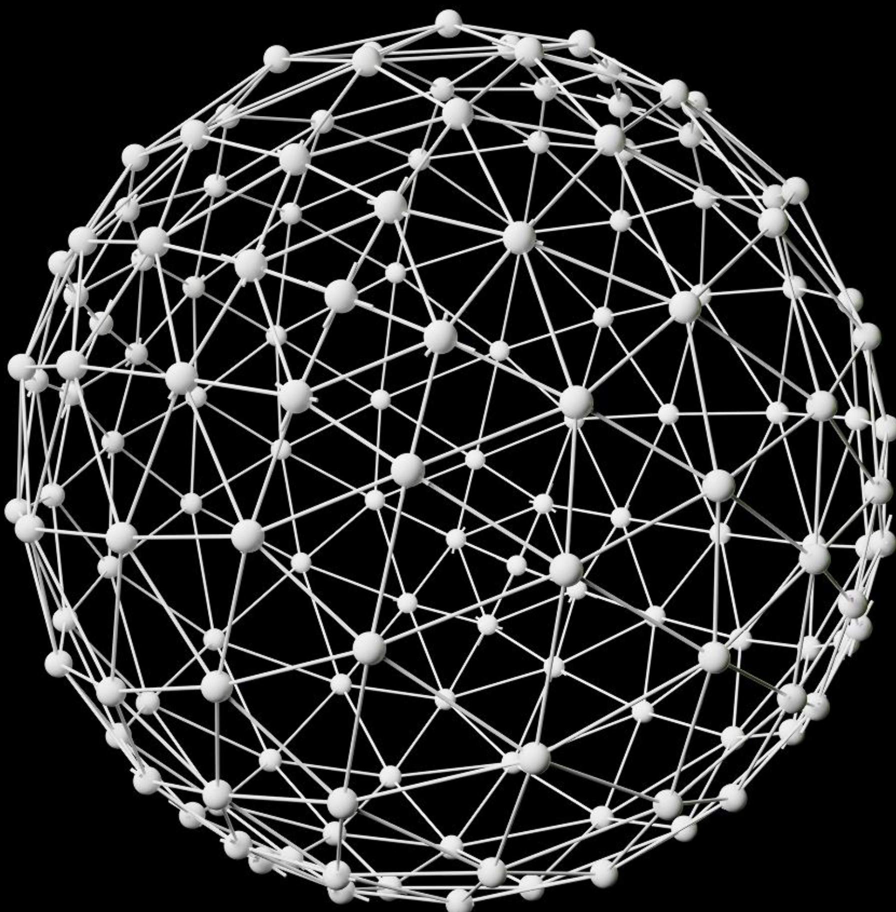
Addressing Supply-Side Disruptions: Optimizing Supply Chain Performance through Supplier Selection and Risk Mitigation

Leveraging the use of Discrete Event Simulation and the Best Worst Method for Data-driven Supplier Selection and Supply Chain Performance Optimization

Master thesis

Mustafa Aydın



TU Delft | Deloitte.

August 2023

Addressing Supply-Side Disruptions: Optimizing Supply Chain Performance through Supplier Selection and Risk Mitigation

A Case Study of Global Polymer Supply Chains

Master thesis submitted to Delft University of Technology

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in Complex Systems Engineering & Management

Faculty of Technology, Policy and Management

By

Mustafa Aydın

4799925

To be defended in public on 8 September 2023 at 10:30 AM

Graduation committee:

Chairperson	: Dr. J. Rezaei, Section of Transport and Logistics
First Supervisor	: Dr. M.Y. Maknoon, Section of Transport and Logistics
Second Supervisor	: Dr. M. Yang, Section of Safety and Security Science
External Supervisor	: S. Fransen, Sr. Consultant Supply Chain and Network Operations at Deloitte
External Supervisor	: J. Schep, Sr. Specialist Lead Supply Chain and Network Operations at Deloitte

Preface

As I sit here, reflecting on the past six months of hard work, I cannot help but feel a mix of emotions. This thesis marks the end of my 5-year journey at the TU Delft, a period filled with challenges, growth, and invaluable experiences. It has been a transformative time that has shaped not only my academic knowledge but also my character.

First and foremost, I would like to express my deepest gratitude to my Deloitte supervisors, Stan Fransen and Jurg Schep, and the entire Supply Chain & Network Operations team. Your guidance, expertise, and support have been instrumental in shaping the direction and quality of this thesis. I am grateful for the opportunity to have worked with such remarkable professionals in the field.

I would also like to extend my heartfelt thanks to my university supervisors. Yousef Maknoon, your encouragement from the very beginning of this journey has been invaluable. Ming Yang, your support and especially your agreement to be my second supervisor meant a lot to me as I struggled to shape my graduation committee. And to Jafar Rezaei, thank you for chairing my graduation committee and providing valuable insights and suggestions during the process of writing my thesis.

To my family and friends, thank you for being my pillars of support throughout my time at the TU Delft. Your unwavering belief in me, understanding during the long hours spent studying, and encouragement during moments of doubt have been the driving force behind my perseverance. I am truly grateful for your love, encouragement, and understanding.

Finally, to the readers of this thesis, I hope you find it informative and engaging. It has been a labor of love, fueled by my passion for supply chain management and the desire to learn more and contribute to the field. May this thesis serve as proof of the knowledge and skills I have acquired during my time at the TU Delft and in the Supply Chain & Network Operations team at Deloitte.

With great appreciation and a sense of fulfillment, I present to you this thesis. May it inspire and ignite further curiosity and exploration in the exciting realm of supply chain management.

Thank you, and enjoy reading.

Mustafa Aydın
Delft, August 2023

Executive Summary

In today's rapidly evolving global landscape, supply chains are encountering increased exposure to disruptions. Challenges such as environmental disturbances or supplier disruptions have become frequent barriers. The primary question driving our research was:

How does a methodical approach to supplier selection, combined with the most effective risk mitigation strategy, impact supply chain performance in the presence of supply-side disruption risks?

Our exploration shed light on a gap within real-world supply chain management practices: the absence of a systematic supplier selection method. This gap can cause significant inefficiencies and business performance downturns if not addressed. Recognizing this, our research ventured into two complementary methodologies. First, the best worst method (BWM) was employed to assess and rank suppliers based on crucial criteria systematically. Concurrently, we used a discrete-event simulation model built on the Simio platform to simulate the dynamics of a supply chain, accommodating a diverse array of suppliers, potential disturbances, and disruptions.

The outcomes were helpful. Within the context of the polymer industry, we found that Material Quality, Supply Reliability, Price, and Lead Time emerged as paramount criteria for supplier selection. The comparison between our BWM rankings and actual supply chain performance outcomes underscores the relevance and efficacy of this approach. Regarding risk mitigation, a clear preference emerged for flexibility-oriented sourcing strategies. These outperformed their redundancy-oriented equivalents, showcasing competence in managing supply-side disruptions and lowering safety stock levels.

The implications of these findings span both societal and scientific dimensions. From a societal viewpoint, introducing a methodical supplier selection process lays the foundation for robust supply chains, vital for critical sectors like healthcare and food. This approach also catalyzes global collaboration and innovation by emphasizing diversified supplier sourcing. From a scientific angle, our study stands as a testament to the efficacy of the BWM for supplier selection. It questions and challenges traditional beliefs, especially those equating higher costs with better risk mitigation. A notable revelation was the rising emphasis on flexibility as a modern supply chain risk management cornerstone.

For the polymer industry, our recommendations advocate for a structured supplier selection method hinged on the BWM. Businesses can minimize safety stock levels by aligning with high-ranked suppliers and diversifying their supplier base across geographies. Furthermore, our simulation model offers a tangible, hands-on tool for decision-makers. This tool allows for scenario testing, enabling businesses to discover the most beneficial strategies for their contexts.

However, it is crucial to note the constraints of our research. Our exploration is primarily tailored to the polymer industry, and the specific assumptions framing our simulation model might not be universally applicable. Hence, while our findings hold profound insights, their broader generalizability might be restricted by data constraints and the unique characteristics of the polymer sector.

In wrapping up, our research affirms that an integrated, methodical supplier selection, coupled with a flexibility-oriented sourcing strategy, results in optimal supply chain performance, especially when navigating supply-side disruptions. Refining these dual aspects can drive companies towards shaping agile supply chains prepared for supply-side risks, yielding cost efficiencies and performance enhancements.

Table of Contents

1. Introduction

1.1 Problem Definition

Supply chains have become increasingly interconnected in the modern era of globalization. This interconnectedness has boosted firms' competitiveness as they expand into markets with lower production costs. However, one disadvantage of this globalization boon is the increased complexity in supply chain management. Firms' ventures into complex, intertwined networks have resulted in increased volatility, decreased supply chain visibility, and, as a result, an increased risk of disturbances and disruptions (Kamalahmadi & Parast, 2016; Xu et al., 2021). The recent grounding of the Evergreen vessel in the Suez Canal and the disruptive impact of the COVID-19 pandemic highlights these difficulties. Both incidents exposed the flaws in today's supply chains, demonstrating how unexpected disruptions have a ripple effect (Chen et al., 2020; Ivanov et al., 2014).

The critical process of supplier selection is critical to the performance of these intricate supply chains. While decision-makers understand how to prioritize their selection criteria, using a systematic supplier selection approach appears to be lacking in the case studied in this research. This lack of methodical selection can lead to supply chain inefficiencies and vulnerabilities.

The existing literature provides various insights into decision-making criteria, emphasizing the importance of sustainability, risk mitigation, industry-specific needs, and the incorporation of new technologies (Rezaei et al., 2016; Yazdi et al., 2022). There is, however, a noticeable gap. The potential for rigorously evaluating supply chain performance by combining the best worst Method (BWM) for supplier selection with a simulation model remains largely unexplored. Recognizing this, we research to investigate and validate this approach.

Furthermore, while there is a wealth of literature on risk mitigation, it falls short of identifying which specific strategies, or combinations of strategies, optimize supply chain performance, considering disturbance and disruption risks. In supplier selection, there is an acknowledged need to balance risk mitigation and cost efficiency (Carvalho et al., 2012; Juttner & Maklan, 2011; Gunasekaran et al., 2015). However, there has been little comprehensive research comparing these risk mitigation strategies in the context of their direct impact on supply chain performance. This presents an intriguing research gap: identifying the best-suited risk mitigation strategies that improve supply chain performance in the face of potential disruptions and disturbances.

The study aims to make the following notable contributions:

Societal Impact: The research promotes the development of more resilient supply chains, which is critical for industries that rely heavily on global networks. The research strengthens supply chain flexibility and ensures continuous access to vital resources during crises by advocating for global collaboration. These advances align with the United Nations Sustainable Development Goals 9 and 12, emphasizing the study's societal importance.

Managerial Contribution: The study emphasizes the value of methodical approaches for supplier selection, such as the best worst method in multi-criteria decision-making (MCDM). Such strategies pave the way for more informed decision-making, ushering in leaner, more efficient supply chains. Furthermore, the research calls into question traditional risk management practices, arguing that flexible sourcing strategies outperform redundancy-focused tactics in risk mitigation. This realization promises more agile supply chain responses without the burden of high costs.

Scientific Contribution: The research validates the best worst method's ability as a dependable, data-informed approach to supplier selection on the academic frontier. Furthermore, it contributes to the discussion of supply chain risk management by shedding light on the role of flexibility and redundancy in risk mitigation through simulation modeling.

1.2 Objective and Research Questions

This research investigates and validates the best worst method (BWM) for supplier selection in supply chains and assesses its impact on supply chain performance using discrete event simulation. We model the system with discrete event simulation and measure supply chain performance by applying this model. Furthermore, the study explores whether supplier selection reduces safety stock levels within the supply chain. Specifically, the research seeks to achieve the following three objectives:

1. Validate the effectiveness of a methodical approach for supplier selection: The research will assess whether suppliers ranked highest based on BWM criteria lead to improved supply chain performance. By comparing the supplier rankings with those used in the best-performing scenarios obtained through discrete event simulation, the study will provide empirical evidence on the efficacy of BWM as a decision-making tool for supplier selection.
2. Compare and evaluate different risk mitigation strategies for enhancing supply chain performance: The research will systematically analyze and compare various risk mitigation strategies, or combinations thereof, in terms of their influence on supply chain performance. By employing discrete event simulation, the study aims to identify the most effective strategies for minimizing disruptions and disturbances in supply chains, thereby enhancing overall performance. This objective aims to contribute to developing evidence-based practices for optimizing supply chain performance amidst disruptions.
3. Investigate the relationship between supplier selection decisions and supply chain performance: The research will examine the relationship between supplier selection decisions made using BWM and the resulting supply chain performance. The study will explore how supplier selection decisions impact supply chain performance by comparing supplier rankings with performance outcomes, encompassing cost, lead time, quality, and other relevant metrics obtained through discrete event simulation.

These three objectives merge to form a single overarching research question:

Main Research Question

Based on the defined problem and objectives, the main research question of this study is:

How does a methodical approach to supplier selection, combined with the most effective risk mitigation strategy, impact supply chain performance in the presence of supply-side disruption risks?

Sub Research Questions

Six related sub-questions are essential in order to address the main research question. These are:

1. *What supply-side disruption risks are faced in the supply chain, and what risk mitigation measures are commonly employed to address them?*

This sub-question aims to explore the existing challenges and risks in global supply chains and understand the risk mitigation measures commonly used by organizations to manage these risks.

2. *What criteria are essential for supplier selection, and what KPIs are important for measuring overall supply chain performance?*

This sub-question identifies and prioritizes the significant criteria for supplier selection and KPIs for measuring overall supply chain performance. It will involve collecting data through expert interviews to capture the perspectives of industry experts.

3. *How can we model a supply chain with multiple suppliers and mitigation strategies to address supply-side disruption risks?*

This sub-question involves the development of a simulation model to represent a supply chain facing the risk of disturbances and disruptions. It requires identifying relevant input parameters and assumptions to accurately capture the supply chain dynamics and the impacts of disturbances. Additionally, implementing redundancy- and flexibility-oriented strategies is explored by incorporating decision rules and processes, enabling the analysis of their effects on supply chain performance.

4. *To what extent does the methodical supplier ranking of higher-ranked suppliers align with the suppliers contracted in the best-performing scenarios?*

This sub-question investigates the alignment between the supplier ranking obtained using the best worst method (BWM) and the model output with the best-performing scenarios. It examines whether contracting a methodically higher-ranked supplier leads to enhanced supply chain performance.

5. *What are the performance differences and trade-offs observed between scenarios implementing different combinations of redundancy- and flexibility-oriented sourcing strategies?*

This sub-question evaluates the performance differences and trade-offs between various scenarios within the model. It involves analyzing the supply chain performance metrics, on-time, in-full delivery, net profit, total cost, inventory levels, and quality for redundancy and flexibility strategies combinations.

6. *How does selecting higher-ranked suppliers reduce safety stock levels in the supply chain?*

The sub-question aims to understand the relationship between a methodical supplier selection approach and its impact on inventory management, focusing on the potential benefits of reducing safety stock levels in improving overall supply chain performance.

1.3 Approach

The research approach includes both qualitative and quantitative methods to study supplier selection, supply chain performance, and the effects of disturbances and disruptions. The study begins with an extensive literature review that explores global supply chains' challenges and risks and examines common risk mitigation measures. Expert interviews with industry professionals and supply chain managers provide qualitative insights into supply chain management in the polymer industry. These insights cover supplier selection criteria, performance evaluation, current challenges, and risk mitigation strategies.

A discrete event simulation model, grounded in literature and expert feedback, incorporates redundancy- and flexibility-oriented strategies to address the impacts of disturbances and disruptions. Multiple scenarios undergo simulation to assess supply chain performance metrics across different strategies. These metrics encompass on-time delivery, net profit, total cost, inventory levels, and quality.

The quantitative research involves creating and distributing a survey to supply chain professionals and experts. This survey gauges the criteria for supplier selection and the KPIs used to measure supply chain performance. Participants rank and prioritize these criteria and KPIs. The gathered data then informs the best worst method (BWM), determining the relative importance of different criteria.

The analysis ranks scenarios using the weights given to the KPIs. It examines the influence of supplier combinations, risk mitigation strategies, and variations in safety stock on supply chain performance. The results lead to conclusions and recommendations, shedding light on using BWM for supplier selection and applying effective risk mitigation strategies to boost supply chain performance and cut costs.

1.4 Thesis Structure

This thesis adheres to the following structure: Chapter 2 reviews related literature, setting the study in its broader context. Chapter 3 provides a clear description of the problem. Chapter 4 outlines the methodology used. Chapter 5 presents the specific case system we have identified. Chapter 6 explains the development of both the conceptual and simulation models. Chapter 7 shares the results, and Chapter 8 discusses these findings, leading to the study's conclusions.

2. Literature Review

The literature review comprehensively examines the existing literature about supply disruption risk in Subchapter 2.1 and supplier selection models in Subchapter 2.2. In Subchapter 2.3, a synthesis of the literature is presented, wherein a comparison is made between the current study and the most closely related research.

2.1 Supply Disruption Risk

The vulnerability of supply chains to unexpected disruptions, either from natural events like earthquakes, floods, and hurricanes or man-made events such as equipment malfunctions, strikes, and terror attacks, has been emphasized by Chen & Xiao (2015). Such events can have cataclysmic effects on the supply chain, interrupting the flow of materials and resulting in significant losses.

Historically, despite having low probabilities, these disruptions can yield high consequences due to the fragility of manufacturing and transportation infrastructures. Recognizing the gravity of such risks, researchers and practitioners have paid significant attention to supply chain disruptions over the past decades.

Tomlin's (2006) seminal work delved into a scenario involving one manufacturer and two suppliers of contrasting reliability and cost profiles. Crucially, he highlighted that adopting a hybrid mitigation strategy is optimal when faced with unreliable suppliers or risk averseness. Specifically, this involves a combination of inventory stockpiling and sourcing partially from reliable suppliers. The intricacies of supply chain design risks have been delineated by Kleindorfer and Saad (2005), segregating them into operational risks (resulting from supply-demand imbalances) and disruption risks (resulting from unexpected breaks in activities). They proffered a conceptual framework addressing risk assessment and mitigation, supported by empirical evidence from the U.S. chemical industry between 1995-2000.

The strategic response to disruptions in supply chains with perishable products and short lifecycles was explored by Tomlin (2009). He presented various mitigation strategies, from contingent sourcing in the event of disruptions to supplier diversification to reduce dependency. Schmitt et al. (2015) brought the lens to multi-location systems under supply uncertainties. Their research underscores the benefits of a decentralized inventory system, mainly when demand predictability is vague and supply disruptions are plausible. Furthermore, Baghalian et al. (2013) presented an intricate model to design a supply chain network, focusing on uncertainties on both supply and demand sides. Their unique approach of using a "potential path concept" shunned the typical flow variable definition between supply chain facilities and was validated through an agri-food industry case study.

Hamdi et al. (2018) thoroughly categorized and analyzed papers on supplier selection under supply chain risk management from 2003 to 2014 in their exhaustive literature review. A fundamental area of focus within supply chain disruption studies is the methodologies to mitigate disruption impacts and identify supply chain resilience. Supply Chain Risk Management (SCRM), as defined by Kumar et al. (2017) and Wieland and Wallenburg (2012), is a holistic approach to managing risks through continuous evaluation, aiming to reduce vulnerabilities and ensure continuity.

Several disruption risk mitigation policies emerge from the literature:

Sourcing: This can be split into flexible sourcing (adopting multiple suppliers for regular orders during disruptions) and resorting to backup suppliers when primary suppliers are incapacitated, cited by multiple authors (Sawik, 2014; Sawik, 2017; Tomlin, 2006).

Pre-positioning Inventory: Refers to maintaining buffer stocks, either as raw materials or finished goods, as seen in multiple works (Sawik, 2013; Schmitt, 2011; Kamalahmadi & Parast, 2017; Tomlin, 2006).

Protecting Suppliers: This strategy aims to shield suppliers from disruptions and enhance their resilience (Kamalahmadi & Parast, 2017; Sawik, 2013).

Acceptance: When mitigation costs exceed disruption losses, companies might opt to remain unprotected (Tomlin, 2006).

Specialized Policies: These are tailored for unique supply chain circumstances, such as earthquakes, where specific risk management strategies become vital.

In synthesizing these insights, Rice and Caniato (2003) suggest that incorporating flexibility and redundancy is paramount in reducing supply chain disruptions' impacts. Nonetheless, recent trends indicate a lesser emphasis on redundancy in favor of flexibility. (Kamalahmadi and Parast, 2016; Ivanov, 2021; Tang & Tomlin, 2008).

In wrapping up, this review emphasizes the profound significance of understanding and mitigating supply chain disruptions. The strategies outlined – sourcing diversification, inventory pre-positioning, to supplier protection – offer a roadmap for businesses to navigate the waters of disruption risks and ensure supply chain risk mitigation against disturbances and disruptions.

2.2 Supplier Selection

Weber and Current (1993) posited that supplier selection is pivotal to any successful business. It is about identifying and integrating suitable suppliers into the demand chain. This integration has been explored widely, especially in the contemporary interconnected global supply chains.

One researcher that prominently stands out in supplier selection literature is Sawik. He has significantly contributed to several seminal papers on the subject. Sawik's research presents a spectrum of ideas, from integrating supplier selection with production to factoring in supply chain disruption risks. For instance, in one of his works (Sawik, 2015), he combines supplier selection with production and distribution, placing it within the context of supply chain disruptions. His emphasis on creating an efficient portfolio approach that integrated supplier selection and finished goods' production schedule (Sawik, 2017) provides invaluable insights. Perhaps most compelling is Sawik's risk-averse approach to supplier selection, emphasizing resilient supply and demand portfolios in complex, multi-tiered global networks (Sawik, 2021).

Digressing slightly from pure supplier selection, Rinaldi et al. (2022) turned the lens toward quantitative models for supply chain risk management. Their study suggests that while the importance of quantitative models, especially proactive ones, cannot be understated, their application, especially in unpredictable situations like pandemics, is challenging. They observed heightened attention to supply chain disruptions in regions like the US and the Eastern Hemisphere, prone to environmental disruptions.

Hamdi et al.'s (2015) contribution highlight an underexplored niche – supplier selection under supply chain risk management (SCRM). Their findings underscore a critical gap in the literature, emphasizing how decision-makers' attitudes can significantly influence the supplier selection process. While reliability and demand risks take center stage in most research, Hamdi et al. (2015) argue that adopting a multi-risk combination strategy will offer a more holistic approach.

Diving deeper into the integration of supplier selection and order allocation, several studies present noteworthy findings. For example, Keskin et al. (2010) concurrently tackle supplier selection and demand allocation. Their holistic model encapsulates various cost parameters related to the supplier-buyer relationship, inventory management, and decision-making. In similar work, Pazhani et al. (2016) propose an integrated model to minimize inventory and transportation costs, supplier selection, and order allocation expenses. Such integrated models, as Mendoza and Ventura (2010) and Esmaeili-Najafabadi et al. (2019) contend, lead to better efficiency and address aspects often ignored, such as multi-sourcing and disruption risks.

Criteria for supplier selection, as documented in numerous studies, range from the tangible to the intangible. While some, like Banaeian et al. (2018) and Gao et al. (2020), stress greening criteria; others emphasize sustainability (Jain and Singh, 2020) or resiliency (Hosseini & Barker, 2016). Sawik (2013, 2014) focuses on the imperative of supply chain risk criteria. The varied criteria underscore the multifaceted nature of supplier selection, highlighting the need for a comprehensive evaluation matrix.

The issue widely acknowledged but not openly discussed is selecting suppliers in the face of potential disruptions. According to Sawik (2014), disruption risks are classified into three categories: local, semi-global (regional), and global. Every type of disruption presents challenges, from localized disruptions involving equipment breakdowns to global disruptions such as the COVID-19 pandemic. Hamdi et al. (2018) provide a comprehensive overview of the existing literature in this field. The nuances of managing supply chains in the face of disruption risks have been examined in studies conducted by Tomlin (2006) and Yu et al. (2009). Tomlin (2006) highlights the significance of reducing inventory and adopting a multi-sourcing approach. Conversely, Yu et al. (2009) examine the consequences of these disruptions on decision-making in sourcing. According to Schmitt and Singh (2012), there is a suggestion that using quantitative risk assessments could provide managers with improved guidance in navigating through periods of turbulence.

In conclusion, supplier selection demands more than identifying vendors, especially in today's volatile global marketplace. It requires a comprehensive approach that factors in criteria like sustainability and risk mitigation and adequately prepares for disruption risks. The literature reviewed underscores the evolving nature of supplier selection and the pressing need to integrate it seamlessly with other supply chain components. As businesses strive for efficiency, the insights from these studies can offer invaluable guidance, ensuring they stay prepared against disruptions, agile, and competitive.

2.3 Synthesis

The field of supply chain research, which has been greatly enhanced by influential studies conducted by Tomlin (2006) and Schmitt et al. (2015), provides valuable perspectives on the dynamics of supply chains. Nonetheless, as stated by Shashi et al. (2019), there remains a gap in understanding which risk mitigation strategy, either focused on flexibility or redundancy, is more effective in improving supply chain performance against the risk of disruption. Our study diligently addresses this knowledge gap to offer insights into the individual and collective effects of these approaches on the performance of supply chains.

Simultaneously, a crucial aspect of the literature is the methodical evaluation of supplier selection processes. While techniques like the best worst method (BWM) have been applied to supplier selection by scholars such as Rezaei et al. (2016), our research goes further. By comparing the BWM approach with tangible supply chain scenarios simulated through a discrete event model, we aspire to unveil not just optimal supplier selection but also the implications of such selections on supply chain efficiency and performance and concerning safety stock levels.

This multifaceted approach offers a novel perspective. On one end, it evaluates the efficacy of risk mitigation strategies under various simulated scenarios. On the other, it critically examines the trade-offs in supplier selection using BWM and correlates these selections with outputs from the discrete event model. Such a synergy provides an avenue to assess the congruence between theoretical supplier rankings and their performance in dynamic supply chain scenarios.

In conclusion, our study investigates supply chain risk management. We aim to offer a complete toolkit for supply chain managers by combining risk mitigation strategies with supplier selection techniques and comparing theoretical findings with practical simulations. This is achieved through the intertwining of these elements. The present toolkit provides a comprehensive understanding of the most effective approaches to mitigate disruptions and offers insights into aligning supplier selection with broader supply chain objectives to enhance operational efficiency, risk mitigation, and cost efficiency.

3. Problem Description

This chapter delineates the problem's conceptual framework in Subchapter 3.1, outlines the foundational assumptions of the system in Subchapter 3.2, and details the variables incorporated into our study in Subchapter 3.3.

3.1 Conceptualization

This study focuses on a centralized supply chain consisting of a single buyer (manufacturer) and three suppliers. Specifically, one supplier is in region one, while the remaining two are in region two. The manufacturer can engage with one to three suppliers to replenish its raw materials by adopting a strategy that focuses on flexibility or a backup supplier. The manufacturer transforms these raw materials into finalized products and distributes them to customers. Disturbances may arise at the manufacturing stage and during transportation, while disruptions can also manifest internally within suppliers or the regions where they are situated. In this centralized supply chain, the core challenge is determining the optimal supplier base and implementing the most effective sourcing strategy while maintaining minimal safety stock levels to ensure efficiency and cost-effectiveness.

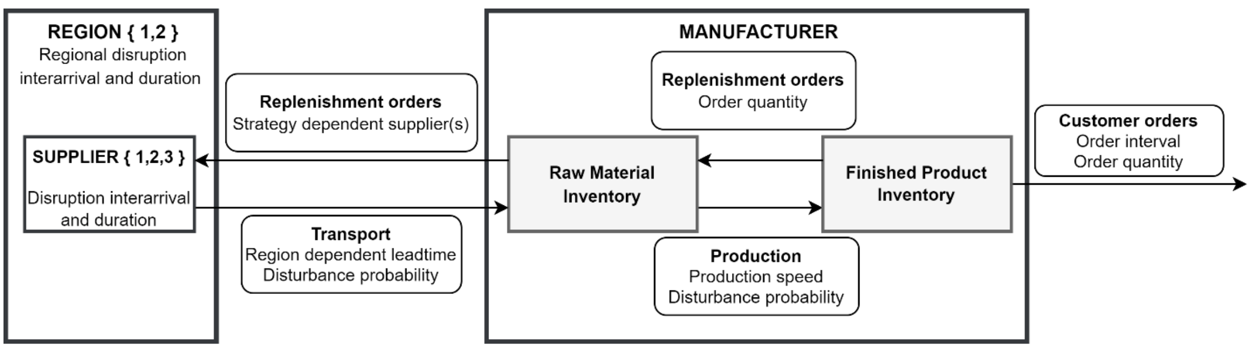


Figure 3.1: *Model conceptualization*

3.2 Assumptions

Table 3.1 contains the fundamental assumptions crucial for establishing the problem's framework in our study. The model development in Chapter 6 comprehensively examines the assumptions made in this study.

Table 3.1: *Key assumptions*

Focus	**Assumption**
Manufacturer	The manufacturer maintains separate inventories for raw materials and finished products.
Manufacturer	Only the manufacturer can produce finished products from raw materials and source raw materials from suppliers.
Manufacturer	The manufacturer can maintain different pre-defined safety stock levels to mitigate supply-sided risks.
Customer orders	The interarrival time and size of customer orders follow a Poisson distribution.
Customer orders	Customer orders are not back ordered; insufficient inventory leads to failed orders and fines.
Suppliers	Each supplier can be in one of two states: available (able to deliver raw materials) or disrupted (unable to deliver anything)
Suppliers	Each supplier has unique properties, including contract costs, cost per unit of raw material, disruption interarrival and duration, material quality, and lead time.
Suppliers	European suppliers are more reliable and costly compared to Asian suppliers.
Transportation	The lead time for suppliers located in Asia is longer, and the disturbance probability is higher than for the supplier in Europe.
Environmental disruptions	EDs have an interarrival and duration. When an environmental disruption occurs, it disrupts all suppliers within the specific region.

3.3 Variables

Table 3.2 presents the decision and input variables in the system and the key performance indicators. The decision variables allow for establishing the safety stock level and making choices regarding the sourcing strategy and the suppliers involved. Key performance indicators (KPIs) are utilized to assess the performance of our system.

Table 3.2: *Variables and KPIs*

	Decision variables
S_c	Chooser with all possible sourcing strategies and supplier combinations.
I_r	Reordering level for the inventory of raw materials at the manufacturer.
I_o	The level of raw material inventory at the manufacturer that is ordered up to when the inventory hits the reordering level.
	Input variables
S	Set of suppliers. S = {1,2,3}
R	Set of regions. R = {Europe, Asia}
$C_{u,s}$	The cost of a unit of raw material at supplier s
$C_{c,s,r}$	The regular contracting costs per year at supplier s
$C_{c,s,b}$	The backup contracting cost per year at supplier s
$C_{c,s,f}$	The flexible contracting cost per year at supplier s
Q_s	The quality of raw materials at supplier s
$T_{iat,d,s}$	The interarrival time of a disruption at supplier s
$T_{d,d,s}$	The duration of a disruption at supplier s
$T_{t,s,r}$	The regular transportation time from supplier s
$T_{t,s,d}$	The disturbed transportation time from supplier s
$P_{td,r}$	The probability of a transportation disturbance occurring in region r
$T_{iat,ed,r}$	The interarrival time of an environmental disruption in region r
$T_{d,ed,r}$	The duration of an environmental disruption in region r
CO_q	The quantity of a customer order
$T_{iat,co}$	The interarrival time of a customer order
$C_{co,u}$	The price of one unit of finished product
$C_{f,m}$	The cost of the fine per unit when a customer order cannot be delivered
$T_{m,prod}$	The processing time of one unit of raw material at the manufacturer
$T_{iat,d,m}$	The interarrival time of a disturbance at the manufacturer
$T_{d,d,m}$	The duration of a disturbance at the manufacturer
$C_{i,m}$	The cost of holding one unit of inventory at the manufacturer
	Key Performance Indicators
$OTIF$	On-Time In-Full Delivery presents the rate of customer orders that have been fulfilled. OTIF = Fulfilled Orders / (Fulfilled Orders + Failed Orders) * 100%
C_{total}	Total Cost includes materials, contracting, inventory storage, and fines for failed customer orders.
NP	Net Profit is defined by the revenue gained from customer orders – total costs.
T_{so}	The Stockout Time measures the number of days the manufacturer is left without any finished products.
LQ_d	The Low-Quality Delay indicator measures the number of instances the production process at the manufacturer experienced delays due to lower raw material quality.

4. Methodology

This chapter outlines the methodology employed, as depicted in Figure 4.1, requiring a sequence of steps executed in a specific order. The chapter is structured as follows: Subchapter 4.1 delves into developing our simulation model, elaborating on the modeling cycle adopted. Subchapter 4.2 details the best worst method for methodical supplier selection, detailing the analysis steps. This integrated research approach allows us to ascertain the optimal risk mitigation strategies and suppliers for a supply chain in the context of disturbance and disruption risks.

