scenarios?,* simulations were conducted. This section outlines the methodology used to conduct the SC simulations, the software used to perform the simulations is anyLogistix, by the AnyLogic Company. AnyLogistix can be used to create digital twins of SCs, and its intention is to ensure lean, robust, and agile SCs. SC managers could use anyLogistix in order to explore network optimization, risk assessment, inventory optimization, and a numerous of other SC aspects [33].

3.3.1 Supply Chain Modelling

In this section a detailed description of the process of modelling the SC will be presented. The simulations will incorporate select strategies identified in the systematic literature review, the choices behind the selection will be explained in this section. Since this is a theoretical SC, inputs for each echelon of the SC needs to be determined. The following section will describe the base case for the simulations, without any mitigation measures. It is worth to mention that several different inputs and parameters were tested before the base case was finalized. The outcomes of the simulations will be presented in the results chapter.

An investigation of tasks and assignments done previously in the course of study, as well as relevant literature on the topic, was examined in order to choose realistic inputs for capacity, lead time, cost of production, selling price, and other relevant details. The model is a simplified model, with no fluctuations and low deviations in demand, and a single product is included in the SC.

Schmitt et al. [34] suggested that representative SC models should include four echelons, with disruptions in form of delays at various stages in the SC. The SC modelled in this study takes this into account and therefore has a four echelon SC, including a Supplier, a Factory, a Distribution Center, and five Customers randomly distributed across a geographical area, the SC network structure can be seen in Figure 5 and Figure 6. The icon description can be seen in Figure 5.

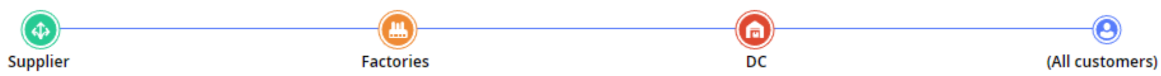

Figure 5: Supply Chain Network Structure

The demand is set to a periodic demand with average weekly demand of forty units per customer with five units in deviation. Which means that the total weekly demand is 200 units, which deviates by 25 units. The distribution center has an initial stock of 250 units, which can cover the demand for the first week, and has a reorder-quantity (RQ) policy with reorder point at 200 units with an order quantity of 200 units. The factory uses an order on demand policy and has no initial stock. Both the DC and the Factory has a capacity of 500 units. The product distributed in the SC has a selling price of 100 USD and costs 55 USD, and one unit converts to 0.2 m^3. The transportation vehicle has a capacity of 500 units per trip, where the cost of transportation is 0.5 USD per unit.

Shipping routes and sourcing decisions has to be defined in order to connect the echelons in the SC to each other. The shipping routes are as following:

- Source: Supplier, Destination: Factory, using the First-In-First-Out (FIFO) strategy.

- Source: Factory, Destination: DC, using FIFO.
- Source: DC, Destination: Customers, using FIFO.

The sourcing decision between all echelons are Fastest with fixed sources for the base case.

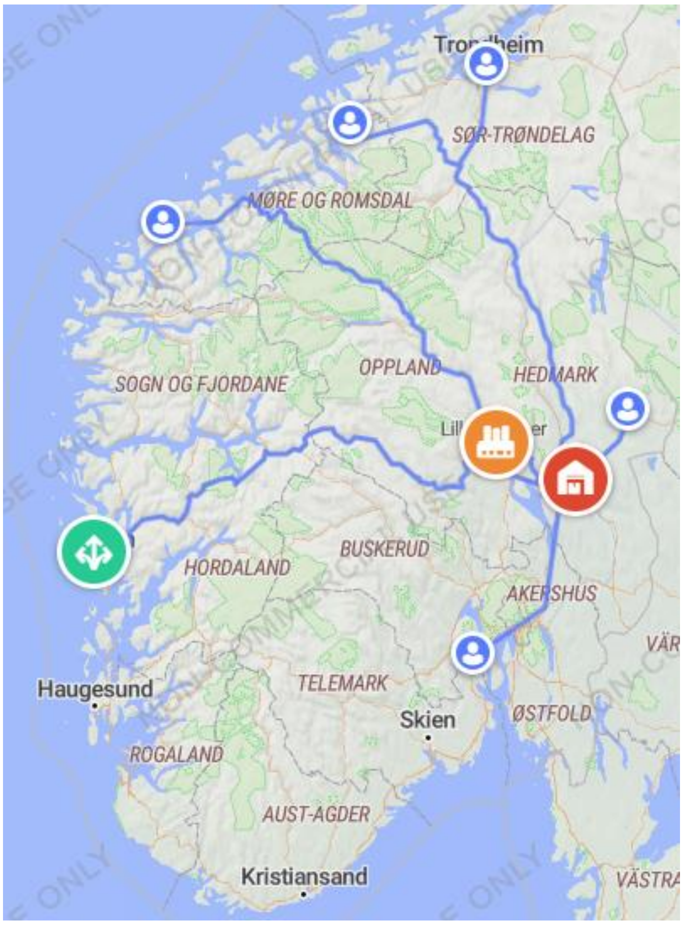

Figure 6: Geographical Supply Chain Network, Base Case

3.3.2 Disruption

The disruption in the simulations is configured in the Events-three in anyLogistix, where two events are defined for the base case, namely disruption and recovery. The two events are modelled as a facility state event types. Two parameters need to be defined during a facility state event, namely the impacted object and the new state of the object. The object of the two events is the factory of the SC. During the disruption the new state of the factory is changed to temporarily closed. For the recovery event, the factory's new state is changed to open. The occurrence type of the disruption is random, meaning that the disruption will occur randomly between the 1st of January and the 28th of February. The recovery is triggered by disruption and has occurrence type set to delay in days, with the occurrence time being 21, which means that the factory will reopen 21 days after the disruption occurs. The probability of each event is 1.0, meaning that the events will occur in all of the iterations of the simulation.

3.3.3 Backup Capacity

In order to implement backup capacity in the simulation model a second factory, and two new events were added to the SC network, as seen in Figure 7. The backup factory has half the capacity of the primary factory and is initially closed in the simulations. The two events implemented were opening of backup capacity and closing of backup capacity, both with event type facility state. The occurrence type for the opening and closing of the backup capacity is set to delay in days. Two different strategies of opening of backup capacity were tested, one which opened immediately and the other started a week after the disruption, which is the trigger for this event. The backup factory will be closed on the same day that the primary factory opens.

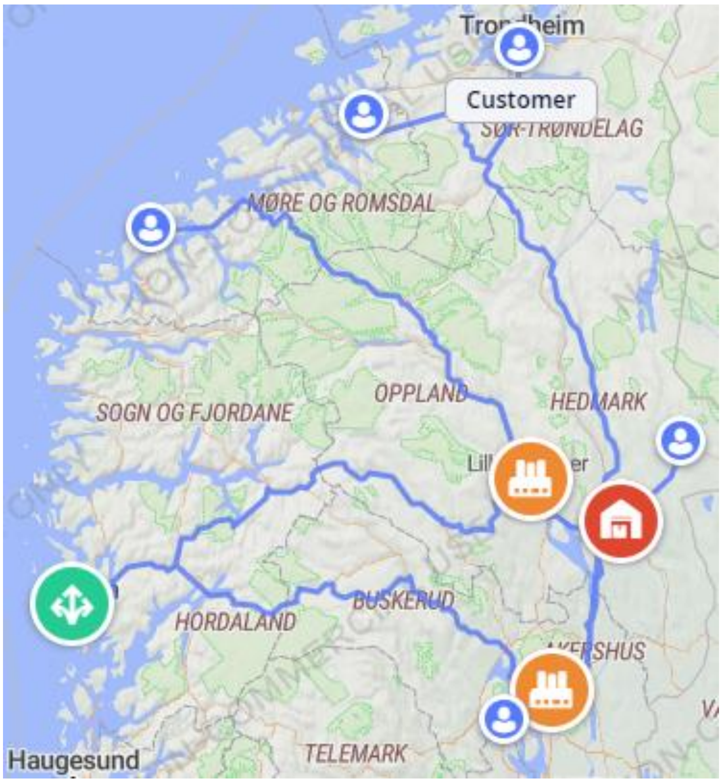

Figure 7: Geographical Supply Chain Network with Backup Capacity

3.3.4 Backup Inventory

Initially the SC operates with the RQ policy. However, the introduction of the backup inventory strategy requires changes in the inventory policy of the SC. A min-max policy with safety stock is adopted, with varying levels of safety stock implemented in different simulations. The remaining aspects of the SC remains the same as the base case, and the geographical SC network is visualized in Figure 6.

