Resilient Digital Supply Chain Twins Modelling: Simulation-based Analysis on the COVID-19 Pandemic Outbreak

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ABSTRACT

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Faridoddin Moazzeni

Over the past few years, Supply Chains (SC) have expanded rapidly in terms of dimensions and complexity (e.g., globalization, outsourcing, etc.). Besides, numerous practitioners and researchers proposed models mainly focused on minimizing SC's total cost. Consequently, the potential financial advantages of reduced stock levels and inventory buffers have made SCs more vulnerable to local and global Low-Frequency High-Impact disruption risks which have long-term destructive effects. For instance, the COVID-19 pandemic outbreak has severely disturbed SCs, especially for essential products, by a sharp increase in demand and raw material supply failure. During this challenging situation, the focus should be shifted from cost minimization to SC's survival, maximizing demand satisfaction, and minimizing delivery time. Consequently, these emerging issues have put forth the need for greater emphasis to develop resilient supply chains.

This study presents a methodological SC simulation modelling framework that enables visualizing the SC and making quick decisions by SC managers in near real-time to ensure resiliency during the disruption. The solution approach is applied as a case study in Luxxeen Co., a Canadian manufacturer of green disposable products, i.e. Toilet Tissues, which is considered an essential product.

First, we develop SC's structural and behavioral conceptual model by customizing the SCOR reference model. Afterwards, we translate it to Discrete Event Simulation formalist and implement it using the "Arena simulation software" platform. Next, we design three COVID-19 pandemic outbreak disruption scenarios in suppliers, transportation networks, and retailers. Finally, three risk mitigation strategies (i.e., Multiple Sourcing, Changing Inventory Control Policy and Buffering) are suggested to ensure SC resiliency in terms of reliability and responsiveness performance metrics. Moreover, by conducting a comparison analysis using "Process Analyzer" and "Optquest" between these scenarios, the best set of actions are proposed for each disruption scenario.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

SCM: Supply Chain Management

SC: Supply Chain

SCOR: Supply Chain Operations Reference

PO: Purchase Order

SO: Supply Order

SCRM: Supply Chain Risk Management

COVID-19: Coronavirus Identified in 2019

HFLI: High-Frequency-Low-Impact

HILF: High-Impact-Low-Frequency

DES: Discrete Event Simulation

SD: System Dynamics

AB: Agent-Based

CHAPTER 1

INTRODUCTION

1.1 Supply Chain Management

Supply Chain Management "SCM" concept firstly emerged into literature in early1980 (Oliver & Webber, 1982). The initial studies mainly were about well-managing resources and assets. The focus was mainly on operations within each echelon of SCs. Over the years, the primary concentration on the efficiency, structure and assessment of the supply chain as a whole has been increasing. For instance, SCM's focus has mainly been to minimize SC total cost and decrease the total cycle time, including supply and delivery (Beamon, 1998; Christopher & Peck, 2004; Jbara, 2018).

Additionally, due to technological advancement and the expansion of the supply chain globally, new types of SCs have appeared, leading to changes in configuration, size and different management methods. For example, today, it is easy to download the software through the internet from various developers online, while the software packages are only delivered via CD-ROMs. Such developments created the concept of "Cyber Supply Chains" (Windelberg, 2016). Over the years, academics found out that more efforts need to be taken into account to address complex relationship networks and process flows among the SC components. These efforts would create a better service or product efficiently (Ellram & Cooper, 2014).

1.2 SCOR Reference Model

The creation of the SCOR model by the Supply Chain Council is an excellent example of developing standardization and providing common benchmarks for comparing performance indicators across industries and organizations to address a portion of modern SC challenges (Ellram & Cooper, 2014). Supply Chain Operations Reference (SCOR) model is a powerful management tool focused on a business process view of the SC to analyze, monitor, assess and optimize established supply chain process systems, demonstrating the practical criteria of defined best practices (Millet et al., 2009).

As the SCs growing in scale and concept, it is getting more at risk. The potential advantages of reduced stock levels, shorter lead times have put SCs in danger of collapse (Tuncel, 2010).

1.3 Vulnerability of SC

In recent years, many destructive events have taken place in the world. According to (Ho et al., 2015; Pettit et al., 2013), in 2011, Toyota corporation lost 72 million dollars profit per day due to earthquakes, tsunami, and the following nuclear disaster. By increasing the SCs in size, they are becoming more vulnerable to catastrophic events.

The probability of disruption risks increases as SCs grow larger geographically and efforts are taken to minimize the length of SC’s operations. Nowadays, to increase productivity, firms are reducing both the volume of inventory and human capital. As a result, the risk of disruption increases, and the error margin reduces. Supply Chain Risk Management (SCRM) controls and manages the SC's risks to achieve resilient SC (Ho et al., 2015; Kleindorfer & Saad, 2005; Knemeyer et al., 2009).

1.4 Supply Chain risk Management

Several researchers provided definitions for SCRM. According to (Ho et al., 2015) SCRM is consists of four main processes, including “Risk Identification,” “Risk Assessment,” “Risk

Mitigation," and "Risk Monitoring." Additionally, for all kinds of "Macro" and "Micro" types of risks in each part of SC, either quantitative or qualitative methods are used for each above process. There is various categorization available in literature in terms of SC risks. According to (Christopher & Peck, 2004), three main categories has been identified. The first type is external to the network. i.e. environmental risk. The second type is in the scale of SC and not to the internal process. i.e. demand and supply risks. The third type is inside the firm. i.e., process and control risks. In the next chapter, we explain each process of SCRM in detail.

1.5 Supply Chain Disruption Risk

The second category of SC risks is classified into two different types, namely Operational and Disruption risks. On the one hand, the operational or High-Frequency Low-Impact (HFLI) risks are associated with typical interruptions in SC operations such as variations in lead-time and demand and risk of damage to the product during shipment, which is shown in Figure 1.1 at the top left corner. This category of risk is outside the scope of our study. On the other hand, the disruption risks belong to Low-Frequency High-Impact (LFHI) events (bottom right corner of Figure 1.1). This specific type of risk can lead to shortages in the supply of raw materials due to which production is delayed, and this degradation spreads in transportation networks and downstream of the supply chain. The disruption of this kind of risk is strong and spread fast through the SC. Moreover, it can even temporarily make one or more echelons of the SC inaccessible. This risk can damage supply chains' performance indicators such as service level service and productivity (Ivanov, 2020a; Kleindorfer & Saad, 2005; Knemeyer et al., 2009).

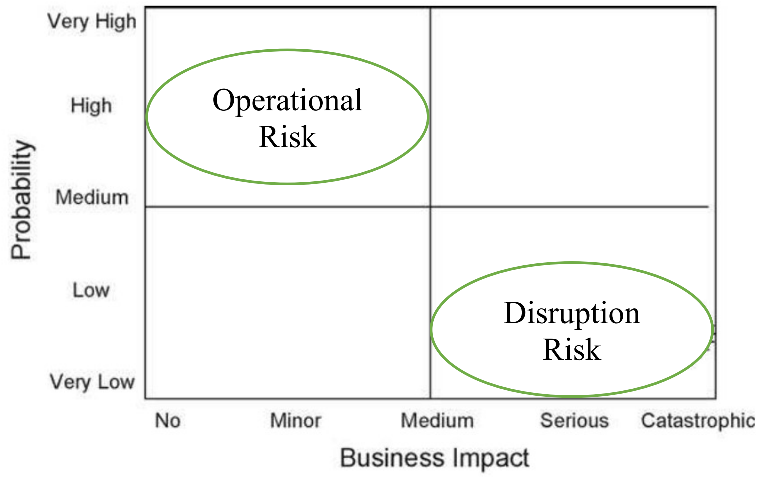

Figure 1.1 Risk Categorization Scheme (Proposed by (Knemeyer et al., 2009))

1.6 What is an "Epidemic Outbreak"?

One specific type of disruption risk that has recently been more considered in the literature is the epidemic outbreaks. This type of risk can have long-term destructive effects on the supply chain. It can also spread at the same time in the population and the supply chain. Besides, it disrupts supply, transportation paths, and demand. The COVID-19 pandemic outbreak is an example of this type of disruption risk that is the main focus of the recent study (Choi et al., 2019; Fahimnia et al., 2018; Govindan et al., 2017; Ivanov, 2020a; Ivanov et al., 2017; Kinra et al., 2019).

1.7 Pandemic and Essential Product's Supply Chain

The impact of this disruption risk during the pandemic outbreak can be more significant and critical depending on the type of the product and/or service of the SC. According to (Hobbs, 2020) food supply chains such as rice, pasta, canned goods, and essential sanitary goods like hand sanitizers and toilet papers were severely disturbed by a sharp increase in demand and a decrease in supply. This increase in demand was a result of the "Panic Buying" behaviour of customers.

Following the COVID-19 pandemic, more effort must be taken into account to make the SC more resilient in terms of KPIs of each echelon of the SC itself and other partners through global networks (Golan et al., 2020).

1.8 Supply Chain Resilience

According to a study conducted by (Golan et al., 2020), the concept of "SC Resilience" refers to SC's managers' capability to efficiently prepare, allowing a way for the SCs to endure, recover from, and respond to disruptions of different duration impacts.

According to (Ivanov & Das, 2020) the emphasis is mostly on the "risk mitigation inventory" as well as providing a "backup supplier" in the traditional context of supply chain resilience. Nevertheless, it may help at the beginning of the disruption. The attention should be on real-time decision-making systems to have a resilient supply chain during epidemic outbreaks due to long-term disruption. For example, based on the progress and spread of the epidemic outbreak throughout the whole SC, the opening and closing timing and duration for supply chain partners should be modified to maintain key performance indicators above the acceptance criteria. The methods and frameworks which are mentioned in literature for obtaining the resilient SC are in more depth in chapter 2. As supply chains become more diverse and complicated and progress into Industry 4.0, new challenges and opportunities bring up (Golan et al., 2020).

1.9 Industry 4.0

Industry 4.0 concept emerged into the literature after the fourth industrial revolution. As shown in Figure 1.2, the first three revolutions took in the past two centuries. The first industrial revolution brought about industry 1.0 in the early 1800s by the "Mechanization" of manufacturing facilities thanks to the invention of water and steam-powered machines. By the beginning of the 19^{th} century, "Electrification" using "electrically-powered mass production technologies" causes the second industrial revolution. The era of industry 2.0 ended in the early 1900s. The Industry 3.0 era started with the 3rd industrial revolution in the early 1960s by application of electrical and information technology (IT) and thanks to "Digitalization" (Drath & Horch, 2014; Liao et al., 2017). Industry 4.0 defines as the technological structure for the SC (Ivanov, 2020b).