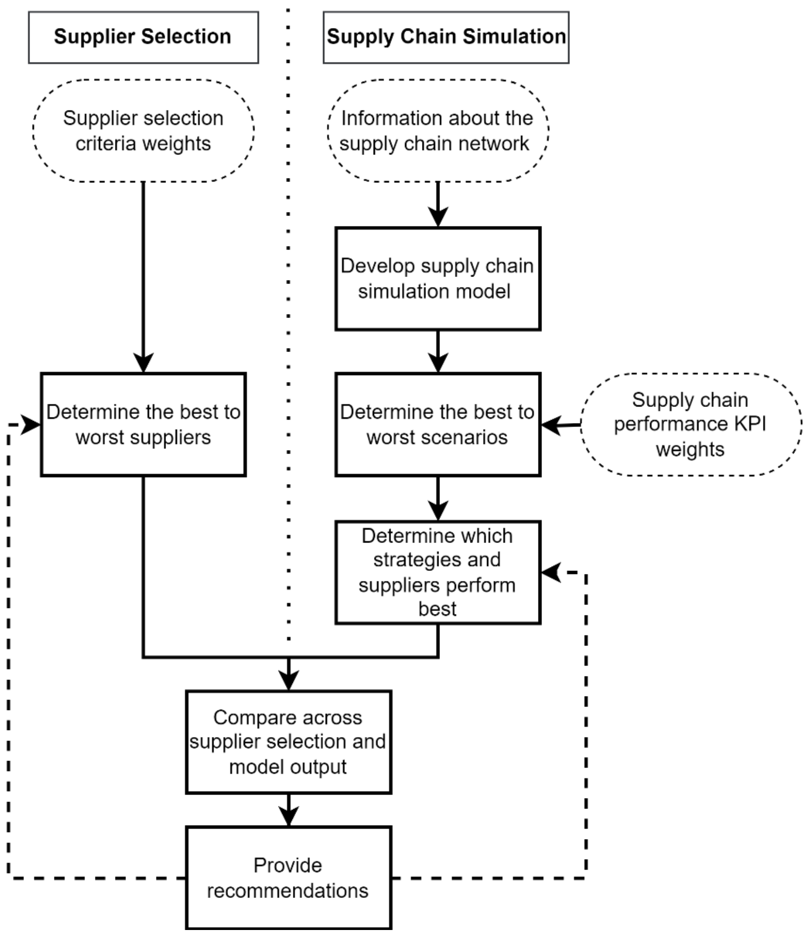


Figure 4.1: *Methodology overview*

The results of the supplier selection conducted with the BWM, as depicted on the left side of Figure 4.1, are compared with the best-performing scenarios, as determined by the supply chain simulation output and depicted on the right side of Figure 4.1. The most effective scenarios will demonstrate the optimal combination of sourcing strategy, supplier selection, and safety stock level, resulting in optimal supply chain performance.

4.1 Discrete-Event Simulation (DES)

In this study, we employ a design cycle approach inspired by the work of Kelton et al. (2013) to facilitate the progression of our model's development systematically. The design cycle consists of four distinct phases, presented in Figure 4.2.

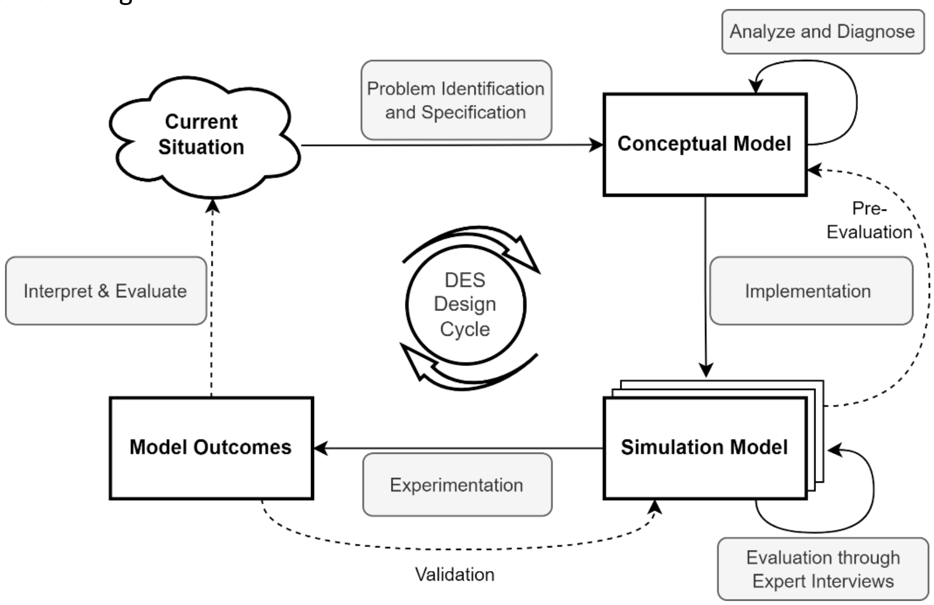


Figure 4.2*: DES design cycle, adopted from Kelton et al. (2013)*

Assessing the Current Situation (Chapter 5):

- Literature Review: A comprehensive dive into scholarly articles, industry reports, and other relevant publications provides a foundational understanding of the existing knowledge concerning disruption risks, supplier selection, and risk mitigation strategies.
- Expert Interviews: Engaging with key stakeholders in the polymer supply chain, from suppliers to manufacturers, offers insights into their perspectives on supply chain management, disruption risks, mitigation strategies, and supplier selection criteria. The interview framework used is found in Appendix A.

Developing the Conceptual Model (Chapter 6):

- Identify Key Components: From the insights obtained in the previous phase, the essential components of the supply chain are isolated. This encapsulates elements like suppliers, manufacturers, and transportation.
- Determine Objectives and Constraints: The model's goals are laid out clearly, as well as the boundaries within which it operates, such as optimizing supplier selection while minimizing safety stock levels.
- Formulate Assumptions: Given any model's inherent limitations to encapsulating real-world dynamics, certain reasonable assumptions are made to streamline the modeling process.

Constructing the Simulation Model (Chapter 6):

- Model Design: The conceptual model developed serves as a blueprint, guiding the design of the simulation model. This encompasses defining interactions between entities, transport mechanisms, and the influences of various parameters.
- Validation: To ensure the accuracy and reliability of the impending simulation, the model is validated through face and expert validation.

Analyzing the Model Outcomes (Chapters 7 & 8):

- Experimentation: The simulation model is deployed across varied scenarios, including combinations of suppliers, risk mitigation strategies, and safety stock levels.
- Analysis: Results from the simulation are dissected to derive conclusions about optimal strategies, prospective risks, and potential improvement zones.
- Recommendations & Implementation: Conclusions drawn from the analytical phase result in actionable recommendations for stakeholders within the supply chain. Guidance on the most efficient ways to implement these suggestions is also provided.

By embracing this methodology, we ensure a robust and systematic progression from understanding the current scenario to deriving actionable insights. This structured approach accentuates the reliability and applicability of our research findings.

4.1.1 Justification for DES

Based on the discrete nature of state variables in supply chain models and the study's emphasis on operational and tactical aspects, DES is preferred over other modeling methods. The discrete nature of DES allows for a more suitable representation of the supply chain's discrete events and entities' separate handling. Moreover, the study's themes do not involve specific discussions of human behavior or the evolution of behavior as significant system properties, further reinforcing the suitability of DES for the research question.

The justification for using DES in the context of the study lies in its ability to address the operational and tactical aspects of supply chain modeling, particularly when considering the discrete nature of state variables in such systems. DES is a suitable simulation technique for the research problem and aligns with the study's focus on supply chain logistics.

4.1.2 Simio for DES

Discrete event simulation (DES) is a widely used methodology to model and analyze dynamic systems with discrete events over a given period (Vázquez-Serrano et al., 2021). Our research employs DES to simulate and assess complex supply chain interactions, including production, inventory, transportation, and supplier engagements. Simio, a versatile simulation software, was chosen due to its user-friendly interface, flexibility, and capability to incorporate uncertainties through probabilistic distributions (Simio LLC, 2022). Using Simio enables us to explore different scenarios and evaluate the effectiveness of various risk mitigation strategies.

Simio's flexibility allows us to tailor the simulation model to our specific research objectives, realistically representing real-world entities and their behaviors. By incorporating probabilistic distributions, we can capture uncertainties like demand fluctuations and disruptions, providing valuable insights into the supply chain's performance under different conditions.

Furthermore, Simio's advanced data analysis and visualization capabilities empower us to examine simulation outcomes effectively, considering key performance indicators like delivery performance, stockout duration, net profit, and total cost. This possibility enables a comparative analysis of different sourcing strategies and supplier configurations, guiding data-driven decisions for optimized supply chain performance and reduced vulnerability to disruptions.

4.1.3 Integration of Expert Feedback and DES

The research methodology of this study places significant emphasis on incorporating expert input into the development of the Discrete Event Simulation (DES) model. Engaging experts enhances the model's realism, improves validity, and provides industry-specific insights.

The iterative approach to DES model development begins by gathering insights from expert interviews and relevant literature. We identify key entities, define their behaviors, and establish interaction rules. However, we consider this initial implementation preliminary and rely heavily on expert feedback.

In the subsequent phase, we present the functional model to experts for evaluation. They provide feedback on model assumptions, the depiction of supply chain dynamics, and the effectiveness of risk mitigation strategies. Insights from these experts bridge the gap between the theoretical model and real-world industry practices.

Based on expert feedback, the model undergoes comprehensive revisions and essential modifications to align with industry practices. The potential adaptations include actions of entities, including novel scenarios, and improved risk mitigation strategies. This iterative process results in a progressively enhanced model that gains recognition and approval from industry experts. Integrating expert input ensures the model's generalizability and applicability to real-world supply chain scenarios.

4.2 The Best Worst Method (BWM)

In our research, we use the BWM for two different purposes, with two different sets of criteria. The first set of criteria is for supplier selection and the ranking of suppliers, based on the method for a three-phased supplier selection proposed by Rezaei et al. (2016), and the second set is for ranking the supply chain scenarios. The objective of using the best worst method in our research is to assess whether suppliers that rank highest based on BWM criteria result in improved supply chain performance. We also rank the results of the scenarios where we implement different mitigation strategies in the simulation model using BWM, following the proposal by Khan et al. (2021) that employs BWM for performance evaluation in the manufacturing industry. This approach allows us to evaluate the effectiveness of the scenarios comprehensively, taking into account multiple KPIs and their relative importance in decision-making processes.

4.2.1 Justification for BWM

Because of its unique traits and benefits, the best worst method (BWM) is particularly appropriate for our research. The organized nature of the BWM provides a methodical framework for comparing and prioritizing criteria as we attempt to improve supply chain efficiency and reduce costs through improved safety inventory levels, taking disturbances and disruptions into account. Using the best worst method brings several significant benefits to our research (Rezaei, 2020):

Our research ensures an explicit knowledge of the evaluation range by selecting the best and worst criteria or alternatives before conducting pairwise comparisons. This method improves our decisions' consistency and increases our comparisons' dependability. Given supply chain management's complexities and uncertainties, consistent and trustworthy pairwise comparisons are critical for educated decisions.

In addition, the BWM's consider-the-opposite method aids in mitigating anchoring bias. We urge decision-makers to evaluate positive and negative elements by employing two opposing reference points in the optimization model, resulting in more objective evaluations. This is especially crucial when reviewing supplier performance and selecting the best vendors to mitigate supply chain risks.

Also, the BWM balances data efficiency with consistency checks. The BWM's ability to provide consistency checks while remaining data-efficient is advantageous because our study entails a detailed evaluation of suppliers based on various criteria. We can collect and analyze data from supply chain specialists effectively, assuring the reliability and validity of our findings without overwhelming decision-makers with numerous pairwise comparisons.

4.2.2 The Steps for Performing BWM

The methodology proposed by Rezaei et al. (2016) for supplier selection involves three phases: screening, selection, and aggregation. However, in our specific case, we have made certain assumptions that allow us to modify this methodology to suit our needs better.

Typically, the screening phase involves evaluating the available suppliers to determine if they meet the minimum requirements. However, in our scenario for ranking the suppliers, we assume that the supplier set we can choose from has already been qualified and meets the minimum requirements. Therefore, we can skip the screening phase and proceed directly to the selection phase, using the best worst method (BWM) to rank the suppliers.

In our research, we will also rank the output scenarios of our simulation model using BWM. However, for this case, we will need to perform a screening. This pre-selection phase involves setting thresholds for specific Key Performance Indicators (KPIs) and filtering out scenarios that score lower than these thresholds. This allows us to narrow down the scenarios for further evaluation and ranking with the BWM.

After completing the selection phase, Rezaei et al. (2016) also suggest an aggregation phase, which is used to adjust the assigned scores based on the importance of materials. However, in our case, we have assumed that each supplier handles only one type of material. Therefore, we do not need to consider the aggregation phase in our supplier selection process.

For the selection phase, there are five steps in the BWM (Rezaei, 2015; Rezaei, 2016). These steps are followed by a sixth consistency check step by obtaining the Input-Based Consistency Ratio as proposed by Liang et al. (2020).

Step 1: *Create a list of selection criteria.*

To make a decision, the criteria $(C_1, C_2, \cdots, C_n)$ must be identified. According to these criteria, the alternatives' performance is assessed.

The list of selection criteria is composed with the help of expert interviews in which we ask them about their most important criteria for supplier selection and their most important key performance indicators. This is further elaborated in Chapter 5.

Step 2: *Select the best and the worst criteria to apply to the decision-making process.*

The most important, most favored, or most desirable criterion is the best, while the least important, least favored, or least important criterion is the worst. In this case, only the criteria themselves—not their values—are considered.

Step 3: *Determine which criterion is preferred over all others.*

For this value, a number between 1 and 9 is used. The Best-to-Others vector that would result would be:

$$A_B = (a_{B1}, a_{B2}, \cdots, a_{Bn}),$$

(1)

where, a_{Bj} indicates the preference of the best criterion B over criterion j.

Step 4: *Determine the preference of each of the other criteria over the worst criterion.*

A number between 1 and 9 is assigned in this case as well. The Others-to-Worst vector would be:

$$A_W = (a_{1W}, a_{2W}, \cdots, a_{nW})^T,$$

(2)

The values for step 2, 3, and 4 are gathered through a survey specifically made for making supply chain professionals rank and give their preferences for supplier selection criteria and KPIs.

Step 5: *Find the optimal weights.*

To determine the optimal weights of the criteria, the maximum absolute differences $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j should be minimized. This can be formulated as follows (Rezaei, 2016):

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$$
$$\text{s.t.}$$
$$\sum_j w_j = 1,$$
$$w_j \geq 0, \text{for all } j$$

(3)

This can be solved by transferring it to the following linear programming formulation:

$$\min \xi^L$$
$$\text{s.t.}$$
$$|w_B - a_{Bj}w_j| \leq \xi^L, \text{for all } j$$
$$|w_j - a_{jW}w_W| \leq \xi^L, \text{for all } j$$
$$\sum_j w_j = 1$$
$$w_j \geq 0, \text{for all } j$$

(4)

Problem ***(4)*** is linear and has a unique solution. By solving this problem, the optimal weights $(w^*{}_1, w^*{}_2, \cdots, w^*{}_n,)$ and the optimal value of ξ^L, called $\xi^{L*}$are obtained. ξ^{L*} is defined as the consistency ratio of the comparison system. The consistency ratio means that the closer ξ^{L*} is to a zero value, the more consistent the decision-maker(s) provides the comparison system. Using BWM, the optimal weights of the criteria, w_j^* , are obtained. With these weights and the normalized scores of the alternatives on the different criteria for different materials, x_{ijk}^{norm}, the final score per alternative for material k, V_{ik} can be calculated using expression ***(5)****:*

$$V_{ik} = \sum_{j=1}^{n} w_j x_{ijk}^{norm}$$

Where,

$$x_{ijk}^{norm} = \begin{cases} \dfrac{x_{ijk}}{\max\{x_{ijk}\}}, \text{if } x \text{ is positive (such as quality),} \\ 1 - \dfrac{x_{ijk}}{\max\{x_{ijk}\}}, \text{if } x \text{ is negative (such as price)} \end{cases}$$

(5)

According to ***(5)****,* a final overall score is obtained for each supplier; however, since we only have one type of raw material in this study, a third phase to correct for the variation in the importance of different raw materials is unnecessary. This phase is typically useful when suppliers can supply multiple materials, but it does not apply to our case. Therefore, the final score obtained for each supplier can be directly used to select the optimal supply base without needing an aggregation phase to integrate material importance and adjust the rank.

Step 6: *Check for input-based consistency.*

The Input-Based Consistency Ratio directly measures the consistency of a decision-maker's (DM) preferences based on the initial input provided. This approach eliminates the need for a full optimization process.

The Input-Based Consistency Ratio (CR^I) is calculated according to Liang et al. (2020) as follows:

$$CR^I = \max_j CR_j^I$$

(6)

Where,

$$CR_j^I = \begin{cases} \dfrac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1 \\ 0 & a_{BW} = 1 \end{cases}$$

(7)

CR^I is the global input-based consistency ratio for all criteria, CR_j^I represents the local consistency level associated with criterion C_j (Liang et al., 2020).

By using the consistency thresholds in table 4.1, as defined by Liang et al. (2020), we can check whether or not the consistency of the DM is acceptable. CR^I now has a meaningful interpretation because we can determine whether the ratio is acceptable before solving the optimization program.

Table 4.1*: Thresholds for different combinations using input-based consistency measurement (Liang et al., 2020)*

	Criteria						
Scales	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667
4	0,1121	0,1529	0,1898	0,2206	0,2527	0,2577	0,2683
5	0,1354	0,1994	0,2306	0,2546	0,2716	0,2844	0,2960
6	0,1330	0,1990	0,2643	0,3044	0,3144	0,3221	0,3262
7	0,1294	0,2457	0,2819	0,3029	0,3144	0,3251	0,3403
8	0,1309	0,2521	0,2958	0,3154	0,3408	0,3620	0,3657
9	0,1359	0,2681	0,3062	0,3337	0,3517	0,3620	0,3662

5. System Identification

This chapter aims to fulfill the objectives of the first two sub-questions, focusing on identifying polymer supply chains and their challenges, risks, and risk mitigation strategies. Understanding the specific vulnerabilities and risks in the polymer supply chains is essential as these constitute potential points of disturbance and disruptions within the supply chain. Once these risks are identified, the next step involves exploring suitable mitigation strategies that can be adopted to manage these risks. This comprehensive exploration of risks and mitigation strategies sets the stage for the subsequent development of the simulation model in Chapter 6.

The findings result from a literature review and expert interviews with senior supply chain professionals working across diverse companies in the polymer industry. The experts are recruited through the client network of Deloitte's Supply Chain & Network Operations practice. The revenue of the companies we interview ranges from $1 billion to $600 billion. Four individuals have contributed, being a Global Supply Chain Director (12 years experience), a Logistics Operations & Procurement Director (15 years experience), a Supply Chain & Digitization Manager (16 years experience), and a Global Director of Supply Chain Network Management (17 years experience). Each interview took about one hour and was conducted via an online call. The interview included questions about the company's key processes and KPIs, supplier selection criteria, risk assessment practices, and risk mitigation practices. The detailed interview framework that is used is placed in Appendix A.

5.1 Introduction to Polymer Supply Chains

The polymer industry plays a vital role in various sectors of the global economy, ranging from packaging and automotive to construction and healthcare. Polymers, large molecules composed of repeating subunits, are essential materials that provide versatility, durability, and functionality to countless products. As the demand for polymer-based goods continues to grow, so does the complexity and global reach of the supply chains supporting the polymer industry (P&S Intelligence, 2022).

The polymer industry operates within a highly interconnected and globalized supply chain network, spanning multiple continents and involving numerous stakeholders, including raw material suppliers, manufacturers, distributors, and end-customers (ChemAnalyst, 2021). This extensive network facilitates the sourcing of raw materials, the production of polymers, and the distribution of finished products to markets worldwide.

The polymerization process is continuous, contributing to a steady and consistent flow of materials within the supply chain. This characteristic is crucial in the supply chain's dynamics and highlights the importance of efficient and reliable material handling and production processes. It is essential to recognize that polymers are not always the end product; they are often compounded to create a wide range of products with varying characteristics. This aspect adds complexity to the supply chain, as the polymers' transformation through compounding expands the diversity of end products and demands adaptable production and distribution strategies.

The polymerization sector is served by only a few major polymerizers globally (ChemAnalyst, 2021). This concentration of key players may influence the overall dynamics of the supply chain, affecting competition, pricing, and availability of raw materials. It underscores the significance of establishing strong supplier relationships and diversifying the supplier base to ensure supply chain performance.

Polymers' high versatility allows for their transformation into various products through compounding. This versatility adds intricacy to the supply chain, extending the range of potential end products and necessitating production planning and material handling flexibility. Adapting to these diverse product variations requires proactive supply chain strategies and robust risk management approaches.

The global nature of the polymer industry's supply chains presents both opportunities and challenges. On the one hand, it allows for access to diverse markets, enables cost-effective production through economies of scale, and facilitates the exchange of knowledge and technology across borders. On the other hand, it introduces risks and complexities associated with managing a complex network of suppliers, navigating international regulations, and mitigating disturbances and disruptions that can impact the flow of materials and products.

5.2 Supply Chain Landscape

The interviews with industry experts enabled us to discover the polymer supply chains in more detail. The polymerization supply chain transforms raw materials, such as petroleum-based feedstocks or sustainable alternatives, into a wide range of polymers and polymer-based products. This subchapter provides an overview of the key stages of the polymerization supply chain, from raw material sourcing to product customization based on customer requirements, ultimately reaching the end customers.

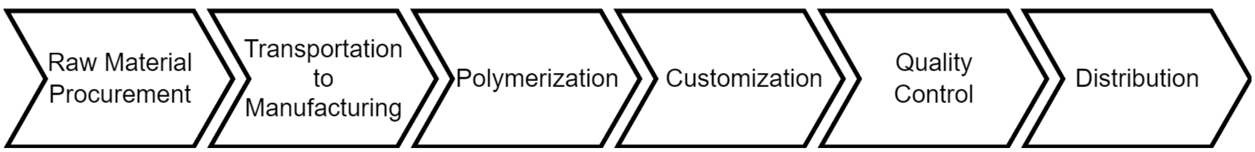


Figure 5.1: *Typical polymer supply chain*

Raw Material Procurement

The polymerization supply chain begins with procuring raw materials, primarily oil-based feedstocks or sustainable alternatives. These raw materials are sourced from various suppliers, including oil refineries or bio-based material producers, depending on the specific feedstock used. The availability and quality of raw materials are critical factors in ensuring a reliable supply chain.

Transportation to Manufacturing Plants

Once the raw materials are procured, they are transported to manufacturing plants, where polymerization takes place. Transportation methods can vary, including pipelines, tankers, or other modes of bulk transportation, depending on the location and logistics of the manufacturing facilities. Efficient transportation networks ensure timely and cost-effective delivery of raw materials to production sites.

Polymerization Process: The raw materials undergo the polymerization process at the manufacturing plants, which involves chemical reactions that transform the monomers into polymers. This process can be carried out through different techniques, such as addition polymerization or condensation polymerization, depending on the desired properties of the end product. The polymerization process requires precise control of temperature, pressure, and reaction conditions to ensure consistent quality and desired polymer characteristics.

Processing for Customization

The polymers may undergo additional processing steps following the polymerization process to meet specific customer requirements. This can include compounding the polymers with additives or modifiers to enhance their properties or further processing them into specific compounds or parts. The customization process aims to create polymers that align with the desired performance attributes requested by the end customers.

Quality Control and Testing

Stringent quality control measures are implemented throughout the polymer supply chain to ensure that the produced polymers meet the required specifications and adhere to industry standards. Quality control involves rigorous testing, analysis, and inspection of the polymers to verify properties such as molecular weight, tensile strength, thermal stability, and other relevant characteristics. These quality control measures are crucial to maintain product consistency and reliability.

Product Distribution to End Customers

Once the polymers are processed and meet the required quality standards, they are distributed to end customers using them in various applications. The end customers can range from manufacturers in industries such as automotive, packaging, construction, textiles, and many others. These customers rely on polymers to produce finished products, incorporating them into their manufacturing processes.

5.3 Key Performance Indicators and Supplier Selection Criteria

In the interviews with industry experts, we asked them about their key performance indicators (KPIs) for measuring their supply chain performance and the criteria used for assessing supplier performance. This step can be identified as the screening (pre-selection) part, followed by performing the BWM to develop the ranking in Chapter 7.

5.3.1 Key Performance Indicators

The interviews identified the following key performance indicators (KPIs) used to measure supply chain performance within the polymer industry:

Table 5.1: *KPIs identified by interviewees*

KPI	Definition
Supply chain reliability	This KPI reflects the ability to consistently and reliably deliver materials and products to customers on time. It measures the effectiveness of supply chain processes in ensuring a timely and uninterrupted flow of goods.
Working capital	This metric evaluates the efficiency of financial resources invested in the supply chain operations. It provides insights into the organization's ability to manage cash flow, optimize inventory levels, and balance financial obligations within the supply chain.
On-Time In-Full delivery	This KPI measures the percentage of customer orders successfully fulfilled on time. It reflects the organization's ability to meet customer demand and deliver products as promised, contributing to customer satisfaction and loyalty.
Total cost	The sum of logistics and manufacturing costs is an important KPI that helps monitor and optimize cost efficiency in supply chain operations. It encompasses various cost elements, including transportation, warehousing, inventory holding, and production expenses.
Inventory levels	Inventory levels represent the quantity of raw materials, work-in-progress, and finished goods an organization holds. They are crucial to maintaining adequate stock levels to meet customer demand while minimizing excess inventory and associated carrying costs.
Net profit	Net profit measures the organization's financial performance by subtracting total expenses from total revenue. It provides a comprehensive view of the profitability of the supply chain operations, considering various cost components and revenue streams.

5.3.2 Supplier Selection Criteria

Supplier selection is the formal procedure employed by businesses to identify, evaluate, and engage with potential suppliers. The process of selecting suppliers is a resource-intensive activity for companies and plays a crucial role in the overall success of businesses. The main objective of supplier selection is to mitigate purchasing risk, optimize overall value for the buyer, and develop close and enduring relationships between buyers and suppliers (Taherdoost & Brard, 2019; Rezaei et al., 2016). Selecting suppliers is commonly conducted by establishing supplier criteria and assessing them using various evaluation methods, such as multi-criteria decision-making. The initial presentation in Table 5.2 highlights the supplier selection criteria identified as the most commonly mentioned in existing academic literature. A more extensive examination of the papers in which the criteria are identified is provided in Appendix C.

***Table 5.2**: Supplier selection criteria in the literature*

Criteria	# of papers	Definition
Quality	15	The supplier's ability to consistently meet quality standards such as quality features (material, dimensions, design, and durability), variety, production quality (production lines, manufacturing procedures, machinery), quality system, and continual improvement (Taticchi et al., 2014).
Price	6	The price criteria are unit price, pricing terms, exchange rates, taxes, and discounts.
Delivery	7	The supplier's ability to satisfy specified delivery schedules such as lead-time, on-time performance, fill rate, returns management, location, transportation, and incoterms.
Production capacity	4	The number of products or services that a supplier can generate utilizing present resources.
Supplier’s profile	4	The state, prior performance, finance, certificates, and references of the supplier's excellence and reputability.
Service	4	The supplier's capacity to deliver intangible items, such as customization (size, shape, color, design, OEM, label service), minimum order quantity, communication (react time, information, language), industry expertise, flexibility, and responsiveness to change.
Technology and capability	7	A supplier's technological aptitude and ability to acquire new technologies and technical resources for R&D techniques and processes.

The supplier selection criteria identified through interviews in the polymerization supply chain align with the criteria found in the existing literature on supplier selection. These criteria play a crucial role in evaluating and selecting suppliers that best meet the needs of the supply chain, considering a supply chain experiencing disturbances and disruptions. This process identified the following key criteria as essential considerations for supplier selection, which we can also quantify, as shown in Table 5.3:

***Table 5.3**: Selected supplier selection criteria*

Criterion	Definition
Quality of Materials	The quality of materials suppliers provide is of utmost importance in the polymerization supply chain. Ensuring the consistent quality of raw materials and polymers is vital to meet the required product specifications and maintain the desired performance attributes. Suppliers with a track record of delivering high-quality materials are preferred to mitigate the risk of product defects or inconsistencies.
Reliability of Supply	Reliability of supply is another critical criterion in supplier selection. Consistent and timely delivery of raw materials and polymers is essential to avoid disruptions in the production process and maintain a smooth supply chain flow. Suppliers with a proven ability to meet delivery schedules and manage inventory levels effectively are valued for their reliability.
Price	Price is a significant consideration in supplier selection, as it directly impacts the overall cost structure of the polymerization supply chain. Balancing competitive pricing with the desired quality standards is crucial to achieving cost-effectiveness without compromising on material performance. Suppliers offering competitive pricing that aligns with the market rates are often preferred, provided they meet the other selection criteria.
Lead Times	Lead times are critical in the polymerization supply chain, referring to the time required for suppliers to deliver materials after an order is placed. Efficient lead times ensure the timely availability of materials, allowing for smooth production planning and minimizing production delays. Suppliers consistently meeting or exceeding lead time expectations are considered advantageous in maintaining an efficient supply chain.

The findings from the interviews conducted with industry experts in the polymerization supply chain highlight that companies do not always follow a highly structured process for supplier selection. Instead, they clearly understand their criteria, often assigning importance to them and assessing suppliers based on these criteria. However, a systematic approach such as a multi-criteria decision-making (MCDM) method is not commonly employed.

This insight is consistent with the interviews, which revealed that organizations rely on their experience and knowledge to evaluate and select suppliers. While they recognize the importance of supplier selection criteria, the process tends to be more intuitive and based on their judgment.

The alignment between the identified supplier selection criteria in the interviews and those in the literature demonstrates a common understanding of the key factors influencing supplier evaluation and selection. The criteria identified in the interviews, including quality of materials, reliability of supply, price, and lead times, are consistent with the literature on supplier selection in the broader context of supply chain management.

5.4 Disturbance and Disruption Risks

This subchapter delves into the nuances of disturbance and disruption risks in the supply chain, elucidating their identification and categorization.

5.4.1 Identification of Disturbances and Disruptions

We employed a two-pronged methodology to comprehensively understand the inherent vulnerabilities in the supply chain, integrating academic research with industry insights. Our initial investigation drew from existing literature, offering a thorough overview of typical supply chain disruptions. Mackay et al. (2019) significantly influenced our exploration with their disruption taxonomy, categorizing disruptions into supply-side, demand-side, and intra-organizational segments. The categorizations mentioned in the expert interviews align with the empirical discoveries of Elvira et al. (2015), who identified similar factors that contribute to disruption within various American industrial sectors.

We conducted expert interviews to gain comprehensive and relevant knowledge based on empirical evidence, guided by the structured interview framework outlined in Appendix A. The conducted interviews provided a nuanced viewpoint, offering clarification on the specific practical obstacles encountered within the supply chain.

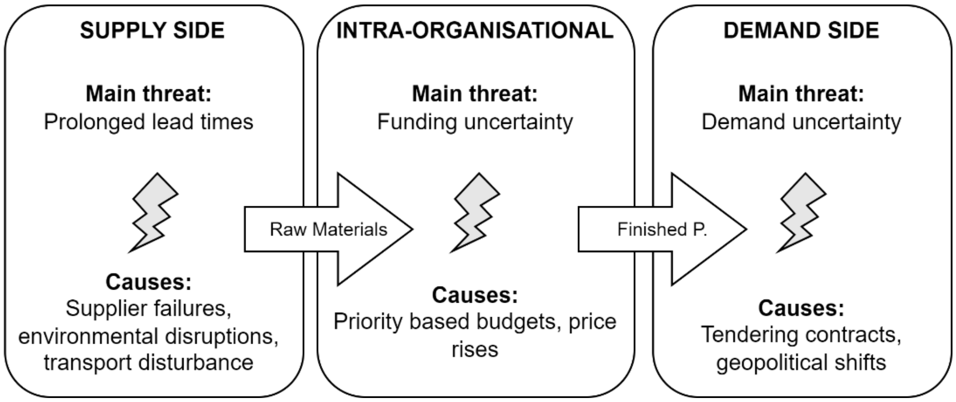


***Figure 5.2**: Disturbances and disruptions in the supply chain and their origins, adopted from Mackay et al. (2019)*

From a supply-side perspective, extended lead times present a significant concern. These prolonged durations can deplete internal and safety inventory reserves without careful management, leading to operational challenges. The interviews offered vital qualitative insights, emphasizing unanticipated shifts driven by external elements such as environmental uncertainties and the variable reliability of maritime logistics. Nonetheless, a silver lining emerged. Interviewees suggested that companies can effectively mitigate these disruptions by strategically choosing suppliers and thoroughly understanding their shortcomings. For more details on methods to address these supply-side risks, refer to Subchapter 5.5.

Upon delving into the realm of intra-organizational dynamics, a notable emergence of administrative dilemmas became apparent. The irregular and unpredictable distribution of funds, specifically designated for efforts to mitigate risks, emerged as a recurring topic in academic research and industry anecdotes. This highlighted the inherent difficulties linked to financial allocation for surplus providers and the complexities of internal administrative coordination.

The demand-side analysis highlights the inherent unpredictability of demand. As highlighted through interviews, the unpredictable fluctuation of demand revealed various obstacles. These challenges include the need for flexible production scalability to meet contractual requirements and the ever-changing impact of geopolitical factors on demand. The consequences of the COVID-19 pandemic served as a clear example of the unpredictable nature of demand, highlighting the urgent challenges that arise during periods of global disruption.