3.3.5 Choosing Disruption Mitigation Strategies

There are two main reasons as to why these strategies were implemented in the simulations. The most important reason is that the results from the systematic literature review indicates that both backup capacity and backup inventory is effective ways of mitigating the negative effects of SC disruptions. This will be shown in the results section of the thesis with numbers to back it up. Furthermore, the two strategies seemed to be less difficult to implement in the simulations. The inputs of all the events in the simulations can be seen in Figure 8.

#	Name	Event Type	Parameters	Occurrence Type	Occurrence Time	Trigger	Probability
	filter	filter		filter		filter	filter
1	Disruption	Facility state	Object: Factory, New state: Temp...	Random	1/1/23 - 2/28/23		1
2	Recovery	Facility state	Object: Factory, New state: Open	Delay (days)	21	Disruption	1
3	Backup	Facility state	Object: Backup Factory, New stat...	Delay (days)	0	Disruption	1
4	Close backup	Facility state	Object: Backup Factory, New stat...	Delay (days)	0	Recovery	1

Figure 8: Events of the Simulations

4 Results and Discussions

This chapter presents the findings from the systematic literature review and simulations conducted as part of this study. The results are organized according to the research questions and objectives. The simulation results provide further understanding of the performance of the supply chain under various scenarios and help evaluate the effectiveness of the proposed strategies. Overall, the results highlight the crucial factors in building a resilient SC.

4.1 Results of the Systematic Literature Review

This section provides an overview of the different supply chain disruption mitigation strategies that were analysed in the systematic literature review, including both reactive and proactive strategies. The purpose of this section is to answer research question 1: *What are the possible reactive and proactive strategies to mitigate the potential negative effects of supply chain disruptions?* These results will be discussed in subsection 4.3.1.

4.1.1 Proactive Strategies

In the context of SC management, proactive strategies refer to the measures implemented prior to the occurrence of disruptions to enhance SC resilience and preparedness. Proactive strategies are crucial in managing SC disruptions, as they enable organizations to anticipate potential disruptions and implement measures to minimize their impact. By taking a proactive approach, companies can reduce the likelihood and severity of disruptions, and improve their overall SC resilience [35]. In this section, five strategies identified in the systematic literature review, will be thoroughly investigated, followed by a summary of the remaining strategies.

4.1.1.1 Backup Supplier

Chakraborty, Chauhan, and Ouhimmou [36] used a game theoretic framework to investigate the potential benefits of having a backup supplier as a proactive measure to mitigate the negative effects of supply chain disruptions. They examined two scenarios in a supply chain involving two suppliers and one retailer: one where the retailer lacks any form of emergency source of supply and the other where the retailer has a backup supplier. The authors found that having a backup supplier is advantageous for the retailer during supply chain disruptions, as it allows them to purchase lower quantities from the primary supplier and still ensure continuity of supply. However, this strategy reduces the profit of the primary suppliers. The authors suggest that having a backup supplier is crucial for retailers, especially when there is probability of disruption, to avoid experiencing significant losses. The desired reserve quantities also increase when the likelihood of disruptions increases.

4.1.1.2 Emergency Inventory

Son and Orchard [37] investigated the effects of two inventory-based strategies in terms of mitigating SC disruptions. One strategy was to maintain strategic inventory reserves, and the other was the use of larger order quantities. The authors compared the effectiveness of the two strategies through the use of numerical experiments. A base case, using economic order quantities, were also examined in order to compare the two strategies with a SC without inventory-based mitigation strategies. Three factors were investigated in order to understand the effectiveness of the two strategies, namely stockouts, disruption frequency and recovery rate. Their results indicate that keeping emergency inventory is the most effective of the two strategies, especially in terms of minimizing the probability of stockouts when a SC is experiencing a disruption. In terms of product availability, keeping strategic inventory reserves outperforms larger orders in all of the authors scenarios, with different frequency and duration of disruption.

4.1.1.3 Ordering and Insurance

A study by Liu et al. [38] aimed to evaluate the effectiveness of business interruption insurance and adjustment of ordering decisions on mitigating the negative effects of SC disruptions. The authors categorized the insurance market into two states: a perfectly competitive market, scenario one, and an imperfectly competitive market, scenario two. Under perfect competition, all companies offer identical insurance policies that are readily available to firms at no extra cost. In contrast, in an imperfect market, insurers may add additional fees to the policy to maximize profits.

To minimize the financial losses during a SC disruption, insurance is regarded as an effective mitigation strategy, according to the authors. This strategy not only helps to mitigate the negative impact but also increases order quantities, thereby improving the resilience of upstream echelons in the supply chain. In a scenario one, businesses opt for full insurance coverage irrespective of their ordering decisions, whereas in scenario two, ordering and insurance decisions comes in addition at all times. Additionally, the study found that business interruption insurance can assist in stabilizing a firm's profit, making it more resilient to disruptions.

4.1.1.4 Backup Capacity

In a study done by Schmitt and Singh [13], the mitigating effects of having backup capacity at a remote facility was investigated. Schmitt and Singh modelled a SC with a packaging plant, one primary manufacturer, a secondary, offshore, manufacturer and two distribution centers. Simulations were conducted in order to investigate the impact of disruptions at either the packaging plant or one of the distribution centers. Three minimum average service levels, 90%, 95%, and 97%, was investigated in order to explore how the minimum service levels affects the impact of the disruptions.

The authors found that similarly to results from [37], increasing inventory levels in SC that are prone to disruptions are an effective way of proactively prepare for potential disruptions, regardless of where the inventory is stored within the SC. Furthermore, disruptions at packaging plant are of higher severity than disruptions in one of the distribution centres. The vulnerability of the SC peaks at the packaging plant, as it is the only packaging plant in the SC, which is highlighted by the authors results where the SC does not fully recover from a disruption at the packaging plant when no mitigation strategy is applied.

The disruption they modelled lasted for 6 weeks, and to mitigate the negative effects of said disruption, two different variants of backup capacity were implemented. One approach was a quick response with lower capacity, where there would be 20% capacity after one week, and one slow response with increased capacity, where 50% capacity would be achieved after 4 weeks, meaning that the same amount of capacity would be obtained with either one of the strategies, since both 20% times 5 weeks and 50% times two weeks adds up to 100%.

Using the quicker response led to higher average fill rate as well as lower minimal fill rate when compared to the slow response. Furthermore, the impact of shorter disruptions was found to be less severe than those of longer disruptions, suggesting that SCs should turn their focus towards mitigating the disruptions of longer durations. Additionally, the authors found that improving the weakest link in the SC, which in this study was the packaging plant, was found to increase the SC resilience, while increase of any other link would not necessarily increase total SC resilience.

4.1.1.5 Rerouting

Huang, Chou, and Chang [39] propose rerouting as a proactive approach to mitigate the negative effects of SC disruptions. To identify critical bottlenecks within a manufacturing system, the authors suggest ranking machine groups based on their utilization levels and rerouting the top 10%. The authors further suggest identifying alternative machine groups with lower utilization levels and implementing a workload rebalancing strategy among these groups. Additionally, the authors present a dynamic system model that includes full load production functions for queueing manufacturing systems, which firms can adopt to increase preparedness for potential disruptions, thus minimizing the effects of the disruptions.