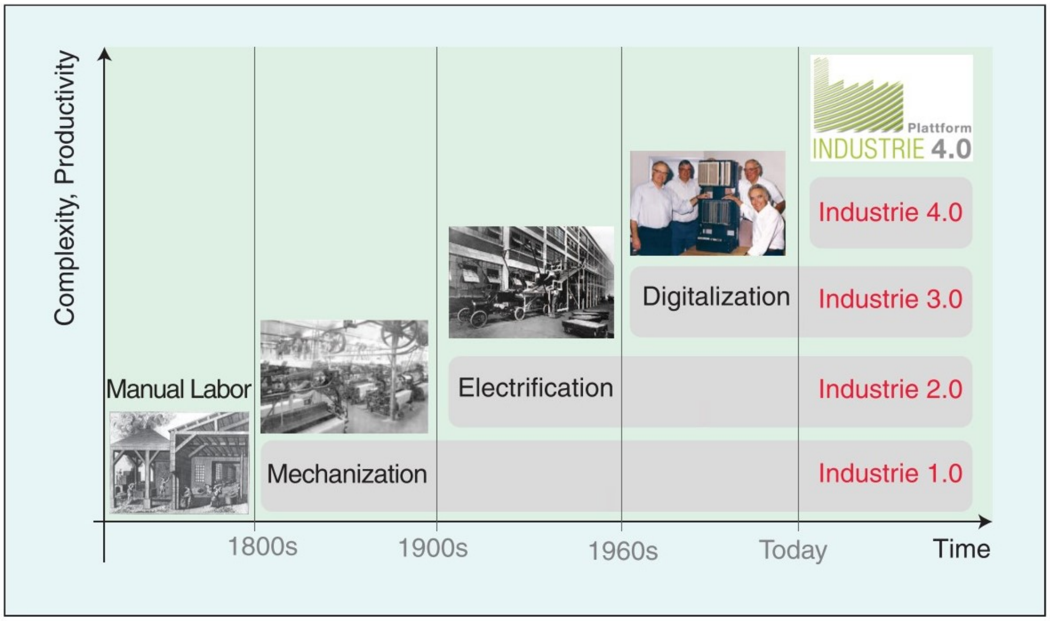

Figure 1.2 An Overview of Four Industrial Revolutions (Drath & Horch, 2014)

According to (Vaidya et al., 2018), nine pillars of industry 4.0 consist of autonomous robots, simulation, horizontal and vertical systems, the industrial IoT (Internet of things), cybersecurity and cyber-physical systems (CPS), the cloud, additive manufacturing, augmented reality, and big data and analytics. Industry 4.0 involves physical objects, their virtual representation and services, and their applications. As a matter of fact, Industry 4.0 comes with opportunities and challenges by itself to supply chains (Drath & Horch, 2014).

Each industrial revolution has had pros and cons to SCs. According to (Ghadge et al., 2020) especially by the fourth industrial revolution and creation of the concept of industry 4.0, new challenges and opportunities have been brought to supply chains.

1.10 Application of Industry 4.0 in SC

In particular, Industry 4.0 is a technical structure for implementing concepts of "cyber-physical" integration in the manufacturing, logistics and supply chains (SC) (Fragapane et al., 2020; Ghadge et al., 2020; Ivanov & Dolgui, 2020a; Liao et al., 2017; Strozzi et al., 2017; Tang & Veelenturf, 2019). this concept has a significant effect on addressing SCM visibility.

Industry 4.0 in digital technology creates a framework by combining the concepts of simulation, optimization and data analytics, enables creating a decision-making tool that effectively manages SC disruption risks, especially for the recent COVID-19 global pandemic. This technology that addresses supply chains' needs is "Digital Supply Chain Twin" (Ivanov & Dolgui, 2020a; Marmolejo & Hurtado, 2020).

1.11 Digital Supply Chain Twin

"A digital SC twin is a computerized, digital SC model that illustrates the network's state in real-time at any given time." digital SC twin represents the physical SC structure, including transportation networks (Battarra et al., 2018; Ivanov & Dolgui, 2020a; Salman & Yücel, 2015). For example, (Ivanov, 2020a) using the digital SC twin concept, present the simulation-based study to show how epidemic outbreaks affect SC performance indicators in the near real-time. This study suggests the successful elements of recovery policies during pandemic outbreaks.

A cycle of continuous improvement can be designed by "Simulation Modeling" for all components of the SC as the "digital SC twin" (Marmolejo & Hurtado, 2020).

1.12 Supply Chain Simulation Modelling

"Simulation Modelling" is considered as one of the quantitative methods to study the SCs. As a result of simulation study by doing computational experiments, numerical results are attained (Jbara, 2018). According to (Heath et al., 2011; Jahangirian et al., 2010) three approaches to conduct simulation studies are Agent-Based Simulation (ABS), System Dynamics (SD), and Discrete Event Simulation (DES), which are explained in the next chapter. By performing the simulating study, the SC behaviour can be analyzed by applying different scenarios. To investigate the effect of disruption risk on the supply chain, "What-If" scenarios enable managers to make quick decisions by using contingency plans and testing their impacts on operational Key Performance Indicators (Jbara, 2018).

According to (Ivanov, 2017), to optimize the simulation study's output data, the methodology can be developed as a "Simulation-based Optimization Technique." Additionally, simulation methodology enables SC managers to analyze supply chains in real-time. Different inventory control policies can be applied in the model. the supply chain structure and behaviour can be visualized. Also, recovery plans can be tested on the SC.

Given the highly unpredictable conditions ahead, supply chain managers are in serious need of tools to simultaneously monitor supply chain components, predict potential global pandemic scenarios, and minimize the SC risk by applying contingency plans.

This study's primary goal is to ensure resiliency during the global COVID-19 pandemic using the digital SC twin concept by Simulation-Based study. The study applies in the essential product manufacturing supply chain as the case study.

1.13 Research Objective

We conduct this study to address the following research questions in Supply chains:

1) How to measure resiliency in SCs? Is DES modelling a suitable methodological framework in this regard?
2) Identify performance metrics to measure resiliency in essential goods SCs, and study different COVID-19 pandemic disruption scenarios.
3) Identify risk mitigation strategies to protect SCs against COVID-19 pandemic outbreak disruption risk and ensure resiliency in essential goods' SC.
4) How can the SC visualization help SC managers make quick decisions in near real-time?

1.14 Thesis Outline

This thesis is organized as follows:

To properly explore this topic and explain the case, firstly, we introduce the critical articles that cover this problem. We discuss essential terms related to SC Management, SCOR Model, SC Risk Management, SC Disruption Risks, Resilient SC, Industry 4.0, digital SC twins, and SC Simulation Modelling in Chapter 1.

Secondly, we reviewed related works that have been done by other researchers in SC analysis, SC resiliency, SC simulation, and SC risk management areas by conducting a literature review. Chapter 3 illustrates the problem statement of the research. The solution approach is covered in chapter 4 to address the research question, followed by the detailed conceptual model and translation to discrete event simulation formalist using process map and Arena simulation software. Chapter 5 implements the model in the essential good (i.e., Toilet Tissues and Paper Towels) manufacturing SC (Luxxeen Co.) as the case study and applies different disruption scenarios to observe its effect KPIs. Besides, we employ multiple sourcing, changing inventory control policy, and buffering to relieve the SC risk and create the resilient digital supply chain twin. The results and discussion include in chapter 6. Finally, chapter 7 presents the conclusion and areas for further research.

CHAPTER 2

LITERATURE REVIEW

In this section, we focus on researches that have been done in various fields of Supply Chain Risk Management, SC Analysis, SC resilience, and COVID-19 pandemic outbreak as the specific type of disruption risk. In this chapter, we conduct a comprehensive literature review about recent studies. The structure of our literature review is shown in Figure 2.1.

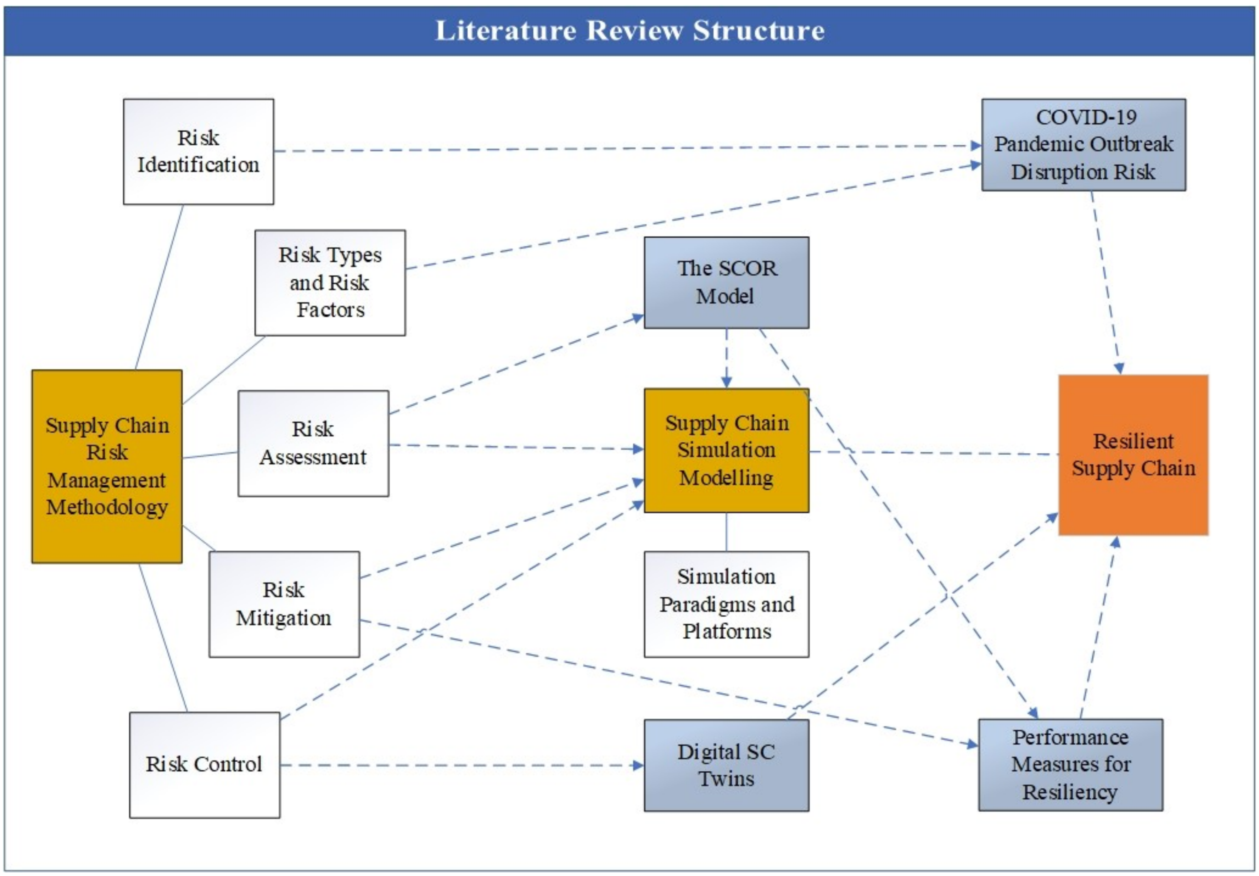

Figure 2.1 Literature Review Structure

2.1 Supply Chain Risk Management

Numerous studies have been conducted on SCRM in the last few years. According to (Ho et al., 2015; Jüttner et al., 2003).