This research aims to comprehensively analyze the disturbances and disruptions encountered in the supply chain by combining academic research with industrial insights. The first step involves identifying and diagnosing these difficulties. However, effectively addressing them will require a comprehensive strategic approach that includes careful selection of suppliers, maintaining adequate safety stock reserves, and taking proactive measures to mitigate known vulnerabilities.

5.4.2 Categorization of Disturbances and Disruptions

This research distinguishes between 'disturbances' and 'disruptions' based on their origin, impact, and duration. Disturbances are typically short-term, often internal deviations that may not necessarily halt the supply chain but may affect its efficiency. On the other hand, disruptions are more severe, longer-lasting, and are caused by external factors, often leading to a stoppage in the supply chain or significant delays.

The identified supply-side disturbance and disruption risks are categorized using a risk classification matrix presented in Table 5.4. This matrix helps us discern between disturbances (short-term, low impact) and disruptions (longer-lasting, mid to high-impact) by classifying the risks into low- and high-probability and low- and high-impact supply-side risks.

***Table 5.4**: Classifying disturbances and disruptions*

RISK MATRIX	Probability	Impact	Description
DISTURBANCES			
Internal manufacturer failures	**LOW**	**LOW**	These failures can be seen as unplanned maintenance, occurring once a year with a relatively short duration.
Transportation delays	**HIGH**	**LOW**	Transportation delays are frequently experienced, but the decision-makers are aware of this risk and can often manage their planning accordingly.
DISRUPTIONS			
Supplier failures	**MID**	**MID**	These failures can occur once to multiple times a year and disable the supplier from delivering for a few weeks.
Environmental disruptions	**LOW**	**HIGH**	The impact of environmental disruptions is high, as it disables all suppliers in the affected region for a month or longer.

Internal Manufacturer Failures: This risk is classified as having a low probability and impact. It represents unplanned maintenance events that may occur once a year, and their duration is short. While these failures are infrequent and have limited consequences, it is essential to be prepared to address them promptly.

Transportation Delays: This risk is categorized as having a high probability but low impact. Transportation delays are frequently experienced in the supply chain, but decision-makers are aware of this risk and can manage their planning to mitigate its effects. Although it occurs frequently, the impact on the supply chain is limited.

Supplier Failures: This risk is assessed as having a medium probability and impact. Supplier failures can occur once to multiple times a year, resulting in disruptions that may last a few weeks. Managing such disruptions requires proactive supplier relationship management and contingency planning.

Environmental Disruptions: This risk is classified as having a low probability but high impact. Environmental disruptions, such as natural disasters or geopolitical shifts, can occur less frequently but have severe consequences. When they happen, all suppliers in the affected region are disabled for an extended period, significantly affecting the supply chain's continuity.

5.5 Risk Mitigation Strategies

Drawing from expert insights and existing literature, this chapter presents potential risk mitigation strategies to manage the identified and categorized disturbances and disruptions. Risk mitigation strategies are standardized practices designed to reduce potential risks. The successful implementation of these strategies requires the participation of all employees, both as executors and decision-makers (Afifa & Santoso, 2022). Strategies for mitigating supply chain risk can be either proactive or reactive, according to Ghadge et al. (2012).

Proactive strategies are centered on preventing risks before they materialize, necessitating preemptive measures. In contrast, reactive strategies involve addressing problems already arising and restoring normal operations in the face of risk-induced uncertainties (Wieland and Wallenburg, 2013). Depending on the degree of unpredictability within the supply chain, organizations may employ proactive or reactive strategies, or a combination of both, to effectively manage the situation. In our research, we make this distinction and define that we are looking into proactive strategies, which include redundancy- and flexibility-oriented strategies (Afifa & Santoso, 2022).

5.5.1 Redundancy Oriented Strategies

Redundancy represents the strategic employment of additional capacity and inventory, which can be used to manage crises such as supply deficits or demand surges (Kamalahmadi et al., 2022). Redundancy is often considered an intuitive approach to enhancing risk mitigation due to its ease of implementation. However, it is vital to apply it judiciously to maximize its potential advantages. Frequently, businesses resort to redundancy as a reactive measure, increasing stock for a specific item after a disruption caused by scarcity. This reactive approach contradicts the principles of Supply Chain Risk Management (SCRM), as it only addresses the symptoms rather than the root causes. As established in the literature review, SCRM should proactively identify and anticipate risk sources, targeting the disruption's origins rather than its repercussions.

Moreover, while effective in certain circumstances, redundancy comes at a significant cost and can potentially scale indefinitely. It is crucial to restrict redundancy to avoid unnecessary expenditure (Rice & Sheffi, 2005). It is worth noting that redundancy does not contribute to a system when no disruption transpires. Redundancy strategies are often viewed as a cost trade-off; supply chain managers must recognize when further investment fails to produce sufficient returns. In polymerization supply chains, for example, the cost of these strategies can be undervalued when a company’s delivery performance and reputation are at stake. Surplus asset investment can lead to inadvertent fixed-cost inflation (Ivanov et al., 2014). Consider, for instance, expanded internal inventory. Without increased demand, this inventory constitutes tied-up capital that might have been more impactful elsewhere in the organization. Thus, it is an essential strategy included in the mitigation policies for experimentation.

The study by Kamalahmadi et al. (2022) is consulted for a suitable redundancy strategy that could improve risk mitigation. They distinguish three types of redundancy strategies: pre-positioning inventory, which is similar to the above-discussed increased internal inventory; having a backup supplier pre-contracted, which can be engaged if the primary supplier fails, maintaining the goods flow; and protecting suppliers, which involves investing (potentially with other clients) in supplier safety and security to ensure operational continuity. These strategies can potentially improve business performance and mitigate the disruptive implications of uncertainty. In the context of this simulation study, a backup supplier and keeping additional stock in the form of safety inventory are selected as the representative redundancy strategies.

Reducing single-source situations is a challenge faced by organizations. Relying on a single source for critical materials or components increases vulnerability to disruptions. However, finding alternative sources or diversifying suppliers can be complex and may involve additional costs. The interviews revealed that organizations are actively working on reducing single-source situations by identifying alternative suppliers, assessing their capabilities, and establishing solid relationships to ensure a reliable and diversified supply base. The study also incorporates the use of safety stock as a redundancy strategy. Safety stock refers to the additional inventory maintained beyond the expected demand to serve as a buffer against uncertainties and disruptions. By keeping different extra stock levels, the organization can ensure a sufficient supply of materials even during supply deficits or demand surges. Safety stock level is determined based on lead times, demand variability, and desired service levels. This strategy provides a cushion to absorb fluctuations in supply and demand, enhancing the delivery performance of the supply chain.

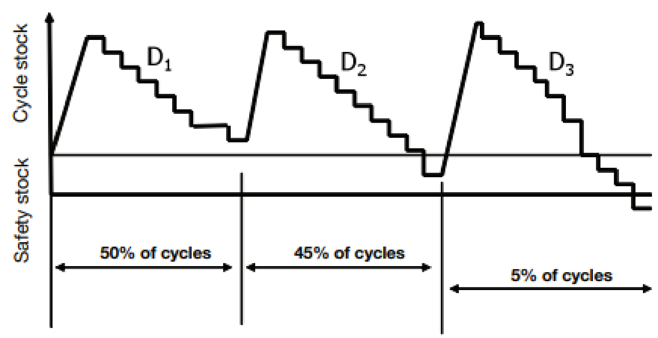


Figure 5.3: *Inventory designed for a 95 percent service level, adopted from (King, 2011)*

The method with which the level of safety inventory is defined in the industry is an essential highlight from the interviews. While some companies make use of a systematic approach based on a formula, which is expressed as: $Safety\ stock = Z \times \sigma_{LT} \times D_{avg}$. In which *"Z"* is the Z-score, sometimes referred to as the standard score in statistics. According to statistical analysis, carrying additional inventory equivalent to 1,65 standard deviations of demand variability is essential to supply demand with a 95% confidence level. This corresponds to a 1,65 Z-score. *"σ_{LT}"* represents the standard deviation of the lead time, and "D_{avg}" represents the average amount of demand within a given period. The companies that do not use this method define their safety stock level by looking at the maximum amount of time their supply chain has experienced a disruption and keep the amount of safety inventory for the expected demand during this period in case of a disruption. This practice, however, can lead to the storage of unnecessary stock, representing a potential area for improvement. Adopting a more systematic, cost-focused approach to managing safety stocks could strike a more effective balance between risk mitigation and cost efficiency.

5.5.2 Flexibility-Oriented Strategy

Kamalahmadi et al. (2022) state, "Flexibility refers to a firm's ability to respond to long-term or fundamental changes in the supply chain and market environment by adjusting the configuration of the supply chain." Flexible supply chains can exercise alternatives more swiftly than competitors in uncertain marketplaces. According to Dominik et al. (2015), these market changes can result from various changes, including those in the environment, demand and supply dynamics, technology, and (geo-) politics. In much of the recent literature, flexibility is crucial in strengthening a supply chain's risk mitigation potential (Pellegrino & Carbonara, 2017; Manuj & Metzer, 2008; Aldrighetti et al., 2021). According to Fang et al. (2012), a supply chain that can mitigate risks can be realized effectively and efficiently by integrating flexibility into system organizations. In addition, flexibility fosters risk mitigation by enhancing adaptability in uncertain circumstances. However, flexibility has a downside because it has a price and is frequently challenging to implement.

Furthermore, not every circumstance will result in an advantage. As a result, the supply chain's uncertainty level should be considered. Since it necessitates a "multi-skilled workforce, versatile equipment, multiple suppliers, or flexible contracts with suppliers" (Yang and Yang, 2009), it necessitates considerable capital investments. At some point, supply chain managers should weigh the high costs against the possible rewards to decide whether the investment is worthwhile (Shishodia et al., 2021; Sodhi & Tang, 2012).

Flexibility strategies work the opposite of redundancy strategies in the supply chain structure; they frequently try to lower buffers to reduce dependency in the form of sunk costs and search for ways structural change might improve the supply chain. Flexible supply chains can boost risk mitigation when implemented correctly and are typically more cost-effective (Ivanov, 2021).

There are several ways to increase flexibility, but in this research, volume flexibility will be the main focus. The strategy works as follows. Firstly, the manufacturer is given the flexibility to choose between two or all three suppliers, providing the opportunity to diversify sourcing and reduce dependency on a single supplier. Secondly, the replenishment amount is split equally among the contracted suppliers when opting for a flexibility-oriented strategy. For instance, in the case of three suppliers, the replenishment orders are divided into three equal portions, ensuring a fair distribution of orders among the suppliers. Finally, in the event of a disruption occurring at one or more of the contracted suppliers, the manufacturer evaluates the status of the available suppliers. If any of the suppliers are operational, the manufacturer sources the raw materials from the non-disrupted supplier(s). The sourcing decision is based on the first supplier that becomes available, ensuring a seamless continuation of the replenishment process and mitigating the impact of the disruption.

6. Model Development

This chapter is devoted to developing the Discrete Event Simulation (DES) model, the cornerstone of this research project. It outlines translating the identified supply chain system, disturbances and disruptions, and corresponding mitigation strategies into a computational model. This DES allows us to simulate different disturbances and disruptions and analyze the efficacy of redundancy- and flexibility-oriented mitigation strategies.

By integrating expert insights with principles of DES, this chapter provides a blueprint of how the supply chain operates under normal conditions, introduces disturbances and disruptions, and how the system responds to these threats based on the applied mitigation strategies.

6.1 Conceptual Model

In this subchapter, we introduce the conceptual model based on the system identification in Chapter 5. The conceptual model will guide the further development of our simulation model.

6.1.1 Defining the Elements of the Model

The conceptual model in Figure 6.1 is a virtual representation of the supply chain system. It encompasses various entities, interactions, and processes in the supply chain, allowing for evaluating and analyzing different scenarios and strategies.

The model captures the dynamic nature of the supply chain by simulating the movement of materials, goods, and information across different stages of the production and distribution process. It incorporates key elements such as the suppliers, the manufacturer's raw material, and the finished product inventory and how these elements interact.

The model considers the interdependencies and interactions between these entities, allowing for examining their impact on overall supply chain performance. It considers factors like lead times, order quantities, production capacities, and supplier reliability to simulate the flow of materials and the fulfillment of customer demand.

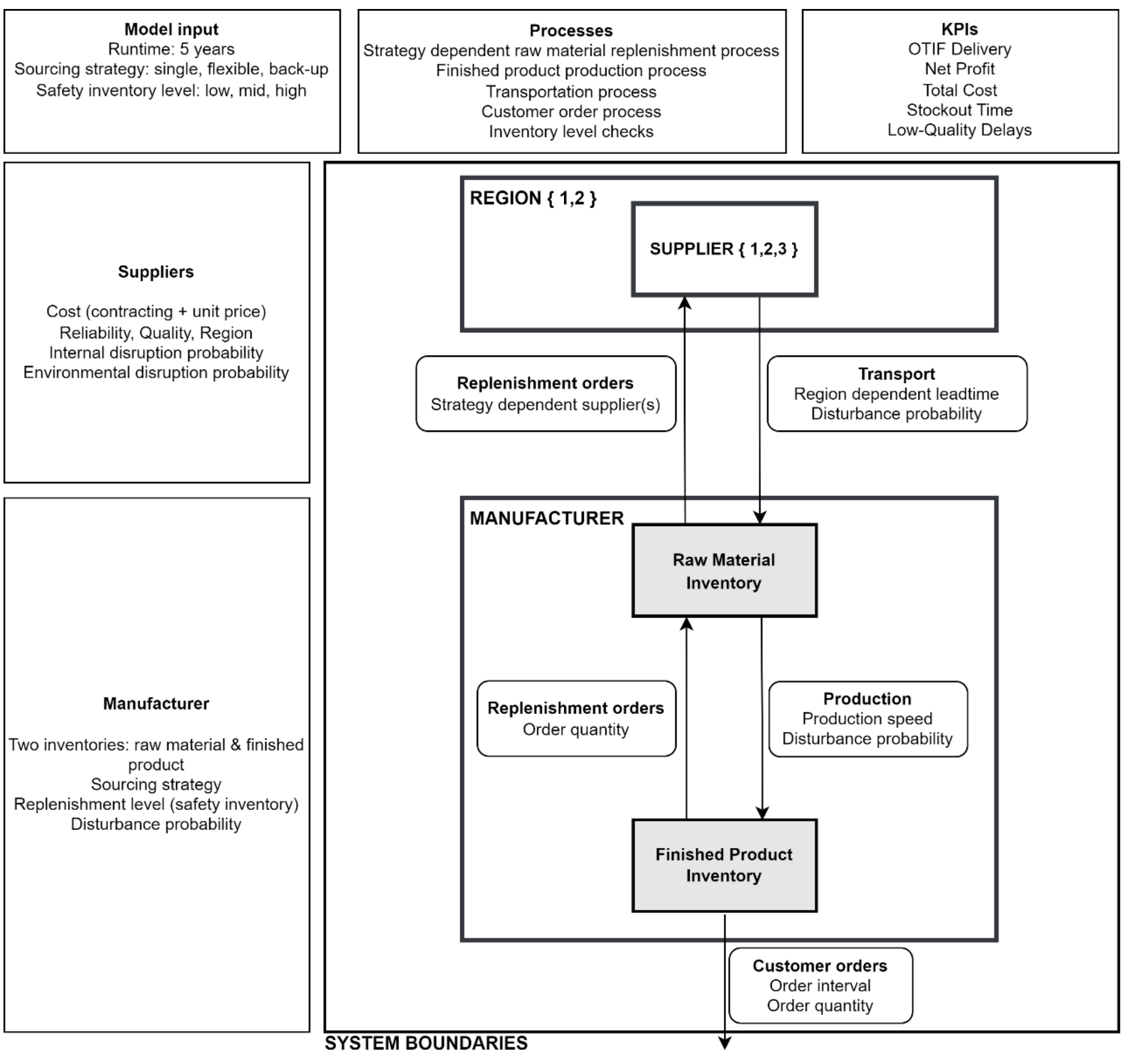


***Figure 6.1**: High-level conceptualization of the system*

6.1.2 Modeling Processes and Interactions

We have conceptualized the processes used in our simulation model. These encompass the various raw material replenishment sourcing processes, the finished product replenishment and production process, the inventory level check process, the customer order process, the transportation process, and the disruption and disturbance processes. To make the best use of space in the primary text and offer a streamlined depiction of process conceptualization, we display only the backup supplier sourcing strategy in this subchapter, as illustrated in Figure 6.2. We detail the other processes in Appendix D.

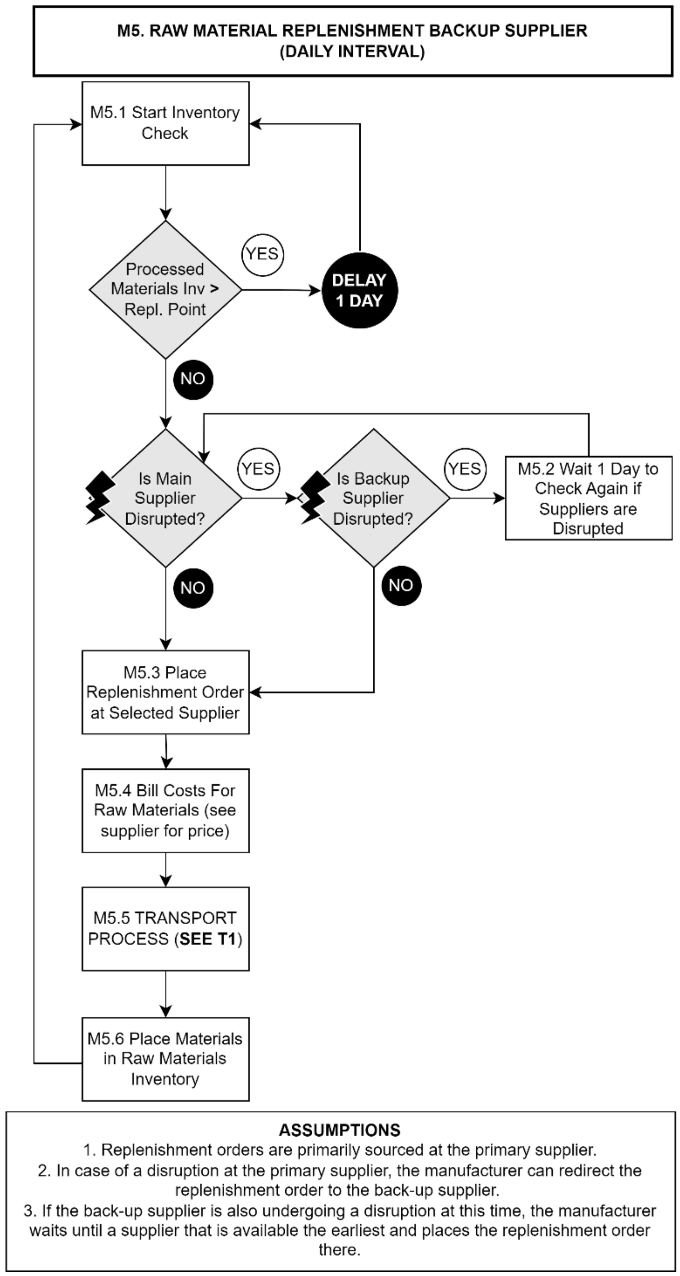


Figure 6.2: *Conceptual view of the back-up supplier sourcing strategy*

6.2 System Definition

This subchapter comprehensively overviews the supply chain system's key components and characteristics. The system comprises the manufacturer, suppliers, and transportation entities, all of which play critical roles in the overall functioning of the supply chain.

The Manufacturer is responsible for converting raw materials into finished products through a production process with a defined production time. However, disturbances affect the production process, which we can view as unplanned maintenance temporarily preventing the manufacturer from processing raw materials into finished products.

Both raw materials and finished products are held in stock and are replenished based on a predetermined replenishment point. The manufacturer maintains cycle stock to meet regular demand and keeps extra inventory as safety stock to mitigate potential disruptions.

Moreover, the manufacturer replenishes raw materials from different suppliers using various sourcing strategies, which Subchapter 6.4 will further elaborate on. The sourcing strategies include backup options and flexible supply, enabling the manufacturer to adapt to changing supply chain conditions.

Assumption M.1: The manufacturer has two inventories, one with raw materials and one with finished products.
Assumption M.2: Only the manufacturer can produce finished products from raw materials, and can only source raw materials from its supplier(s).
Assumption M.3: The replenishment and replenish up to points are defined in the beginning of the run through the safety inventory level input variable.
Assumption M.4: There is a fixed cost per unit that the manufacturer has to pay for storing raw materials and finished products.
Assumption M.5: The manufacturer can keep different pre-defined levels of safety stock to mitigate supply-sided risks.
Assumption M.6: The manufacturer can make use of all combinations of sourcing strategies, from single sourcing to flexible sourcing from 2/3 suppliers, to maintaining a back-up supplier.
Assumption M.7: Based on the suppliers that are contracted, the manufacturer pays contracting costs and a cost per unit of replenished raw material.
Assumption M.8: The production process can be disturbed which results in unplanned maintenance. This results in the manufacturer not being able to replenish its finished products for some time.
Assumption M.9: There is a trade-off between contracting more costly and reliable suppliers, and contracting less costly and less reliable suppliers and keeping a higher level of safety stock.

Customer orders are received weekly. If a sufficient inventory of finished products exists, we fulfill the orders and move the requested amount out of the system. However, if there is insufficient inventory, the customer order is considered a failed order and is not placed on backorder.

Assumption C.1: The interarrival time of customer orders is determined with a Poisson distribution.
Assumption C.2: Every customer order quantity is determined with a Poisson distribution and does not increase during the run.
Assumption C.3: Customer orders are not put in backorder. If there is insufficient inventory of finished product the order counts as failed. A failed order results in the manufacturer having to pay a fine to the customer for non-fulfilment.
Assumption C.4: If there is a sufficient amount of finished product in the manufacturer's inventory, the order amount is removed from the system and the order is successful.
Assumption C.5: The customer pays the manufacturer a fixed price per unit of finished product.

In the system, the manufacturer can choose from **three suppliers** based on the predetermined replenishment strategy**.** Each supplier has characteristics related to the quality of materials, supply reliability, price, and lead times.

Supplier 1 is located in Europe and offers materials of the highest quality. They exhibit high supply reliability, but this comes at a higher price. However, Supplier 1 compensates for the price premium by providing shorter lead times.

On the other hand, Suppliers 2 and 3 are both located in Asia. Supplier 2 offers materials of intermediate quality and demonstrates moderate supply reliability and lead times. The price charged by Supplier 2 is also at an intermediate level. Supplier 3 provides relatively lower-quality materials with lower supply reliability and longer lead times.

However, the price of materials from Supplier 3 is comparatively lower. We should note that these are relative indications for the parameters and that all suppliers meet the minimum requirements to have a role as raw material suppliers in the supply chain. Table 6.1 presents the supplier profiles.

***Table 6.1**: Supplier profiles*

Criteria \ Supplier	Supplier 1 (Europe)	Supplier 2 (Asia)	Supplier 3 (Asia)
Quality of materials	High	Intermediate	Low
Reliability of supply	High	Intermediate	Low
Price	High	Intermediate	Low
Lead time	Low	High	High

Assumption S.1: A supplier has two states, a state in which it is available and can deliver raw materials to the manufacturer, and a state in which it is disrupted and cannot deliver anything.
Assumption S.2: Suppliers have infinite inventory of 1 type of material, which is raw material.
Assumption S.3: Each of the 3 suppliers have their own properties for contract costs, cost per unit of raw material, disruption frequency and duration, quality of materials, and lead time.
Assumption S.4: A supplier in Europe is more reliable and costly then the suppliers located in Asia.
Assumption S.5: There is a trade-off between keeping more reliable and costly suppliers and keeping less reliable and less costly suppliers.

Transportation is vital in the supply chain, particularly in moving raw materials between the manufacturer and suppliers. The lead times for transportation vary depending on the supplier's location. Supplier 1, located in Europe, benefits from a shorter lead time for transportation, contributing to faster delivery of raw materials. On the other hand, Suppliers 2 and 3, located in the same region in Asia, have longer lead times for transportation. However, disturbances can occur in transportation, leading to longer lead times. It is worth noting that the probability of disturbances in transportation is higher for Suppliers 2 and 3 than for Supplier 1.

Assumption T.1: The lead time for suppliers located in Asia is longer than the supplier in Europe.
Assumption T.2: The probability of a disturbance occurring during transport which increases the transportation duration is higher for shipments from Asia.
Assumption T.3: There is no fixed or variable cost for transportation.
Assumption T.4: Transportation only takes place from the suppliers to the manufacturer.

Environmental disruptions can occur at the suppliers within their respective regions, impacting their ability to deliver raw materials to the manufacturer for an extended period. These disruptions are characterized by temporary unavailability of supplies. Notably, the intervals between environmental disruptions occurring differ based on the supplier's location. The supplier in Europe (Supplier 1) has longer intervals between environmental disruptions compared to the suppliers located in the same region in Asia (Suppliers 2 and 3).

Assumption ED.1: Environmental disruptions can occur in both regions (Asia and Europe).
Assumption ED.2: When an environmental disruptions occurs, it disrupts all suppliers in the specific region.
Assumption ED.3: The frequency of environmental disruptions is low, but the impact high.
Assumption ED.4: The probability of an environmental disruption occurring in Asia is higher than in Europe.

We understand the system's components and characteristics by describing the model's manufacturer, suppliers, transport, and environmental disruptions. This information forms the basis for the subsequent development of the Discrete Event Simulation (DES) model, allowing us to analyze the effects of disruptions and evaluate the effectiveness of risk mitigation strategies on the overall supply chain performance.

6.3 Measuring Performance

Within this section, we delineate the Key Performance Indicators (KPIs) utilized to assess the performance of the supply chain system in the simulation model. The derivation of these KPIs stems from insights gathered through expert interviews in Subchapter 5.3, ensuring that they are both relevant to industry priorities and aligned with our research objectives.

Table 6.2*: Key performance indicators in the simulation model*

KPI	Definition
$\boldsymbol{OTIF}$: On-Time In-Full Delivery	Measures the percentage of customer orders delivered in full and on time. It indicates the system's ability to meet customer demand and fulfill orders within the expected timeframe. A higher OTIF Delivery percentage signifies a more reliable and efficient supply chain operation, while a lower percentage indicates potential disruptions or delays in order fulfillment.
$\boldsymbol{NP}$: Net Profit	Measures the system's financial performance by calculating the revenue generated from customer orders minus the costs incurred. It provides insights into the profitability and sustainability of the supply chain. Maximizing net profit is a common objective for organizations, as it ensures business viability and growth.
$\boldsymbol{C_{total}}$ *:* Total Costs	Represents the sum of the costs associated with the supply chain, including contracting costs, replenishment costs, cost of fines for failed customer orders, and inventory holding costs. It encompasses both direct and indirect expenses. Managing total costs is crucial for optimizing profitability and ensuring competitiveness in the market. Monitoring and minimizing costs while maintaining operational efficiency is a key focus for supply chain management.
$\boldsymbol{T_{so}}$ *:* Stockout Time	Measures the duration the manufacturer experiences a shortage or depletion of inventory for finished products. It reflects the ability of the system to maintain adequate inventory levels and avoid stockouts. Minimizing stockout time is essential for meeting customer demand and preventing lost sales opportunities.
$\boldsymbol{LQ_d}$: Low-Quality Delays	Measure the instances when additional time is required in the production process when lower-quality materials are sourced from suppliers. It captures the impact of material quality on the overall production timeline. Delays due to low-quality materials can lead to decreased efficiency, increased costs, and potential failed customer orders. Monitoring and minimizing low-quality delays are critical for maintaining smooth operations and achieving timely order fulfillment.

6.4 Risk Mitigation Strategies

In this subchapter, we discuss the logic of the risk mitigation strategies used in the simulation model. Appendix D presents the detailed conceptualization of the different sourcing strategies with their respective assumptions.

6.4.1 Redundancy-oriented Strategies

In the simulation model, redundancy-oriented strategies include the backup sourcing strategy, which offers an alternate supply during main supplier disruptions, and the safety stock mitigation strategy, which uses extra inventory as a buffer against supplier disruptions.

6.4.1.1 Backup Sourcing Strategy

The backup sourcing strategy aims to provide an alternative supply source in the event of disruptions the main supplier faces. The model examines three suppliers and integrates all potential combinations with these suppliers into the backup sourcing strategy.

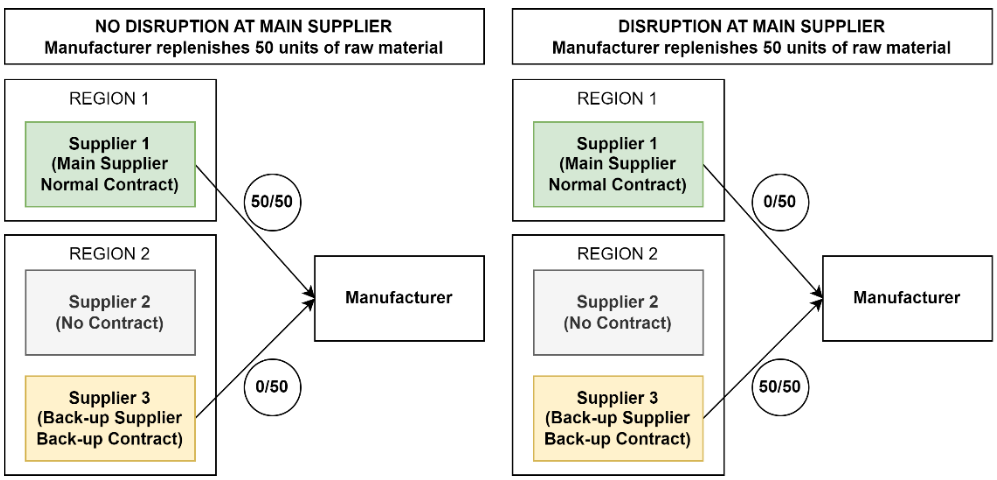


Figure 6.3: *Back-up supplier logic*

The strategy operates as follows:

1. Main Supplier: The manufacturer replenishes raw materials from the main supplier under normal circumstances when the supplier is not undergoing any disruptions.
2. Backup Supplier: If the main supplier experiences a disruption, the manufacturer checks if the backup supplier is operational. If the backup supplier is available, the manufacturer replenishes the entire order from the backup supplier.
3. Dual Disruption: In cases where the main and backup suppliers are undergoing disruptions, the manufacturer waits until one of the two suppliers becomes operational again. After identifying an operational supplier, the manufacturer procures the necessary raw materials exclusively from the stated supplier.

Assumption BS.1: The manufacturer can contract one main supplier and one back-up supplier simultaneously.
Assumption BS.2: Maintaining a back-up supplier has fixed contracting costs per year, independent of a disruption taking place at the main supplier or not.
Assumption BS.3: In case of a disruption at both the main and back-up supplier, replenishment takes place from the manufacturer that is first repaired again.

6.4.1.2 Safety Stock Mitigation Strategy

The safety stock mitigation strategy aims to mitigate the risk of supplier disruptions by maintaining additional inventory as a buffer. The simulation model assigns three safety stock levels to every possible sourcing strategy: low, mid, and high. The higher the safety stock level, the more inventory the manufacturer holds for potential disruptions.

The manufacturer establishes varying replenishment points to effectively implement an increased safety stock level. This method ensures that the manufacturer sustains increased inventory, which is utilized to fulfill demand in the event of supplier disruptions. However, it is essential to recognize that keeping extra inventory in the form of safety stock incurs additional costs.

The manufacturer assesses the inventory level daily and adds a cost associated with carrying extra inventory. This cost reflects the tradeoff between holding higher safety stock levels to mitigate the risk of suppliers being unable to deliver and the financial burden of carrying excess inventory.

Assumption SS.1: The manufacturer prefers holding a low level of safety stock over a high level of safety stock.
Assumption SS.2: The manufacturer can only set the level of desired safety stock at the beginning of the run.
Assumption SS.3: Both the raw material and the finished product inventory keep the same amount of safety stock.

Figure 6.4 illustrates the manufacturer's dynamics of finished product inventory levels over time. The inventory level remains consistently above the defined safety stock level in a scenario without disturbances and disruptions. The manufacturer's capacity to replenish its finished product inventory promptly is due to its utilization of the raw materials in stock for production.

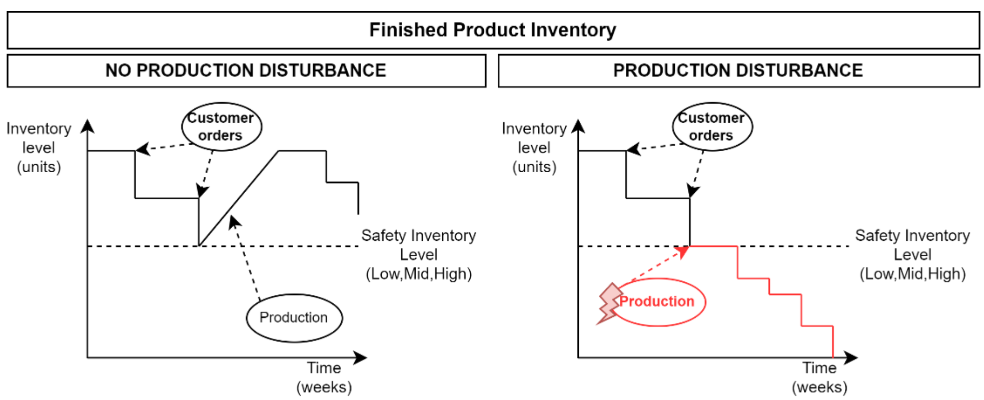


***Figure 6.4**: Illustration of the safety stock mitigation strategy for finished products*

However, when accounting for disturbances and disruptions, as shown on the right side of Figure 6.4, there are situations where the manufacturer encounters difficulties in producing new finished products. Unplanned maintenance or insufficient availability of raw materials are potential factors contributing to this situation. Consequently, the inventory level can decline to zero, leading to failed customer orders due to the inability to fulfill the demand. These disruptions directly impact the manufacturing process, interrupting the flow of finished products and causing temporary production constraints. The resulting inventory depletion poses significant challenges in meeting customer requirements and highlights the importance of effective risk management and mitigation strategies within the supply chain.