4.1.1.6 Overview of Proactive Mitigation Strategies

The above examples present these strategies as possible proactive strategies for mitigating SC disruptions:

- Rerouting
- Ordering
- Insurance
- Emergency inventory
- Backup suppliers (Sourcing)
- Backup capacity

In this section, a short insight of the remaining proactive mitigation measures discovered in the systematic literature review will be provided. Most of the strategies discovered in the systematic literature review were proactive, with some of the proactive strategies being mathematical models, such as [39], which firms can apply to increase their resilience. In Figure 9, an overview of the discovered proactive mitigation strategies is presented, which visualizes that backup inventory is the most common strategy from the papers included in the systematic literature review.

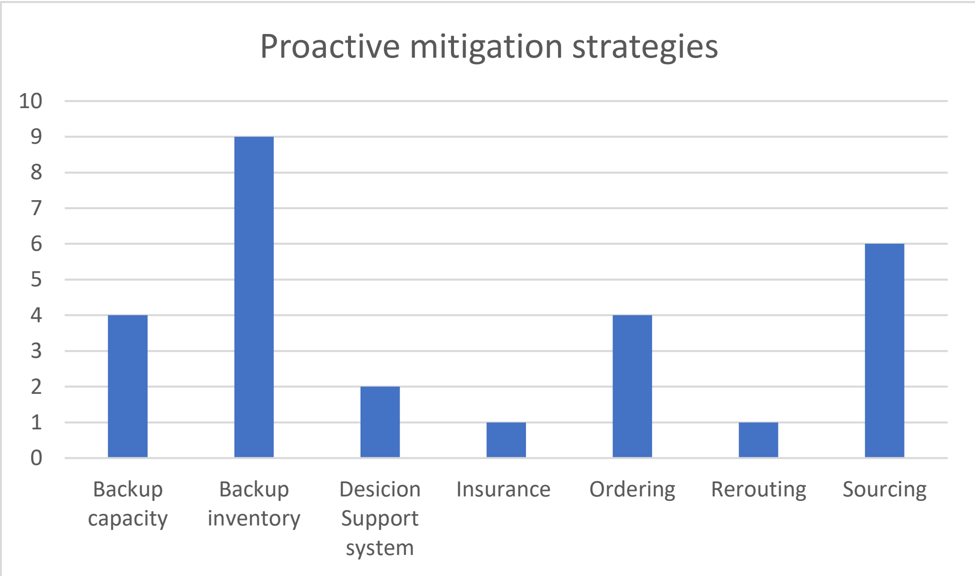

Figure 9: Proactive Mitigation Strategies

Sanci et al. [40] did a case study at the Ford Motor Company, the authors proposed a decision support framework which will help choosing the best mitigation strategy depending on disruption risk. They propose backup capacity at either the primary or secondary supplier, backup inventory, ordering and sourcing decisions as proactive strategies. Sanci et al. additionally proposes reactive strategies which will be presented in the next section. Lücker, Seifert, and Biçer [41] similarly studied how backup inventory and backup capacity could contribute to mitigation of SC disruptions. The authors found that, when risk of disruptions is low, it is more cost efficient to reserve capacity than building up backup inventory due to holding cost. In another study carried out by Lücker, Chopra and Seifert [42] the interplay between holding reserve inventory and having backup capacity is investigated. The authors found that when the holding cost upstream in the SC is not significantly lower than downstream, it is desirable to have backup inventory downstream in the SC. Likewise, the authors suggest that backup capacity is desirable downstream, especially if there is backup inventory upstream.

In a study done by Li et al. [43] the authors created a framework made specifically for food SCs, which could help managers to discover and investigate new types of deviations as they occur. This framework is intended to function as an early warning and provide proactive control over the SC. Similarly to [40], Li et al. have developed a decision support system, which is intended for users without expertise in data mining or statistics, which makes the decision support system easier to apply than a conventional decision support system. The authors' intention is to make managers capable of discovering possible disruptions or deviations at an early stage, thereby enabling proactive mitigation. This will be possible through the proposed knowledge from their research, where the causes of previously observed problems in food SCs is stored, as well as solutions to the problems.

The authors of [44] propose a mixed-integer nonlinear programming model that simultaneously optimizes supplier selection and order allocation in SCs considering the risk of disruptions. There are multiple suppliers, one buyer and one customer in the SC studied in their research. The authors investigate the effects of proactive strategies, in form of emergency inventory and protected suppliers, and found that these proactive strategies offer opportunities in increasing the total profit of SC while simultaneously reducing the impact of disruptions. Their result demonstrates that the probability of disruption is the key factor in determining the allocation of demand number of suppliers. When the risk of disruption increases the wholesale price is the key factor for selection of suppliers, whereas suppliers with low probability of disruptions are selected when disruption risk is low, according to their mixed-integer nonlinear programming model.

In a study conducted by Azadegan, Modi and Lucianetti [45], the effects of redundancy and operational slack as potential mitigation strategies were investigated. They define operational slack as backup inventory and capacity, and redundancy by having multiple and flexible sourcing options. The authors aim to investigate the effects of disruptions due to unforeseen and surprising disruptions and to measure how minor and major surprises effects the customer satisfaction.

Shan et al. [19] investigated the effects of having multiple suppliers could help build a more resilient SC. The authors highlight that relying on a single supplier can make the SC less prepared for disruptions, because the disruptions can have severe impact on a firm's operations if the sole supplier is disrupted. The authors suggest identifying multiple sources that can deliver the same products, thus diversifying the suppliers, making the downstream echelons in the SC less dependent on the suppliers.

Govindan, Mina, and Alavi [46] developed a decision support system in order to mitigate the negative effects epidemic outbreaks has on healthcare SCs, where they divide the community into four risk-based groups, and by two groups based on age and diseases such as diabetes or heart problems. The intention behind the decision support system is to reduce the impact on healthcare SCs by managing the increased demand in the healthcare SC, as well as ensuring that the people who are more vulnerable to the epidemic gets the help they need. The output is divided into five classes, which include following community guidelines, quarantine, hospitalization, and being kept under intensive care. Their results indicate that their proposed decision support system is contributing to mitigation of the negative effects of the epidemic disruption.

4.1.2 Reactive strategies

Reactive strategies are a crucial factor when managing SC disruptions as they are implemented in response to unexpected events. The purpose of this section is to provide an overview of the possible reactive strategies identified in the literature review along with their key findings. By understanding the different types of reactive strategies and their potential benefits, organizations can effectively respond to supply chain disruptions and minimize their impact. Despite their reactive nature, these strategies can still enhance supply chain resilience and improve overall supply chain performance. Therefore, it is important to explore the various reactive strategies available to SCs, when managing disruptions. Firstly, three reactive strategies will be presented in-depth, followed by an overview of the remaining reactive strategies found in the systematic literature review.

4.1.2.1 Restoring the Production Plant

The impacts of the Tohoku earthquake that occurred in March 2011, and how the impact was mitigated, was investigated in a study conducted by Matsuo [47]. The earthquake led to extensive damage to transportation networks and had a significant impact on high-tech component plats. For instance, Renesas Electronics, which produced automotive microcontroller units for major car companies such as Toyota, Nissan, and Honda. As a result, Toyota faced the disruption of approximately 500 components shipped from 200 separate locations, leading to a complete halt of its production plants in Japan for two weeks following the earthquake. It took until June 2011 for the company to partially resume operations and until November of the same year to fully restore production to its pre-disruption level.