According to (Fan & Stevenson, 2018) Supply Chain Risk Management seeks to improve the opportunity to reduce risk. SCRM has come up with risk management based on the framework outlined below to prepare and take action before, during, and after Macro and Micro risks to the SC as a whole.

2.1.1 Supply Chain Risk Management Framework

(Ho et al., 2015) conducted a literature review study. One of the goals they pursued was to propose a conceptual framework to address the SCRM issue from different angles. To this end, they have reviewed and categorized studies conducted in this field between 2003 and 2013. According to their proposed framework, risk identification, risk assessment, risk mitigation, and risk monitoring are the four main SCRM processes.

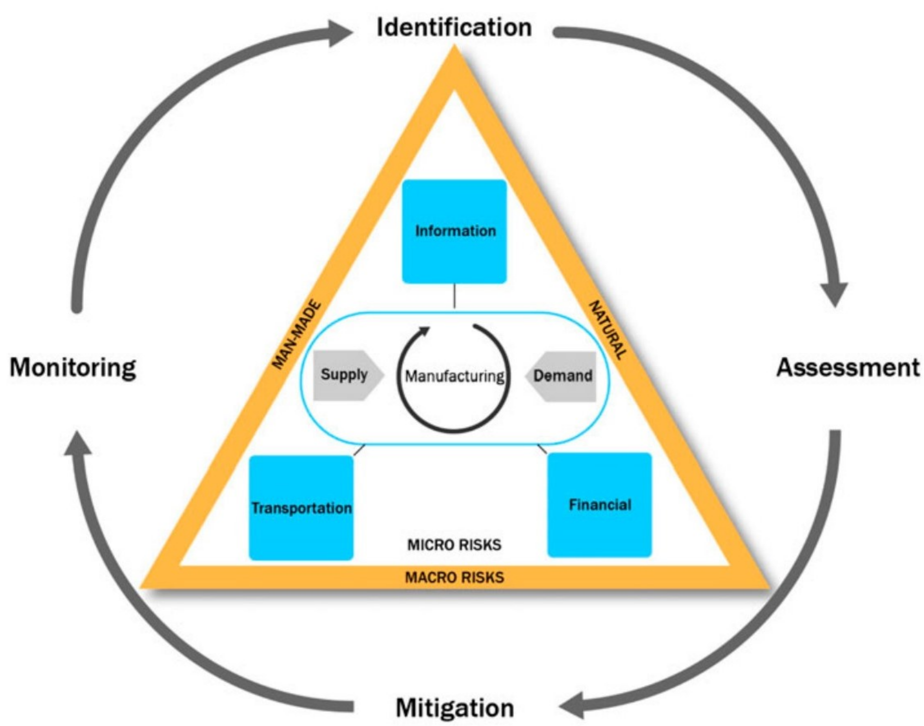

Figure 2.2 Conceptual Framework of SCRM (Developed by (Ho et al., 2015))

They also proposed that risks are divided into "Macro" and "Micro" risks. "Macro risks" include natural disasters and human-made risks. Even though "Micro risks" related to transportation risks, financial risks, and informational risks are considered infrastructural risk factors. Most authors focused on the other three factors, i.e., supply, manufacturing, and demand risk factors.

2.1.1.1 Supply Chain Risk Management Processes

2.1.1.1.1 Risk identification

This initial phase helps SC practitioners identify potential risk types and risk factors by utilizing qualitative (Sachdeva et al., 2012) and quantitative (Gaudenzi & Borghesi, 2006) approaches. For instance, (Rogers et al., 2000) proposed Hazar and Operability Study (HAZOP) to identify risks in design and operational issues. They also proposed Reliability Block Diagram (RBD) to identify the risks and reliability of the system. (Haimes et al., 2002) proposed Hierarchical Holographic Modeling (HHM) to identify risks when risks are highly dependent on subsystems and their connections evaluation. Moreover (Tsai et al., 2008) utilized the analytic hierarchy process (AHP) method and (Trkman & McCormack, 2009) proposed a conceptual model to identify risks in SC. Furthermore, (Hunt, 1996) proposed the "Process Mapping" method for reengineering business processes.

2.1.1.1.2 Risk Assessment

In this stage, the probability of a risk and the amount of damage it causes is assessed quantitatively or qualitatively calculated by data analysis, expert opinion, and scenario analysis (Cohen & Kunreuther, 2009; Harland et al., 2003; Zsidisin et al., 2004).

According to (Ho et al., 2015), 26.92% of authors developed quantitative methods for risk assessment between 2003- 2013, which is the second-highest rate of utilizing this method for 159 reviewed studies. There are several studies that have developed quantitative methods. For instance, (Marhavilas et al., 2011) projected Fault-Tree Analysis (FTA) as a quantitative method to assess combined equipment, human, and potential external accident. Additionally, (Y. Wu, 2006) Presented Analytic Hierarchy Process (AHP) constructs a hierarchy of hazard to assess the SC hazard.

(Bekker & Guittet-Remaud, 2012; Dehkhoda, 2016; Ivanov, 2017) developed simulation studies to detect potential risk threatening the SC partners. This method addresses micro and macro risks to the SC by providing the current state model simulation model and tests various scenarios to Check the risk disturbance effects on performance measures and monitor SC behaviours over time. The optimization method is used in studies such as (Ben-Haim, 2012; Gümüş et al., 2012; Namdar et al., 2018; Popovic et al., 2012) to name a few. According to (Fan & Stevenson, 2018), almost 19% of researchers between 2000 to 2016 had utilized mathematical programing (e.g., Linear programing, Multi-objective mixed integer linear programing, Quadratic programing, etc.). For instance, (Kenné et al., 2012) conducted stochastic dynamic programming to minimize the sum of holding and backlog costs in single production planning for manufacturing and reverse logistics networks.

The "SC Risk Structure" and the "SC Risk Dynamics Model" are two system-oriented approaches proposed by (Oehmen et al., 2009). They aimed to make the risk assessment of complex global SCs easier. The first method used root cause analysis to clarify SC risk factors and relationships, while the second method used modelling to represent the risk development parameters.

2.1.1.1.3 Risk Mitigation

Mitigation is the process of systematically decreasing risk to a manageable level. It can be used to reduce the likelihood of risk events and the consequences (Fan & Stevenson, 2018; Norrman &

Jansson, 2004). (Ho et al., 2015) classified risk mitigation method into eight categories: Macro, Demand, Manufacturing, Supply, Transportation, Financial, Information, and General risk mitigation. (Chopra & Sodhi, 2014; Spekman & Davis, 2004) proposed that “risk-sharing” and “corporate social responsibility” play a vital role in mitigating risks. Moreover, “Postponement” by deferring customer demand is another risk mitigation approach (Manuj & Mentzer, 2008).

(Chopra & Sodhi, 2014) sought to determine the impact of “IT,” “Risk Pooling,” and “Multiple Suppliers” on increasing resiliency and responsiveness in small and medium enterprises.

To ensure resiliency, (Gao et al., 2019) proposed a method to evaluate potential issues as a result of disruption risk using the “REI method” for “total lost sales” risk. Besides, (Kinra et al., 2019) investigated the effects of disruption, i.e. ripple effect. They suggested an approach to help SC practitioners prioritize risk mitigation strategies when assessing risk likelihood is challenging.

2.1.1.1.4 Risk Monitoring

According to (Fan & Stevenson, 2018; Ho et al., 2015), risk monitoring, on the other hand, has received less attention in the literature. Almost 3% of papers published between 2000 to 2016 were related to risk monitoring, either proposing an approach or implementing it. The “Risk Management Framework,” which includes the “Risk Control” as the final step, was presented by (Bandaly et al., 2012; Dehkhoda, 2016). Based on the authors, the current SC risk is monitored in this phase, and new risks to the SC are managed.

As a new routine, SC practitioners have a tendency to monitor supply chain information and material flows by merging them with risk assessment practices. As a result, by monitoring changes in risk sources and KPIs, an acceptable approach can be implemented quickly. (Bühler et al., 2016; Lavastre et al., 2012).

Furthermore, the new concept of "Digital SC Twins" has emerged in literature in recent years. For example, (Ivanov & Dolgui, 2020a; Marmolejo & Hurtado, 2020; Srai et al., 2019; Uhlemann et al., 2017) suggested that digital technologies utilized in "digital SC twins" enable for real-time visualization of SC.

2.1.1.2 SC Risk Factors and SC Risk Types

According to a study by (Cavinato, 2004), physical, financial informational, relation and innovational are constructed five major types of risk. (Chopra, S., 2004) categorized risk types in different ways into disruption risks, delays risks, forecast risks, procurement risks are to name a few. Risks are divided into three categories by (Manuj & Mentzer, 2008), i.e., supply risks, demand risks, operational risks. Besides, (Ho et al., 2015) proposed various events and scenarios that drive a particular risk type are referred to as "Risk Factors."

(Manuj & Mentzer, 2008) named demand variability, forecast errors and competitor moves as Demand factors. Fire accidents, external legal issues, political and economic stability are considered macro factors. (T. Wu et al., 2007) proposed fire accidents, external legal issues, and political stability to be categorized as macro factors. Additionally, wrong partners and suppliers' supplier management are related to supply factors (Schoenherr et al., 2008). Furthermore, (Wagner & Neshat, 2010) named lean inventory and centralized storage of finished product are considered as two production factors.

(Kleindorfer & Saad, 2005) proposed the conceptual framework in terms of risk assessment and risk mitigation stages. They particularly focused on the disruption risk category. Their studied disruption risk threatening the SC, e.g., natural disasters, strike, and terrorism activities. The experimental results from 1995 to 2000 on disasters in the US chemical industry. They suggested a management system to address disruption risk issues.

Other kinds of disruption risk were identified by (Dolgui et al., 2020). The ripple effect is a term that refers to structural dynamics and describes a case in which a disruption in the upstream supply chain spreads downstream, posing a significant disruption. On the other hand, the bullwhip effect is mentioned in operational dynamics, and its destructive effect moves upward to upstream. They subsequently conducted a simulation study to investigate the structural and functional dynamics of the relationship between the ripple effect and the bullwhip effect. The findings revealed that bullwhip would arise due to the ripple effect, posing a significant disruption risk. To mitigate both risks, they proposed a reserved production inventory control policy.

(Ivanov, 2020a) defined COVID-19 pandemic outbreak as a new risk factor that causes the disruption risk that spreads across the supply chain with high uncertainty and long-term destructive effects.