Figure 6.5 presents the raw material inventory levels at the manufacturer over time. Like the finished product inventory, the inventory level will not drop under the safety inventory level in a world without disturbances and disruptions, as the manufacturer will replenish its raw materials in time at its supplier(s). In the real world, suppliers can experience disruptions, which results in failed replenishment, or transport can be disturbed, which will consume its safety stock. If the inventory goes to 0, there are no raw materials for producing finished products.

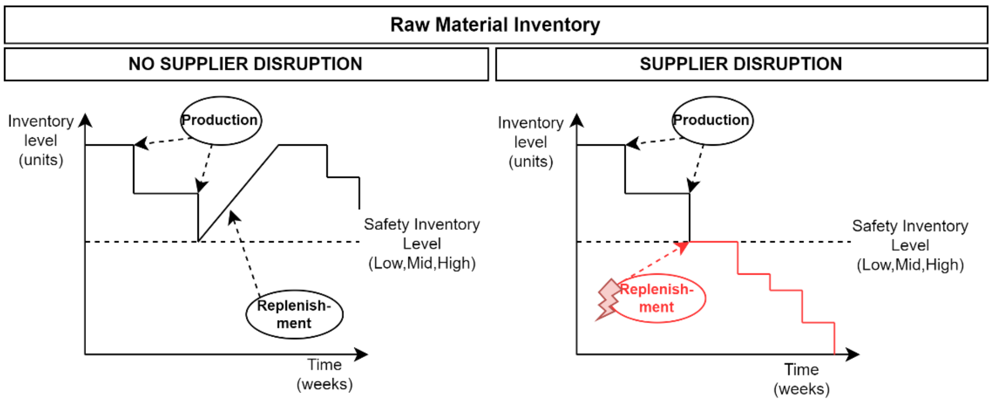


Figure 6.5*: Illustration of the safety stock mitigation strategy for raw materials*

The redundancy strategies implemented in the model involve various tradeoffs and carefully managed considerations. These tradeoffs include:

1. Cost of Contracting: Engaging more reliable suppliers, either as main or backup suppliers, often comes with a higher cost in terms of contracting. The manufacturer must balance the cost of engaging more reliable suppliers against the potential benefits of reduced disruptions and enhanced supply chain continuity.

2. Cost of Materials: Each supplier has their own price per unit for their raw materials. Similar to the contracting costs, engaging a more reliable supplier is also more expensive for the manufacturer. The goal is to discover the best combination of suppliers to mitigate disruptions while keeping the costs for raw material low.

3. Cost of Safety Stock: While safety stock mitigates the risk of supplier disruptions, it also incurs additional costs for the manufacturer. The decision to maintain higher safety stock levels must consider the financial implications and weigh them against the potential benefits of uninterrupted supply.

6.4.2 Flexibility-oriented Strategy

In the simulation model, the flexibility-oriented strategy encompasses the capability of a manufacturer to contract multiple suppliers dynamically. Figure 6.6 presents the logic of the flexible sourcing strategy.

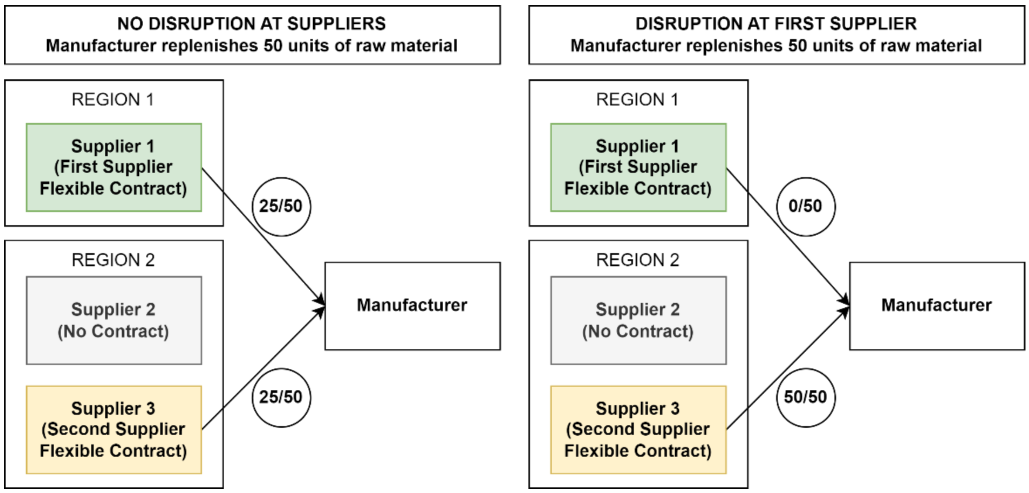


Figure 6.6: *Flexible sourcing logic*

The strategy operates as follows:

1. Supplier Options: The manufacturer can source raw materials from two or all three suppliers. This flexibility allows the manufacturer to diversify its sourcing approach and reduce dependency on a single supplier.
2. Split Replenishment: When selecting a flexibility-oriented strategy, the replenishment amount is divided equally among the contracted suppliers. For the case of three suppliers, the replenishment orders are split into three equal portions, ensuring a fair distribution of orders among the suppliers.
3. Disruption Response: In the event of a disruption occurring at one or more of the contracted suppliers, the manufacturer assesses the status of the available suppliers. If any of the suppliers are operational, the manufacturer sources the raw materials from the non-disrupted supplier(s). The sourcing decision is based on the first available supplier, ensuring a seamless continuation of the replenishment process.

Assumption FS.1: The manufacturer can have flexible contracts with 2 or 3 suppliers.
Assumption FS.2: The necessary replenishment amounts are evenly distributed among the contracted suppliers.
Assumption FS.3: When one of the contracted suppliers is undergoing a disruption, the replenishment order is rerouted to the first available contracted supplier.

The flexibility strategy involves various tradeoffs and carefully managed considerations. Some of the tradeoffs include:

1. Increased Complexity: Managing multiple suppliers and coordinating split replenishments adds complexity to the supply chain operations. This complexity requires additional resources and capabilities in coordination, communication, and logistics, which may increase operational costs.
2. Supplier Dependence: While flexible sourcing reduces dependence on a single supplier, it increases the reliance on multiple suppliers. The performance and reliability of each supplier become critical, as

disruptions in one supplier can still impact the supply chain's overall efficiency. Careful supplier selection and relationship management are essential to mitigate this risk.

3. Cost Considerations: Implementing a flexible sourcing strategy incurs additional costs, including managing relationships with multiple suppliers and coordinating the logistics of split replenishments. One should carefully assess these costs compared to the advantages of heightened supply chain flexibility and risk mitigation.

6.5 Parametrization and Implementation

This section bridges the gap between our theoretical foundations and practical execution in the simulation model. Initially, we discuss how we have integrated and set the parameters based on the defined assumptions and terms. It is worth noting that while creating a comprehensive model, we have simplified certain aspects to ensure its usability and analysis. Further validation of these parameters occurs through expert discussions detailed in Subchapter 6.6. Subsequently, we outline the steps to implement this parametrized system in the discrete event simulation tool Simio. Readers seeking a detailed walkthrough of the Simio model can refer to Appendix E.

6.5.1 Model Description

The developed simulation model assesses critical trade-offs in supplier selection and the efficacy of flexibility and redundancy strategies in uncertain supply chains. The model considers three suppliers from two regions, each having distinct characteristics affecting overall reliability. The costs considered are unit costs, contract costs (primary, flexible, and backup), inventory holding costs, and fines for non-delivery. The model aims to track costs and demonstrate how additional costs can enhance supply chain reliability through risk mitigation strategies. The Simio model uses various values, including inter-arrival times and order sizes, and resupplies the raw material inventory from three suppliers ($\boldsymbol{S} = \{1,2,3\}$) in a specific region ($\boldsymbol{R} = \{Europe, Asia\}$) with differing contract and unit costs, lead times, reliability, and quality. We implement the model variables in data tables in Simio to enhance the simulation model's generalizability and adaptability for business cases requiring precise data input.

6.5.2 Manufacturer

The simulation model, concentrating on supply-side disturbances and disruptions, places a reduced emphasis on demand variability, ensuring a precise analysis of supply chain intricacies. For customer orders, the model follows a Poisson(10) distribution to determine order quantity and employs a Poisson(7) days distribution for order interarrival time. The manufacturer's pricing structure is set at $30 per unit, with a penalty of $15 for undelivered items. This penalty represents a substantial 50% deduction, reflecting the importance of timely delivery. Conversely, the penalty can be adjusted based on the customers' dependency on the manufacturer.

Inventory incurs a daily holding cost of $0,20 per unit, accounting for associated storage and maintenance. We employ a Triangular(1, 2, 3) hours distribution to delineate the production time for a single unit. Disruptions at the manufacturer are accounted for using triangular distributions to define both occurrence intervals and resolution durations based on insights from expert interviews.

The manufacturer's system includes internal processes, raw material and finished product inventories, and safety stock levels. Production is contingent on raw materials, subject to processing time and potential disturbances. The safety stock levels are categorized into low, medium, and high thresholds.

Raw material replenishment is steered by the pre-decided sourcing strategy, which remains constant during the simulation run. This strategy offers a choice between single suppliers, flexible sourcing, and a backup plan with premium charges.

Customer orders are integrated with predefined quantities and interarrival times. The process, upon order reception, assesses inventory sufficiency. Successful orders enhance revenue, whereas insufficient stocks lead to cancellations, penalties, and increased costs.

***Table 6.3**: Manufacturer parameters*

Parameters	Unit	Value
CO_q: Customer order quantity	#	Dist.Poisson(10)
$T_{iat,co}$: Order interarrival	days	Dist. Poisson(7)
$C_{co,u}$: Price finished product	$	30,0
$C_{f,m}$: Fine for not delivering	$	15,0
$C_{i,m}$: Inventory holding cost	$ / unit/ day	0,20
$T_{m,prod}$: Processing time	hours/unit	Dist.Triangular(1,2,3)
Disturbance parameters		
$T_{iat,d,m}$: Count between failures	days	Dist.Triangular(350,364,378)
$T_{d,d,m}$: Time To Repair	days	Dist.Triangular(7,14,21)

6.5.3 Suppliers

In the simulation model, suppliers are critical entities determining the manufacturer's steady supply of raw materials. The following sections detail the parameters and characteristics that outline these suppliers.

Inventory Consideration: In the simulation, we bifurcate supplier availability into active and disrupted states. We set the supplier's inventory to an infinite value, indicating a continuous ability to fulfill demands when active.

Pricing Mechanism: We assign varied pricing structures to different suppliers. Supplier 1 sets the highest price, whereas Supplier 3 sets the lowest. We attribute these price disparities to differences in supplier efficiency, reliability, and operational costs.

Contractual Agreements: We set supplier contracting costs based on their reliability. Supplier 1, with its superior reliability, incurs higher costs. Meanwhile, Supplier 3, with its reduced reliability, attracts lower costs. Backup suppliers command additional costs because of the raw material quantities they reserve. Conversely, contracts that accommodate fluctuating delivery volumes come at a reduced price.

Quality Parameters: While the quality difference among suppliers is minimal due to initial screenings, even minor variations can influence the risk of disturbances during the manufacturing process. Higher quality ratings indicate reduced potential for manufacturing disruptions.

Operational Interruptions: Experts determined the average duration and intervals between supplier disruptions. These metrics provide insight into a supplier's reliability and recovery speed.

Environmental Factors: The model incorporates external environmental challenges, such as regional fires or floods, which can affect supplier operations. For instance, certain events in Europe can disrupt Supplier 1, while incidents in Asia can impact multiple suppliers. Expert consultations were used to define the frequency and impact of such disruptions.

In the simulation's framework, we represent each supplier as a node and a server entity. We denote the constant availability of raw materials by maintaining an infinite stock at the raw inventory node. When disruptions occur in supplier operations, we shift the server entity to a "failure state." We base the metrics for these disruptions on the Simio PERT distribution, which allows us to capture the inherent variability in disruption intervals and durations, ensuring a nuanced representation of supplier reliability.

Furthermore, each supplier's contract and unit costs are set based on the chosen sourcing strategy. These costs vary due to different commitments and the ability to adjust delivery volumes. Each supplier also has a unique price for raw materials, reflecting their quality and reliability standards.

In summary, suppliers come with a quality indicator representing the grade of their raw materials. The model also accounts for broad environmental disruptions, with parameters established for their occurrence and duration.

***Table 6.4**: Supplier parameters*

		Europe	**Asia**	
Parameters	**Unit**	**Supplier 1**	**Supplier 2**	**Supplier 3**
Inventory size	#	Infinity	Infinity	Infinity
$\boldsymbol{C_{u,s}}$: Cost of raw material	$ / unit	10	7	5
$\boldsymbol{C_{c,s,r}}$: Fixed contracting cost	$ / year	2000	1500	1200
$\boldsymbol{C_{c,s,f}}$: Flexible contracting cost	$ / year	1500	1125	900
$\boldsymbol{C_{c,s,b}}$: Backup contracting cost	$ / year	2500	1875	1500
$\boldsymbol{Q_s}$: Quality	%	99,0	97,0	95,0
Disruption parameters				
$\boldsymbol{T_{iat,d,s}}$: Count between failures	days	Dist.Tri(280,294,310)	Dist.Tri(148,162,176)	Dist.Tri(120,130,140)
$\boldsymbol{T_{d,d,s}}$: Time To Repair	days	Dist.Tri(14,28,42)	Dist.Tri(42,56,70)	Dist.Tri(46,70,84)
Environmental disruption parameters				
$\boldsymbol{T_{iat,ed,r}}$: Count between failures	days	Dist.Poisson(1400)	Dist.Poisson(900)	Dist.Poisson(900)
$\boldsymbol{T_{d,ed,r}}$: Time To Repair	days	Dist.Tri(50,60,70)	Dist.Tri(60,75,90)	Dist.Tri(60,75,90)

6.5.4 Transportation

Transportation in the simulation model is pivotal, bridging the gap between suppliers and the manufacturer. The transportation parameters have been derived and refined based on expert insights. The following sections delve into the specifics of transportation dynamics.

Lead Times: The lead times, pivotal for planning and executing manufacturing processes, represent the average duration required to transport goods from Europe and Asia to the manufacturer. Expert consultations have provided these values, offering insights into regional transportation nuances.

Disturbance Probability: The likelihood of encountering transportation disturbances, such as delays or other unexpected events, varies based on the region. Specifically, shipments from Asia exhibit a higher probability of disturbances than those from Europe. This data underlines the necessity to strategize around the unique challenges posed by Asian transportation routes.

Transport Time Distribution: A triangular distribution appropriately captures the unpredictability of transportation durations. This distribution outlines the minimum, most probable, and maximum transportation times, offering a comprehensive spectrum of possible transport durations. The model can more accurately mimic real-world variability and uncertainties in transport times by employing this distribution.

In the model's framework, each supplier has a dedicated transportation path leading to the manufacturer. Data tables define the transport times associated with each path, the probability of potential disturbances, and their resulting altered transport times. As a replenishment order embarks on its transport route, the model leverages pre-defined probabilities to determine whether it is transported within the regular timeframe or encounters delays.

***Table 6.5**: Transportation parameters*

		Europe	**Asia**	
Parameters	**Unit**	**Supplier 1**	**Supplier 2**	**Supplier 3**
$\boldsymbol{T_{t,s,r}}$: Normal lead time	weeks	2	4	4
Disturbance parameters				
$\boldsymbol{P_{td,r}}$: Probability of disturbance	%	10,0	20,0	20,0
$\boldsymbol{T_{t,s,d}}$: Disturbed lead time	weeks	Dist.Triangular(2,3,4)	Dist.Triangular(4,5,6)	Dist.Triangular(4,5,6)

6.5.5 Experiment Setup

This subchapter details the 39 scenarios used for experimentation. These encompass all potential sourcing strategies: single, backup, and flexible. Each strategy is paired with three levels of safety inventory: low (30 units, which is 25% lower), mid (40 units), and high (50 units, which is 25% higher). These levels were pinpointed through an internal optimization in Simio using OptQuest, aiming for a 95% On-Time In-Full Delivery (OTIF) when contracting with supplier 1. Specifically, the mid-level (40 units) meets this 95% OTIF Key Performance Indicator (KPI). Experimenting with three different safety stock levels for every possible sourcing strategy allows us to determine if contracting with certain suppliers or adopting specific sourcing strategies lets us maintain a reduced safety stock level. The OptQuest optimization results can be found in Appendix H.

The key performance indicators identified in Subchapter 5.3.1 measure the performance of these scenarios. These are On-Time In-Full Delivery, Net Profit, Total Cost, Stockout Time, and Low-Quality Delays.

We run 100 replications for each scenario. We chose this number after a series of tests where we checked the impact of 50, 100, and 150 replications on the KPI estimates within a 95% confidence interval. The 95% confidence interval provides a range within which we are 95% confident that the true value of a KPI lies, with the interval's width being influenced by data variability and the number of replications.

Our analysis revealed that moving from 50 to 100 replications provided more stable and consistent KPI estimates. However, increasing the replications further to 150 did not significantly enhance the accuracy of the results while simultaneously demanding considerable computational resources. Given these observations, we determined that 100 replications balance statistical robustness and computational efficiency for our model configuration.

By analyzing the KPIs from the 100 replications, we can make informed decisions and draw reliable conclusions about the performance of our system. The 95% confidence interval ensures our estimates are statistically robust, instilling confidence in the range of values in which the true population parameters reside.

Single Sourcing Scenarios

The single-sourcing scenarios with varying safety inventory levels are experimented with separately before experimenting with all possible scenarios. The goal is to discover if the better-performing scenarios incorporate the supplier that has ranked the highest with the use of the BWM for supplier selection, paired with a lower level of safety inventory.

Table 6.6: *Single sourcing scenarios*

#	Scenario	Replications	Sourcing Strategy	Reordering level	Order up to
1	Supplier1_LowSS	100	ReplOrderRawManufacturer1	30	30
2	Supplier1_MidSS	100	ReplOrderRawManufacturer1	40	40
3	Supplier1_HighSS	100	ReplOrderRawManufacturer1	50	50
4	Supplier2_LowSS	100	ReplOrderRawManufacturer2	30	30
5	Supplier2_MidSS	100	ReplOrderRawManufacturer2	40	40
6	Supplier2_HighSS	100	ReplOrderRawManufacturer2	50	50
7	Supplier3_LowSS	100	ReplOrderRawManufacturer3	30	30
8	Supplier3_MidSS	100	ReplOrderRawManufacturer3	40	40
9	Supplier3_HighSS	100	ReplOrderRawManufacturer3	50	50

Flexible and Back-up Sourcing Scenarios

After experimenting with single-sourcing setups, we integrate all other possible multi-sourcing options into one experiment setup. This setup will enable us to discover which sourcing strategy paired with what safety stock level is used in the best-performing scenarios. In addition, this setup allows us to discover if the suppliers contracted in the best-performing scenarios align with the results of the supplier ranking obtained with the BWM.

Table 6.7: *Flexible sourcing scenarios*

#	Scenario	Replications	Sourcing Strategy	Reordering level	Order up to
10	FlexS1-S2_LowSS	100	ReplOrderRawManufacturerFlex1and2	30	30
11	FlexS1-S2_MidSS	100	ReplOrderRawManufacturerFlex1and2	40	40
12	FlexS1-S2_HighSS	100	ReplOrderRawManufacturerFlex1and2	50	50
13	FlexS1-S2-S3_LowSS	100	ReplOrderRawManufacturerFlex1and2and3	30	30
14	FlexS1-S2-S3_MidSS	100	ReplOrderRawManufacturerFlex1and2and3	40	40
15	FlexS1-S2-S3_HighSS	100	ReplOrderRawManufacturerFlex1and2and3	50	50
16	FlexS1-S3_LowSS	100	ReplOrderRawManufacturerFlex1and3	30	30
17	FlexS1-S3_MidSS	100	ReplOrderRawManufacturerFlex1and3	40	40
18	FlexS1-S3_HighSS	100	ReplOrderRawManufacturerFlex1and3	50	50
19	FlexS2-S3_LowSS	100	ReplOrderRawManufacturerFlex2and3	30	30
20	FlexS2-S3_MidSS	100	ReplOrderRawManufacturerFlex2and3	40	40
21	FlexS2-S3_HighSS	100	ReplOrderRawManufacturerFlex2and3	50	50

***Table 6.8**: Back-up supplier scenarios*

#	Scenario	Replications	Sourcing Strategy	Reordering level	Order up to
22	S1BackupS2_LowSS	100	ReplOrderRawManufacturerS1BackupS2	30	30
23	S1BackupS2_MidSS	100	ReplOrderRawManufacturerS1BackupS2	40	40
24	S1BackupS2_HighSS	100	ReplOrderRawManufacturerS1BackupS2	50	50
25	S1BackupS3_LowSS	100	ReplOrderRawManufacturerS1BackupS3	30	30
26	S1BackupS3_MidSS	100	ReplOrderRawManufacturerS1BackupS3	40	40
27	S1BackupS3_HighSS	100	ReplOrderRawManufacturerS1BackupS3	50	50
28	S2BackupS1_LowSS	100	ReplOrderRawManufacturerS2BackupS1	30	30
29	S2BackupS1_MidSS	100	ReplOrderRawManufacturerS2BackupS1	40	40
30	S2BackupS1_HighSS	100	ReplOrderRawManufacturerS2BackupS1	50	50
31	S2BackupS3_LowSS	100	ReplOrderRawManufacturerS2BackupS3	30	30
32	S2BackupS3_MidSS	100	ReplOrderRawManufacturerS2BackupS3	40	40
33	S2BackupS3_HighSS	100	ReplOrderRawManufacturerS2BackupS3	50	50
34	S3BackupS1_LowSS	100	ReplOrderRawManufacturerS3BackupS1	30	30
35	S3BackupS1_MidSS	100	ReplOrderRawManufacturerS3BackupS1	40	40
36	S3BackupS1_HighSS	100	ReplOrderRawManufacturerS3BackupS1	50	50
37	S3BackupS2_LowSS	100	ReplOrderRawManufacturerS3BackupS2	30	30
38	S3BackupS2_MidSS	100	ReplOrderRawManufacturerS3BackupS2	40	40
39	S3BackupS2_HighSS	100	ReplOrderRawManufacturerS3BackupS2	50	50

6.6 Model Validation

In this section, we validate our simulation model's logic, processes, and overall behavior. This validation consists of two main parts: historical output validation and face and expert validation.

6.6.1 Historical Output Validation

Carrying out historical output validation is challenging due to the lack of real-world data on past supplier disruptions. Much of this data is confidential; when available, it is not detailed or systematically recorded. However, our simultaneous work on the model development and expert interviews allowed us to adjust disruption parameters based on insights.

6.6.2 Face and Expert Validation

Our simulation model in Simio was checked and improved by talking with industry experts. This validation was part of the development of our DES model. These discussions were essential for ensuring our model is accurate and reflects what happens in the real world.

There were two main benefits of talking with these experts:

1. **Understanding Sourcing Strategies**: We learned more about the real-world logic of sourcing strategies by talking with professionals in the polymer industry. These talks helped us adjust our model to make it more realistic.
2. **Checking Model Parameters**: We reviewed the model's details with two procurement experts in Deloitte’s Supply Chain and Network Operations team. This review helped ensure that our model used realistic numbers and relationships, making the results more reliable.

Key points derived from our expert discussions are:

Model Setup Evaluation: We extensively reviewed our initial design featuring one manufacturer and three suppliers. The experts confirmed the realism of this structure but pointed out the oversimplification in sourcing just one type of raw material. While this was a strategic choice on our part for the study, they noted that a more comprehensive model in future research could yield nuanced results. Notably, using the BWM to rank suppliers remains feasible even with multiple raw materials as long as the model considers different materials' relative importance.

Sourcing Strategies: The discussion around our dual sourcing strategies (redundancy and flexibility) was illuminating. A crucial piece of feedback regarded the fee structure of backup suppliers. Experts highlighted that backup suppliers usually charge more due to the immediate stock availability they offer. Acting on this, we revised our model to reflect a 25% fee increase for backup suppliers. Regarding the flexibility-oriented strategy, experts concurred on its feasibility but also emphasized that real-world dynamics might make suppliers less flexible than depicted in the model.

Penalties for Non-delivery: The conversation turned to the repercussions of failing to deliver and the resultant penalties. The experts informed us that these penalties might vary based on the client's industry and level of reliance. Our model adopts a uniform approach for simplicity, but this feedback underlines the potential for more granular analysis in future studies.

Inventory Check Dynamics: The daily inventory verification by the manufacturer was a focal point. Experts confirmed that this mirrors industry practices. They also brought up the increasing trend of automation in this area but pointed out that human intervention, especially for verification, remains essential.

7. Case Study Results

The results chapter consists of multiple subchapters. In Subchapter 7.1, we present the experiment results for the nine single-sourcing and all 39 scenarios. In Subchapter 7.2, we obtain the ranking with the BWM for the set of suppliers in our system. Next, in Subchapter 7.3, we analyze the experiment results and obtain two different rankings, one for the single supplier scenarios' performance and another for all scenarios' performance. These findings enable us to discover which strategy, flexibility or redundancy, performs best. In Subchapter 7.4, we compare the BWM supplier ranking with the best-performing single supplier scenarios and the best-performing filtered scenarios. We discuss the performance of the two sourcing strategies and which combination of suppliers with which type of contract allows the manufacturer to keep a lower safety stock.

Ultimately, these findings enable us to answer our main research question in Chapter 8.

7.1 Simulation Model Output

In this subchapter, we present the results of the experiments performed in Simio. Subchapter 6.5.5 presented the used experiment setup.

First, in subchapter 7.1.1, we show the experiment results of the scenarios with a single supplier paired with a low, medium, and high level of safety inventory. These findings enable us to tell in subchapter 7.3.2 if the supplier ranking obtained with the best worst method in subchapter 7.2 aligns with the simulation model performance and the suppliers contracted in the best-performing scenarios. Second, in subchapter 7.1.2, we show the experiment results with all possibilities of suppliers, risk mitigation strategies, and levels of safety inventory at the manufacturer. In subchapter 7.1.3, we validate the model output. These results will enable us to discover which scenario performs best in subchapter 7.3.4.

7.1.1 Single Supplier Scenarios

After conducting 100 replications for each scenario involving a single contracted supplier, we have the results presented in Table 7.1. The distributions of the KPIs, along with their confidence intervals, are included in Appendix F.

***Table 7.1**: Results of single supplier scenarios*

Scenario	Stockout Time	TC	NP	OTIF	Low Quality Delays
Supplier1_LowSS	16,29	50049,2	22044,1	92,22	3,59
Supplier1_MidSS	5,20	57505,4	19205,8	96,12	3,70
Supplier1_HighSS	1,93	64835,0	13005,7	97,75	3,55
Supplier2_LowSS	123,20	40488,6	4062,32	59,20	5,47
Supplier2_MidSS	84,59	39857,0	18508,3	75,58	7,11
Supplier2_HighSS	50,68	43546,3	22833,2	85,45	7,67
Supplier3_LowSS	129,44	36990,8	4060,95	54,72	8,35
Supplier3_MidSS	101,88	35612,3	18894,4	70,47	10,62
Supplier3_HighSS	72,91	38047,9	24539,6	80,01	11,25
Unit	days	$	$	%	#

We cannot tell which of these scenarios performs best as we have multiple KPIs. In subchapter 7.3.2, we perform the best worst method to this set of 9 scenarios to rank the scenarios from best to worst performing.

7.1.2 All Scenarios

We ran 100 replications using the experiment setup, encompassing all possible combinations of supplier contracting strategies paired with low, mid, and high safety stock levels, yielding the results presented in Table 7.2.

***Table 7.2**: Results of all scenarios*

Scenario	Stockout Time	TC	NP	OTIF	Low Quality Delays
Supplier1_LowSS	16,29	50049,20	22044,10	92,22	3,59
Supplier1_MidSS	5,20	57505,40	19205,80	96,12	3,70
Supplier1_HighSS	1,93	64835,00	13005,70	97,75	3,55
Supplier2_LowSS	123,20	40488,60	4062,32	59,20	5,47
Supplier2_MidSS	84,59	39857,00	18508,30	75,58	7,11
Supplier2_HighSS	50,68	43546,30	22833,20	85,45	7,67
Supplier3_LowSS	129,44	36990,80	4060,95	54,72	8,35
Supplier3_MidSS	101,88	35612,30	18894,40	70,47	10,62
Supplier3_HighSS	72,91	38047,90	24539,60	80,01	11,25
S1BackupS2_LowSS	8,34	60673,40	13369,30	94,72	3,87
S1BackupS2_MidSS	0,81	68177,10	10034,10	99,20	4,02
S1BackupS2_HighSS	0,14	75690,30	2213,39	99,93	4,23
S1BackupS3_LowSS	10,56	58238,70	15606,00	94,19	4,01
S1BackupS3_MidSS	1,65	65747,10	12028,80	98,18	4,36
S1BackupS3_HighSS	0,38	73174,00	4967,57	99,43	4,38
S2BackupS1_LowSS	34,59	55076,50	7848,79	81,84	6,13
S2BackupS1_MidSS	4,76	58240,80	17333,70	96,47	7,02
S2BackupS1_HighSS	0,12	66241,50	12115,80	99,69	7,91
S2BackupS3_LowSS	48,54	45971,00	10469,20	74,33	8,23
S2BackupS3_MidSS	11,74	45699,20	27800,80	94,15	9,88
S2BackupS3_HighSS	0,62	53169,30	24685,50	99,41	10,14
S3BackupS1_LowSS	37,41	51990,40	11042,60	82,08	8,85
S3BackupS1_MidSS	5,34	54877,20	20863,20	96,26	9,89
S3BackupS1_HighSS	1,02	62244,20	15552,70	99,06	10,93
S3BackupS2_LowSS	72,49	46043,70	7145,45	70,31	9,44
S3BackupS2_MidSS	37,91	45169,00	24153,20	89,22	11,60
S3BackupS2_HighSS	17,43	51513,80	23005,90	94,13	12,37
FlexS1-S2_LowSS	4,29	53860,40	22488,20	96,75	6,11
FlexS1-S2_MidSS	0,26	61698,10	16746,20	99,70	6,18
FlexS1-S2_HighSS	0,05	69381,90	9235,23	99,96	6,24
FlexS1-S3_LowSS	5,95	51153,80	25170,40	96,48	7,20
FlexS1-S3_MidSS	0,18	58771,10	19226,20	99,24	7,43
FlexS1-S3_HighSS	0,23	66288,70	12081,80	99,73	7,72
FlexS2-S3_LowSS	34,58	30077,80	37912,70	86,93	10,08
FlexS2-S3_MidSS	14,49	35795,90	38551,60	94,24	10,55
FlexS2-S3_HighSS	17,35	42855,70	33033,20	95,77	10,71
FlexS1-S2-S3_LowSS	18,18	53808,10	16733,30	90,33	6,74
FlexS1-S2-S3_MidSS	26,37	57883,40	17099,50	94,73	7,24
FlexS1-S2-S3_HighSS	28,76	62238,30	12864,90	95,50	7,78
Unit	days	$	$	%	#

Like our results of single supplier scenarios, we have multiple KPIs, and we cannot tell which of these scenarios performs best. In Subchapter 7.3.3, we first perform a threshold analysis to filter out the underperforming scenarios and then apply the best worst method to the remaining filtered set of scenarios to rank them from best to worst performing in Subchapter 7.3.4.

7.1.3 Validation of Model Output

As we have already validated the simulation model's logic, processes, and overall behavior in Subchapter 6.6, we now validate the model's actual output as presented in Subchapter 7.1.1 and Subchapter 7.1.2.

We looked in detail through the tables with the results for all the scenarios with the research supervisors working in Deloitte's Supply Chain & Network Operations team. We have reviewed the KPIs' values and the relation between them. All was in line with our desired outcomes, which was as expected as we continuously worked with experts when developing the model. Our decisions and assumptions were also in collaboration with these experts.

The supervisors advised us to perform a threshold analysis before continuing with further analyses. Subchapter 7.3.3 presents this threshold analysis.

We also looked at the results during two group discussions within the team—one with around 10 Supply Chain Planning professionals and another with 10 Procurement professionals. While we did not delve into the details, we highlighted the top 10 best-performing scenarios during these discussions.

Stockout Time and Service Level Relationship: A consensus was reached that lower stockout times generally lead to higher OTIF percentages. This correlation is evident across many scenarios, particularly with a high safety stock level. The group agreed that maintaining an optimal safety stock level is paramount for achieving desired service levels.