As explained in chapter 2.4.1, the lean philosophy of Toyota leads to more vulnerable SCs, as the philosophy consists of strategies that lower the inventory levels and backup inventory, which was evident after the earthquake. All of Toyotas first-tier suppliers purchased their micro controller units from the same company, namely Renesas Electronics, and from a single factory, the Naka plant. The Naka plant suffered significant damaged during the earthquake, with ceilings and walls collapsing, as well as the destruction of hundreds of precision machines. Renesas estimated that it would take six months to resume to mass production, with an additional two months required to resume shipping due to lead time. In a reactive response, suppliers, partners, customers, and even competitors collaborated to support the recovery of the production plant. The recovery operations continued around the clock, seven days a week, and peaked with over 2500 people involved at one time. The combination of efficient project management and these collaborative efforts resulted in a significant reduction of the recovery time, which was reduced by fifty percent. Nevertheless, the disruption still had a notable impact on Toyota since the company lacked an alternative source of microcontroller units.

4.1.2.2 Information sharing

The effects of information sharing as a reactive strategy to mitigate the negative effects of SC disruptions was investigated in a study conducted by Sarkar and Kumar [48]. The authors adopted the beer distribution game in a laboratory setting, and considered disruptions at both the retailer and the manufacturer in a multi-echelon SC. To understand whether or not information sharing is an effective way to mitigate SC disruptions the authors compare the simulations with information sharing between echelons to a base state where no information of the disruption is shared. Even though the disruption itself spanned only five periods, Kumar and Sarkar decided to extend the beer distribution game to fifty periods, recognizing that the effects of disruption can endure beyond its duration.

Their results indicate that sharing information during upstream SC disruptions can significantly reduce order variance, as compared to disruptions without sharing of information. Moreover, when upstream disruption occurs and information is shared, the order variance levels are comparable to the base level without disruption. However, the study found no notable effect of information sharing when the retailer is disrupted, concluding that sharing information during downstream echelon disruptions does not significantly mitigate the negative impacts of the disruption.

4.1.2.3 Redesigning the Supply Chain

In a study carried out by Hughes et al. [49] a reactive mitigation strategy where one would respond with a plastic redesign of the SC, meaning that a significant redesign of the SC must be carried out. The authors explore options as to how SCs can be redesigned to function in a different way after disruptions occur. In order for the redesign to be considered plastic the redesign must fulfil four checkmarks according to the authors, a significant redesign, a pressing need for a redesign, the redesign requires new skills, new investments, and leadership support, and the response has to be permanent, not temporary. The authors further identified five reasons to consider plasticly redesigning a SC which is, limitations regarding restauration of the SC, forced redesign, value in opportunity of a redesign, sustained uncertainty, and shift in strategy.

4.1.2.4 Overview of reactive mitigation strategies

The three examples presented above highlights the following approaches as potential reactive mitigation strategies:

- Restoring the production plant
- Information sharing
- Redesigning the Supply Chain

In this section, an insight to the remaining reactive mitigation strategies discovered in the systematic literature review will be presented. In Figure 10, an overview of the discovered reactive mitigation strategies is presented.

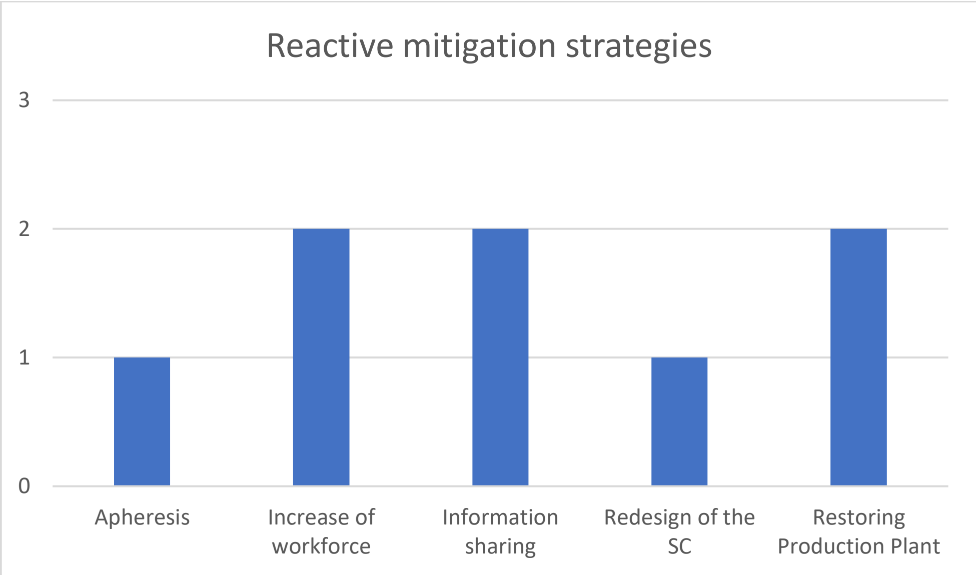

Figure 10: Reactive Mitigation Strategies

As mentioned in the previous section, Sanci et al. [40] presented a reactive strategy as well as the four proactive strategies found in their study. The reactive strategy from their study is recovery of capacity of the primary supplier, similar to [47]. The authors suggests that over time and extra shifts can help restoring the regular capacity of the primary supplier.

Li et al. [50] studied the effects of manufacturers sharing information of private demand. The authors of this article decides that the downstream manufacturers should have one of two proactive strategies implemented in the SC, either diversification by having a dual sourcing strategy, or subsidization for improvement of the reliability of the SC. Their results indicate that that information sharing can improve the resilience of the SC. This study focuses on sharing information of demand rather than information about disruptions such as [48] did.

In their research on the blood SC, Samani, Hosseini-Motlagh and Homaei [51] identified apheresis as a reactive strategy to address blood shortages during disruptions. Apheresis is a procedure that involves extracting desired blood components such as platelets, red blood cells, or plasma from a donor, storing them and returning the remaining blood to the donor.

This strategy is therefore limited to blood SC and is therefore not applicable to other sectors of SCs.

4.2 Results of Simulations

This section presents the results of the simulations conducted to investigate the dynamics of the SC under various scenarios, The outcomes include key performance measures such as recovery time and service levels, evaluated with different mitigation strategies. The results of the simulations and the effects of the strategies will be compared and discussed in subsection 4.3.2. The following strategies has been tested: 1) No strategy (base case), 2) backup inventory, 3) backup capacity. Firstly the base case was tested without disruptions to understand the capabilities of the SC. The SC has an average service level of 1.00 without disruptions, meaning that all the demand is covered when no disruption is occurring. The following sections will explore how things changes when disruptions are occurring, and how the mitigation strategies help mitigating the negative effects of SC disruptions. The SC will show a failure when the service level drops below 90% and is recovered once it surpasses 95% service level.

4.2.1 Base Case

A simulation of the base case with disruption is carried out in order to better understand the effects of the disruption modelled in the thesis. Compared to the base case without disruption, the average service level drops to 0.844 over the course of the simulation, which is lasting for four months, from the 1st of January until the 30th of April. This indicates a drop of over 15% of average service level. This will be the base case scenario of which the other simulations with disruptions strategies implemented will compare to.

4.2.2 Backup Capacity

The backup capacity simulations were tested with two different approaches, the first one implements backup capacity on the day of disruption, whereas it takes a week before implementation of backup capacity in the second approach.

4.2.2.1 Backup Capacity on the Day of Disruption

This approach implements the backup capacity mitigation strategy once the disruption occurs in the SC. When implementing a backup factory with 50% of capacity on the day of disruptions the average service level increases to 0.989. This is an increase of 17% compared to the base case with disruption. The maximum number of days needed to restore service level to at least 0.95 was 7 days for this simulation. Figure 11 shows a chart of the average service level with 10 iterations, where the lowest average service level is below 0.80. There are no notable effects of the halt in production after the backup capacity is up and running.