2.1.1.2.1 COVID-19 Pandemic as the New Type of Disruption Risks

(Rizou et al., 2020) examined the possibility (or impossibility) of COVID-19 spreading through the food supply chain and concluded that the risk of propagating is low. additionally, given the large number of people involved in the food SC, he found that more safety measures should be considered. (Mollenkopf et al., 2020) has published a conceptual paper on the service industry that looks at the SC ecosystem's role in employee health and safety during the COVID-19 pandemic outbreak. This research is the basis for other research on transformative lenses.

(Guan et al., 2020) used the "global trade modelling framework" to investigate supply chain behaviours based on lockdown scenarios. They concluded that enforcing lockdowns sooner, more strictly, and for a shorter period would reduce overall losses. They discovered that steadily lifting the restrictions (assuming there was no need to re-quarantine) reduced overall damage to global supply chains. The more complex the supply chain, the more severe the damage to COVID-19.

Moreover, (Hobbs, 2020) investigated the impacts of the COVID-19 pandemic on the food supply chain. Customers' consumption patterns changed abruptly due to fears of food shortages, and a potential supply failure was investigated. Workforce shortages, communications network disruptions, and the closing of the US-Canada border are distinguished among the concerns that have been studied. The researchers also looked at the long-term impacts of the COVID-19 pandemic outbreak on online distribution networks' growth.

(Larue, 2020) has examined the issues caused by the COVID-19 Pandemic outbreak, such as people losing their jobs due to the closing of many businesses, particularly the agricultural industry and restaurants. Naturally, supply chains face a sharp drop in demand and production on hand and an increase in demand for essential foods on the other hand.

2.2 Supply Chain Risk Analysis

(Jbara, 2018) has divided the types of supply chain analysis methods into two types: Descriptive methods and Quantitative methods. We already explained different quantitative and qualitative methods, including four main processes of SC. Here we mainly focus on the SCOR model as the "Descriptive" methods and simulation modelling as the "Quantitative" method.

(2018, Jbara) outlined the SCOR model as an example of descriptive methods. This technique provides comprehensive information on supply chain components and performance metrics for measuring and analyzing them. These tools also include practices for supply chain modelling. Because the SC domain knowledge is extracted from it in this research, the SCOR model is discussed below.

2.2.1.1 SCOR Model Studies

(Mrabet, 2012) presents a new standpoint of the Supply Chain Operation Reference (SCOR) model including Plan, Source, Make, Deliver, Return and Enable subsystems which are shown in Figure 2.3.

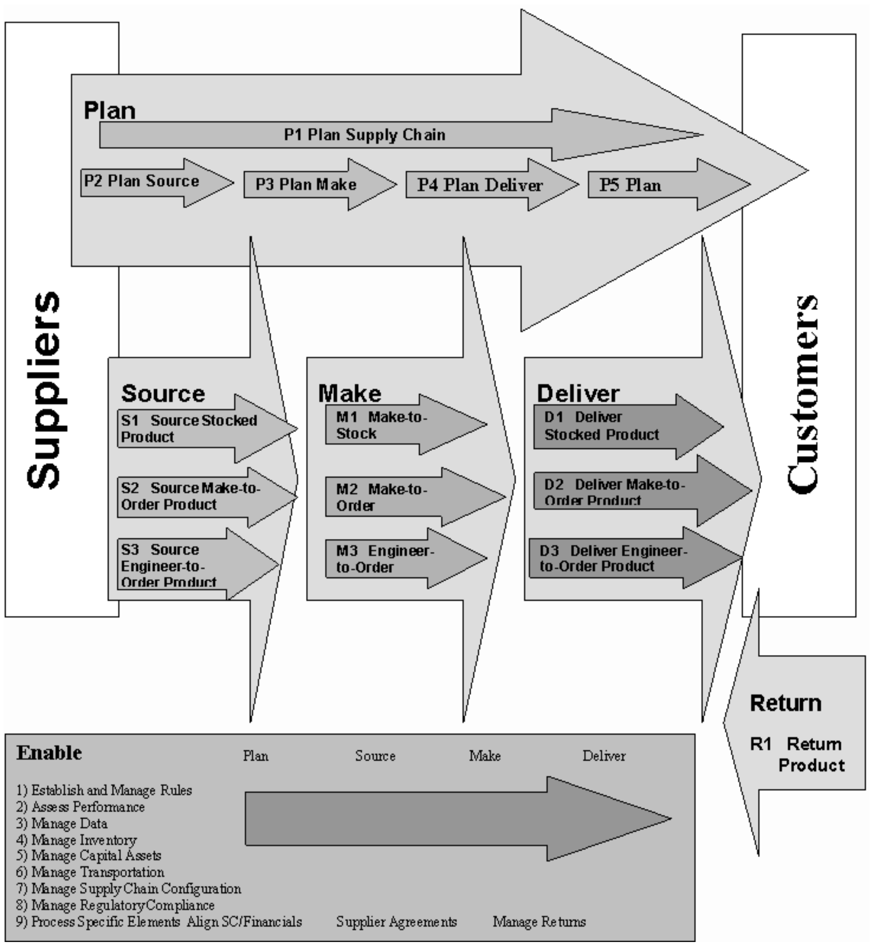

Figure 2.3 SCOR Model Subsystems View (Proposed by (Bolstorff & Rosenbaum, 2003))

(Thilakarathna et al., 2015) conducted a systematic literature review focused on the process and performance attributes of the SCOR model. They presented recommendations in terms of performance improvement, particularly in apparel SCs. Their goal was to increase competitiveness in the apparel industry and provide the guidelines to facilitate other industries to assess the SCOR model's pertinency. Moreover, (Jbara, 2018) adopted the SCOR model to build the conceptual model that later is translated to Discrete Event Simulation formalist. We include the SCOR processes and performance library in the appendix section of this study.

On the other hand, the descriptive methods can be combined with quantitative methods, i.e., simulation, to develop a comprehensive SC analysis study. For example, by combining the agent-based simulation and the SCOR model, (Long, 2014) developed a generic approach for simulation modelling for distributed SC network modelling. A hierarchical framework was proposed for the model's construction, and a standard process was used to create agent blocks. The purpose of combining these two principles was to speed up modelling and, given the standard nature of the SCOR model, to allow the above model to be generalized to other supply chains.

2.2.1.2 Supply Chain Simulation

According to (Borshchev, 2014), based on the available data and the project's purpose, the modellers look at it from three different perspectives: Discrete Event Simulation, System Dynamics, and Agent-Based Simulation are three main paradigms. If the simulation project is for a system where entities go through several consecutive processes, DES is the best method for the modeller. In contrast, If "the level of details" is low and the point of view is more general, such as "feedback loop," SDM is used by modellers. Besides, in the case, that modeller considers each object of the system individually as a whole, and in relation to other objects, ABS modelling is preferred. Lastly, these paradigms can be combined in one project to create a "Hybrid Simulation Modeling." The Anylogic software is a good example that enables "Hybrid Simulation" Modeling (Table 2.1).

	Criteria	Discrete Event Simulation	System Dynamics Simulation	Agent-Based Simulation
1	Data Requirement	High	Low	Medium
2	Type of Modeling Procedure	Bottom-Up	Top-Down	Bottom-Up
3	Model Complexity	High	Low	Medium
4	Maturity of the Simulation	Mature	Mature	Need Development
5	Construct Behavior Change While Execution	No	Yes	Yes

Table 2.1 Comparison of SC Paradigms (Interpreted from (Heath et al., 2011))

2.2.1.2.1 DES Formalists

Several authors have utilized DES formalists (Jbara, 2018; Namdar et al., 2018; Paul & Chowdhury, 2020a) . According to (Jahangirian et al., 2010), discrete event simulation is the most popular paradigm for researchers from 1997 to 2006, but it has lower stakeholder engagement than other methods like system dynamics. (Carvalho et al., 2012) conducted the simulation-based study using Arena simulation software and DES as the formalist. (Ivanov, 2017) using a simulation study, demonstrated how the ripple effect of capacity disruption propagates downstream of the SC. He selected a four-stage supply chain and used "Anylogistix" software to simulate how disruptions in the supply chain affect distribution centers and end-users and the extent to which financial and operational performance metrics are impacted by specifying two disruption scenarios. Later, he examines how risk mitigation strategies (such as change control policies, backup suppliers, and backup inventory levels) would aid in the recovery of KPIs. (Cimino et al., 2010) compared a number of SC platforms, i.e., Anylogic, Arena, and FlexSim platform, in terms of their application domains. We included Anylogistix and Tecnomatix Plant Simulation in Table 2.2.

No.	Software	Publisher	Main Task	Modelling Paradigm	source
1	AnyLogic	The AnyLogic Company	A multimethod modelling tool for general use	DES SD AB Hybrid	(Cimino et al., 2010)
2	Anylogistix		specified for supply chain and logistics enables to create Digital SC Twins	DES	(Ivanov, 2017)
3	Arena (software)	Rockwell Automation	A discrete event simulation program with the ability to model continuous processes	DES	(Carvalho et al., 2012)
4	Tecnomatix Plant Simulation	Siemens PLM Software	For production systems and processes, simulation and optimization, Tecnomatix is a complete suite that assists in digitalizing manufacturing operations	DES	(Kliment et al., 2014)

No.	Software	Publisher	Main Task	Modelling Paradigm	source
5	FlexSim	FlexSim Software Products, Inc.	For modelling simulations in 3D, with a drag-and-drop interface	DES	(Cimino et al., 2010)

Table 2.2 Simulation Software Comparison

2.2.1.3 Digital Supply Chain Twins Studies

(Marmolejo & Hurtado, 2020) conducted a literature review study for articles published Between 2017 and 2019 and on the topic of "digital SC twins." In today's variable industry, the demand for real-time data has grown. Organizations are increasingly attempting to develop their own Digital SC utilizing digitalization and data analytics to enable real-time data access.

The Literature Review article was written by (Büyüközkan & Göçer, 2018), who indicated that it does not matter whether the product or service is digital or physical. The digital supply chain refers to how SCs are managed and how technical technologies, including cloud computing and the Internet of Things (IoT), is used. Besides, the authors examined the concept from both an academic and industrial standpoint.

(Srai et al., 2019), presented examples of how the Digital Twin Supply Chain (DTSC) was built in the pharmaceutical and organic food industries. They concluded that developing DTSC improves "traceability," "visibility," and "authentication," particularly in "make-to-order" manufacturing SCs.

(Ivanov, Dolgui, & Sokolov, 2019) Brought a new principle to the literature by looking at the effect of digitalization on supply chain management (SCM) and, as a result, SC risk management. They also bring together innovation, information, digitalization, and risk management to respond to how digitalization helps SC practitioners mitigate disruption risks. They also developed the decision-making model, which including "Optimization," "Simulation," and "Data Analytics," illustrated in Figure 2.4, which was found to be motivating in the recent study.