Total Cost and Stockout Relationship: There is an inherent cost to holding stock, and while higher safety stock scenarios indicate substantial costs, these are essentially investments to ensure product availability. The group noted the evident trade-offs and discussed the implemented sourcing strategies to strike the right balance.

Supplier Differences: The group identified the distinct performance differences among the suppliers. Supplier 1, for instance, showcased consistent and robust results across various safety stock levels. In contrast, Supplier 3 has some reliability concerns, especially at lower safety stock levels, which warrants its importance in being contracted with other suppliers or wholly avoided.

Backup Strategies: The diversification benefits of backup sourcing strategies were evident. However, the group noted the inherent costs, especially with strategies employing higher safety stocks. It was suggested to evaluate the real-world implications further and potentially optimize the stock levels for these backup strategies.

These expert-led discussions provided invaluable insights, aligning well with the initial hypotheses and observations obtained with the expert interviews. The team is confident in the model's representation and sees avenues for strategic use in the future.

7.2 Supplier Ranking with the BWM

In this subchapter, we use the best worst method to rank the three suppliers in our system based on the supplier selection criteria and the outcomes of the BWM survey (Appendix B) completed by five senior supply chain professionals from the polymer industry. This process yields a ranking of the suppliers from best to worst. The BWM-based supplier selection process follows the five steps outlined in the methodology.

Step 1: *Create a list of selection criteria.*

The development of the list with selection criteria is discussed in Subchapter 5.3. The four criteria are composed through a literature review and interviews with supply chain experts in the polymer industry.

Table 7.3*: Final supplier selection criteria*

Criterion	Definition
Quality of Materials	Suppliers' consistent delivery of high-quality materials ensures product specifications and desired performance attributes are met.
Reliability of Supply	Timely and consistent delivery of raw materials and polymers from suppliers avoids disruptions and maintains a smooth supply chain flow.
Price	Balancing competitive pricing with desired quality standards is crucial for achieving cost-effectiveness in the polymerization supply chain.
Lead Times	Efficient lead times in material delivery enable smooth production planning and minimize production delays, contributing to an efficient supply chain.

Step 2: *Select the best and the worst criteria to apply to the decision-making process.*

As we have our list with supplier selection criteria, the next step is to make experts working in the polymer industry select their most important(best) criterion, rank the relative importance on a Likert scale from 1 – 9 in relation to the other criteria and their least important(worst) criterion, and rank the relative importance on the same scale again to the other criteria. Distributing this survey among the target group resulted in five responses. The exact survey used for gathering this information is attached in Appendix B.

Table 7.4 shows the five respondents' most important (best) and least important (worst) criteria.

Table 7.4*: Best and worst criteria identified by respondents 1 to 5*

Criterion	Identified as 'Best' by respondent no.	Identified as 'Worst' by respondent no.
Quality of materials	-	-
Reliability of supply	1,2,3,5	-
Price	4	3
Lead time	-	1,2,4,5

Step 3: *Determine which criterion is preferred over all others.*

Table 7.5 presents the relative importance of their best criterion in relation to the other criteria on a 1 – 9 Likert scale.

Table 7.5*: Best-to-Others (BO) vectors for respondents 1 to 5*

Respondent no.	Best	Quality	Reliability	Price	Lead time
1	Reliability	4	1	5	9
2	Reliability	2	1	4	9
3	Reliability	3	1	9	7
4	Price	5	4	1	9
5	Reliability	5	1	3	9

***Step 4:** Determine the preference of each of the other criteria over the worst criterion.*

In Table 7.6, we see the relative preference of each of the other criteria over the worst criterion. Again, this is rated on a 1 – 9 Likert scale.

***Table 7.6**: Others-to-Worst (OW) vectors for respondents 1 to 5*

Respondent no.	**1**	**2**	**3**	**4**	**5**
Worst:	Lead time	Lead time	Price	Lead time	Lead time
Criteria					
Quality	6	7	6	5	5
Reliability	9	9	9	7	9
Price	5	6	1	9	7
Lead time	1	1	3	1	1

***Step 5:** Find the optimal weights.*

After performing the calculations for calculating the optimal weights for each criterion, we result with the weights in Table 7.7. We can already see that the reliability criterion weight is the highest compared to the other criteria. The quality and price criteria have approximately the same weight, and the lead time criterion's weight is the lowest. This finding aligns with one of our interview findings, stating that a supplier's reliability outweighs all other factors, especially when considering disturbances and disruptions. In addition, a lead time is less relevant when the reliability is high.

***Table 7.7**: Optimal weights per criterion*

Criteria	**Weight**
Quality	0,220
Reliability	0,516
Price	0,200
Lead time	0,064
$\boldsymbol{\xi^{L*}}$	0,159

ξ^{L*} is the consistency indicator for the comparisons. The closer the value of the consistency indicator is to 0, the more consistent the comparison system is, as provided by the decision-makers (Rezaei et al., 2016). A value of 0,159 implies a moderate level of inconsistency in the comparison system provided by the decision-makers. While it is not too close to 0, indicating a certain level of inconsistency, it is still within an acceptable range for us. In addition, we obtain the Input-Based Consistency Ratios in Step 6 as it provides a better measure for the consistency of the decision-makers' (DM's) preferences based on the initial input provided.

***Step 6**: Check for input-based consistency.*

In Table 7.8, all input-based consistency ratios are below the threshold of 0,2681, confirming the high consistency of decision-makers' preferences. This threshold is specific to systems with four criteria and nine scales. With all values beneath this benchmark, it underscores the robustness and practical utility of the input-based consistency measure in real-world decision-making, allowing for quick feedback and adjustments.

***Table 7.8**: Input-Based CRs for respondents 1 to 5*

Respondent	Input-Based CR
1	0,2222
2	0,2083
3	0,1667
4	0,2639
5	0,2222
Associated Threshold	**0,2681**

Before moving on to the definitive supplier ranking, we fill Table 7.9 with the quantitative values for our supplier's parameters. The uptime percentage for reliability, price, contracting, material costs, and lead time is based on the average value for 100 replications in a single supplier setting with a runtime of 5 years.

***Table 7.9:** Supplier performance absolute values*

Criterion	Quality	Reliability	Price	Lead time
Supplier 1	99,0	88,0	37000	14,70
Supplier 2	97,0	70,0	20700	29,30
Supplier 3	95,0	64,0	15000	29,30
Unit	%	uptime %	$ / 5 years	days

Table 7.10 presents the overall supplier score by multiplying the normalized values for the criteria with their respective weights.

***Table 7.10:** Normalized and overall supplier scores*

Criterion	Quality	Reliability	Price	Lead time	Overall supplier score
Weight	0,220	0,516	0,200	0,064	
Supplier 1	1,000	1,00	0,000	1	0,800
Supplier 2	0,500	0,25	0,741	0	0,387
Supplier 3	0,000	0,00	1,000	0	0,200

Table 7.10 presents us with the definitive supplier scores and respective rankings. The ranking shows Supplier 1 has the highest overall supplier score, followed by Suppliers 2 and 3. In subchapter 7.3.2, we rank the single supplier scenarios in the simulation model to discover if the best-ranked supplier, supplier 1, is also contracted in the best-performing single supplier scenario. Ideally, this will go paired with a low level of safety inventory.

By prioritizing reliability over cost in the scoring process, the experts emphasized the significance of consistent and timely deliveries in the supply chain. While cost is undoubtedly a critical factor in supplier selection, the experts recognized that disturbances and disruptions caused by unreliable suppliers could have more severe consequences on the overall supply chain performance. Hence, they weighted the criteria risk-averse, leading to a ranking that reflects the importance of reliability in the supplier selection process.

7.3 Scenario Analysis

Analyzing the simulation results is a crucial step in understanding the performance of different strategies and the impact of supplier utilization on the levels of safety inventory at the manufacturer.

First, we obtain the optimal weights for the KPIs with the best worst method. Second, we rank the single supplier scenarios using the optimal weights obtained. This ranking reveals which suppliers we contract and the safety stock level utilized in the best-performing scenario(s). Third, we perform a threshold analysis of the results of all 39 scenarios to filter out the underperforming scenarios. Last, we use the obtained optimal weights again to rank the scenarios that have passed the threshold analysis, which will enable us to discover which sourcing strategy (redundancy or flexibility), paired with which suppliers and what level of safety stock is the most effective in enhancing supply chain performance, considering disturbances and disruptions in the supply chain.

7.3.1 Obtaining KPIs' Optimal Weights

This subchapter uses the best worst method to obtain the optimal weights for the five key performance indicators for measuring our simulation model's supply chain performance. The BWM survey (Appendix B), filled in by five senior supply chain professionals working in the polymer industry, is used to collect the professionals' most and least important KPIs and the relative importance of these to the most and least important KPI to the other KPIs.

The optimal weights found in step 5 of performing the BWM are reused in Subchapter 7.3.2 to rank the single supplier scenarios from best to worst and in Subchapter 7.3.4 to rank the scenarios that remain after performing the threshold analysis in Subchapter 7.3.3. This results in ranking the scenarios from the best to worst performing scenario.

Step 1: *Create a list of selection criteria.*

Much like the process used to create our list of supplier selection criteria, we obtain the initial list of key performance indicators (KPIs) through expert interviews. After the interviews, we incorporate the KPIs that emerge most frequently into the final list of KPIs. To ensure precise measurements within the simulation model, we operationalize these KPIs. Specifically, 'Inventory levels' were translated into 'Stockout time,' and 'Quality of produced products' was operationalized as 'Low-quality delays.' This operationalization provided a more precise and relevant measure for simulation purposes. For the completeness of these steps, we also add the selected KPIs in Table 7.11:

Table 7.11*: Final KPIs used for BWM*

KPI	Definition
Stockout Time	Measures the duration during which the manufacturer experiences a shortage or depletion of inventory for finished products. Minimizing stockout time is essential for meeting customer demand.
Total Cost	Represents the sum of the costs associated with the supply chain, including contracting costs, replenishment costs, cost of fines for failed customer orders, and inventory holding costs.
Net Profit	Measures the system's financial performance by calculating the revenue generated from customer orders minus the total costs incurred. It provides insights into the profitability of the supply chain.
On-Time In-Full Delivery	Measures the percentage of customer orders delivered in full and on time. A higher OTIF Delivery percentage signifies a more reliable and efficient supply chain operation, while a lower percentage indicates potential disruptions in order fulfillment.
Low Quality Delays	Measure the instances when additional time is required in the production process when lower-quality materials are sourced from suppliers. It captures the impact of material quality on the overall production timeline. Lower is better.

Step 2: *Select the best and the worst criteria to apply to the decision-making process.*

As we have our list with Key Performance Indicators, the next step is to make experts working in the polymer industry select their most important(best) KPI, rank the relative importance on a Likert scale from 1 to 9 in relation to the other KPIs, and their least important(worst) KPI, and rank the relative importance on the same scale again to the other KPIs. We have attached the exact survey used to gather this information in Appendix B.

Table 7.12 presents the five respondents' most important (best) and least important (worst) KPIs.

Table 7.12*: Best and worst KPIs identified by respondents 1 to 5*

KPI	Identified as 'Best' by respondent no.	Identified as 'Worst' by respondent no.
Stockout time		1, 3, 4, 5
Total cost		2
Net profit	2, 4	
OTIF delivery	1, 5	
Low-Quality delays	3	

Step 3: *Determine which criterion is preferred over all others.*

Table 7.13 presents the relative importance of their most important (best) KPI in relation to the other KPIs on a 1 – 9 Likert scale.

Table 7.13*: Best-to-Others (BO) vectors for respondents 1 to 5*

Respondent no.	Best	Stockout time	Total cost	Net profit	OTIF delivery	Low-Quality delays
1	OTIF Delivery	9	5	4	1	7
2	Net Profit	8	9	1	2	7
3	LQ delays	9	8	7	7	1
4	Net Profit	9	7	1	6	8
5	OTIF Delivery	9	8	2	1	7

Step 4: *Determine the preference of each of the other criteria over the worst criterion.*

Table 7.14 presents the relative preference of each of the other KPIs over the least important(worst) KPI. Again, this is rated on a 1 – 9 Likert scale.

Table 7.14*: Others-to-Worst (OW) vectors for respondents 1 to 5*

Respondent no.	1	2	3	4	5
Worst:	Stockout time	Total cost	Stockout time	Stockout time	Stockout time
KPIs					
Stockout time	1	3	1	1	1
Total cost	5	1	2	3	2
Net profit	6	9	3	9	8
OTIF delivery	9	7	3	4	9
Low-Quality delays	4	3	9	3	4

Step 5: *Find the optimal weights.*

Upon completing the computations to determine the optimal weights for each KPI, we have the weights detailed in Table 7.15. Notably, the OTIF Delivery KPI holds the highest weight, indicating that professionals in the polymer industry consider it the most crucial KPI overall. Following is the Net Profit KPI, which is also reasonable, as a supply chain that achieves timely customer deliveries but lacks profitability is ultimately unsustainable in the long term.

Table 7.15: *Optimal weights per KPI*

KPI	Weight
Stockout time	0,070
Total cost	0,105
Net profit	0,344
OTIF delivery	0,316
Low-Quality delays	0,165
ξ^{L*}	0,113

We first use the optimal weights in Table 7.17 to rank the single supplier scenarios in Subchapter 7.3.2 and second to rank the scenarios in Subchapter 7.3.4 that have passed the threshold analysis.

ξ^{L*} is the consistency indicator for the comparisons. The closer the value of the consistency indicator is to 0, the more consistent the comparison system is, as provided by the decision-makers (Rezaei et al., 2016). A value of 0,113 implies a relatively low level of inconsistency in the comparison system provided by the decision-makers. The consistency ratio being close to 0 indicates that the decision-makers' evaluations and comparisons of the criteria and scenarios were relatively consistent, enhancing the reliability of the obtained weights. In addition, we obtain the Input-Based Consistency Ratios in Step 6 as it provides a better measure for the consistency of the decision-makers' (DM's) preferences based on the initial input provided.

Step 6: *Check for input-based consistency.*

In Table 7.16, all input-based consistency ratios are below the threshold of 0,3062, confirming the high consistency of decision-makers' preferences. This threshold is specific to systems with five criteria and nine scales. With all values beneath this benchmark, it underscores the robustness and practical utility of the input-based consistency measure in real-world decision-making, allowing for quick feedback and adjustments.

Table 7.16*: Input-Based CRs for respondents 1 to 5*

Respondent	Input-Based CR
1	0,2639
2	0,2083
3	0,1667
4	0,2083
5	0,2639
Associated Threshold	**0,3062**

7.3.2 Ranking Single Supplier Scenarios

In this subchapter, we use the optimal weights for the KPIs obtained with the best worst method to rank the nine single supplier scenarios in our simulation model based on the KPIs that measure our simulation model's supply chain performance.

To obtain the overall score of the scenarios, we use the optimal weights obtained in Table 7.15. Then, we obtain the overall score by normalizing the absolute values from the results table in Subchapter 7.1.1, multiplying the optimal weight with the normalized value for each KPI, and adding this up for each row. We present Table 7.17 by sorting the overall scenario score from the highest to the lowest ranking scenario.

Table 7.17*: Overall scores of single supplier scenarios*

Scenario	**Stockout Time**	**TC**	**NP**	**OTIF**	**LQ Delays**	
Weight:	0,070	0,105	0,344	0,316	0,165	**Overall score**
Supplier1_LowSS	0,887	0,506	0,878	0,872	0,995	0,857
Supplier1_MidSS	0,974	0,251	0,740	0,962	0,981	0,815
Supplier2_HighSS	0,618	0,728	0,917	0,714	0,465	0,737
Supplier1_HighSS	1,000	0,000	0,437	1,000	1,000	0,702
Supplier3_HighSS	0,443	0,917	1,000	0,588	0,000	0,657
Supplier2_MidSS	0,352	0,855	0,705	0,485	0,538	0,599
Supplier3_MidSS	0,216	1,000	0,724	0,366	0,082	0,498
Supplier2_LowSS	0,049	0,833	0,000	0,104	0,751	0,247
Supplier3_LowSS	0,000	0,953	0,000	0,000	0,377	0,162

After analyzing the scenarios presented in Table 7.17, we observed the following performance rankings:

- The best-ranking scenario features supplier 1, contracted with a low safety stock level at the manufacturer.
- The second highest ranking scenario was similar, involving supplier 1, but with a medium safety stock level.
- The third and fourth highest-ranking scenarios utilized a high safety stock level. Notably, the third-ranking scenario involved supplier 2 while maintaining a high safety stock level.

When we contrast these results with the supplier ranking in Subchapter 7.2, several points become apparent:

- When contracted, the best supplier, supplier 1, results in the best supply chain performance, particularly with lowered safety stock levels.
- We found that more reliable suppliers, such as supplier 1, with lower safety stock levels, consistently outperform less reliable suppliers, even when these less reliable suppliers are paired with higher safety stock levels.

From a cost perspective, we observe two additional patterns:

- Supplier 3, coupled with medium safety stock, proved the least costly option, followed closely by supplier 3 with low safety stock. These outcomes mainly arose from these suppliers' lower contracting and unit costs.
- Despite having an average total cost, the best-performing scenario boasted higher relative Net Profit and OTIF, highlighting the significance of these two KPIs.

We conducted the ranking and subsequent discussion for single supplier scenarios without an initial threshold analysis. We aimed to see if the model output aligns with the BWM supplier ranking. Had we performed a threshold analysis focusing on the OTIF KPI, only scenarios scoring above 95% would have been cut. This cut would exclude all scenarios except those where supplier 1 is contracted with a medium or high safety stock level.

We apply thresholds in Subchapter 7.3.3 to evaluate the performance of various scenarios more realistically, considering all potential sourcing strategies and combinations of suppliers.

7.3.3 Threshold Analysis

With the threshold analysis, we filter out scenarios from the subsequent BWM analysis if they score below specific thresholds on certain Key Performance Indicators (KPIs) within the experiment results set. This method guarantees that we only consider scenarios that meet the predetermined performance standards for further evaluation and ranking.

To determine the thresholds for the KPIs, we carefully consider the key objectives and priorities of the supply chain, which is to have a supply chain that can withstand disturbances and disruptions while being profitable in the long run. The selected KPIs should reflect the critical factors that drive supply chain performance and align with the overall goals of the manufacturer. This study chooses three KPIs for the threshold analysis: On-Time-In-Full (OTIF) delivery, Net Profit, and Low-Quality Delays. We set the thresholds in Table 7.18 by discussing the results in Subchapter 7.1.2 with two procurement professionals in Deloitte's Supply Chain & Network Operations team:

Table 7.18: *Threshold values for the KPIs*

KPI	**Threshold**
OTIF Delivery	>= 95,00%
Net Profit	> 0,00$
Low-Quality Delays	< 10,00

For OTIF delivery, a key metric assessing the percentage of orders reaching customers on time and in full, we set a threshold of 95%. Any scenarios with an OTIF delivery below this mark will not proceed to the BWM analysis. This threshold emphasizes the high priority given to customer satisfaction and the quality of service.

For net profit, a primary indicator for gauging the financial health of the supply chain, the threshold is set at zero or positive net profit. Scenarios falling into negative net profit territory are discarded from the BWM analysis. By setting this bar, we ensure consideration is given only to scenarios that align with the financial aspirations of the organization.

Lastly, scenarios featuring more than ten low-quality delays are also filtered out. This step is essential as it highlights priority scenarios, streamlines resource use, presents realistic situations and strengthens risk management strategies. Supply chains may not be prepared to address many low-quality delays, so focusing on scenarios that mirror the supply chain's real-world potential is crucial.

In Table 7.19, the specific cells that do not meet one of the thresholds are strike-through. When a scenario has one or more cells with a strikethrough, it excludes that scenario from subsequent analysis. We present the scenarios that get excluded in grey.

***Table 7.19**: Filtering the 39 scenarios*

Scenario	Stockout time	TC	NP	OTIF	Low Quality Delays
Supplier1_LowSS	16,29	50049,20	22044,10	~~92,22~~	3,59
Supplier1_MidSS	5,20	57505,40	19205,80	96,12	3,70
Supplier1_HighSS	1,93	64835,00	13005,70	97,75	3,55
Supplier2_LowSS	123,20	40488,60	4062,32	~~59,20~~	5,47
Supplier2_MidSS	84,59	39857,00	18508,30	~~75,58~~	7,11
Supplier2_HighSS	50,68	43546,30	22833,20	~~85,45~~	7,67
Supplier3_LowSS	129,44	36990,80	4060,95	~~54,72~~	8,35
Supplier3_MidSS	101,88	35612,30	18894,40	~~70,47~~	~~10,62~~
Supplier3_HighSS	72,91	38047,90	24539,60	~~80,01~~	~~11,25~~
S1BackupS2_LowSS	8,34	60673,40	13369,30	~~94,72~~	3,87
S1BackupS2_MidSS	0,81	68177,10	10034,10	99,20	4,02
S1BackupS2_HighSS	0,14	75690,30	2213,39	99,93	4,23
S1BackupS3_LowSS	10,56	58238,70	15606,00	~~94,19~~	4,01
S1BackupS3_MidSS	1,65	65747,10	12028,80	98,18	4,36
S1BackupS3_HighSS	0,38	73174,00	4967,57	99,43	4,38
S2BackupS1_LowSS	34,59	55076,50	7848,79	~~81,84~~	6,13
S2BackupS1_MidSS	4,76	58240,80	17333,70	96,47	7,02
S2BackupS1_HighSS	0,12	66241,50	12115,80	99,69	7,91
S2BackupS3_LowSS	48,54	45971,00	10469,20	~~74,33~~	8,23
S2BackupS3_MidSS	11,74	45699,20	27800,80	~~94,15~~	9,88
S2BackupS3_HighSS	0,62	53169,30	24685,50	99,41	~~10,14~~
S3BackupS1_LowSS	37,41	51990,40	11042,60	~~82,08~~	8,85
S3BackupS1_MidSS	5,34	54877,20	20863,20	96,26	9,89
S3BackupS1_HighSS	1,02	62244,20	15552,70	99,06	~~10,93~~
S3BackupS2_LowSS	72,49	46043,70	7145,45	~~70,31~~	9,44
S3BackupS2_MidSS	37,91	45169,00	24153,20	~~89,22~~	~~11,60~~
S3BackupS2_HighSS	17,43	51513,80	23005,90	~~94,13~~	~~12,37~~
FlexS1-S2_LowSS	4,29	53860,40	22488,20	96,75	6,11
FlexS1-S2_MidSS	0,26	61698,10	16746,20	99,70	6,18
FlexS1-S2_HighSS	0,05	69381,90	9235,23	99,96	6,24
FlexS1-S3_LowSS	5,95	51153,80	25170,40	96,48	7,20
FlexS1-S3_MidSS	0,18	58771,10	19226,20	99,24	7,43
FlexS1-S3_HighSS	0,23	66288,70	12081,80	99,73	7,72
FlexS2-S3_LowSS	34,58	30077,80	37912,70	~~86,93~~	~~10,08~~
FlexS2-S3_MidSS	14,49	35795,90	38551,60	~~94,24~~	~~10,55~~
FlexS2-S3_HighSS	17,35	42855,70	33033,20	95,77	~~10,71~~
FlexS1-S2-S3_LowSS	18,18	53808,10	16733,30	~~90,33~~	6,74
FlexS1-S2-S3_MidSS	26,37	57883,40	17099,50	~~94,73~~	7,24
FlexS1-S2-S3_HighSS	28,76	62238,30	12864,90	95,50	7,78
Unit	days	$	$	%	#

After filtering out the 23 scenarios with values for the KPIs that do not meet the thresholds, we remain with 16 scenarios for further analysis with the BWM. We see that 17 of the scenarios that are filtered out do not meet the threshold of 95% for the OTIF KPI. In the nine filtered-out scenarios that do not meet the Low-Quality Delay threshold of 10, we see that six also do not meet the OTIF threshold. We do not see any scenarios being filtered out by not having a negative net profit.

By looking into the filtered-out scenarios in more detail, we see that the OTIF threshold is not met in scenarios in which both of the less reliable and lower-ranked suppliers (supplier 2 and supplier 3) are contracted, and a low or medium-level of safety stock is kept at the manufacturer.

The majority of scenarios involving a combination of suppliers 2 and 3 did not meet the threshold criteria. The primary reason stemmed not only from increased production delays due to the procurement of lower-quality raw materials but also from the combined reliability of these suppliers. Unfortunately, their reliability proved insufficient to manage disturbances and disruptions effectively within the supply chain, causing failure to meet the OTIF threshold of 95%. The lowered delivery performance is also due to the suppliers being located in the same region, which led to simultaneous and prolonged disruptions during environmental disruptions. Importantly, environmental disruptions were found to be more frequent in Asia than in Europe, further accentuating the significance of having a diverse supplier base in different regions.

The scenarios in which supplier 2 and supplier 3 are contracted consistently breached the threshold of a maximum of 10 low-quality delays, further emphasizing the significant role of thresholds on ranking. This complex interplay between supplier reliability, quality of raw materials, and performance thresholds illuminates an essential discussion point. It underscores the value of contracting a highly reliable supplier 1 to ensure robust supply chain performance and risk mitigation despite the potential additional costs.

We present the remaining 16 scenarios for ranking from best to worst in Subchapter 7.3.4 in Table 7.20. Appendix G presents the distributions of the percentiles and the confidence intervals for these KPIs. In Subchapter 7.3.4, we normalize the values of the KPIs across the scenarios to derive the final overall score for each scenario.

***Table 7.20**: The 16 remaining scenarios*

Scenario	Stockout time	Total cost	Net profit	OTIF delivery	Low-quality delays
Supplier1_HighSS	1,93	64835	13005,7	97,746	3,55
Supplier1_MidSS	5,20	57505,4	19205,8	96,124	3,70
S1BackupS2_MidSS	0,81	68177,1	10034,1	99,204	4,02
S1BackupS2_HighSS	0,14	75690,3	2213,4	99,927	4,23
S1BackupS3_MidSS	1,65	65747,1	12028,8	98,180	4,36
S1BackupS3_HighSS	0,38	73174	4967,57	99,429	4,38
FlexS1-S2_LowSS	4,29	53860,4	22488,2	96,753	6,11
FlexS1-S2_MidSS	0,26	61698,1	16746,2	99,699	6,18
FlexS1-S2_HighSS	0,05	69381,9	9235,23	99,962	6,24
S2BackupS1_MidSS	4,76	58240,8	17333,7	96,473	7,02
FlexS1-S3_LowSS	5,95	51153,8	25170,4	96,478	7,20
FlexS1-S3_MidSS	0,18	58771,1	19226,2	99,239	7,43
FlexS1-S3_HighSS	0,23	66288,7	12081,8	99,731	7,72
FlexS1-S2-S3_HighSS	28,76	62238,3	12864,9	95,499	7,78
S2BackupS1_HighSS	0,12	66241,5	12115,8	99,691	7,91
S3BackupS1_MidSS	5,34	54877,2	20863,2	96,262	9,89
Unit	days	$	$	%	#

7.3.4 Ranking Remaining Scenarios

This subchapter ranks the remaining 16 scenarios from best to worst. As we have already obtained the optimal weights across the KPIs in Subchapter 7.3.1, we do not have to perform the five steps of the BWM again. Table 7.21 calculates the overall scenario score by multiplying the normalized values for each scenario's KPIs with their respective weights. We present the table by sorting the overall scenario score from the best to the worst scenario.

***Table 7.21**: Overall scores of the 16 remaining scenarios*

Criterion	**Stockout Time**	**TC**	**NP**	**OTIF**	**LQ Delays**	**Overall score**
Weight:	0,070	0,105	0,344	0,316	0,165	
FlexS1-S2_MidSS	0,993	0,570	0,633	0,941	0,585	0,741
FlexS1-S3_MidSS	0,995	0,690	0,741	0,838	0,388	0,726
FlexS1-S2_LowSS	0,852	0,890	0,883	0,281	0,596	0,644
FlexS1-S3_LowSS	0,794	1,000	1,000	0,219	0,424	0,644
S1BackupS2_MidSS	0,974	0,306	0,341	0,830	0,926	0,633
FlexS1-S3_HighSS	0,994	0,383	0,430	0,948	0,342	0,614
FlexS1-S2_HighSS	1,000	0,257	0,306	1,000	0,576	0,613
S2BackupS1_HighSS	0,998	0,385	0,431	0,939	0,312	0,607
Supplier1_HighSS	0,935	0,442	0,470	0,503	1,000	0,598
Supplier1_MidSS	0,821	0,741	0,740	0,140	0,976	0,595
S1BackupS3_MidSS	0,944	0,405	0,428	0,601	0,872	0,590
S1BackupS3_HighSS	0,989	0,103	0,120	0,881	0,869	0,543
S1BackupS2_HighSS	0,997	0,000	0,000	0,992	0,893	0,531
S2BackupS1_MidSS	0,836	0,711	0,659	0,218	0,453	0,504
S3BackupS1_MidSS	0,816	0,848	0,812	0,171	0,000	0,480
FlexS1-S2-S3_HighSS	0,000	0,548	0,464	0,000	0,333	0,272

In the analysis of the 16 scenarios, we observed the following rankings based on the overall performance:

- The scenario with supplier 1 and supplier 2 contracted through a flexible sourcing strategy, paired with a medium level of safety stock at the manufacturer, emerged as the best-performing scenario.
- The second-best scenario is similar to the first, but with supplier 3 as the second supplier instead of supplier 2.
- The third and fourth places are also noteworthy, with supplier 1 and supplier 2 contracted through a flexible sourcing strategy as the third-best scenario. However, the manufacturer has a low safety stock level in these scenarios. For the fourth-best scenario, we see supplier 1 and supplier 3 with a flexible strategy and again with low safety stock.

Additionally, from a cost perspective:

- The third-best scenario incorporating supplier 1 and supplier 2 contracted through a flexible sourcing strategy, with a low safety stock level, has the lowest cost while yielding the highest net profit across all 16 scenarios.
- The scenarios with a backup strategy score lower due to higher costs for backup supply, which impacts the margin, resulting in low normalized scores for total costs and net profit. We also see that the backup supplier strategy scenarios utilize medium to high safety stock levels, resulting in higher costs and a lower overall score.

Furthermore, it is interesting that the scenario where all three suppliers are contracted with a flexible contract scores the worst. This result indicates that a diversified approach with a mix of two suppliers and sourcing strategies is more effective in mitigating risks and enhancing overall supply chain performance than contracting all available suppliers.

7.4 Comparison of Supplier Ranking and Model Output

When examining the single supplier scenarios and the scenarios that passed the threshold analysis, the initial point of discussion should be the underlying ranking methodology. Scenarios were ranked based on weights derived from the best worst method (BWM) for key performance indicators (KPIs). In the context of the polymer industry, supply chain professionals identified On-Time-In-Full (OTIF) Delivery and Net Profit as the crucial KPIs. However, it is worth noting that a different focus might have resulted in a different ranking, inviting a potential area of discussion.

Most scenarios involving a combination of suppliers 2 and 3 did not meet the threshold criteria. The principal reason was the increased production delays from sourcing lower-quality raw materials. These scenarios consistently exceeded the threshold of a maximum of 10 low-quality delays, further illustrating the impact of thresholds on ranking, constituting another discussion point.

Turning to the alignment between supplier ranking results and overall supply chain performance, there appears to be a strong correlation. Supplier 1 is consistently contracted in higher-ranking scenarios in single-sourcing situations, often coupled with a low safety stock level. This arrangement aligns with minimizing the internal inventory held at the manufacturer.

For multiple supplier sourcing, supplier 1 also features prominently in top-ranking scenarios. The optimal performing scenarios frequently employ a flexible sourcing strategy. The selection of the top-ranked suppliers appears to enhance system performance significantly. However, the type of strategies implemented alongside this selection also plays a vital role. The flexible sourcing strategy is the most effective approach to boosting overall supply chain performance. Its relative cost-effectiveness compared to the backup sourcing strategy and its inherent ability to distribute replenishment evenly across contracted suppliers and switch suppliers in case of disruption underpin this effectiveness.

Using top-ranked suppliers is common in scenarios with lower safety inventory levels, often combined with low-to-middle safety stock under a flexible sourcing strategy. Higher safety stock levels tend to impact margins adversely.

The alignment observed between the supplier ranking and top-performing scenarios reflects the supply chain professionals' preference for reliability over cost, which underpins the initial supplier ranking. If cost were prioritized, achieving such an alignment could be more challenging. Suppliers 2 or 3 might rank higher initially, but the model output would likely still indicate that better-performing scenarios are associated with the more reliable suppliers, as the relative importance of the KPIs would remain the same.

These findings underscore the versatility and precision of the methods employed in this research. Utilizing the BWM independently for supplier selection provides feasibility and streamlines the decision-making process by honing in on the most suitable suppliers for a specific case. This signifies that BWM is a valid standalone method when rapid evaluations are required.

In addition, the simulation model bridges the theoretical with the practical. While abstract concepts and strategies are debatable, this model grounds these discussions by examining tangible outcomes from various supplier configurations and sourcing strategies. Its adaptability to real-world data increases the validity of the findings and enhances its relevance as a decision-making tool for supply chain professionals. Thus, the combination of both the BWM and the simulation model in this thesis offers a holistic approach to supplier selection and supply chain optimization, providing both strategic insights and actionable results.