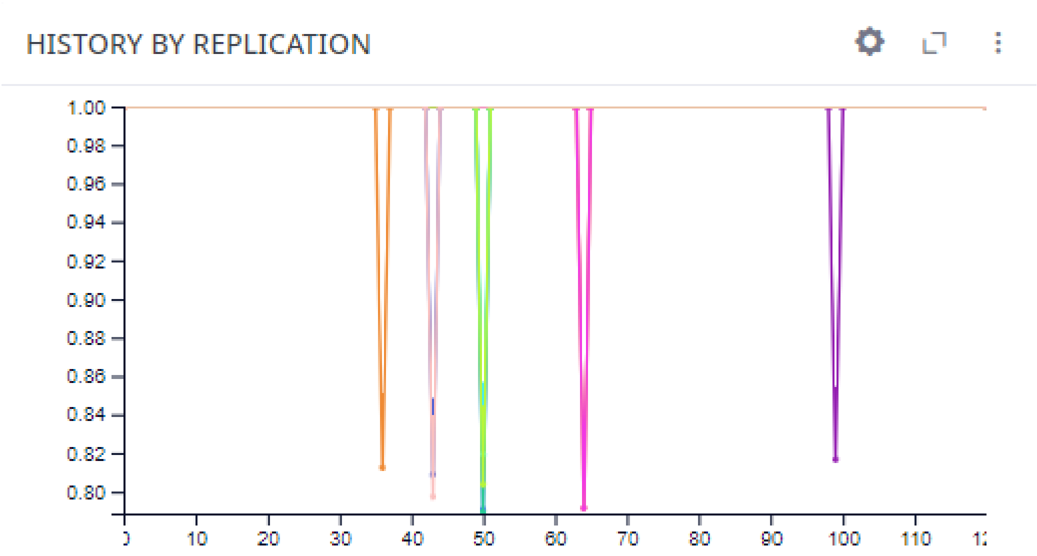

Figure 11: Average Service Level Ratio

4.2.2.2 Backup Capacity a Week After Disruption

This approach implements the backup capacity mitigation strategy one week after the disruption occurs in the SC. The average service level ratio of the SC using this approach is 0.978. The maximum days needed to recover is 14 days with this approach, with the minimum average service level plummeting to 0.0 in the middle of the disruption. One can see that there are some iterations where the disruptions impact service levels even after the primary factory is reopened.

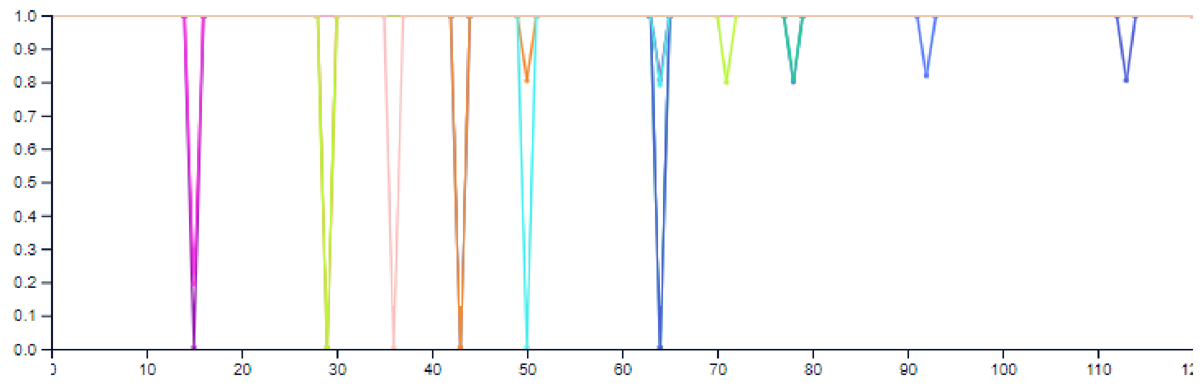

Figure 12: Average Service Level Ratio

4.2.3 Backup Inventory

Simulations of three different levels of backup inventory were conducted in order to find out how the level of backup inventory affected the mitigation of the disruption. The three levels of backup inventory are 200 units, 300 units and 400 units.

The average service level ratio is 0.933 when having 200 units of backup inventory in the SC modelled in this thesis. This is an increase when compared to the base case, and show that covering one week of average demand helps improve the resilience of the SC. However, the simulations show that the worst case of total time to recover is 21 days, with the best case being 7 days. This shows that the fluctuations in demand affects the resilience of the SC.

When increasing the backup inventory by a 100 units the total average service level increases to 0.967, which is an increase of 0.034. In 8 out of 10 iterations the total recovery time needed is 7 days, which is 14 for the remaining two iterations, as opposed to the above strategy of 200 units as backup inventory where three iterations resulted in 21 days to recover, one iteration resulted in 7 days to recover, and the remaining iterations resulted in 14 days to recover. This indicates a notable increase of resilience when the backup inventory is increased.

Another increase of 100 units of backup inventory resulted in an average service level ratio of 0.989, which is just over 1 percent less than the base case without disruption. The recovery time needed is 7 days in all iterations of the simulation.

4.3 Discussions

In this section, the results of the thesis will be discussed. The discussion is divided into three parts, where the results of the systematic literature review, and the results of the simulations will be discussed, as well as a general discussion.

4.3.1 Systematic Literature Review

The purpose of this discussion is to analyse and discuss the proactive and reactive strategies identified in the systematic literature review conducted for this thesis. Each strategy provides resilience to the SC and in this section the difficultness of implementation and their effectiveness will be discussed. The review revealed twelve strategies, seven proactive and five reactive, whereas some of them were found in multiple papers, with a total of twenty-seven mentions of proactive strategies and eight mentions of reactive strategies. This indicates a consensus among researchers regarding the effectiveness of proactive strategies in mitigation of disruptions. Proactive strategies allow SC managers to prepare for potential disruptions and take precautions before they occur, reducing the negative effects of SC disruptions.

One key factor highlighted in the systematic literature review is the importance of backup inventory. Researchers widely agree that maintaining backup inventory can help mitigate disruptions, as it is mentioned as an effective mitigation strategy in a total of nine out of the twenty-one papers from the systematic literature review. In order to determine the optimal level of backup inventory, SC managers should conduct a risk assessment that considers the probability of disruptions and compares the inventory holding costs to the potential cost savings. Implementation wise it is regarded as a relatively straightforward approach, making it an accessible and attractive mitigation strategy for SCs seeking to increase their resilience.

Similarly, backup capacity is identified as another essential factor in building resilient SCs. Although it could be said that this is a reactive strategy that is activated upon disruption, it is regarded as a proactive strategy in this thesis due to the need of proactive planning and installation of the backup capacity. Evaluating the cost of establishing backup capacity against the potential cost saved upon disruptions is a crucial factor when deciding whether or not to implement this strategy. This strategy enables continuation of production despite disruptions and can be relatively easily implemented in a SC, making it practical for enhancing resilience in a SC.

Diversified sourcing is another strategy that receives significant support in the literature. It is evident that having multiple suppliers reduces dependency and increases flexibility in the SC, which leads to mitigation of negative effects of disruptions. Shan et al. [19] supports this, and also mentions the importance of identifying suppliers which can deliver the same products in order to create less dependency. The many options regarding sourcing decisions can make optimizing the implementation of this strategy challenging, however extensive research exists to guide managers in making informed decisions, and the main take from this is that dual-sourcing or multi-sourcing is an effective way to create resilience and reduce dependency.

Decision support systems have emerged as valuable tools for disruption mitigation management. The systematic literature review revealed various applications of decision support systems, such as healthcare, early warning systems, and choice of mitigation strategies. By leveraging data, analytics, and simulation models, decision support systems can help SC managers making informed decisions before, during, and after disruptions, leading to effective mitigation of disruptions.