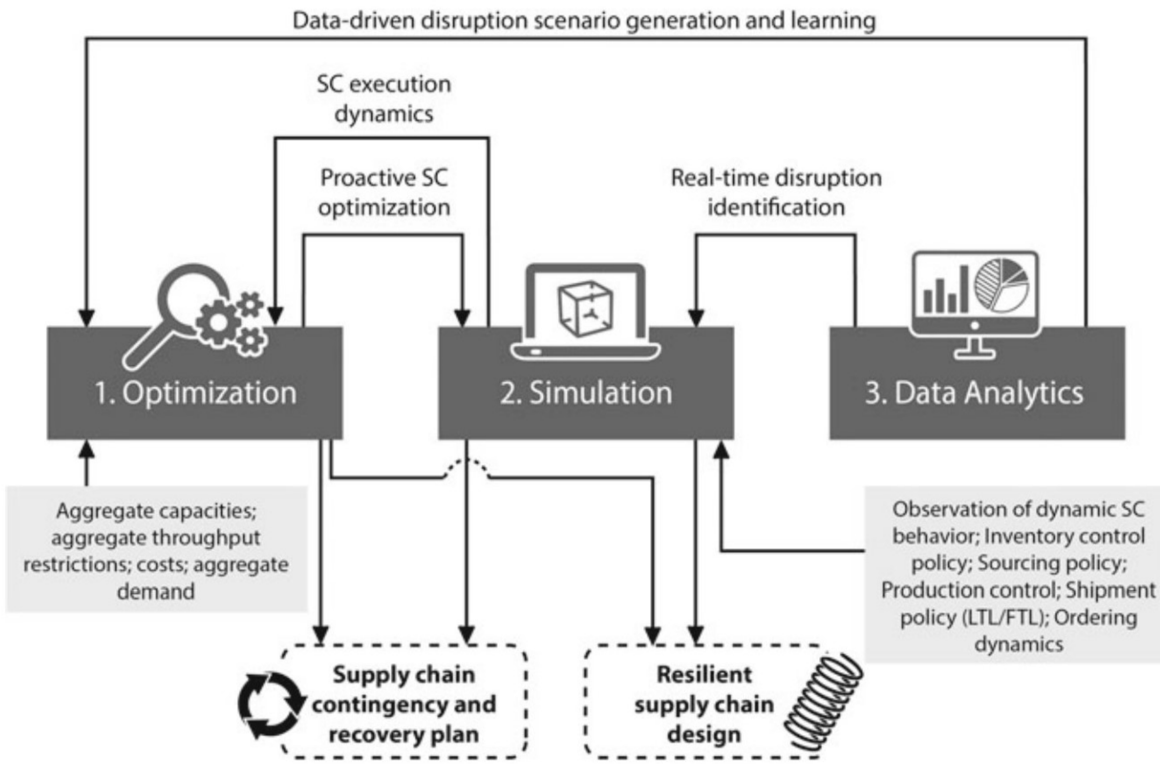

Figure 2.4 Concepts of Decision-Support System for SC Risk Analytics (Proposed by (Ivanov, Dolgui, & Sokolov, 2019))

(Ivanov, Dolgui, Das, et al., 2019) sought to demonstrate digital SC twins' role to manage disruption risks and ensure resiliency. Besides, an "SC Risk Analytics Framework" has also been developed by authors. This study revealed how digital technologies like industry 4.0, blockchain, and real-time data analytics affect SCRM and the perspective of moving toward a cyber-physical system and how this combination would establish Low-Certainty-Need (LCN) supply chains. (Ivanov & Dolgui, 2020a) created the SC Twins digital concept, demonstrating the supply chain's network situation and performance metrics in real-time. By integrating real risk data, simulation modelling, and data analytics with industry 4.0 technologies, i.e., RFID sensors, ERP, digital SC twins, can help visualize the supply chain and achieve resilient SC. Additionally, COVID-19 pandemic disruption risk was discussed in this study.

2.3 Resilient Supply Chain Studies

(Ivanov et al., 2017) conducted a literature review to integrate quantitative methods into empirical research and show the importance of simultaneously addressing disruption events and recovery policies. Using this study's findings, supply chain managers would classify and use available quantitative techniques for disruption risk and recovery planning in various situations.

The real case study of smartphone production (Ivanov, 2018) examined the four-stage supply chain. He designed a resilient supply chain that reduces the ripple effect and improves sustainability. To perform the simulation research, he used “Anylogostix” software. As a result, he discovered that “Multiple Sourcing” and reducing storage space in factories and distribution centres increased sustainability.

The goal of (Namdar et al., 2018) was to create a resilient supply chain. They assessed single sourcing, multiple sourcing, collaboration, and visibility as sourcing strategies to mitigate disruption risks. Besides, to investigate designed scenarios, they used optimization modelling. They discovered that to build resilience SC, “buyers warning capacity” is the most crucial factor.

(Carvalho et al., 2012) simulated a three-tiered SC with four suppliers divided into two tiers and one outsourcer. The goal was to create a resilient SC that could withstand a disruption. To accomplish this, a customized SCOR model was used to create SC processes. Moreover, they used Arena simulation software and DES as the formalist. They also used a risk mitigation technique as “buffering.” By combining the risk mitigation strategy and potential disruption, they came up with six scenarios that were tested in terms of “lead time ratio” and “total cost.” The paper mentioned above is the most relevant research to this thesis.

The primary focus of (Xu et al., 2014) was to establish a quantitative methodology for investigating SC resilience against random supply disruption. They designed Figure 2.5 as a “measure of SC resilience” conceptual model by integrating redundancy into the triangular resilience model that includes rapidity and robustness in addition to redundancy. They designed the mathematical model and then added self-adaptation and self-recovery as disciplines. They used the “Anylogic” software to simulate the proposed approach. They modelled a supply chain that included four vendors, three DCs, and four retailers. Afterward, the author measured the system’s performance in terms of customer satisfaction by generating 15 scenarios in which one of the suppliers is removed in each scenario to represents the disruption.

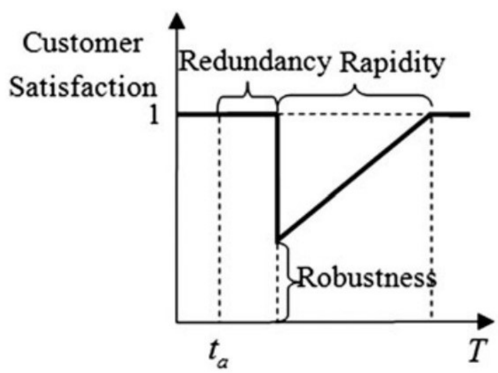

Figure 2.5 Measure of SC Resilience Conceptual Definition (Proposed by (Xu et al., 2014))

2.3.1 Performance Measures for Resiliency

(Karl et al., 2018) conducted the systematic literature review to examine the impact of non-financial performance metrics on resilient supply chain construction. They reviewed more than 55 articles published in the first two decades of the 21st century. “order and delivery lead time,” “supplier delivery efficiency,” “on-time delivery,” and “customer satisfaction” are the most important performance metrics to ensure resiliency. They also identified performance metrics to be monitored before, during and after a disruption to make resilient SC which is presented in Table 2.3.

		Focal Company						Supplier		Customer	
		Capacity utilization	*Quality of delivered goods*	*Order Lead Time*	*Delivery Lead Time*	*On-time delivery of goods*	*Stock level*	*Supplier delivery efficiency*	*Supplier rejection rate*	*Consumer Satisfaction*	*Damage return rate*
Pre-disruption	*Security*					✓		✓		✓	
	Knowledge Management	✓	✓		✓			✓		✓	
	Visibility										
	Information Sharing						✓			✓	
	Trust		✓			✓		✓	✓		
	Risk Management			✓	✓		✓	✓			
	Robustness						✓				
During-disruption	*Visibility*										
	Information Sharing				✓		✓			✓	
	Collaboration		✓					✓		✓	✓
	Agility	✓		✓	✓		✓			✓	
	Flexibility	✓		✓	✓	✓					
	Redundancy			✓			✓			✓	
	Supply chain design		✓	✓						✓	
Post-disruption	*Knowledge Management*		✓	✓	✓	✓		✓		✓	
	Visibility										
	Information Sharing				✓		✓			✓	
	Collaboration			✓	✓	✓			✓		

Table 2.3 Non-financial Performance Metrics for Resilient SC (Defined by (Karl et al., 2018))

2.3.2 COVID-19 Pandemic Outbreak Disruption Risk and Resilient SC

(Ivanov, 2020b) has defined a new definition by combining the concepts of resiliency, agility, and sustainability as viability which means SCs are capable of surviving in a changing world by structure reconstruction and long-term impact performance replanting. He proposed that the Viable SC framework enables firms to guide their decision on rebuilding after long-term disruption crises such as the COVID-19 pandemic outbreak. He considered resiliency as the core element o VSC to ensure viability. Figure 2.6 illustrates Organizational, Informational, Process-Functional, Informational, Financial, and Technological structures for the viable SC model.

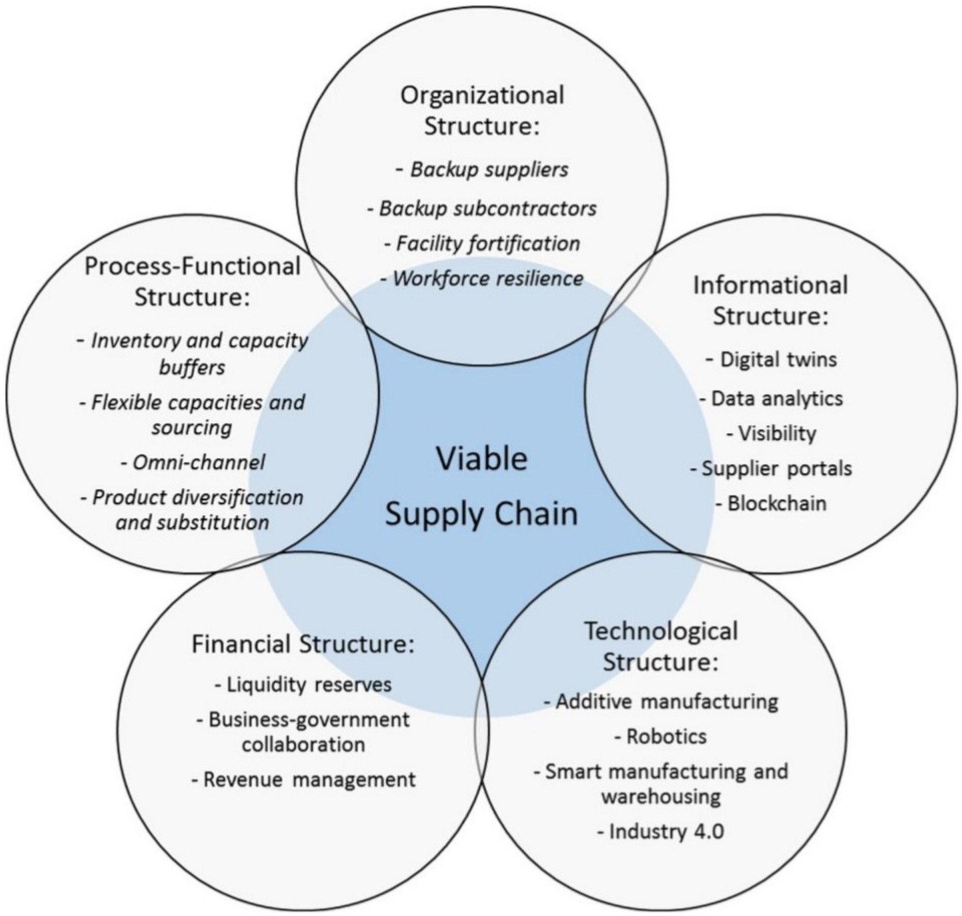

Figure 2.6 Multi- structural VSC view (Proposed by (Ivanov, 2020b))

(Ivanov & Dolgui, 2020b) looked at SC resiliency from a different point of view. They developed the "Intertwined Supply Networks" framework, which is critical for supply chains that must withstand COVID-19 pandemic disruption risk over time (e.g., food service and mobility systems). in this case, the resiliency should be satisfied in the level of "viability."