8. Discussion and Conclusion

This final chapter delves into various sourcing strategies, from contracting a single supplier guided by the best worst method to exploring redundancy and flexibility-oriented sourcing. Through comprehensive analysis, the study emphasizes the significance of strategic supplier selection, risk mitigation, and context-specific considerations in optimizing supply chain performance.

8.1 Interpretation and Synthesis

This section thoroughly examines the results of every sourcing and risk mitigation strategy. This analysis focuses on the implications of employing different sourcing strategies, namely the single supplier sourcing strategy, the backup supplier sourcing strategy, and the flexible sourcing strategy. Consequently, the discussion areas mentioned are synthesized to comprehend each strategy's consequences and importance within the supply chain performance and risk management framework.

8.1.1 Contracting a Single Supplier

Contracting a single supplier has proven to be a practical approach when guided by the best worst method (BWM) for supplier ranking. Implementing BWM allowed for a systematic evaluation of suppliers, resulting in a well-ordered ranking based on predefined criteria. This ranking facilitated the selection of the most reliable and efficient supplier for the supply chain.

In examining the scenarios, it was evident that the supplier ranked as number one, with low safety stock levels, performed exceptionally well. This finding underscores the importance of methodical supplier selection, as it directly contributed to achieving the best possible supply chain performance. Moreover, adopting this approach enabled the supply chain to maintain lower safety stock levels, thereby minimizing inventory carrying costs and improving overall efficiency.

The alignment between supplier selection by BWM and actual system performance within the polymer supply chain is noteworthy. The relation between the BWM ranking and the actual performance substantiates the reliability and effectiveness of this method in guiding supplier selection decisions. However, it is essential to acknowledge that the BWM survey was filled in by supply chain professionals working specifically in the polymer industry. Further research encompassing different industries and contexts would be imperative to establish its overall validity.

The results highlight the expertise of senior supply chain professionals in the polymer industry in setting priorities for supplier selection. Their ability to navigate disruptions and disturbances within the supply chain while prioritizing performance-enhancing factors showcases the strategic significance of supplier selection in achieving optimal supply chain performance.

8.1.2 Redundancy-oriented Sourcing Strategy

Contracting a backup supplier emerged as a viable risk mitigation strategy, yet it came with its considerations and trade-offs. Including a backup supplier was costly and did not yield the best performance results compared to other sourcing strategies. Additionally, scenarios involving a backup supplier necessitated medium to high levels of safety stock, which could incur higher inventory carrying and management costs and is not desired by decision-makers in the supply chain.

An intriguing finding was the absence of any scenario with a backup supplier strategy and low safety stock levels that met the threshold analysis criteria. This observation stands out, especially given that the flexibility strategy demonstrated superior performance with low to medium safety stock levels. This finding raises questions about the practicality and effectiveness of employing a backup supplier in scenarios with lower safety stock levels.

The logic behind the backup supplier strategy warrants exploring its implications fully. The strategy incorporates flexibility by allowing the manufacturer to wait for the available supplier if both contracted suppliers face disruptions. This aspect aims to maintain some level of continuity in the supply chain.

However, it is crucial to recognize that even a backup supplier can be susceptible to disruptions, and its availability cannot always be guaranteed. As a consequence, the performance of the supply chain, particularly concerning the On-Time-In-Full (OTIF) delivery KPI, would be significantly impacted if the backup supplier is consistently available.

Considering the potential uncertainties and costs associated with the backup supplier strategy, careful evaluation is necessary to balance risk mitigation and cost efficiency. While including a backup supplier adds an extra layer of risk mitigation, the trade-off regarding safety stock levels and costs must be thoroughly weighed against its benefits in reducing supply chain disruptions.

8.1.3 Flexibility-oriented Sourcing Strategy

The flexibility-oriented sourcing strategy emerged as the top-performing approach among the two sourcing strategies explored in our research. Notably, the four best-performing scenarios all involved contracts with a flexibility strategy, mainly when one supplier is based in Europe and the other in Asia.

An intriguing finding was that a combination of contracting the most reliable and best-ranked supplier using the best worst method (BWM) with a lower-ranked, less reliable supplier yielded the best performance outcomes. This combination also enabled the supply chain to maintain a lower safety stock level, a significant advantage in cost efficiency and inventory management. The top two scenarios, with medium safety stock levels, and the third and fourth scenarios, with low safety stock levels, all implemented the flexible supplier contracting setup.

Furthermore, flexibly contracting suppliers in two regions, specifically Europe and Asia, resulted in the best overall performance. This geographical diversification proved critical in minimizing the impact of environmental disruptions on supply chain operations. We noticed that scenarios exclusively contracted in Asia did not pass the threshold analysis due to the vulnerability to disruptions when both suppliers were affected. This finding highlights the importance of spreading the supplier base geographically to enhance supply chain performance.

The flexibility strategy's logic focuses on addressing supplier availability's practical challenges. In real-world scenarios, suppliers may not always be readily available to deliver more products, particularly during disruptions or fluctuations in demand. To overcome this challenge, developing contracts with suppliers that enable flexibility in adjusting order quantities and delivery schedules is crucial. Organizations can better navigate supply chain uncertainties and respond effectively to changing conditions by adopting open and adaptive supplier relationships.

8.1.4 Synthesis

Both redundancy and flexibility-oriented strategies are implemented to enhance the risk mitigation of supply chains in the face of disruptions on the supply side. One notable shared characteristic among these entities is their dedication to maintaining a continuous and uninterrupted flow of operations within the supply chain. The redundancy strategy aims to enhance supply chain performance by leveraging additional suppliers, which may increase safety stock levels. On the other hand, the flexibility strategy focuses on establishing adaptable relationships with suppliers, enabling adjustments in order quantities and delivery schedules. The interaction between the two variables becomes apparent when striving to achieve lower safety stock levels. Flexibility-oriented strategies consistently exhibit superior outcomes, while redundancy strategies require higher stock levels, raising doubts about effectiveness in contexts prioritizing lean inventory management. Both strategies aim to achieve efficient supply chain operations in the face of disruptions. However, it is crucial to comprehensively understand and evaluate each approach to manage and reduce risks effectively.

The case study focused on a tendency towards reduced safety inventory driven by cost and resource optimization considerations. Large internal stockpiles constrain organizational agility and may increase financial demands, particularly in managing various product assortments. Therefore, supply chain managers strategically reduce safety stock levels in order to achieve a balance between operational efficiency and risk mitigation.

Utilizing the flexibility sourcing strategy, in conjunction with the best worst method for supplier selection, results in achieving desired low safety stock levels. Implementing a well-organized selection process, supported by established metrics of historical reliability, plays a crucial role in identifying the most reliable suppliers, consequently enhancing the efficiency of the supply chain.

Within the polymer industry, senior professionals in the supply chain field possess the skill to prioritize their selection criteria, ensuring that their choices align with the desired performance metrics for the supply chain. The alignment between BWM-driven selection and DES-model performance underscores the significance of this approach in the polymer supply chain. However, the particularity of this alignment regarding this specific case, combined with the cautious nature of the BWM participant, highlights the need for expanded research in diverse contexts to achieve more widespread applicability.

Supplier reliability has emerged as a prominent aspect in selecting suppliers. The incorporation of key performance indicators by BWM, focusing on metrics such as On-Time-In-Full (OTIF) and Net Profit, influenced the selection of suppliers and shaped the composition of the most successful scenarios. Acknowledging that the significance attributed to key performance indicators can vary in different contexts is crucial. This is because decision-makers may prioritize different KPIs, such as cost, quality, or stock levels, depending on industry-specific nuances, organizational goals, or specific requirements within the supply chain.

When examining the intricacies of threshold analysis, modifying the threshold values has the potential to generate diverse outcomes. For example, suppliers 2 and 3 become acceptable in the given scenarios by removing the low-quality delay threshold. However, such configurations may expose the supply chain to regional disruptions, thus highlighting the advantages of having geographically diversified suppliers.

In conclusion, the systematic process of selecting suppliers, combined with implementing risk mitigation strategies, plays a crucial role in improving the overall performance of the supply chain. While strategies such as supplier contracting and safety stock analysis are essential, decision-makers' unique characteristics and preferences in specific situations highlight the necessity of customized assessments and continuous evaluations of supplier performance to uphold supply chain excellence.

8.2 Implications

This chapter underscores our research's broader societal, managerial, and scientific implications, emphasizing the impact of systematic supplier selection and risk mitigation on global supply chains, business practices, and the academic field of supply chain risk management.

8.2.1 Societal Implications

One of the societal implications of our research is that by promoting a systematic approach to supplier selection, we contribute to building supply chains that are better prepared to withstand disturbances and disruptions, not only within the polymer industry but across various sectors. As supply chains become better prepared for disturbances and disruptions, they can ensure a stable flow of essential goods and services to communities worldwide. This enhanced preparedness supports critical industries like healthcare, food, and medical supplies, leading to improved access to vital resources during times of crisis. By mitigating the risks posed by unforeseen challenges, our research encourages societal well-being by enabling supply chains to function efficiently, supporting economic continuity, and safeguarding the welfare of people globally (Raj et al., 2022).

Another societal implication of our research is the emphasis on global collaboration in supply chain management. Our findings indicate that relying solely on nearby suppliers in the same region may be less effective in coping with disturbances and disruptions. In contrast, having alternative suppliers in different regions of the world proves to be more effective in maintaining a supply chain's performance under the risk of disruptions. By encouraging global collaboration, businesses can diversify their supply sources and enhance supply chain flexibility. Global collaboration reduces dependencies on a single region and enables companies to switch to alternative suppliers during times of crisis. Moreover, encouraging collaboration across borders facilitates knowledge sharing and technological transfer (Rammal et al., 2023), leading to more innovative risk mitigation strategies.

Our research supports two United Nations Sustainable Development Goals (SDGs): Goal 9: Industry, Innovation, and Infrastructure, and Goal 12: Responsible Consumption and Production (United Nations, 2023). Within the context of the polymer industry, we dedicated our research to improving supply chain performance under supply-side disruption risk. Aligned with SDG 9, our research seeks to enhance the overall industrial infrastructure within the polymer sector. By employing the best worst method and various risk mitigation strategies, we aim to make supply chains more adaptable to disturbances and disruptions and better equipped to withstand challenges in an ever-changing global landscape. In alignment with SDG 12, while we may not explicitly include sustainability criteria, our research contributes to responsible consumption and production practices through a more efficient supply chain approach. By minimizing excess inventory and optimizing material flows, our work supports reducing waste and resource usage, thus indirectly promoting sustainable production patterns.

8.2.2 Managerial Implications

Adopting a structured supplier selection process, such as the best worst method in multi-criteria decision-making (MCDM), is imperative for enhancing supply chain performance, considering the risk of disturbances and disruptions. With methodical supplier selection, thoughtful sourcing strategies, and proactive measures to address contract flexibility challenges, businesses can achieve a more efficient, agile, and reliable supply chain, poised to navigate disruptions and maintain competitive advantage in a dynamic supply chain landscape.

Leveraging methodologies like the best worst method or other multi-criteria decision-making (MCDM) techniques is crucial to ensure a more systematic and practical supplier selection process. Our research identified that the current supplier selection practices often lack this structured approach, highlighting the significance of employing MCDM for comprehensively assessing supplier capabilities. Our findings underscored the vital role of supplier selection in optimizing supply chain performance, especially when facing disturbances and disruptions in the supply chain. Implementing a systematic MCDM-based supplier selection approach can significantly enhance the performance and efficiency of the supply chain.

A methodological supplier selection process can result in lower safety stock levels, which has several advantages. Organizations can improve their agility and reduce the financial burden on budgets by reducing the need for excessive internal stocks, as a diverse range of products represented in inventories can be costly to maintain. As a result, managers are incentivized to avoid keeping high levels of safety stock, resulting in a more efficient and agile supply chain.

Incorporating a geographically diverse supplier base should be a strategic consideration for supply chain managers. By strategically choosing suppliers in different regions, companies can reduce their dependence on a single geographical area and distribute risk across various locations. In case of environmental disruption, having suppliers in unaffected areas allows the supply chain to continue functioning with minimal interruptions.

Tailoring the sourcing strategy to align with the specific needs of the supply chain is crucial for success. While considering multiple suppliers may seem advantageous, our research revealed that contracting with more than two suppliers may not always be cost-efficient and may not outweigh the performance benefits. Supply chain managers should carefully assess the trade-offs associated with multiple contracts to strike the right balance. Our developed simulation model is an invaluable decision-making tool, enabling managers to explore different scenarios and identify the best set of suppliers that yield the best possible supply chain performance based on real-world data about suppliers' delivery performance. Communicating the findings of this research as part of budgetary allocation is crucial. Supply chain managers should present the costs of maintaining an additional supplier and the performance improvements achieved through this approach. This practice will facilitate stakeholders in comprehending the reasoning behind the selected risk mitigation strategy and making well-informed decisions regarding resource allocation.

In dealing with the challenges of flexible contracts, supply chain managers can adopt proactive measures to mitigate potential disruptions. Managers should foster open communication and collaboration with suppliers to address the assumption that a flexibly contracted supplier can quickly replenish another disrupted supplier's amount. Managers can better understand their suppliers' capabilities and limitations by sharing production and inventory planning information. Also, fostering strong relationships with suppliers can lead to mutual understanding and joint contingency plans, allowing the supply chain to respond more effectively to unexpected disturbances and disruptions and maintain flexibility.

8.2.3 Scientific Implications

The scientific implications of this research are profound and offer significant contributions to supply chain risk management. Firstly, by proving the efficacy of the best worst method (BWM) for supplier selection, as Rezaei et al. (2016) advocated, this study establishes a robust foundation for practitioners and researchers to adopt systematic and data-driven approaches in supplier evaluation. The validation of the

BWM's suitability as a multi-criteria decision-making (MCDM) method ensures that supply chain decision-makers can confidently rely on this method to make well-informed choices regarding suppliers, ultimately enhancing the supply chain's efficiency and performance.

Moreover, the discovery that the strategies most effective at reducing the impact of disturbances and disruptions are not necessarily the most costly ones introduces a shift in traditional risk management practices. The revelation that flexible sourcing strategies outperform redundancy-oriented approaches, as supported by Shashi et al. (2019), encourages supply chain managers to rethink their risk mitigation strategies. Emphasizing flexibility over redundancy can lead to more agile and adaptable supply chains, allowing businesses to respond swiftly and efficiently to unexpected disruptions without incurring excessive costs.

In line with Ivanov (2021) and Tang & Tomlin (2008), who emphasized the importance of flexible supply chains in risk mitigation, our research applies these insights by determining the most effective strategy through rigorous simulation modeling. We comprehensively evaluate their impacts by incorporating redundancy and flexibility-oriented strategies into the analysis. The demonstration that a flexibility-oriented approach outperforms redundancy strategies reaffirms flexibility's importance as a core principle in modern supply chain risk management.

This research equips supply chain managers with actionable insights by providing empirical evidence that suppliers contracted using a flexible sourcing strategy significantly boost risk mitigation while being more cost-effective than maintaining high safety stock levels or relying heavily on backup suppliers. These findings lead to a more informed decision-making process when selecting suppliers and devising risk management strategies, culminating in a supply chain better prepared to withstand disruptions and more agile and competitive in the dynamic market landscape.

8.3 Conclusion, Limitations, and Future Research

In this chapter, we delve into the conclusive findings derived from our exploration of methodical supplier selection and risk mitigation's impact on supply chain performance, followed by highlighting limitations and areas for future research.

8.3.1 Conclusion

The study explored the impact of a methodical approach to supplier selection and the most effective risk mitigation strategy on supply chain performance in the presence of supply-side disruption risks. Through a series of sub-research questions, we have delved into various aspects of supplier selection, risk mitigation, and supply chain modeling. Now, we can address the main research question:

"How does a methodical approach to supplier selection, combined with the most effective risk mitigation strategy, impact supply chain performance in the presence of supply-side disruption risks?"

Our findings provide valuable insights into the relationship between supplier selection, risk mitigation strategies, and supply chain performance. The key conclusions derived from the study are:

Risks and Risk Mitigation Measures: The main challenges and risks in the supply chain primarily arise from the supply side, encompassing supplier disruptions, environmental disruptions, prolonged lead times, and internal manufacturer failures. Risk mitigation measures such as backup sourcing, varying safety stock levels, and flexible contracts with suppliers are commonly employed to tackle these uncertainties.

Supplier Selection Criteria and KPIs: The essential criteria for supplier selection in the polymer industry were identified as Quality of Materials, Reliability of Supply, Price, and Lead Time. Crucial KPIs measuring overall supply chain performance include On-Time In-Full Delivery, Net Profit, Total Cost, Stockout Time, and Low-Quality Delays. The relative importance assigned to these criteria and KPIs by industry professionals was determined using the best worst method (BWM).

Supply Chain Modeling: Developing a Discrete-Event Simulation model in Simio allowed us to effectively quantify and represent a supply chain with multiple suppliers, disturbances, and disruptions. The integration of redundancy- and flexibility-oriented strategies in the model facilitated the assessment of their impact on risk mitigation and supply chain performance.

Alignment of Methodical Supplier Ranking: The BWM effectively ranked suppliers based on their performance criteria, and this ranking aligned with the suppliers selected in the best-performing scenarios. Selecting higher-ranked suppliers through the BWM lowered safety stock levels when the suppliers were flexibly contracted.

Performance Differences and Trade-offs: The flexibility-oriented sourcing strategy proved more effective in mitigating disturbances and disruptions than the redundancy-oriented strategy. The best-performing scenario involved flexible contracts with the highest-ranked suppliers and medium safety stock levels.

Finally, our study demonstrates that a methodical approach to supplier selection, explicitly utilizing the BWM and a flexibility-oriented sourcing strategy, leads to the best possible supply chain performance when facing supply-side disturbances and disruptions. However, it is essential to recognize that the relative importance assigned to the supplier selection criteria and the key performance indicators may vary in different contexts or cases, potentially impacting the composition of the best-ranking suppliers and best-performing scenarios.

8.3.2 Limitations

While our research presents valuable insights into supplier selection and risk mitigation in the supply chain, it is essential to acknowledge certain limitations that provide opportunities for future research and continuous improvement in supply chain risk management.

Data Constraints: One of the limitations of our research is the reliance on data obtained from expert interviews. While we validated the simulation model and findings with senior professionals at Deloitte, the data collection process was restricted to this method. Company-specific data, crucial for a comprehensive analysis, was not accessible due to confidentiality concerns. Moreover, gathering company data proves to be challenging, as it often requires a lengthy process of approval and coordination.

Supply-Side Focus: Our research primarily concentrated on supply-side risk mitigation in polymer supply chains. While this approach provides valuable insights into enhancing supply-sided risk mitigation, it does not encompass demand-sided disturbances and disruptions. The exclusion of demand-related factors may limit the comprehensive understanding of the overall risk landscape faced by supply chains.

Limitations of the best worst method (BWM): The BWM used for supplier selection and supply chain performance measurement has limitations. The method's criteria for measuring supply chain performance, such as total cost and net profit, are not independent. Tavana et al. (2023) underscore this limitation by asserting that, although BWM is a popular and dependable method, its traditional form assumes the decision criteria are independent. This assumption is a critical oversight, especially since real-world scenarios often involve intricate interdependencies between decision criteria.

Reliability of Supplier Data: The BWM requires information on supplier reliability and delivery performance over extended periods. However, such historical data might not always be readily available, making it challenging to assess and rank suppliers accurately. Relying on limited or incomplete supplier performance data could affect the robustness of the BWM model's outcomes.

8.3.3 Future Research

Our research lays the groundwork for several future research avenues in supply chain risk management. To further enhance the practical application and relevance of our findings, we propose the following areas for future research:

Measuring True Resilience KPIs: Future research could focus on developing and implementing true resilience Key Performance Indicators (KPIs) to evaluate supply chain resilience accurately. By using real-world data and incorporating performance metrics that truly reflect supply chain robustness, researchers can gain deeper insights into the actual resilience levels of supply chains.

Exploring Supplier Contract Rules: Investigating different combinations of rules for setting up backup and flexible supplier contracts based on real-world data would be valuable. This research could explain optimal contract structures that maximize supply chain adaptability and minimize disruptions.

Model Extension and Generalizability: Future research can explore ways to extend or generalize the model with basic knowledge of the Simio software to improve the applicability of the simulation model. The extension could involve incorporating more materials into the model and utilizing the aggregation phase of the BWM for supplier selection to enable a broader scope of supply chain scenarios.

Incorporating Sustainability Criteria: As sustainability becomes a critical consideration in supply chain management, future research should incorporate sustainability criteria for supplier selection. By integrating environmental, social, and governance (ESG) factors, supply chains can make more responsible and sustainable decisions, aligning with global sustainability objectives.

Addressing Demand-Side Disruptions: Considering demand-sided disruptions would provide a more comprehensive analysis of supply chain risks. Future research can explore how sudden changes in demand, tendering offers, and other demand-related factors can impact supply chain performance.

List of References

Afifa, Y. N., & Santoso, I. (2022). Proactive risk mitigation strategies and building strategic resilience in the food supply chain: a review. *Food Research*, *6*(2), 9–17. https://doi.org/10.26656/fr.2017.6(2).257

Aldrighetti, R., Battini, D., & Ivanov, D. (2021). Increasing supply chain resilience through efficient redundancy allocation: a risk-averse mathematical model. *IFAC-PapersOnLine*, *54*(1), 1011–1016. https://doi.org/10.1016/j.ifacol.2021.08.120

Baghalian, A., Rezapour, S., & Farahani, R. Z. (2013). Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case. *European Journal of Operational Research*, *227*(1), 199–215. https://doi.org/10.1016/j.ejor.2012.12.017

Banaeian, N., Mobli, H., Fahimnia, B., Nielsen, I., & Omid, M. (2018). Green supplier selection using fuzzy group decision making methods: A case study from the agri-food industry. *Computers & Operations Research*, *89*, 337–347. https://doi.org/10.1016/j.cor.2016.02.015

Carvalho, H., Barroso, A. P., Machado, V., Azevedo, S. G., & Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Business Strategy and the Environment, Early View*, *62*(1), 329–341. https://doi.org/10.1016/j.cie.2011.10.003

ChemAnalyst. (2021). *Polymer Market Size, Growth | Global Report, 2030*. https://www.chemanalyst.com/industry-report/polymer-market-306

Chen, K., & Xiao, T. (2015). Outsourcing strategy and production disruption of supply chain with demand and capacity allocation uncertainties. *International Journal of Production Economics*, *170*, 243–257. https://doi.org/10.1016/j.ijpe.2015.09.028

Chopra, S., & Sodhi, M. S. (2004). Managing Risk To Avoid Supply-Chain Breakdown. *MIT Sloan Management Review*, *46*(1), 53–61. https://www.tlog.lth.se/fileadmin/tlog/Chopra_and_Sodhi_2004.pdf

Christopher, M., & Peck, H. (2004). Building the Resilient Supply Chain. *The International Journal of Logistics Management*, *15*(2), 1–14. https://doi.org/10.1108/09574090410700275

Cigolini, R., Pero, M., Rossi, T., & Sianesi, A. (2014). Linking supply chain configuration to supply chain performance: A discrete event simulation model. *Simulation Modelling Practice and Theory*, *40*, 1–11. https://doi.org/10.1016/j.simpat.2013.08.002

Esmaeili-Najafabadi, E., Azad, N., & Nezhad, M. S. F. (2021). Risk-averse supplier selection and order allocation in the centralized supply chains under disruption risks. *Expert Systems With Applications*, *175*, 114691. https://doi.org/10.1016/j.eswa.2021.114691

Esmaeili-Najafabadi, E., Nezhad, M. S. F., Pourmohammadi, H., Honarvar, M., & Vahdatzad, M. A. (2019). A joint supplier selection and order allocation model with disruption risks in a centralized supply chain. *Computers & Industrial Engineering*, *127*, 734–748. https://doi.org/10.1016/j.cie.2018.11.017

Fang, H., Li, C., & Xiao, R. (2012). Supply chain network design based on brand differentiation and resilient management. *Journal of Information and Computational Science*, *9*(14), 3977–3986. https://www.researchgate.net/publication/289407583_Supply_chain_network_design_based_on_brand_differentiation_and_resilient_management

Gao, H., Ju, Y., Gonzalez, E. D. S., & Zhang, W. (2020). Green supplier selection in electronics manufacturing: An approach based on consensus decision making. *Journal of Cleaner Production*, *245*, 118781. https://doi.org/10.1016/j.jclepro.2019.118781

Ghadge, A., Dani, S., & Kalawsky, R. S. (2012). Supply chain risk management: present and future scope. *The International Journal of Logistics Management*, *23*(3), 313–339. https://doi.org/10.1108/09574091211289200

Giri, B. C., & Bardhan, S. (2014). Coordinating a supply chain with backup supplier through buyback contract under supply disruption and uncertain demand. *International Journal of Systems Science: Operations & Logistics*, *1*(4), 193–204. https://doi.org/10.1080/23302674.2014.951714

Gunasekaran, A., Subramanian, N., & Rahman, S. (2015). Supply chain resilience: role of complexities and strategies. *International Journal of Production Research*, *53*(22), 6809–6819. https://doi.org/10.1080/00207543.2015.1093667

Hamdi, F., Ghorbel, A., Masmoudi, F., & Dupont, L. (2015). Optimization of a supply portfolio in the context of supply chain risk management: literature review. *Journal of Intelligent Manufacturing*, *29*(4), 763–788. https://doi.org/10.1007/s10845-015-1128-3

Hosseini, S., & Barker, K. (2016). A Bayesian network model for resilience-based supplier selection. *International Journal of Production Economics*, *180*, 68–87. https://doi.org/10.1016/j.ijpe.2016.07.007

Hosseini, S. M., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E-logistics and Transportation Review*, *125*, 285–307. https://doi.org/10.1016/j.tre.2019.03.001

Ivanov, D. (2021). *Introduction to Supply Chain Resilience: Management, Modelling, Technology*. Springer.

Ivanov, D., Sokolov, B., & Dolgui, A. (2014). The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management. *International Journal of Production Research*, *52*(7), 2154–2172. https://doi.org/10.1080/00207543.2013.858836

Jain, N., & Singh, A. (2020). Sustainable supplier selection under must-be criteria through Fuzzy inference system. *Journal of Cleaner Production*, *248*, 119275. https://doi.org/10.1016/j.jclepro.2019.119275

Jüttner, U., & Maklan, S. (2011). Supply chain resilience in the global financial crisis: an empirical study. *Supply Chain Management*, *16*(4), 246–259. https://doi.org/10.1108/13598541111139062

Jüttner, U., Peck, H., & Christopher, M. (2010). Supply chain risk management: outlining an agenda for future research. *International Journal of Logistics*, *6*(4), 197–210. https://doi.org/10.1080/13675560310001627016

Kamalahmadi, M., & Parast, M. M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. *International Journal of Production Economics*, *171*, 116–133. https://doi.org/10.1016/j.ijpe.2015.10.023

Kamalahmadi, M., & Parast, M. M. (2017). An assessment of supply chain disruption mitigation strategies. *International Journal of Production Economics*, *184*, 210–230. https://doi.org/10.1016/j.ijpe.2016.12.011

Kamalahmadi, M., Shekarian, M., & Parast, M. M. (2022). The impact of flexibility and redundancy on improving supply chain resilience to disruptions. *International Journal of Production Research*, *60*(6), 1992–2020. https://doi.org/10.1080/00207543.2021.1883759

Kelton, W. D., Smith, J. S. ., & Sturrock, D. T. . (2013). *Simio and simulation: Modeling, Analysis, Applications*. Createspace Independent Publishing Platform.

Keskin, B. B., Íster, H., & Çetinkaya, S. (2010). Integration of strategic and tactical decisions for vendor selection under capacity constraints. *Computers & Operations Research*, *37*(12), 2182–2191. https://doi.org/10.1016/j.cor.2010.03.008

Khan, M. M., Bashar, I., Minhaj, G. M., Wasi, A. I., & Hossain, N. U. I. (2023). Resilient and sustainable supplier selection: an integration of SCOR 4.0 and machine learning approach. *Sustainable and Resilient Infrastructure*, 1–17. https://doi.org/10.1080/23789689.2023.2165782

Khan, S. A., Kusi-Sarpong, S., Naim, I., Ahmadi, H., & Oyedijo, A. (2021). A best-worst-method-based performance evaluation framework for manufacturing industry. *Kybernetes*, *51*(10), 2938–2963. https://doi.org/10.1108/k-03-2021-0202

King, P. L. (2011, July). Understanding safety stock and mastering its equations. *APICS Online*. https://web.mit.edu/2.810/www/files/readings/King_SafetyStock.pdf

Kleindorfer, P. R., & Saad, G. H. (2005). Managing disruption risks in supply chains. *Production and Operations Management*, *14*(1), 53–68. https://doi.org/10.1111/j.1937-5956.2005.tb00009.x

Kumar, M., Basu, P., & Avittathur, B. (2017). Pricing and sourcing strategies for competing retailers in supply chains under disruption risk. *European Journal of Operational Research*, *265*(2), 533–543. https://doi.org/10.1016/j.ejor.2017.08.019

Liang, F., Brunelli, M., & Rezaei, J. (2020). Consistency issues in the best worst method: Measurements and thresholds. Omega, 96, 102175. https://doi.org/10.1016/j.omega.2019.102175

Mackay, J., Munoz, A., & Pepper, M. (2019). Conceptualising redundancy and flexibility towards supply chain robustness and resilience. *Journal of Risk Research*, *23*(12), 1541–1561. https://doi.org/10.1080/13669877.2019.1694964

Manuj, I., & Mentzer, J. T. (2008). Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management*, *38*(3), 192–223. https://doi.org/10.1108/09600030810866986

Mendoza, A., & Ventura, J. A. (2010). A serial inventory system with supplier selection and order quantity allocation. *European Journal of Operational Research*, *207*(3), 1304–1315. https://doi.org/10.1016/j.ejor.2010.06.034

Pazhani, S., Ventura, J. A., & Mendoza, A. (2016). A serial inventory system with supplier selection and order quantity allocation considering transportation costs. *Applied Mathematical Modelling*, *40*(1), 612–634. https://doi.org/10.1016/j.apm.2015.06.008

Pellegrino, R., & Carbonara, N. (2017). How do supply chain risk management flexibility-driven strategies perform in mitigating supply disruption risks? *International Journal of Integrated Supply Management*, *11*(4), 354. https://doi.org/10.1504/ijism.2017.10010917

P&S Intelligence. (2022). Polymer market. In *P&S Intelligence*. https://www.psmarketresearch.com/market-analysis/polymer-market

Raj, A., Mukherjee, A. A., De Sousa Jabbour, A. B. L., & Srivastava, S. K. (2022). Supply chain management during and post-COVID-19 pandemic: Mitigation strategies and practical lessons learned. *Journal of Business Research*, *142*, 1125–1139. https://doi.org/10.1016/j.jbusres.2022.01.037

Rammal, H. G., Rose, E. L., & Ferreira, J. (2023). Managing cross-border knowledge transfer for innovation: An introduction to the special issue. *International Business Review*, *32*(2), 102098. https://doi.org/10.1016/j.ibusrev.2022.102098

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, *53*, 49–57. https://doi.org/10.1016/j.omega.2014.11.009

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, *64*, 126–130. https://doi.org/10.1016/j.omega.2015.12.001

Rezaei, J. (2020). A Concentration Ratio for Nonlinear Best Worst Method. *International Journal of Information Technology & Decision Making*, *19*(03), 891–907. https://doi.org/10.1142/s0219622020500170

Rezaei, J., Nispeling, T., Sarkis, J., & Tavasszy, L. (2016). A supplier selection life cycle approach integrating traditional and environmental criteria using the best worst method. *Journal of Cleaner Production*, *135*, 577–588. https://doi.org/10.1016/j.jclepro.2016.06.125

Rice, J. R., & Sheffi, Y. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review*, *47*(1), 41–48. https://dialnet.unirioja.es/servlet/articulo?codigo=1328931

Rinaldi, M., Murino, T., Gebennini, E., Morea, D., & Bottani, E. (2022). A literature review on quantitative models for supply chain risk management: Can they be applied to pandemic disruptions? *Computers & Industrial Engineering*, *170*, 108329. https://doi.org/10.1016/j.cie.2022.108329

Ruiz-Torres, A. J., & Mahmoodi, F. (2006). A supplier allocation model considering delivery failure, maintenance and supplier cycle costs. *International Journal of Production Economics*, *103*(2), 755–766. https://doi.org/10.1016/j.ijpe.2005.09.008

Sawik, T. (2005). A cyclic versus flexible approach to materials ordering in make-to-order assembly. *Mathematical and Computer Modelling*, *42*(3–4), 279–290. https://doi.org/10.1016/j.mcm.2005.03.002

Sawik, T. (2013). Selection of resilient supply portfolio under disruption risks. *Omega*, *41*(2), 259–269. https://doi.org/10.1016/j.omega.2012.05.003

Sawik, T. (2014). Joint supplier selection and scheduling of customer orders under disruption risks: Single vs. dual sourcing. *Omega*, *43*, 83–95. https://doi.org/10.1016/j.omega.2013.06.007

Sawik, T. (2015). Integrated Supply Chain Scheduling under Multi-Level Disruptions. *IFAC-PapersOnLine*, *48*(3), 1515–1520. https://doi.org/10.1016/j.ifacol.2015.06.301