Insurance is identified as a proactive measure to mitigate potential financial losses resulting from disruptions. Although insurance does not directly provide capacity or products to a SC, it offers a mechanism to proactively manage the cost implications of disruptions. By transferring the risk to insurance providers, SC stakeholders can mitigate the financial impact of disruptions and enhance overall resilience.

Effective ordering quantities and lead time management are identified as important factors for disruption mitigation. Properly managing order quantities can help SCs reduce the impact of disruptions by optimizing inventory levels. Additionally, expediting processes during disruptions can help expedite the flow of goods and minimize delays in the SC. Proactive rerouting can also enhance the resilience of the SC by identifying bottle necks and weaker sections of the SC. The rerouting strategy highlights the importance of continuous optimization, improvement, and adaptability to changing conditions in order to mitigate disruptions effectively.

Information sharing is a reactive strategy which involves sharing information about the disruption in real-time. The systematic literature review suggests that information sharing is most efficient during upstream disruptions. Information sharing could propose challenges such as confidentiality, competitiveness, and secrecy, which can make this strategy somewhat difficult to implement. The strategy will require establishing mechanisms for secure sharing of information between different parts of the SC, which can lead to improved coordination and responsiveness during disruptions.

Redesigning of the SC can be an effective way of building resilience, it will, however, require a lot of effort, financially and through gaining of new skills. The SC managers must carefully evaluate the cost and compare them to the benefits of redesigning before applying this strategy as the changes done to the SC is not intended to be reverted.

In summary the literature review has revealed several strategies which can help improving the resilience of a SC, making it more capable of mitigating disruptions. There are big differences in complexity regarding implementations of the strategies explored, ranging from increase of backup inventory to complete redesigns of a SC. Building redundancy and flexibility is consistently supported as a significant way to build resilient SCs, indicating that SC managers should consider diverging from the core tenets of the lean philosophy by increasing backup inventory levels. Redundancy and flexibility can be achieved through multi sourcing, having two or more manufacturing facilities, keeping backup inventory, and building backup capacity. Furthermore, proactive approaches are widely supported, as it enables organizations to anticipate and increase preparedness for potential disruptions. By implementing these strategies into supply chain management practices and modifying them to specific situations, organizations can build resilient SCs capable of mitigating the negative effects of supply chain disruptions and ensuring continuity of its operations.

In addition, the growing focus on SC disruption mitigation has likely led to increased adaptation of disruption mitigation strategies among competitors. Consequently, firms that lack robust disruption mitigation strategies may face the risk of losing market share to their competitors following a disruption. Therefore, it is imperative for companies to prepare for disruption in order to safeguard their position in the market.

Furthermore, effective preparedness for disruptions can lead to profitable outcomes for the SC, especially if the affected SC can outperform its competitors by restoring to normal productivity quicker. By quick recovery of operations, a resilient SC can attract customers who value reliability and consistency in the face of disruptions, thus gaining a competitive advantage. This advantage can potentially result in increased profitability and market share for the prepared SC.

4.3.2 Simulations

The simulations conducted on the SC demonstrate the effectiveness of both backup capacity and backup inventory as strategies for increasing resilience and mitigating the negative effects of SC disruptions. The results indicate that building additional capacity and maintaining backup inventory can significantly enhance the ability of the SC to recover from disruptions.

Implementing backup inventory seems to be the least difficult strategy to implement, while also being able to increase resilience effectively, with the lowest average service level from the simulations is 0.933.

However, it is important to note that the choice of inventory policy has a substantial impact on the resilience of the SC. The simulations reveal that different inventory policies can lead to varying levels of resilience and performance outcomes. Factors such as demand variability, lead times, cost implications, and service levels needs to be considered. This highlights the critical role of inventory management decisions when building resilient SCs.

While the theoretical nature of the SC modelled in this study may limit its direct applicability to real-world SCs, the indications provided by the simulations offer valuable insights. They indicate that both backup capacity and backup inventory strategies, when implemented effectively, can contribute to effectively mitigating the negative effects of SC disruptions. These insights can serve as a starting point for further exploration and analysis within the context of specific SCs.

4.3.3 General Discussion

It is important to note that gaining SC resilience is an ongoing process which requires continuous improvement and learning. Regularly evaluating the effectiveness of disruption mitigation strategies and analyzation of disruption probability as well as causes is a key factor in achieving a resilient SC.

Emerging technologies such as internet of things, big data analytics, RFID, and additive manufacturing can potentially improve the resilience of a SC, since these technologies enables real-time monitoring, predictive analytics, increased visibility, and secure information sharing. Furthermore, examination of real-world case studies can provide valuable insights and practical examples of successful disruption mitigation strategies, which can help other SC increasing their resilience, which shows that collaboration between SC partners could be beneficial in terms of mitigating disruption.

The findings of both the systematic literature review and the simulations carried out in this thesis supports backup inventory and backup capacity as effective strategies for mitigating disruptions. These results contribute to a growing consensus in the field that deviating from traditional lean practices can be beneficial in increasing SC resilience.

The results presented in this thesis further reinforces the recommendation to explore alternative approaches that go beyond the traditional lean concepts in order to enhance resilienc and effectively mitigate disruptions. This becomes increasingly important in today's global and turbulent SCs. It is crucial for SC managers and practitioners to adapt their mitigation strategies and embrace innovative practices that can better prepare for the challenges of the modern SCs.

5 Conclusion & Further Research

This section serves as a summary of the main findings and contributions of the thesis on SC disruption mitigation. It provides an overview of the key insights gained from the research and presents suggestions for further research within the field.

5.1 Conclusion

In conclusion, this thesis aimed to explore and analyse proactive and reactive disruption mitigation strategies, which can improve the resilience of SCs and mitigate the negative effects of SC disruptions. Through the systematic literature review, twelve unique strategies were identified, including eight proactive and five reactive strategies, which have demonstrated potential for increasing SC resilience and preparedness of disruptions.

The consensus among researchers indicates the effectiveness of proactive strategies in preparing for potential disruptions, thus reducing their impact. Backup inventory emerged as a key factor in enhancing SC resilience and mitigating the negative effects of disruptions, with a majority of the reviewed papers supporting its effectiveness. Another strategy that was found to be effective in mitigating disruptions were backup capacity. Both of these strategies were evaluated through simulations, which confirmed their effectiveness in improving the resilience of the SC and reducing the negative effects of disruptions. The strategies are also relatively easy to implement, which makes them attractive to SC managers.

In light of these findings, the recommendation of this thesis is the implementation of mitigation strategies to increase preparedness for disruptions in the SC. Specifically, incorporating backup capacity or inventory into SCs can significantly improve resilience. The insights provided in this thesis serve as a guideline for SC managers seeking to enhance the resilience and preparedness of their SCs, making them capable to mitigate real-world disruptions.

Overall this thesis contributes to the understanding of SC disruption mitigation by identifying effective strategies and highlighting the challenges involved. By adopting the recommended strategies and leveraging the insights gained from this research, SC managers can improve the resilience and better navigate the uncertainties of a dynamic business environment.

5.2 Further Research

There is still much research that can be conducted within the field, and the following can serve as an inspiration for other researchers to continue investigating the important topic of supply chain disruption mitigation.

In order to enhance the understanding of SC disruption mitigation strategies it is recommended to expand the literature review. This could provide more reactive and proactive strategies implemented in various SCs in different industries.

Secondly, conducting more extensive simulations, using more of the strategies explored in the systematic literature review conducted in this study, will give a better insight into effectiveness of the strategies. This will help getting a clearer understanding of the potential profitability of the different mitigation strategies. Additionally, making the simulation more realistic can help getting results which better reflects real-world scenarios.

Another recommendation is to specialize the simulations and literature study by focusing on a specific field within SCs. By specializing factors such as logistics, inventory management, or demand forecasting, researchers can explore the unique challenges and characteristics specific to that field. This will enable the development of industry specific strategies and solutions.