(Paul & Chowdhury, 2020b) Several strategies enable companies to fulfill market demand for essential products such as toilet paper during the COVID-19 pandemic outbreak. The authors suggested four strategies to increase the service level and satisfy more portion of the market demand. The suggested strategies include resource sharing among all manufacturers, collective emergency sourcing, producing basic quality items, and packaging the product with a minimum standard size.

(Ivanov, 2020a) conducted a simulation study to assess the short and long-term effect of COVID-19 pandemic disruption risk on supply chain performance metrics. He then pointed at how simulation research will help SC executives predict the future. To model the global SC of lighting equipment manufacture, they used DES formalist. "SIM Global Network Examination" verified model and Anylogostix simulation software. The model was then updated to include COVID-19 pandemic disruption risk scenarios based on the available data. He examined metrics for "production inventory dynamics," "customer performance," "financial performance," and "lead time performance," among others. The most important finding was that the timing of facility closures and openings upstream and downstream of the supply chain is more important than the rate of expansion and upstream dispersion. The main concept of the recent study design came from this research.

(Paul & Chowdhury, 2020a) the main goal was to develop an improved production plan using the mathematical modelling approach in the event of a COVID-19 pandemic disrupting the production of an inessential product, namely toilet tissue. According to the authors, a supply shortage combined with a sharp rise in consumer demand causes a double disruption, putting the supply chain at risk of failure. Lastly, to ensure that the revised production plan can be implemented in dual-disruption (supply and demand) mode, they verify the suggested plan by numerically evaluating the model and observing its effect on total profit KPI.

A methodological framework is missing to integrate the concepts mentioned above to create resilient SC. Table 2.4 represents the most relevant studies in the area.

No.	Year of Publication	Reference	Goal	Region	Disruption type/Factor	Method
1	2020	Ivanov, D. (2020a)	SC Resiliency-Risk Assessment-Risk Mitigation	Germany	COVID-19 Pandemic	DES
2	2020	Paul, S. K., & Chowdhury, P. (2020a)	Develop Production Recovery Model-	Australia	COVID-19 Pandemic	Case Study for Essential Products (i.e., Toilet Papers)-Mathematical Modelling
3	2020	Chowdhury, P. (2020b)	SC Resiliency - Risk Mitigation Strategies	Australia	COVID-19 Pandemic	Case Study for Essential Products (i.e., Toilet Papers)
4	2020	(Golan et al., 2020)	Resilient Analysis in SC modelling	The U.S.A	-	Literature Review

No.	Year of Publication	Reference	Goal	Region	Disruption type/Factor	Method
5	2020	Ivanov & Dolgui, 2020a	SC resiliency- Digital SC Twin	Germany	COVID-19 Pandemic	-
6	2018	Jbara, 2018	SCRM	France	-	Simulation and Model-based Approach
7	2018	Karl et al., 2018	SC resiliency and KPIs	Brazil	-	Literature Review
8	2017	(Ivanov, 2017)	SC Resiliency	Germany	Ripple Effect	Case Study- Simulation Modelling
9	2015	Ho et al., 2015	SCRM	China	-	Literature Review
10	2014	Xu, M., Wang, X., & Zhao, L. (2014)	SC Resiliency	China	Random Supply Disruption	Quantitative Approach- SC Simulation

Table 2.4 Top Articles Addressing SC Resiliency

CHAPTER 3

PROBLEM STATEMENT

As discussed in the first chapter, with the expansion of the supply chain in terms of dimensions and complexity, more extensive research is required to address new challenges. Over the years, the focus has been chiefly on minimizing SC total cost and decrease the total cycle time. For instance, concepts like “Lean Manufacturing,” “Just in Time,” “Outsourcing,” etc., emerged into the industries resulted in minimizing in-hand inventory. This over-focus on the profit side of SC’s KPIs puts them at significant risk and makes them more vulnerable to low-frequency, high-Impact risks (Beamon, 1998; Christopher & Lee, 2004; Ellram & Cooper, 2014; Ho et al., 2015; Jbara, 2018; Windelberg, 2016). There is a growing need for resiliency in supply chains to survive due to the recent COVID-19 pandemic.

According to (Ivanov, 2020a; Paul & Chowdhury, 2020a) the coronavirus disease (COVID-19) outbreak started in December 2019, and World Health Organization (WHO) announced it as a pandemic on 11 March 2020 due to its rapid spread worldwide. According to (Worldometers, 2021), COVID-19 Pandemic Outbreak affected 221 countries and with more than 110 million cases and more than 2.4 million deaths as of 21 February 2021. According to (Ivanov, 2020a), 94% of the Fortune 1000 companies were severely disrupted due to the COVID-19 pandemic outbreak.

According to (CTV News, 2020; Hobbs, 2020; Paul & Chowdhury, 2020b) foods and most wanted goods for daily life, like, i.e. Toilet Papers and Paper Towels SCs, were severely disturbed by a sharp increase in demand due to the “Panic Buying” behaviour of customers and a decrease in raw materials inventory because of supply failure.

As discussed in Chapter 2, previous work has been done on Digital SC twins, SC modelling, SC simulation, SC Risk Management, and SC resilience, but not enough research or literature is available to merge these concepts. Also, there is no agreement on the exact definition of resilient supply chain management. Especially literature scares in terms of the pandemic outbreak as a unique type of disruption risks to SCs to address recent challenges. This concept has received little attention in the last century.

A framework is missing for effective implementation resilience practices in SC to help supply chain practitioners to conduct comprehensive and reliable simulation study including model development approaches.

Moreover, a decision-making tool is missing to help SC managers predict potential disruptions scenarios and test contingency plans by the simulation to make quick decisions in near real-time. SC practitioners required clarified metric performance criteria to achieve resiliency in supply chains (Spiegler et al., 2012).

Additionally, they need data analytics tools and observation technologies to visualize SC components and transportation networks, assess measures for disruption and recovery times, and keep an eye on KPIs using designed managerial dashboards (Ivanov & Dolgui, 2020a).

According to (Paul & Chowdhury, 2020b) during this challenging situation, the focus should be shifted from cost minimization and optimization in terms of profit to SC survival and satisfying more customer demand, minimizing delivery time, and social responsibility. This study focuses on non-financial key performance indicators regarding “Reliability” and “Responsiveness” (SCC, 2010). A case study with the “Luxxeen Company” in the Montreal region is conducted.

Luxxeen Productions Inc. is a Canadian Inc. is a privately owned manufacturer ranging high-quality branded facial tissue and toilette paper products. “Toilet Tissues” is chosen as an example of the essential product during the COVID-19 pandemic outbreak in the current study. According to the CEO of Luxxeen co., in early 2020, they faced a 100% delay in supply of “Raw Material A,” which is single-sourced and is located in the USA. Likewise, the company was faced with an increase of almost 100% in demand in mid-2020 for toilet papers. This surge in demand resulted in a significant delay in delivery time to retailers.

All the problems mentioned above will be sequentially addressed step by step to achieve the goal of designing a resilient supply chain.

CHAPTER 4

SOLUTION APPROACH

4.1 Chapter Overview

We present the methodological framework to conduct a comprehensive and reliable simulation study, including model development approaches. As we discussed earlier, this methodology facilitates SC practitioners to assess, mitigate and monitor the disruption risk influenced by pandemic outbreaks disruption risks ensuring resiliency. The framework enables the development and implementation of resilience practices in SC.

Firstly, we utilize (Banks et al., 2010; Chellanthara, 2013) simulation study procedure, including four phases and twelve steps to develop our thesis framework. Secondly, we developed a "framework for the modelling approach," including six based on (Jbara, 2018). The first phase includes creating the SC structure's conceptual model, SC behaviour, and SC pandemic outbreak risks. To accomplish this phase, we extracted our SC's domain knowledge from the SCOR reference model, including its level of details, process library (i.e., Source, Make, and Deliver), and performance library. We present clarified performance metrics criteria to achieve resiliency in supply chains by extracting standard performance metrics from the SCOR reference model regarding reliability and responsiveness.

For the second phase of the framework, " Input Analysis," we perform "Data Collection" followed by fitting input disruption using "Arena Input Analyzer," The third phase of the framework presents the translation algorithm to DES formalist. We also develop the translation guide to implement the DES using the Arena software simulation modules library.

In the fourth phase of the framework, we verify and validate the model by running it by random inputs and simplified assumptions and comparison via animation.

In the fifth phase of the framework, we design the CS for resiliency. To mitigate disruption risks, we propose three contingency plans to ensure resiliency in the supply chain.

The last phase of this framework includes an experiment with the model using disruption scenarios and risk mitigation strategies. We present three disruption scenarios starting from a disruption in the supply side, propagates downstream through networks, and from there to retailers. In this thesis, to build a simulation study, we utilize Figure 4.1, which shows 12 steps that should be followed (Banks et al., 2010; Kelton, 2002; Poluha, 2007).