Sawik, T. (2017). A portfolio approach to supply chain disruption management. *International Journal of Production Research*, *55*(7), 1970–1991. https://doi.org/10.1080/00207543.2016.1249432

Sawik, T. (2021). On the risk-averse selection of resilient multi-tier supply portfolio. *Omega*, *101*, 102267. https://doi.org/10.1016/j.omega.2020.102267

Schmitt, A. J. (2011). Strategies for customer service level protection under multi-echelon supply chain disruption risk. *Transportation Research Part B-methodological*, *45*(8), 1266–1283. https://doi.org/10.1016/j.trb.2011.02.008

Schmitt, A. J., & Singh, M. (2012). A quantitative analysis of disruption risk in a multi-echelon supply chain. *International Journal of Production Economics*, *139*(1), 22–32. https://doi.org/10.1016/j.ijpe.2012.01.004

Schmitt, A. J., Sun, S. A., Snyder, L., & Shen, Z. M. (2015). Centralization versus decentralization: Risk pooling, risk diversification, and supply chain disruptions. *Omega*, *52*, 201–212. https://doi.org/10.1016/j.omega.2014.06.002

Shashi, Centobelli, P., Cerchione, R., & Ertz, M. (2019). Managing supply chain resilience to pursue business and environmental strategies. *Business Strategy and the Environment*, *29*(3), 1215–1246. https://doi.org/10.1002/bse.2428

Shishodia, A., Sharma, R., Rajesh, R., & Munim, Z. H. (2021). Supply chain resilience: A review, conceptual framework and future research. *The International Journal of Logistics Management*. https://doi.org/10.1108/ijlm-03-2021-0169

Simio LLC. (2022). *The Story of Simio*. Simio | Forward Thinking. https://www.simio.com/about-simio/

Sodhi, M. S., & Tang, C. S. (2012). Managing Supply Chain Risk. In *International series in management science/operations research*. Springer Science+Business Media. https://doi.org/10.1007/978-1-4614-3238-8

Taherdoost, H., & Brard, A. (2019). Analyzing the Process of Supplier Selection Criteria and Methods. *Procedia Manufacturing*, *32*, 1024–1034. https://doi.org/10.1016/j.promfg.2019.02.317

Tako, A. A., & Robinson. (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems*, *52*(4), 802–815. https://doi.org/10.1016/j.dss.2011.11.015

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics*, *103*(2), 451–488. https://doi.org/10.1016/j.ijpe.2005.12.006

Tang, C. S., & Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics*, *116*(1), 12–27. https://doi.org/10.1016/j.ijpe.2008.07.008

Taticchi, P., Garengo, P., Nudurupati, S. S., Tonelli, F., & Pasqualino, R. (2014). A review of decision-support tools and performance measurement and sustainable supply chain management. *International Journal of Production Research*, *53*(21), 6473–6494. https://doi.org/10.1080/00207543.2014.939239

Tavana, M., Mina, H., & Santos-Arteaga, F. J. (2023). A general Best-Worst method considering interdependency with application to innovation and technology assessment at NASA. *Journal of Business Research*, *154*, 113272. https://doi.org/10.1016/j.jbusres.2022.08.036

Tomlin, B. (2006). On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*, *52*(5), 639–657. https://doi.org/10.1287/mnsc.1060.0515

Tomlin, B. (2009). Disruption-management strategies for short life-cycle products. *Naval Research Logistics*, *56*(4), 318–347. https://doi.org/10.1002/nav.20344

United Nations. (2023). *Sustainable Development Goals*. https://sdgs.un.org/goals

Vázquez-Serrano, J. I., Peimbert-García, R. E., & Cárdenas-Barrón, L. E. (2021). Discrete-event simulation modeling in Healthcare: A Comprehensive review. *International Journal of Environmental Research and Public Health*, *18*(22), 12262. https://doi.org/10.3390/ijerph182212262

Weber, C. A., & Current, J. R. (1993). A multiobjective approach to vendor selection. *European Journal of Operational Research*, *68*(2), 173–184. https://doi.org/10.1016/0377-2217(93)90301-3

Wieland, A., & Wallenburg, C. M. (2012). Dealing with supply chain risks. *International Journal of Physical Distribution & Logistics Management*, *42*(10), 887–905. https://doi.org/10.1108/09600031211281411

Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: a relational view. *International Journal of Physical Distribution & Logistics Management*, *43*(4), 300–320. https://doi.org/10.1108/ijpdlm-08-2012-0243

Xu, L., Mak, S. Y. F., & Brintrup, A. (2021). Will bots take over the supply chain? Revisiting agent-based supply chain automation. *International Journal of Production Economics*, *241*, 108279. https://doi.org/10.1016/j.ijpe.2021.108279

Yang, B., & Yang, Y. (2009). Postponement in supply chain risk management: a complexity perspective. *International Journal of Production Research*, *48*(7), 1901–1912. https://doi.org/10.1080/00207540902791850

Yazdi, A. K., Mehdiabadi, A., Wanke, P., Monajemzadeh, N., Correa, H. L., & Tan, Y. (2022). Developing supply chain resilience: a robust multi-criteria decision analysis method for transportation service provider selection under uncertainty. *International Journal of Management Science and Engineering Management*, *18*(1), 51–64. https://doi.org/10.1080/17509653.2022.2098543

Yu, H., Zeng, A. Z., & Zhao, L. (2009). Single or dual sourcing: decision-making in the presence of supply chain disruption risks. *Omega*, *37*(4), 788–800. https://doi.org/10.1016/j.omega.2008.05.006

Appendix A: Expert Interview Framework

We conducted expert interviews with senior supply chain professionals in the polymer industry. These individuals were identified and approached through the client network of Deloitte's Supply Chain & Network Operations practice. Their respective companies had a revenue range from $1 billion to $600 billion.

Here is a brief profile of the professionals interviewed:

1. **Global Supply Chain Director**: This expert had a rich experience spanning 12 years in the supply chain domain.
2. **Logistics Operations & Procurement Director**: With 15 years of experience, this individual brought in-depth insights into logistics operations and procurement strategies.
3. **Supply Chain & Digitization Manager**: Having 16 years of experience, this professional provided valuable information regarding the integration of digitization within supply chains.
4. **Global Director of Supply Chain Network Management**: With a vast 17 years of experience, insights from this individual contributed significantly to our understanding of global supply chain networks.

Interview Process:

- **Mode**: Each interview was conducted via an online call.
- **Duration**: Approximately one hour was dedicated to each interview.
- **Focus**: The main focus of the interviews was to gather primary data on the intricacies of supply chain strategies, with special attention to the polymer industry.

Due to the confidentiality agreements in place, summaries or detailed transcripts of these interviews cannot be provided in this research. Nevertheless, the insights gathered from these discussions have greatly informed the findings presented in the main body of the research.

***Table A.1**: Expert interview framework*

Section	Interview Questions
Background & Role	1. Could you please introduce yourself and briefly describe your role in your company and industry?
Challenges	2. Could you share some significant challenges your organization faces in managing the supply chain?
	3. Can you provide an instance where you had to manage a significant disruption or risk in your supply chain? What was the outcome?
Key Processes & KPIs	4. Could you provide a high-level overview of the key processes involved in your company's supply chain?
	5. What are the most important KPIs your organization uses to measure supply chain performance and why?
Supplier Selection Criteria	6. When it comes to selecting suppliers for your organization, what are the key criteria or factors you consider? How do you prioritize them?
	7. Are there any specific resiliency-oriented or environmental considerations that influence your supplier selection process?
Trends	8. From your perspective, what are the critical trends impacting your industry's supply chains?
Risk Management	9. How does your organization identify potential risks and vulnerabilities in your supply chain?
	10. What measures or strategies have been implemented to manage these identified risks?
	11. How does your organization balance the costs and benefits of implementing risk mitigation strategies?

Section	Interview Questions
Resilience	12. How does your organization measure resilience within your supply chain? Are there specific KPIs for this? 13. Could you share an example of a risk event that significantly impacted your supply chain, and how your company managed and recovered from it?
Advice & Recommendations	14. In terms of enhancing resilience and reducing risk, what role does flexibility (sourcing from multiple suppliers) and redundancy (backup suppliers and keeping safety stock) play in your supply chain management strategy? 15. In terms of enhancing resilience and reducing risk, how do the supplier selection criteria contribute to these goals? 16. Do you have any advice or insights you’d like to share with me about supply chain risks and resilience in your industry?
Additional Information	17. Is there anything else you'd like to add that we haven't already discussed?

Appendix B: BWM Survey

Supplier Selection & Supply Chain KPIs

Start of Block: Supplier Selection

Q1 Dear Participant,

We appreciate your participation in this survey. Your input will significantly contribute to understanding the relative importance of different Key Performance Indicators (KPIs) in supply chain management and various criteria in supplier selection.

Purpose of the Survey: The primary aim of this survey is to rank different supply chain KPIs and supplier selection criteria based on their perceived importance using a method called the Best-Worst Method (BWM). Your responses will help us derive the relative weights of these KPIs and criteria, which will guide decision-making, performance measurement in supply chain management, and supplier selection processes.

About the Best-Worst Method (BWM): The Best-Worst Method is a novel multi-criteria decision-making technique that helps to rank different options or criteria based on their importance. It does this by asking respondents to identify the most important (best) and least important (worst) criteria among a given set and then rate how much more important the best criterion is compared to the others and how much less important the worst criterion is compared to the others.

For example, let's say we have three criteria: A, B, and C.
If you consider A as the best and B as the worst, you might be asked:
a) "On a scale of 1 to 9, where 1 means equally important and 9 means absolutely more important, how much more important is criterion A (the best) compared to B and C?"
b) "On a scale of 1 to 9, where 1 means equally important and 9 means absolutely less important, how much less important is criterion B (the worst) compared to A and C?"

The data collected from these responses is used to calculate the relative weights of the criteria, with a mechanism to ensure consistency of responses.

Your Participation: We kindly ask for your honest and thoughtful answers. There are no 'right' or 'wrong' answers; we are interested in your personal opinion. All your responses will remain anonymous and confidential and will be used only for the purpose of this research.

Please proceed with the survey when you are ready. Thank you for your invaluable contribution.

Q1 In the context of supplier selection, which of the following criteria do you consider the **most** important (best)? Please select one.

- ◯ Quality of Materials (1)
- ◯ Reliability of Supply (2)
- ◯ Price (3)
- ◯ Lead Time (4)

Q2 On a scale of 1 to 9, where 1 means 'equally important' and 9 means 'absolutely more important', how much more important is the criterion you selected in the previous question, compared to the other criteria for supplier selection? Please provide a score for each.

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 (7)	8 (8)	9 (9)
Quality of Materials (1)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Reliability of Supply (2)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Price (4)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Lead Time (6)	◯	◯	◯	◯	◯	◯	◯	◯	◯

Q3 In the context of supplier selection, which of the following criteria do you consider the **least** important (worst)? Please select one.

- Quality of Materials (1)
- Reliability of Supply (2)
- Price (3)
- Lead Time (4)

Q4 On a scale of 1 to 9, where 1 means 'equally important' and 9 means 'absolutely less important', how much less important is the criterion you selected in the previous question, compared to the other criteria for supplier selection? Please provide a score for each.

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 (7)	8 (8)	9 (9)
Quality of Materials (1)	○	○	○	○	○	○	○	○	○
Reliability of Supply (2)	○	○	○	○	○	○	○	○	○
Price (4)	○	○	○	○	○	○	○	○	○
Lead Time (6)	○	○	○	○	○	○	○	○	○

Q5 Among the following Key Performance Indicators (KPIs) for supply chain management, which one do you consider the **most** important (best)? Please select one

- ◯ Inventory Levels (1)
- ◯ Total Cost (2)
- ◯ Net Profit (3)
- ◯ On-Time In-Full Delivery (4)
- ◯ Quality of Produced Products (5)

Q6 On a scale of 1 to 9, where 1 means 'equally important' and 9 means 'absolutely more important', how much more important is the criterion you selected in the previous question, compared to the other criteria for measuring supply chain performance? Please provide a score for each.

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 (7)	8 (8)	9 (9)
Inventory Levels (1)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Total Cost (2)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Net Profit (4)	◯	◯	◯	◯	◯	◯	◯	◯	◯
On-Time In-Full Delivery (6)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Quality of Produced Products (7)	◯	◯	◯	◯	◯	◯	◯	◯	◯

Q7 Among the following Key Performance Indicators (KPIs) for supply chain management, which one do you consider the **least** important (worst)? Please select one

- ◯ Inventory Levels (1)
- ◯ Total Cost (2)
- ◯ Net Profit (3)
- ◯ On-Time In-Full Delivery (4)
- ◯ Quality of Produced Products (5)

Q8 On a scale of 1 to 9, where 1 means 'equally important' and 9 means 'absolutely less important', how much less important is the criterion you selected in the previous question, compared to the other criteria for measuring supply chain performance? Please provide a score for each.

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 (7)	8 (8)	9 (9)
Inventory Levels (1)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Total Cost (2)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Net Profit (4)	◯	◯	◯	◯	◯	◯	◯	◯	◯
On-Time In-Full Delivery (6)	◯	◯	◯	◯	◯	◯	◯	◯	◯
Quality of Produced Products (7)	◯	◯	◯	◯	◯	◯	◯	◯	◯

Q9 What is your job title? (do not mention any personally identifiable information or company information)

____

End of Block: Supplier Selection

Appendix C: Supplier Selection Papers

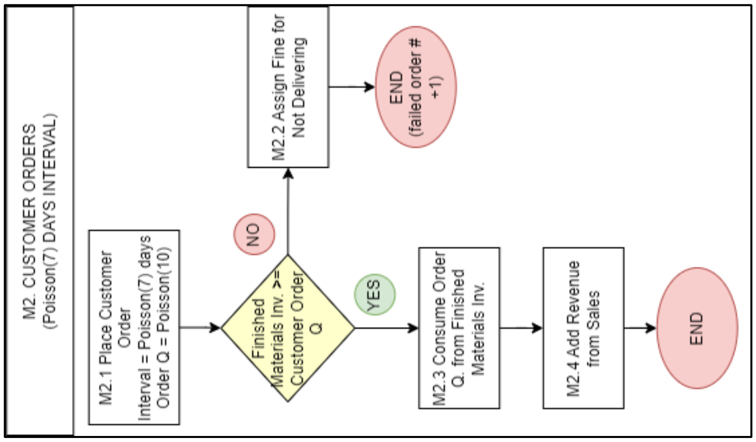
Table C.1: Supplier selection criteria in the literature

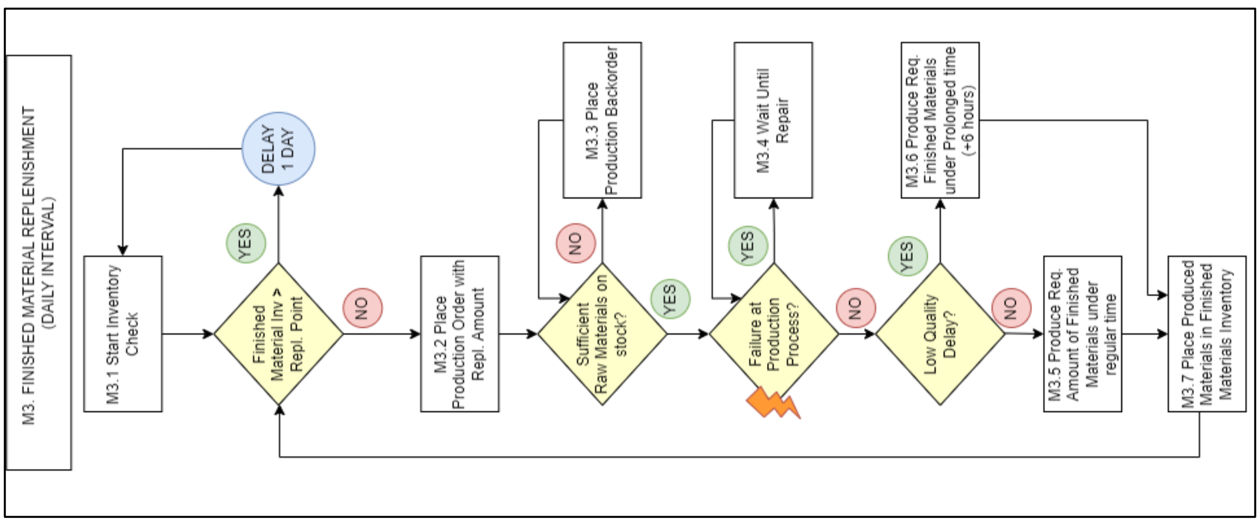
Criteria	# of papers	Authors
Quality	15	Thanaraksakul & Phruksaphanrat (2009), Sarkar & Mohapatra (2006), Florez-Lopez (2007), Wadhwa & Ravindran (2007), Xia & Wu (2007), Shyur & Shih (2006), Chan & Kumar (2007), Jharkharia & Shankar (2007), Gencer & Gürpinar (2007), Wang, Cheng, & Huang (2008), Jing Ring Yu (2008), Cakir & Canbolat (2008), Hsu & Hu (2009), Ustun & Demirtas (2008)
Price	6	Thanaraksakul & Phruksaphanrat (2009), Sarkar & Mohapatra (2006), Florez-Lopez (2007), Xia & Wu (2007), Wadhwa & Ravindran (2007), Watt, Kayis, & Willey (2010)
Delivery	7	Thanaraksakul & Phruksaphanrat (2009), Sarkar & Mohapatra (2006), Florez-Lopez (2007), Shyur & Shih (2006), Jing Ring Yu (2008), Ustun & Demirtas (2008), Wadhwa & Ravindran (2007)
Production capacity	4	Thanaraksakul & Phruksaphanrat (2009), Sarkar & Mohapatra (2006), Xia & Wu (2007), Tahriri (2008)
Supplier's profile	4	Chan & Kumar (2007), Jharkharia & Shankar (2007), Gencer & Gürpinar (2007), Ustun & Demirtas (2008)
Service	4	Chan & Kumar (2007), Wang, Cheng, & Huang (2008), Jing Ring Yu (2008), Ustun & Demirtas (2008)
Technology and capability	7	Thanaraksakul & Phruksaphanrat (2009), Shyur & Shih (2006), Jharkharia & Shankar (2007), Gencer & Gürpinar (2007), Ustun & Demirtas (2008), Ha & Krishnan (2008), Bottani & Rizzi (2008)

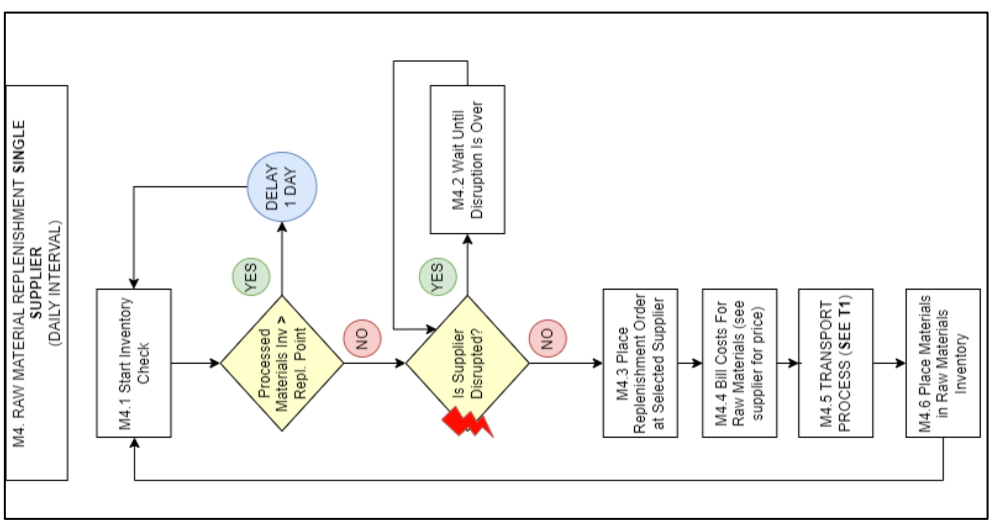
Appendix D: Process Conceptualization

INTERNAL MANUFACTURER PROCESSES (M)

From top to bottom: Customer Orders (M2), Finished Material Replenishment/ Production (M3), Raw Material Replenishment Single Supplier (M4).

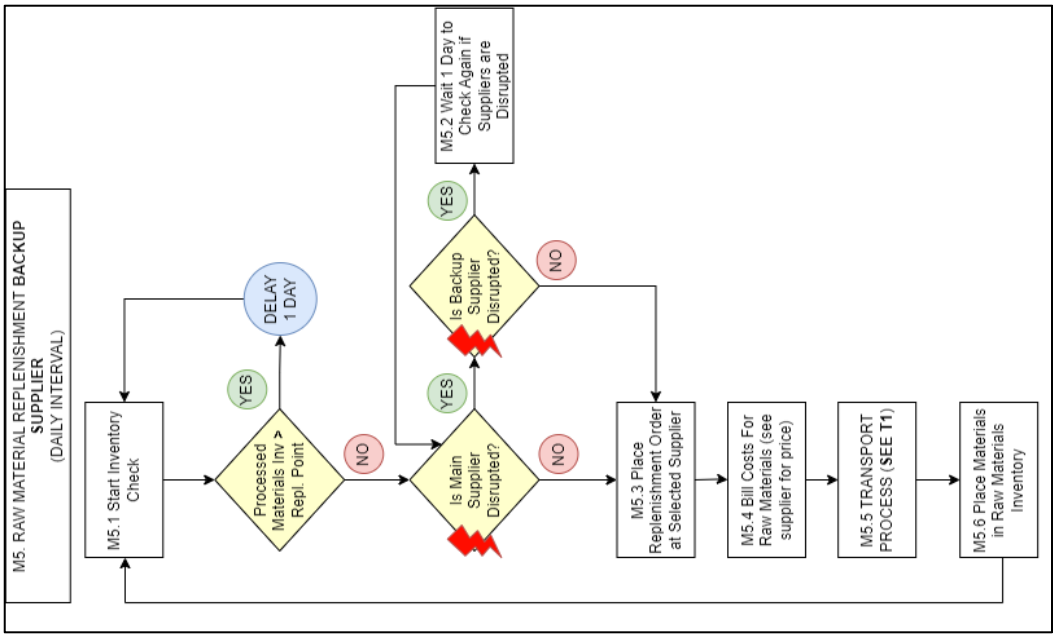


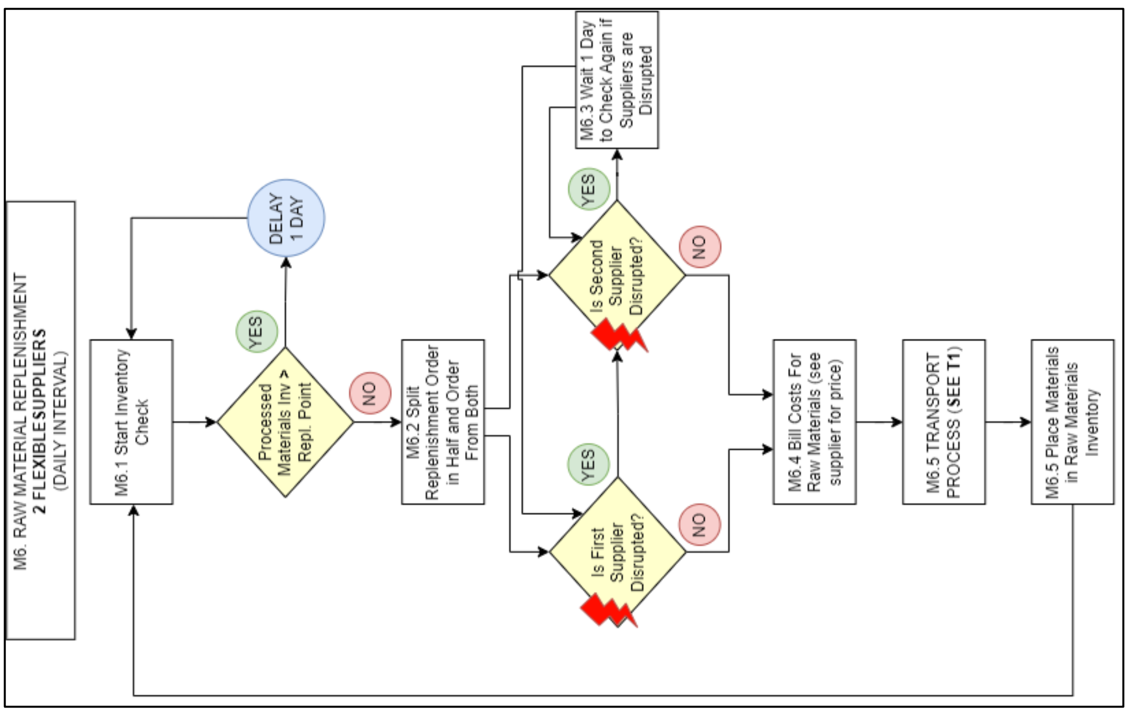




INTERNAL MANUFACTURER PROCESSES (M)

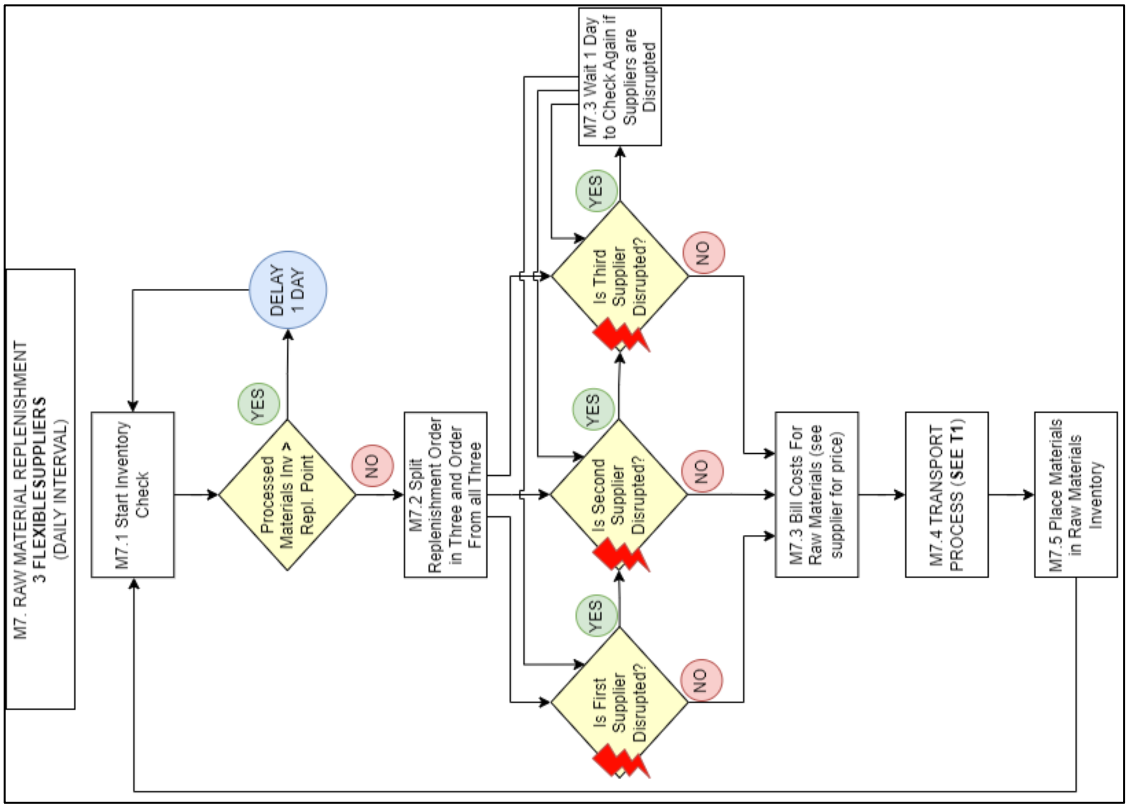
From top to bottom: Raw Material Replenishment Backup Supplier (M5), Raw Material Replenishment 2 Flexible Suppliers (M6)





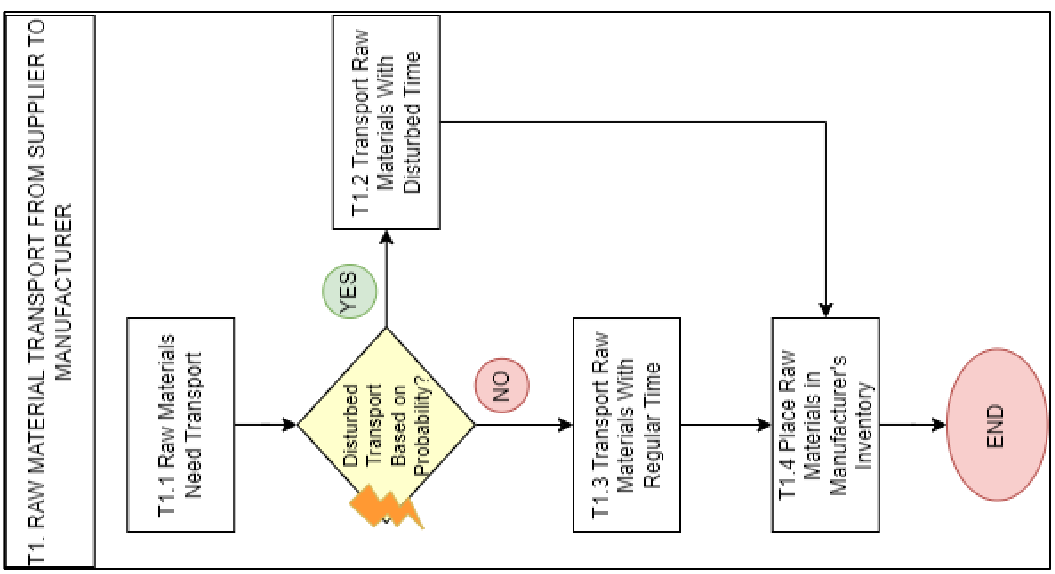
INTERNAL MANUFACTURER PROCESSES (M)

Raw Material Replenishment 3 Flexible Suppliers (M7)



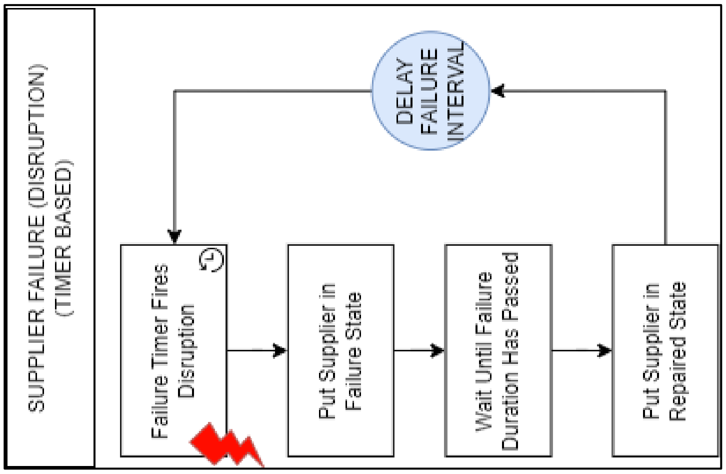
TRANSPORT PROCESS (T)

Raw Material Transport from Supplier to Manufacturer (T1)

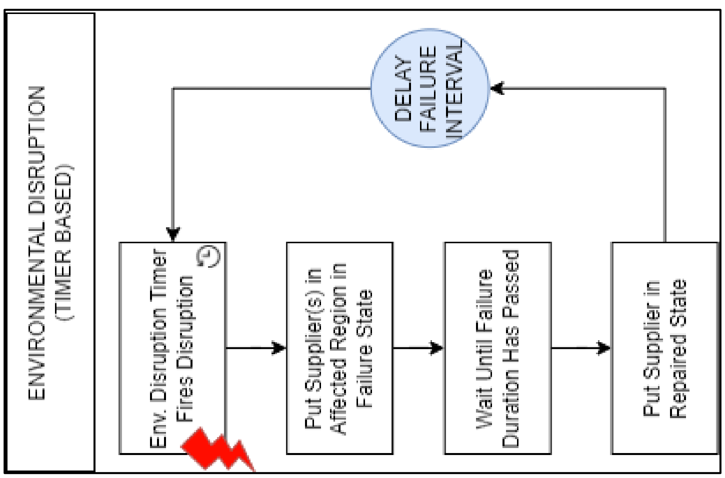


SUPPLIER DISRUPTION PROCESS

Supplier Disruption



Environmental Disruption



Appendix E: Simulation Model in Simio

In this Appendix, we present our simulation model's facility view, one of our data tables, the elements in the model, and two of the implemented replenishment processes. This is to give the reader a view into the development of the simulation model in Simio. The Simio file is also available to download on the 4TU.ResearchData platform with the following DOI: 10.4121/a93bcdc7-07ac-4b4d-b60f-dd3b7ce658d8.

FACILITY VIEW

In the facility view, we see our three suppliers, the manufacturer, and the transportation paths that connect the suppliers to the manufacturer. We can track the model's performance during a run with the monitors for the KPIs, the disturbances and disruptions, and the revenue and different costs. The manufacturer's raw material and finished product inventory is also tracked with the plot.