Furthermore, it is recommended to collaborate with firms in order to validate the effectiveness and real-world impact. Additionally, this collaboration will provide an opportunity to model a real-world SC, as opposed to a purely theoretical one as the SC presented in this thesis. This will enable incorporation of real data and parameters, making the results more accurate and representative of the complexities and dynamics observed in real-world SCs.

Another suggestion is to investigate the effects of adding two or more disruption mitigation strategies simultaneously. It is essential to evaluate the cost efficiency and feasibility of implementing multiple disruption mitigation strategies simultaneously. By testing different combinations of strategies, researchers can assess the potential synergies, trade-offs, and overall impact on the SC. This analysis will help identifying the optimal combination of strategies that enhances performance while considering cost of implementation and operations of the strategies.

The evolving landscape of SC management makes it crucial to explore how advanced technologies, such as additive manufacturing, Internet of Things, artificial intelligence, blockchain, and other advanced technologies, can help mitigate negative effects of SC disruptions. Investigate the potential challenges and benefits of incorporating these advanced technologies, and assess how they can contribute to increased resilience, agility, and efficiency of SCs.

By exploring these suggestions, a deeper understanding of disruption mitigation strategies, their profitability, efficiency, implementation challenges, and the role of advanced technologies as mitigation measures can be achieved. This will contribute to the ongoing improvement and optimization of SC management practices.

5.3 Limitations

In this chapter the limitations of this thesis will be highlighted. While the study has provided valuable insights and recommendations, it is important to acknowledge the boundaries and constraints that exist within the research framework. By recognizing these limitations, a better understanding of the scope and applicability of the findings can be achieved.

One of the primary limitations of the simulation part of this research is the absence of real-world data. The analysis and simulations conducted in this thesis rely on hypothetical scenarios and assumptions and are purely theoretical. Although the systematic literature review has provided an understanding of existing strategies, the lack of concrete, real numbers limit the precision and accuracy of the findings from the simulations.

Another limitation of this study is the sample size of literature reviewed. This limitation could lead to potential gaps in the understanding of certain strategies. Researchers should continue to expand the literature review by exploring additional sources and incorporating emerging research to overcome this limitation and ensure a more comprehensive analysis.

The use of the simulations to evaluate the effectiveness of the SC disruption mitigation strategies introduces a level of simplification as opposed to real-world scenarios. The model and assumptions during the simulations does not fully capture the challenges and dynamics of actual SCs. While the simulations provide a valuable analysis of the strategies, they are a simplification of reality. Future research should aim to increase complexity and realism of simulation models, implementing a broader range of variables, uncertainties, and dynamic factors to better reflect real-world conditions.

Bibliography

[1] N. Bugert and R. Lasch, “Supply chain disruption models: A critical review,” *Logistics Research,* pp. 1-35, 2018.

[2] L. V. Snyder, Z. Atan, P. Peng, Y. Rong, A. J. Schmitt and B. Sinsoysal, “OR/MS models for supply chain disruptions: a review,” *IIE TRANSACTIONS,* pp. 89-109, 2016.

[3] J. Blackhurst, C. W. Craighead, D. Elkins and R. B. Handfield, “An empirically derived agenda of critical research,” *International Journal of Production Research,* pp. 4067-4081, 1 October 2005.

[4] S. M. Wagner and B. Christoph, “An empirical investigation into supply chain vulnerability,” *Journal of Purchasing and Supply Managment,* pp. 301-312, November 2006.

[5] P. Chapman, M. Christopher, U. Jüttner, H. Peck and R. Wilding, “Identifying and Managing Supply-Chain Vulnerability,” *Focus,* pp. 59-70, 2002.

[6] G. Topham, “How the Suez canal blockage can seriously dent world trade,” 26 March 2021. [Online]. Available: https://www.theguardian.com/business/2021/mar/26/how-the-suez-canal-blockage-can-seriously-dent-world-trade. [Accessed 8 December 2022].

[7] S. Fan, Z. Yang, J. Wang and J. Marsland, “Shipping accident analysis in restricted waters: Lesson from the Suez Canal blockage in 2021,” *Ocean Engineering,* 16 November 2022.

[8] M.-A. Russon, “The cost of the Suez Canal blockage,” BBC, 29 March 2021. [Online]. Available: https://www.bbc.com/news/business-56559073. [Accessed 8 December 2022].

[9] M. Penn, “Statistics Say Large Pandemics Are More Likely Than We Thought,” 23 August 2021. [Online]. Available: https://globalhealth.duke.edu/news/statistics-say-large-pandemics-are-more-likely-we-thought. [Accessed 9 December 2022].

[10] I. Ali, A.Arslan, M, Chowdhury, Z. Khan and S. Y. Tarba, “Reimagining global food value chains through effective resilience to COVID-19 shocks and similar future events: A dynamic capability perspective,” *Journal of Business Research,* pp. 1-12, March 2022.

[11] H. Farrell and A. Newman, “Will the Coronavirus End Globalization as We Know It?,” *Foreign Affairs,* 16 March 2020.

[12] G. Geriffi, “What does the COVID-19 pandemic teach us about global value chains? The case of medical supplies,” *Journal of International Business Policy,* pp. 287-301, 15 July 2020.

[13] A. J. Schmitt and M. Singh, “A quantitative analysis of disruption risk in a multi-echelon supply chain,” *International Journal of Production Economics,* pp. 22-32, 2012.

[14] Y. Sheffi, J. James B. Rice, J. M. Fleck and F. Caniato, “SUPPLY CHAIN RESPONSE TO GLOBAL TERRORISM: A SITUATION SCAN,” in *Supply Chain Conference*, Milan, 2003.

[15] A. J. Schmitt and L. V. Snyder, "Infinite-horizon models for inventory control under yield uncertainty and disruptions," *Computers & Operations Research,* pp. 850-862, 2012.

[16] K. Barwise and G. O'Meara, "Supply Chain Disruption – the Risk to Global Economic Recovery," September 1 2022. [Online]. Available: https://www.fticonsulting.com/insights/articles/supply-chain-disruption-risk-global-economic-recovery. [Accessed 12 January 2023].

[17] S. Hosseini, D. Ivanov and A. Dolgui, "Review of quantitative methods for supply chain resilience analysis," *Transportation Research, Part E: Logistics and Transportation Review,* pp. 285-307, 2019.

[18] S. Rezapour, R. Z. Farahani and M. Pourakbar, "Resilient supply chain network design under competition: A case study," *European Journal of Operational Research,* pp. 1017-1035, 2017.

[19] X. Shan, S. Xiong and C. Zhang, "Mitigating supply disruption risks by diversifying competing suppliers and using sales effort," International Journal of Production Economics, 2023.

[20] G. Svensson, "Vulnerability in business relationships: the gap between dependence and trust," *Journal of Business & Industrial Marketing,* pp. 469-483, 2004.

[21] K. Scholten and S. Schilder, "The role of collaboration in supply chain resilience," *Supply Chain Management,* pp. 471-484, 8 June 2015.

[22] D. Ivanov and A. Dolgui, "A digital supply chain twin for managing the disruption risks and resilience inthe era of Industry 4.0," *PRODUCTION PLANNING & CONTROL,* pp. 775-788, 2021.

[23] S. H. Khajavi, J. Partanen and J. Holmström, "Additive manufacturing in the spare parts supply chain," *Computers in Industry,* pp. 50-63, 2014.

[24] R. Hajar and N. Saida, "Supply chain management, between resilience and sustainability: A literature review.," in *2022 14th International Colloquium of Logistics and Supply Chain Management (LOGISTIQUA)*, El Jadida, Morocco, 2022.

[25] M. Christopher and H. Lee, "Mitigating supply chain risk through improved confidence," *International Journal of Physical Distribution & Logistics Management,* pp. 388-396, 2004.