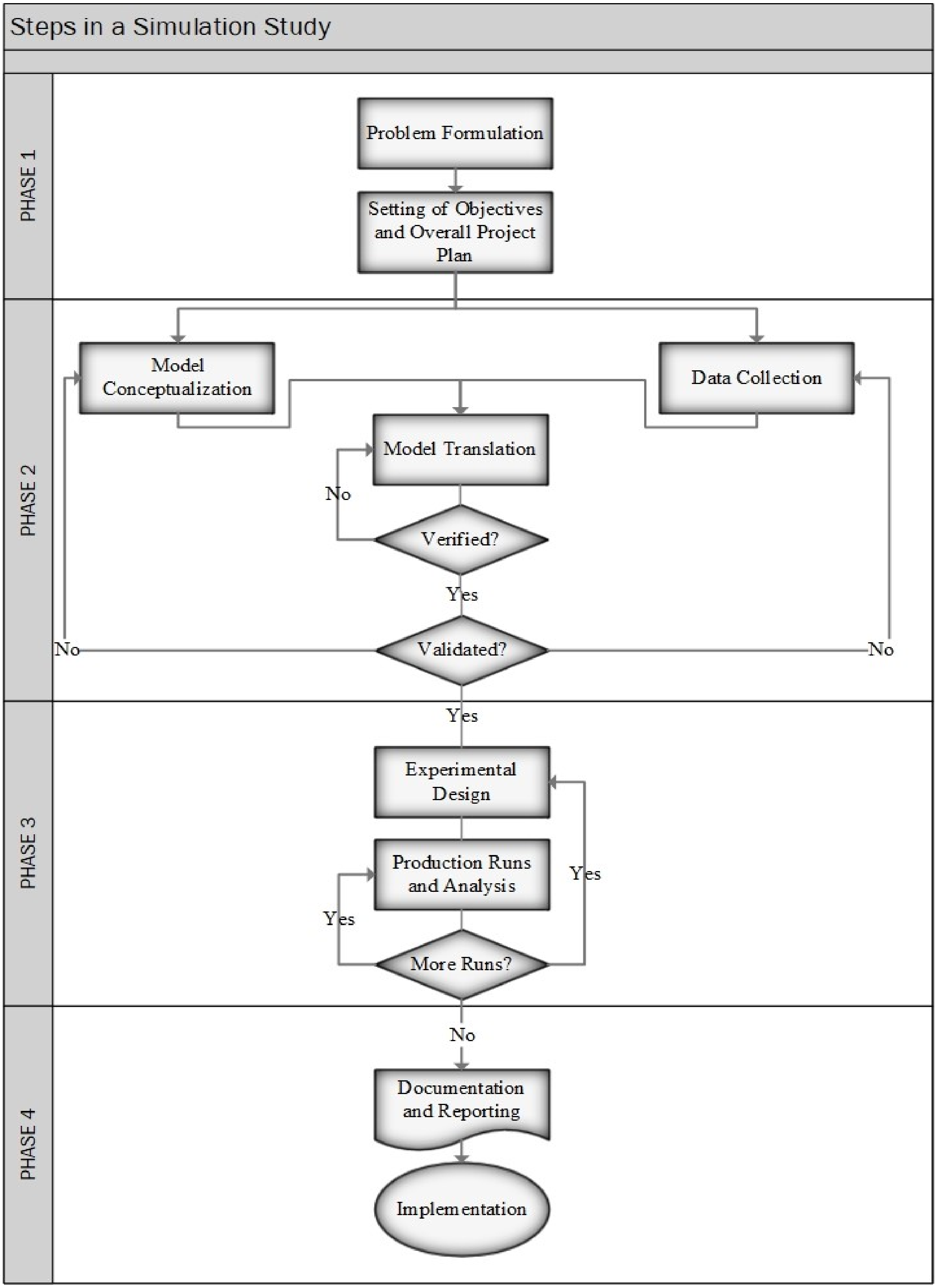

Figure 4.1 Steps in a Simulation Study (Proposed by (Banks et al., 2010))

Phase 1

The first step is "Problem formulation," which is defining the problem's statement. The problem statement should be clear and understood by analysts and policymakers. We already defined the problem statement in chapter 3. The second step, "Setting of objectives and overall project plan," defines the study's objectives. We already explained in chapter two why a simulation study is the most suitable approach to address the problem statement. Additionally, in this step, the plan to accomplish each step of this project and the expected results of each step of the study is defined (Banks et al., 2010).

Phase 2

According to (Banks et al., 2010; Kelton, 2002), building the SC conceptual model is the next step as " Model conceptualization.". The conceptual model defines SC elements and their interactions. The supply chain structure, behaviour, SC risks, and the relations between the risks and the SC elements are captured. The next step is "Data collection," considered as one of the very early steps in preparing this simulation project to determine what data we need as the model input. The requisite data aspect is closely linked to the model's complexity. In the next step, "Model Translation," the conceptual model is translated to Discrete-Event Simulation formalist. Moreover, the model should be the recognizable format for the computer. In this study, Arena simulation software is used as special-purpose simulation software.

"Verification" is the method of verifying that the model behaves as expected, which is done in the sixth step. Also, it is recognized as debugging the model (Kelton, 2002). This critical step is done if the input data and the model's entire logic represent the simulation software accurately. For verifying the model, different techniques are utilized. For example, the model is tested under various conditions and check the outputs if it is reasonable. Besides, the values of variables, attributes, and counters are observed after every event. Besides, "Validation" is done in the seventh step to ensure that the model behaves like the real-world system (Kelton, 2002).In other words, by contrasting it to real system behaviour, the model is calibrated. Moreover, the model is compared with an expert opinion. Besides, the model is determined by comparing via animation to check if it performed as expected.

Phase 3

In the "Experimental Design" step, the length of the initialization period and simulation runs, the number of replications to be applied on each run, and the type of simulation concerning terminating or nonterminating are decided. In the ninth step, using output Analyzer, different scenarios are applied to the system and performance metrics and KPI's are measured and analyzed. On the $10^{th,}$ the decision must be made as to whether or not to repeat more runs on the model (Banks et al., 2010).

Phase 4

Based on (Banks et al., 2010), the program reports and documents aid other analysts can use the model in similar cases. The program report shows how the program operates. The progress report includes a crucial written history of a list of tasks done and determinations made. The tasks mentioned above should be done in the 11th step. Lastly, all previous steps should be completed to be successful in this step; well fundamental assumptions have been adequately conveyed.

4.2 Development of the Modelling Approach of the Framework

4.2.1 Overview

To provide a comprehensive framework for modelling (Figure 4.2), according to (Jbara, 2018), we develop the following multi-step modelling approach framework, which includes six phases of conceptual modelling, input analysis, translation into the simulation model, verification and validation, resilient SC modelling and experiments the model using disruption scenarios and contingency plans.

In this framework's first phase, we model the SC's structure, including SC actors (namely suppliers, transportation networks, a manufacturer, and retailer), SC products, and the SC infrastructures. To model SC behaviour, we first present the SCOR reference model, including its level of details, process types, i.e., Source, Make, and Deliver. Then we customize the SCOR model to identifying and define operations of the SC of this study. To do so, we study the original operations by direct observation, using available documents and interviews with the process owner, and consult with experts. Then extracted operations are compared to the SCOR reference model. the processes are modified when needed. Besides, we present information flow, material flow, and financial flow within the SC using the "Process Map" by MS Visio. Furthermore, we present clarified metric performance criteria to achieve resiliency in supply chains by extracting standard performance metrics from the SCOR reference model regarding reliability and responsiveness.

For the second phase of the framework, we utilized a three steps procedure with "Data Collection" followed by "Fitting input Disruption using Input Analyzer" and "Goodness of Fit."

In phase 3, we translate the conceptual model into the DES formalist. We describe the DES's components, followed by designing a flowchart to explain how to convert a process map of the conceptual model to simulation language. We develop the relevant modules in Arena software and establish their relations. Besides, we define simulation system attributes and variables.

The model is verified and validated in phase 4. We design resilient SC in phase 5 of the framework. To mitigate disruption, we propose three risk mitigation strategies to ensure resiliency in the supply chain.

In the last phase, we apply three disruption scenarios that start from the disruption on the suppliers' side and spread downstream. To mitigate disruption, we propose and test three risk mitigation strategies to ensure resiliency in the supply chain for each potential disruption scenario.

Lastly, we compare KPIs due to each pair of disruption and contingency plans using an Output Analyzer, Process Analyzer, and OptQuest for Arena. In this step, we also determine the run setup, including the number of replications and warmup period.