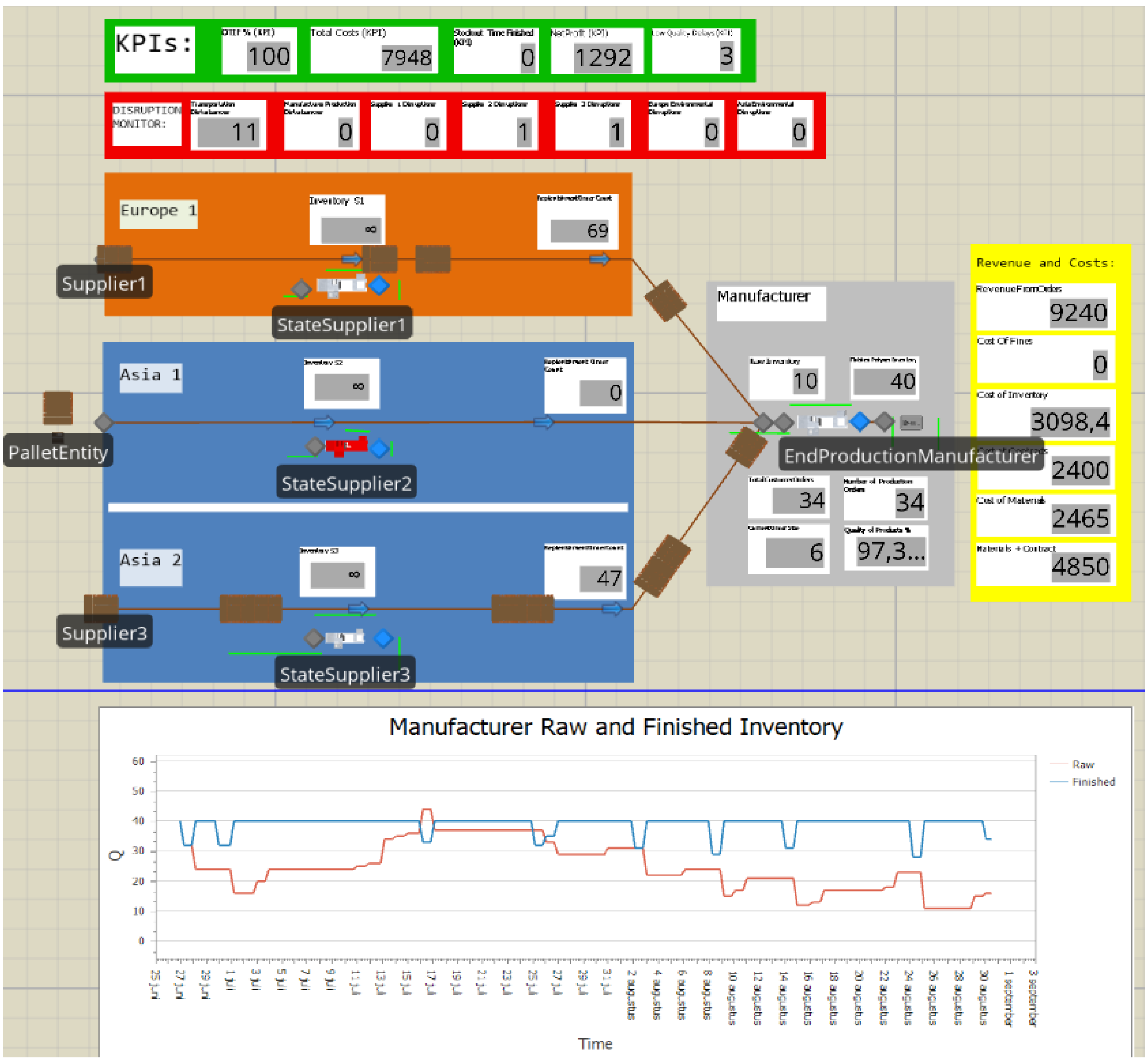
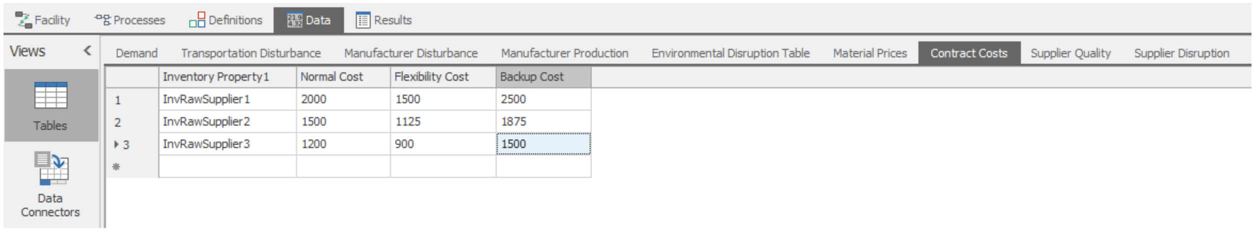


Figure E.1: *Simio facility view*

DATA TABLES

The data tables contain the parameters that are defined in the parametrization section, Subchapter 6.5.



	Inventory Property1	Normal Cost	Flexibility Cost	Backup Cost
1	InvRawSupplier1	2000	1500	2500
2	InvRawSupplier2	1500	1125	1875
3	InvRawSupplier3	1200	900	1500

***Figure E.2**: Data tables in Simio*

DEFINITIONS - ELEMENTS

In the definitions tab, we have the different types of elements which are used to assign inventories to the suppliers and manufacturer, define the material types in the model, and timers that fire off disruptions.

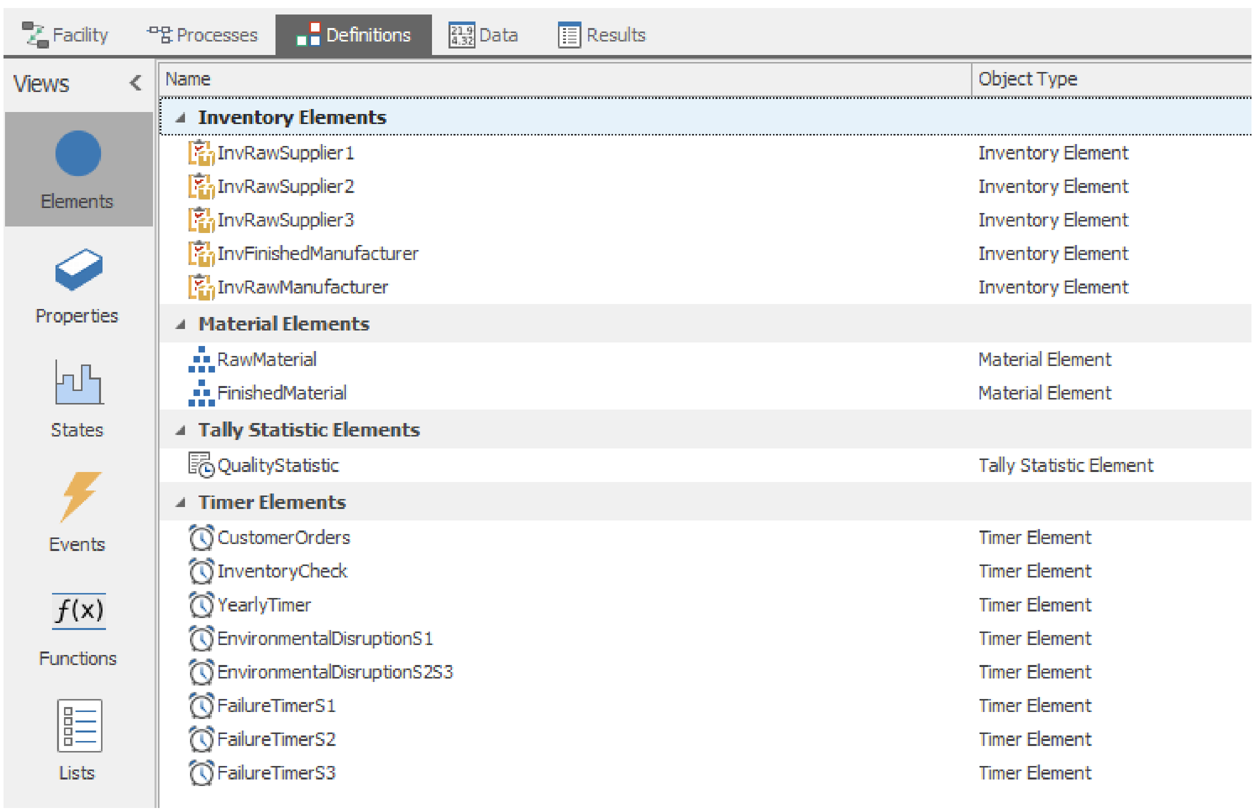


***Figure E.3**: Definitions and elements*

PROCESSES

The simulation model contains more than 30 processes. These processes are implemented according to the conceptual processes as defined in Appendix D. We present the processes for raw material replenishment with a single supplier (M4) and with a back-up supplier (M5), and the processes that are triggered when the customer order timer fires a customer order (M2).

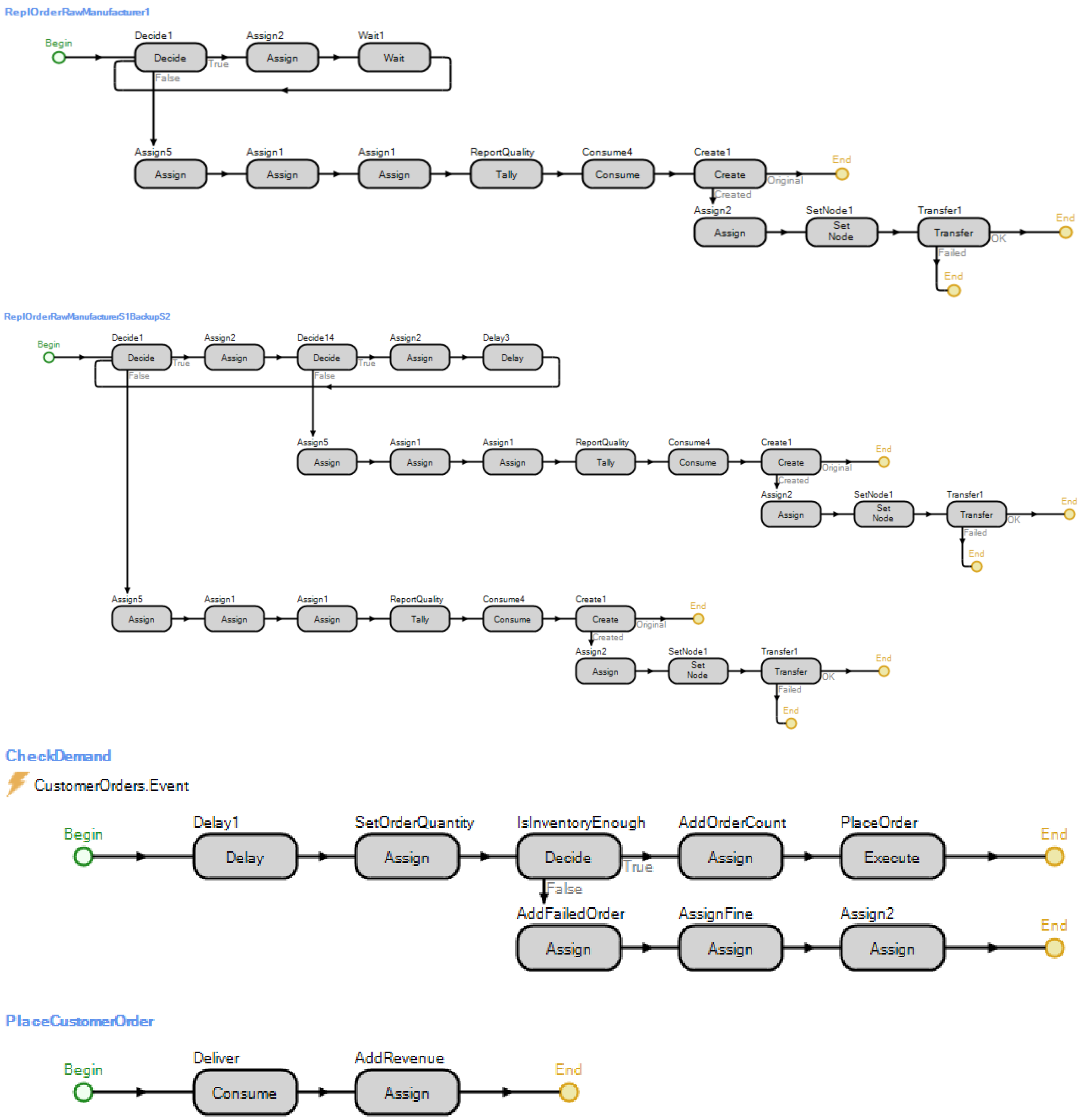


Figure E.4: *Processes in Simio*

Appendix F: Plots of Single Supplier Scenarios

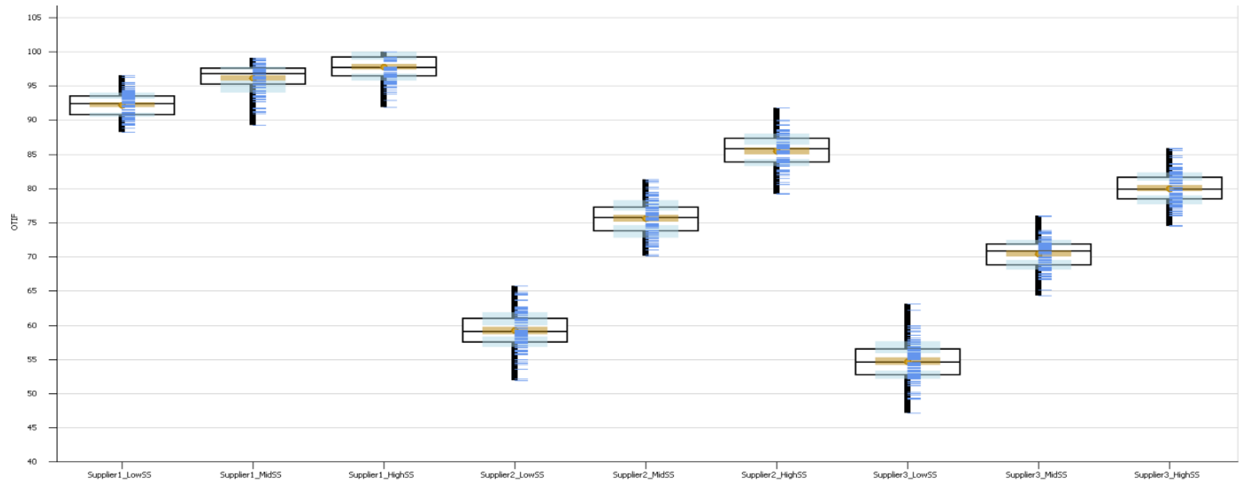


Figure F.1: *Plot OTIF Delivery*

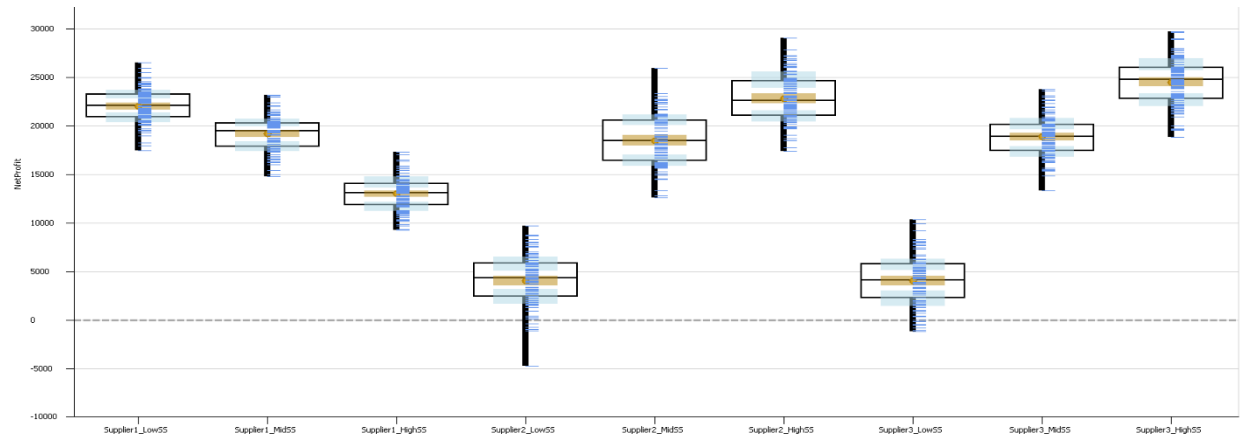


Figure F.2: *Plot Net Profit*

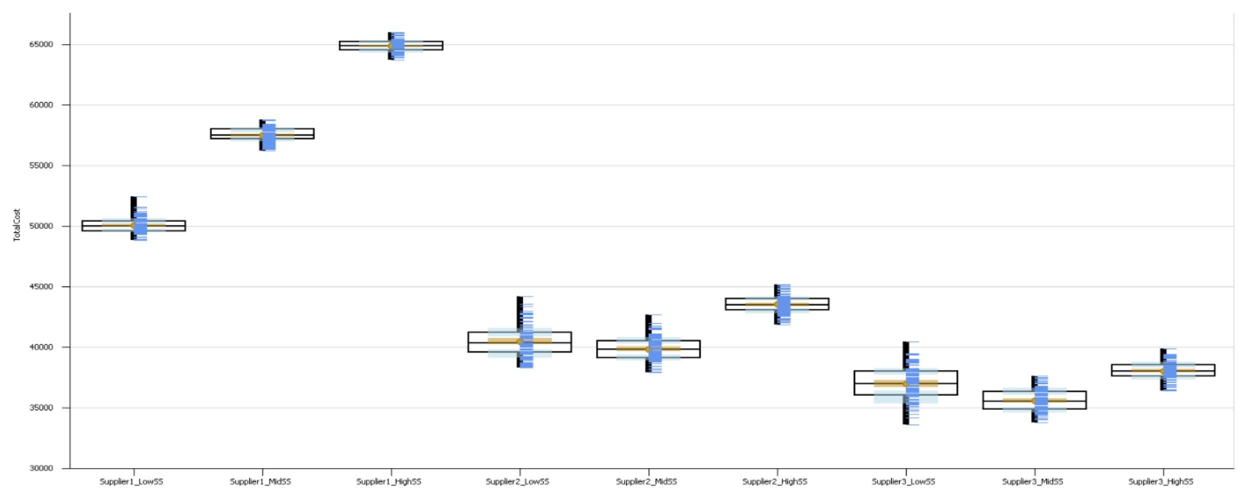


Figure F.3: *Plot Total Cost*

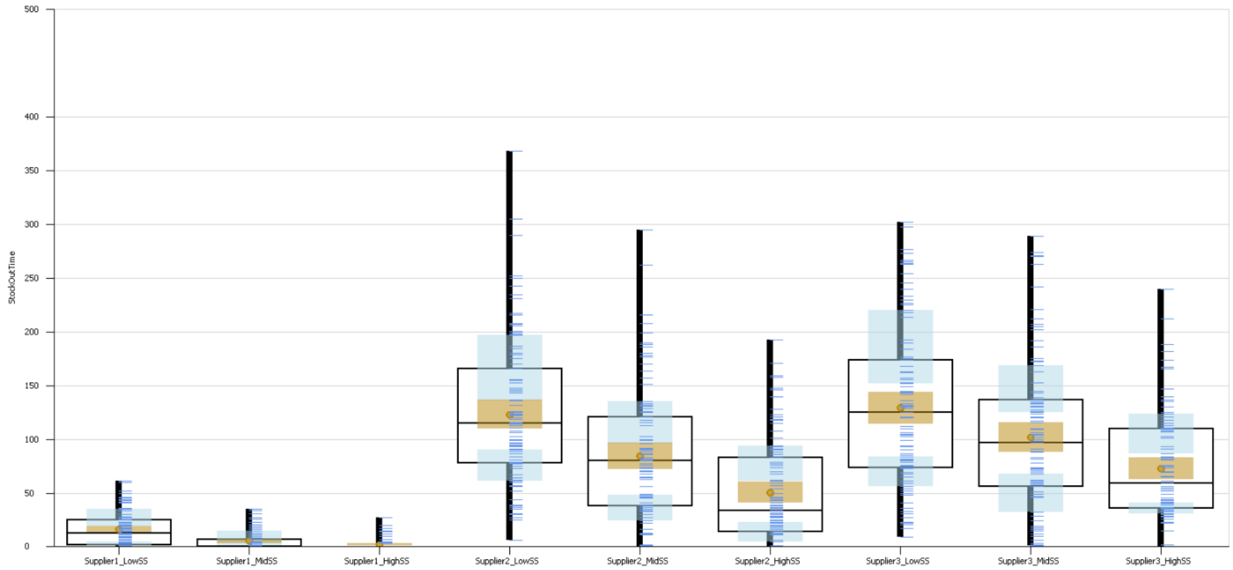


***Figure F.4**: Plot Stockout Time*

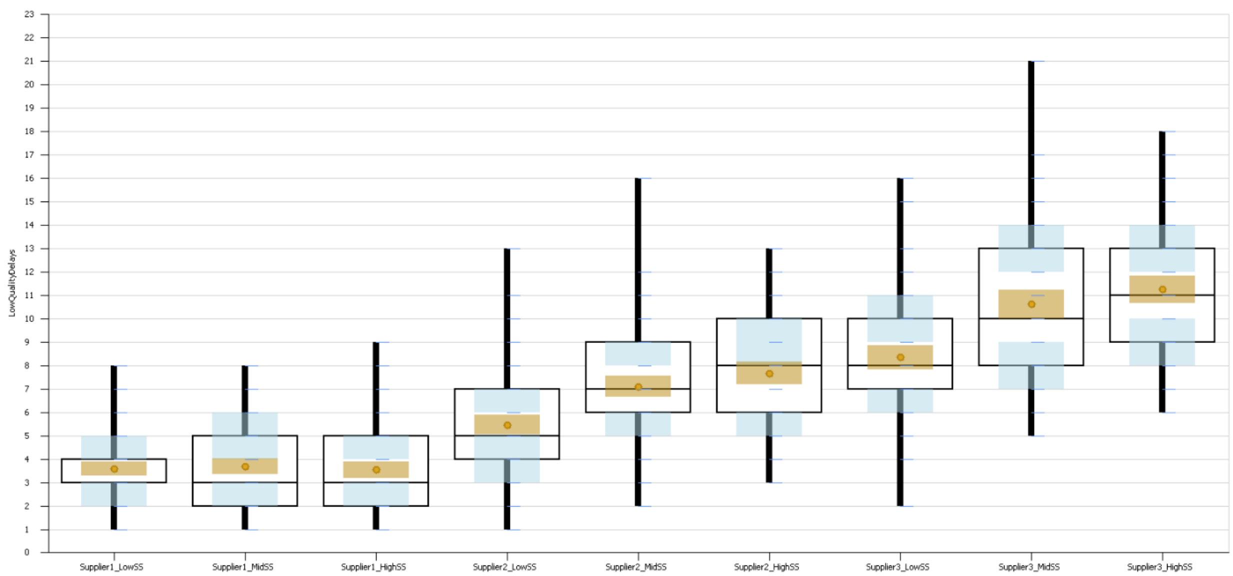


***Figure F.5**: Plot Low Quality Delays*

Appendix G: Plots of Filtered Scenarios

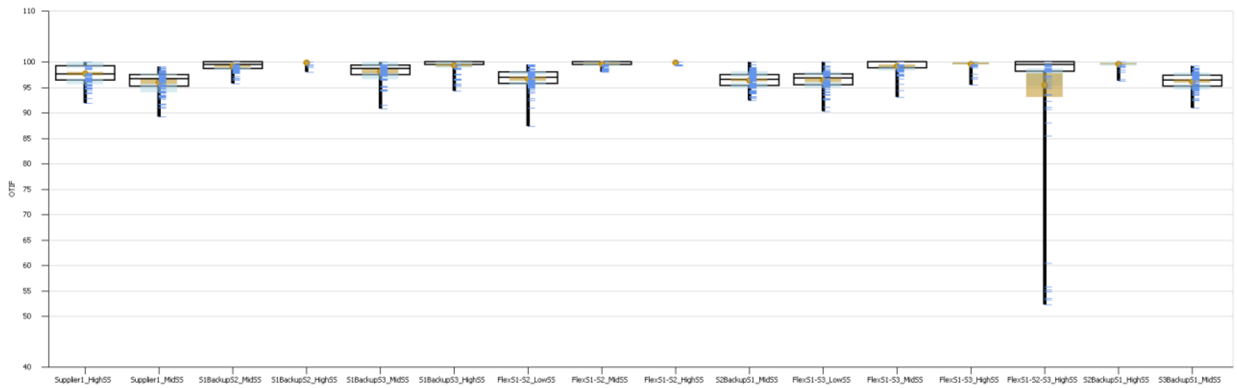


Figure G.1: *Plot OTIF Delivery*

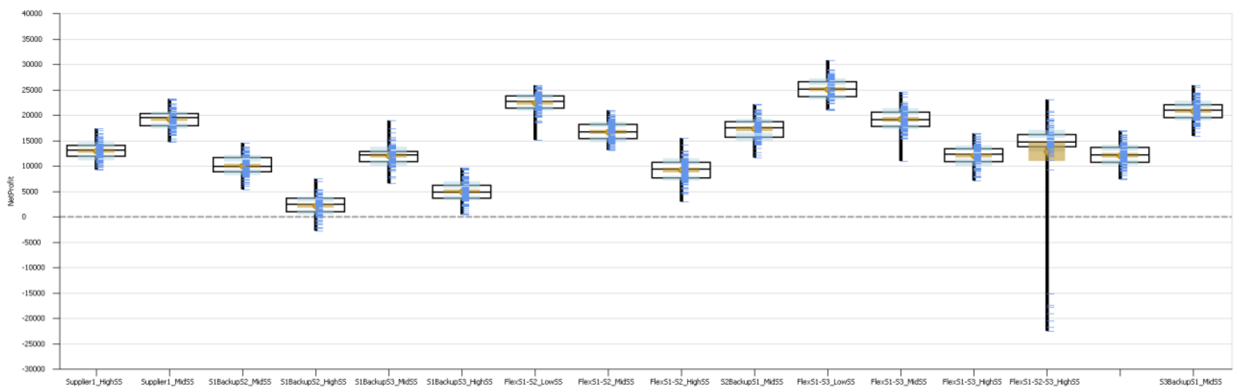


Figure G.2: *Plot Net Profit*

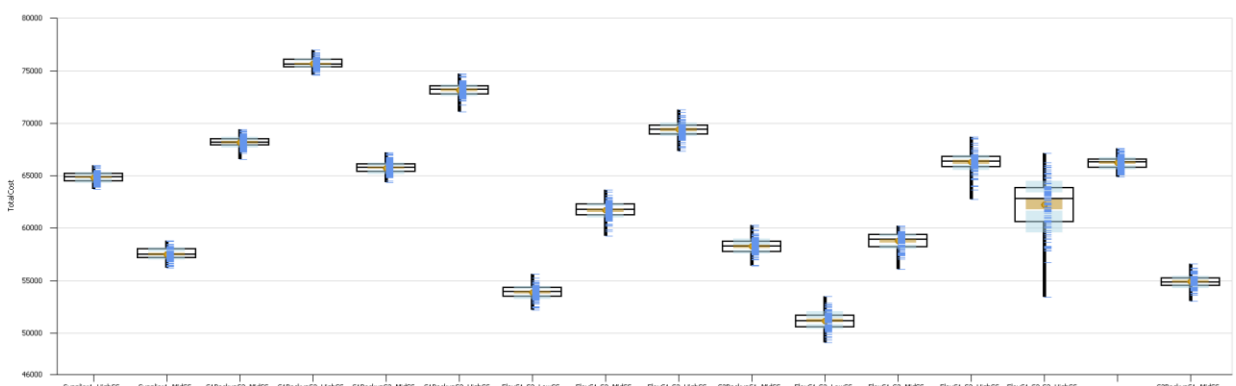


Figure G.3: *Plot Total Cost*

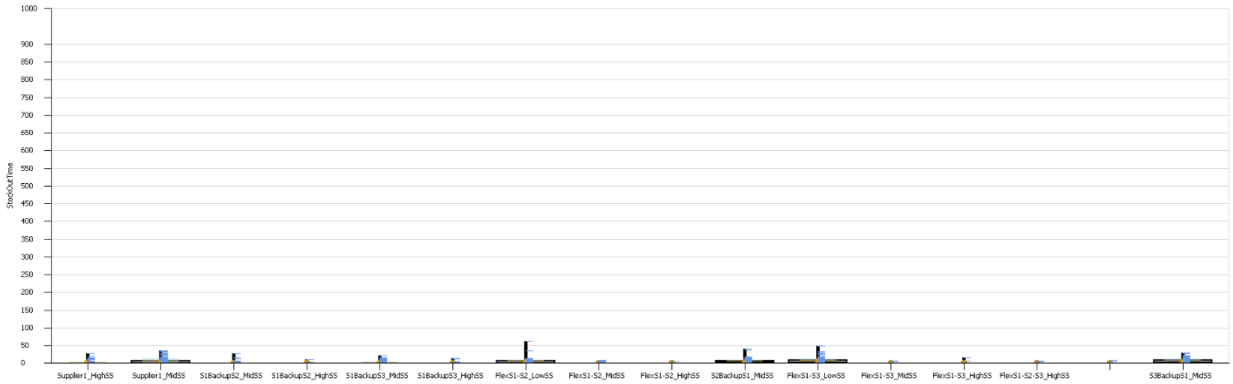


Figure G.4: *Plot Stockout Time*

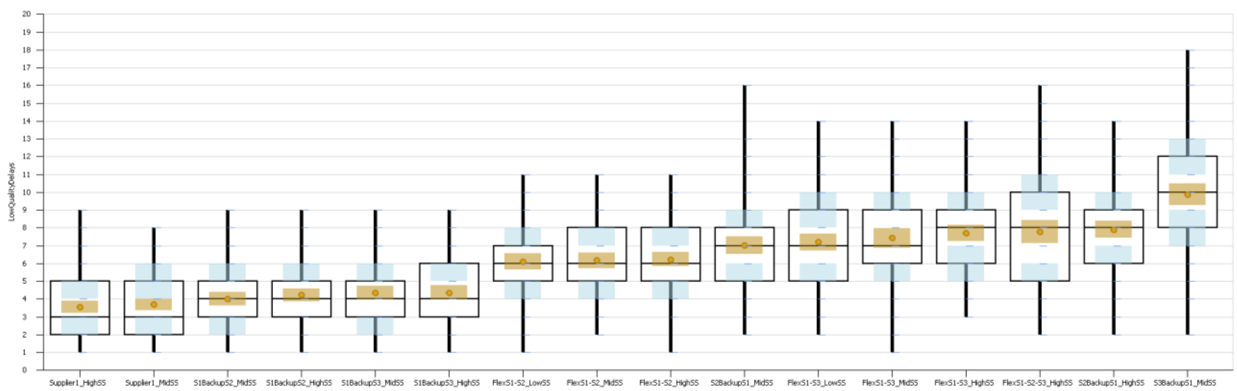
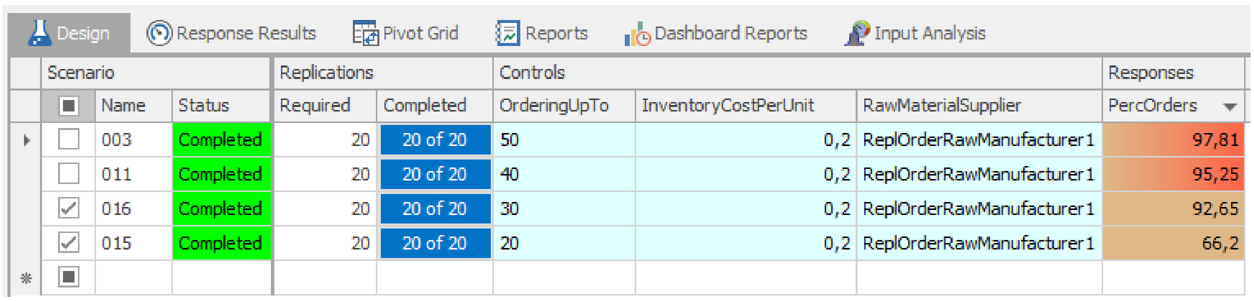


Figure G.5: *Plot Low Quality Delays*

Appendix H: OptQuest in Simio

OptQuest is an optimization tool integrated into several simulation software platforms, including Simio. The goal of this tool is to aid users in finding the best solutions to their problems without manually experimenting with every potential combination of input variables.

Contained within this appendix is a visual representation of the OptQuest results. The illustration highlights that a safety stock level of 40 units is the minimum required to achieve an On-Time In-Full Delivery (OTIF) rate of 95% when only contracting with supplier 1.


Design | Response Results | Pivot Grid | Reports | Dashboard Reports | Input Analysis

Scenario			Replications		Controls			Responses
	Name	Status	Required	Completed	OrderingUpTo	InventoryCostPerUnit	RawMaterialSupplier	PercOrders
☐	003	Completed	20	20 of 20	50	0,2	ReplOrderRawManufacturer1	97,81
☐	011	Completed	20	20 of 20	40	0,2	ReplOrderRawManufacturer1	95,25
☑	016	Completed	20	20 of 20	30	0,2	ReplOrderRawManufacturer1	92,65
☑	015	Completed	20	20 of 20	20	0,2	ReplOrderRawManufacturer1	66,2

***Figure H.1**: OptQuest results*