[26] K. B. Hendricks and V. R. Singhal, "An Empirical Analysis of the Effect of Supply Chain Disruptions on Long-Run Stock Price Performance and Equity Risk of the Firm," *Production and Operations Management,* pp. 35-52, 2005.

[27] United Nations, "Climate Change Impacts and Adaptation for Coastal Transport Infrastructure: A Complation of Policies and Practices," United Nations, Geneva, 2020.

[28] World Economic Forum, "The Global Risks Report 2019," World Economic Forum, Geneva, 2019.

[29] B. Walker, S. Carpenter, J. Anderies, N. Abel, G. Cumming, M. Janssen, L. Lebel, J. Norberg, G. D. Peterson and R. Pritchard, "Resilience Management in Social-ecological Systems: a Working Hypothesis for a Participatory Approach," *Conservation Ecology,* 19 June 2002.

[30] S. Seuring and S. Gold, "Conducting content-analysis based literature reviews in supply chain management," *Supply Chain Management: An International Journal,* pp. 544-555, 3 August 2012.

[31] D. Denyer, D. Tranfield and P. Smart, "Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review," *British Journal of Management, 14,* pp. 207-222, 2003.

[32] Scimago, "SJR," [Online]. Available: https://www.scimagojr.com/.

[33] anyLogistix, "anyLogistix supply chain software," AnyLogic Company, [Online]. Available: https://www.anylogistix.com/. [Accessed 25 May 2023].

[34] T. G. Schmitt, S. Kumar, K. E. Stecke, G. F. W. and M. A. Ehlen, "Mitigating disruptions in a multi-echelon supply chain using adaptive ordering," *Omega,* pp. 185-198, 2017.

[35] A. Gunasekaran, N. Subramanian and S. Rahman, "Supply chain resilience: role of complexities and strategies," *International Journal of Production Research,* pp. 6809-6819, 2015 November 2015.

[36] T. Chakraborty, S. S. Chauhan and M. Ouhimmou, "Mitigating supply disruption with a backup supplier under uncertain demand: competition vs. cooperation," *International Journal of Production Research,* pp. 3618-3649, 2020.

[37] J. Y. Son and R. K. Orchard, "Effectiveness of policies for mitigating supply disruptions," *International Journal of Physical Distribution and Logistics Management,* pp. 684-706, 2013.

[38] Z. Liu, M. Li, Y. Lei and X. Zhai, "A joint strategy based on ordering and insurance for mitigating the effects of supply chain disruption on risk-averse firms," *International Journal of Production Economics,* 2022.

[39] H. Y. Huang, Y. C. Chou and S. Chang, "A dynamic system model for proactive control of dynamic events in full-load states of manufacturing chains," *International Journal of Production Research,* pp. 2485-2506, 2009.

[40] E. Sanci, M. S. Daskin, Y.-C. Hong, S. Roesch and D. Zhang, "Mitigation strategies against supply disruption risk: a case study at the Ford Motor Company," *International Journal of Production Research,* pp. 5956-5976, 2022.

[41] F. Lücker, R. W. Seifert and I. Biçer, "Roles of inventory and reserve capacity in mitigating supply chain disruption risk," *International Journal of Production Research,* pp. 1238-1249, February 2019.

[42] F. Lücker, S. Chopra and R. W. Seifert, "Mitigating Product Shortage Due to Disruptions in Multi-Stage Supply Chains," *Production and Operations Management,* pp. 941-964, April 2020.

[43] Y. Li, M. R. Kramer, A. J. M. Beulens and J. G. A. J. Van Der Vorst, "A framework for early warning and proactive control systems in food supply chain networks," *Computers in Industry,* pp. 852-862, 2010.

[44] E. Esmaeili-Najafabadi, M. S. F. Nezhad, H. Pourmohammadi, M. Honarvar and M. A. Vahdatzad, “A joint supplier selection and order allocation model with disruption risks in centralized supply chain,” *Computers and Industrial Engineering,* pp. 734-748, 2019.

[45] A. Azadegan, S. Modi and L. Luccianetti, “Surprising supply chain disruptions: Mitigation effects of operational slack and supply redundancy,” *International Journal of Production Economics,* 2021.

[46] K. Govindan, H. Mina and B. Alavi, “A decision support system for demand management in healthcare supply chains considering the epidemic outbreaks: A case study of coronavirus disease 2019 (COVID-19),” *Transportation Research, Part E: Logistics and Transportation Review,* June 2020.

[47] H. Matsuo, “Implications of the Tohoku earthquake for Toyota's coordination mechanism: Supply chain disruption of automotive semiconductors,” *International Journal of Production Economics,* pp. 217-227, 2015.

[48] S. Sarkar and S. Kumar, “A behavioral experiment on inventory management with supply chain disruption,” *International Journal of Production Economics,* pp. 169-178, November 2015.

[49] M. M. Hughes, Z. Zhou, W. Zinn and A. M. Knemeyer, “Plastic response to disruptions: Significant redesign of supply chains,” pp. 80-108, January 2023.

[50] G. Li, M. Liu and H. Zengh, “Subsidization or Diversification? Mitigating Supply Disruption with Manufacturer Information Sharing,” *Omega,* October 2022.

[51] M. R. G. Samani, S.-M. Hosseini-Motlagh and S. Homae, “A reactive phase against disruptions for designing a proactive platelet supply network,” *Transportation Research, Part E: Logistics and Transportation Review,* 2020.

[52] N. Mohammadzadeh and S. H. Zegordi, “Coordination in a triple sourcing supply chain using a cooperative,” *Computers & Industrial Engineering,* pp. 194-215, 2016.

Appendix A: 70 best journals on operations management and supply chain

Advances in Production Engineering and Management	Journal of Manufacturing Systems
Annals of Operations Research	Journal of Manufacturing Technology Management
CIRP Annals	Journal of Operations Management
Computers and Industrial Engineering	Journal of Purchasing and Supply Management
Computers and Operations Research	Journal of Rail Transport Planning and Management
Computers in Industry	Journal of the Operational Research Society
Decision Sciences	Management Science
EURO Journal on Transportation and Logistics	Manufacturing and Service Operations Management
European Journal of Operational Research	Manufacturing Review
Expert Systems with Applications	Mathematical Methods of Operations Research
Flexible Services and Manufacturing Journal	Mathematics of Operations Research
IEEE Transactions on Systems, Man, and Cybernetics: Systems	Naval Research Logistics
Industrial Management and Data Systems	Omega
International Journal of Advanced Manufacturing Technology	Operations Management Research
International Journal of Logistics Management	Operations Research
International Journal of Logistics Research and Applications	Operations Research Letters
International Journal of Management Science and Engineering Management	Operations Research Perspectives
International Journal of Operations and Production Management	OR Spectrum
International Journal of Physical Distribution and Logistics Management	Production and Operations Management
International Journal of Production Economics	Production Planning and Control
International Journal of Production Research	Public Transport
International Journal of Shipping and Transport Logistics	Research in Transportation Business and Management
International Journal of Sustainable Transportation	Robotics and Computer-Integrated Manufacturing
International Journal of Systems Science	Supply Chain Forum
International Journal of Systems Science: Operations and Logistics	Supply Chain Management
International Journal of Transportation Science and Technology	Sustainable Cities and Society
International Transactions in Operational Research	Transport Reviews
Journal of Advanced Transportation	Transportation
Journal of Air Transport Management	Transportation Research Part C: Emerging Technologies
Journal of Business Logistics	Transportation Research Part A: Policy and Practice
Journal of Cleaner Production	Transportation Research Part D: Transport and Environment
Journal of Engineering and Technology Management - JET-M	Transportation Research Part E: Logistics and Transportation Review
Journal of Environmental Economics and Management	Transportation Research Series B: Methodological
Journal of Management	Transportation Science
Journal of Manufacturing Processes	Transportmetrica A: Transport Science

NTNU

Norwegian University of
Science and Technology