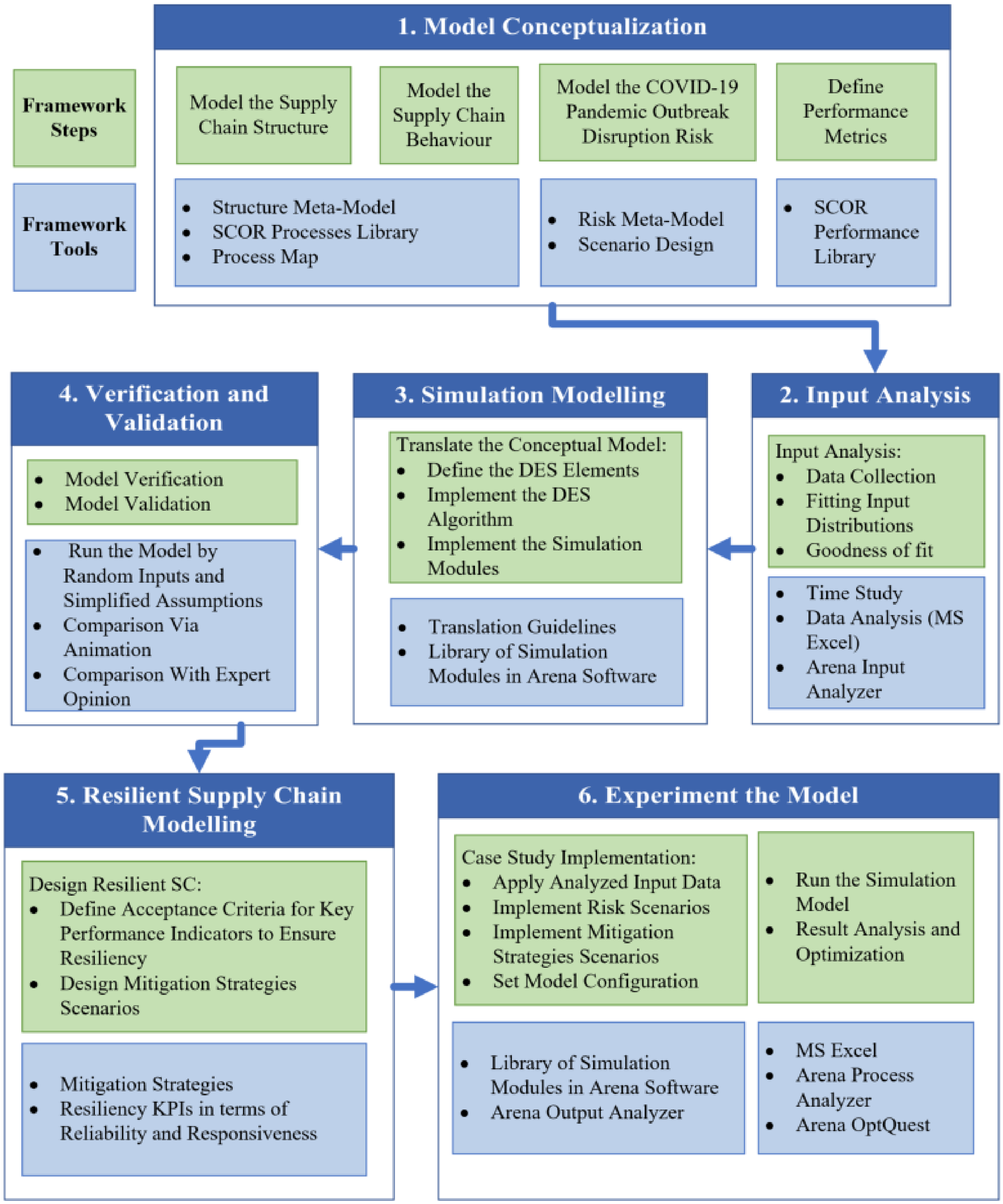

Figure 4.2 Modelling Approach Framework

4.2.2 Model conceptualization

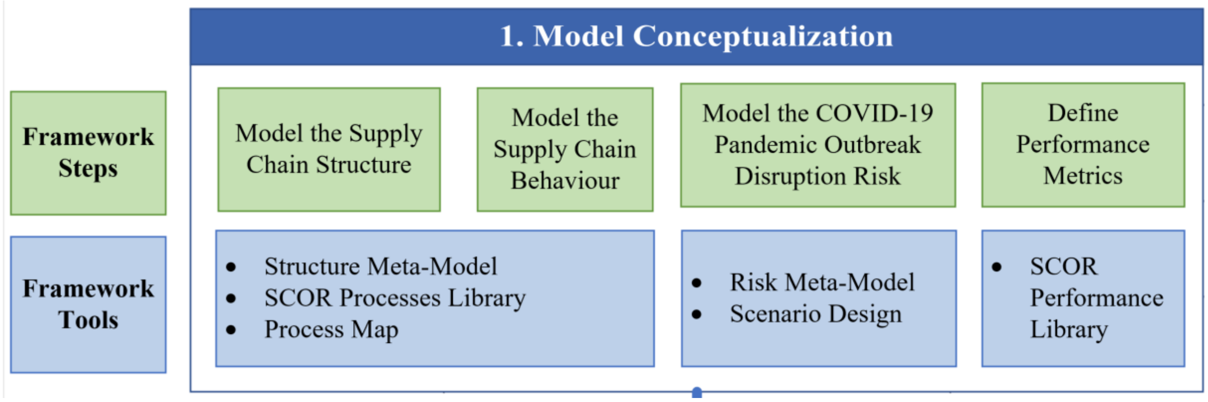

Figure 4.3 Model Conceptualization Framework

4.2.2.1 Supply Chain's Structure

In this section, we model the main structure of the supply chain. The supply chain actors, including suppliers, the route and means of transportation, and retailers, are modelled. Also, the product under study and SC's infrastructure, including resources and buffers, are studied. In this section, we present the definition for each SC structure partner, and the required data should be captured from the SC to be able to model the SC and develop a simulation modelling study. The captured data are presented in chapter five, which is implementing the framework in the case study.

4.2.2.1.1 Supply Chain Actors

This section defines supply chain actors in three echelons containing suppliers (namely S1, S2, and S3), manufacturers, retailers, and transportation networks. Based on the literature, different combinations of actors were studies, but few of them, i.e., (Ebrahimi et al., 2012) have chosen the same combination to study. (Figure 4.4).

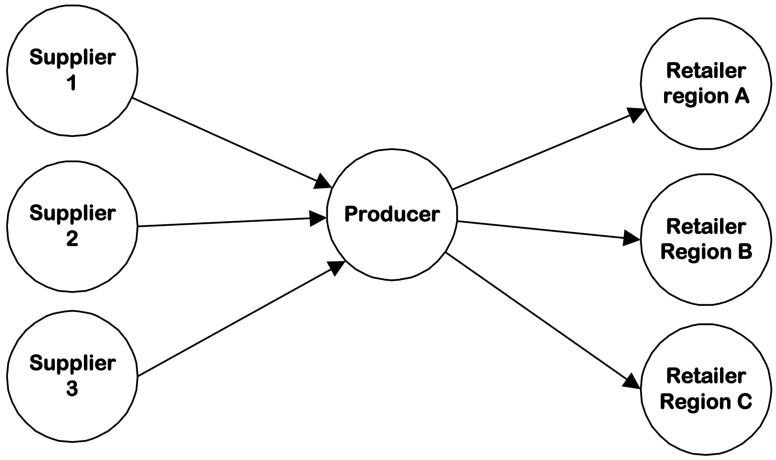

Figure 4.4 SC's Actors in a Three Echelons

Actors of the SC are in a relationship through the "contract." This contract consists of "minimum and maximum lead time," "minimum and maximum quantity of order," and "contracted product."

4.2.2.1.1.1 Suppliers

Suppliers are located upstream of the SC. These suppliers are responsible for supplying three different raw materials (A, B, and C) required to produce the final product. In this study, Suppliers are geographically located in the United States and Canada.

These suppliers are in direct contact with the manufacturer through a contract. Suppliers receive a "Supply Order" from the manufacturer based on (r, Q) control policy. Supply expected lead time, SO quantity and technical specification are reflected in SOs. In this study, the SC follows the "Single Sourcing" policy for raw materials.

4.2.2.1.1.2 Transportation Network

The transportation network is also a component of the supply chain structure. It is the network of transferring raw materials and products from one physical place to another static site. This network includes both the commuting route and the means of transportation, which should be reflected in the contract.

4.2.2.1.1.3 Manufacturer

The focus of this study is on the manufacturing company. The manufacturing company is in contact with retailers through a sales contract and a supply contract with suppliers. This study's selected manufacturing company is located in Montreal, Canada, which is explained in detail in the next chapter.

4.2.2.1.1.4 Retailers

Retailers are considered as end-users in this study and located downstream of the SC. Retailers send the Purchase Order to the manufacturer. A purchase order contains the "product specification," "order quantity," and "expected delivery time," which are also reflected in the contract.

4.2.2.1.2 Product

In this study, we considered single product SC. This product is essential for customers during a pandemic outbreak. Moreover, the following information should be captured:

- Product technical information and specification
- Bill of Material defines the raw materials and required number of perquisite raw materials to produce one unit of the final product

4.2.2.1.3 The Infrastructure

We consider "Resources" and the "Buffers" as the infrastructure elements.

4.2.2.1.3.1 Resources

human resources working in the manufacturing company (e.g., production worker, logistics officer, etc.) and machines are examples of "resources," which is one of SC infrastructure elements. They are playing their specific role in the SC to produce a product. All the above should be identified to conduct a simulation study.

4.2.2.1.3.2 Buffers

Also, in SC, raw materials and final products are stored in buffers. They contain essential data to conduct simulation study as follows:

- Maximum Inventory Level
- Review Period
- Order Point
- Safety Stock for Raw Materials

4.2.2.2 Modelling the supply chain's behaviour

We modelled supply chain behaviour, including SC processed and operations, material, information, and financial flow. For this purpose, at the very beginning, we take advantage of the SCOR reference model. operations are extracted by customization of the reference model. Consequently, information flow, material flow, and financial flows are modelled based on the SC operations. As it is shown in Figure 4.5, in the typical SC, on the one hand, the material flow originates from the supplier to the manufacturer and from there to downstream of SC which are retailers considered as final users in this study. However, on the other hand, the information flow is generated by retailers by issuing POs and going to the manufacturer. Finally, the manufacturer sends supply orders (SOs) to suppliers based on its inventory control policy.

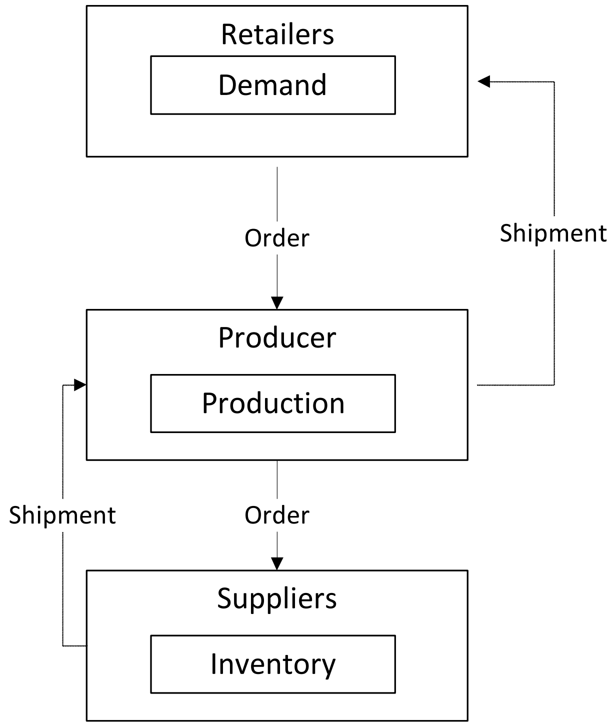

Figure 4.5 Big picture of 3-Echelon SC behaviour

4.2.2.2.1 The SCOR Model (Supply Chain Operations Reference)

As discussed earlier in chapter two, we utilize the SCOR model as the best practice for extracting SC domain knowledge (Poluha, 2007). The Supply Chain Operations Reference-model (SCOR) was created and supported as a cross-industry standard supply chain diagnostic tool by the Supply Chain Council in 1996 (SCC, 2010).

As a series of processes at three hierarchical levels (Figure 4.6), the SC operations are captured by the SCOR model. SCOR model Level I is top-level that defines the process types. This level consists of five main process types, i.e., Plan, Source, Make, Deliver, and Return. The next level (Level II) defines process categories, e.g., level of configuration where it is possible to define a supply chain using core process categories. Finally, the SCOR model's Level III process operations break down processes into process components, defining inputs and outputs, performance indicators of processes (Hanus, 2015; Jbara, 2018; Palma-Mendoza, 2014; SCC, 2010).

	Level		Examples	Comments
	#	Description		
Within scope of SCOR	1	Process Types (Scope)	Plan, Source, Make, Deliver, Return and Enable	Level-1 defines scope and content of a supply chain. At level-1 the basis-of-competition performance targets for a supply chain are set.
	2	Process Categories (Configuration)	Make-to-Stock, Make-to-Order, Engineer-to-Order Defective Products, MRO Products, Excess Products	Level-2 defines the operations strategy. At level-2 the process capabilities for a supply chain are set. (Make-to-Stock, Make-to-Order)
	3	Process Elements (Steps)	• Schedule Deliveries • Receive Product • Verify Product • Transfer Product • Authorize Payment	Level-3 defines the configuration of individual processes. At level-3 the ability to execute is set. At level-3 the focus is on the right: • Processes • Inputs and Outputs • Process performance • Practices • Technology capabilities • Skills of staff

Figure 4.6 The Description Levels of SCOR Reference Model (Defined by (SCC, 2010))

To implement the conceptual SC in this study, we have customized the processes shown in Table 4.1 (extracted up to level 2 of SCOR), based on available literature and knowledge, direct observations, and consultation with experts. The processes are modified when needed to be mapped by the SCOR reference standard model. Besides, we present information flow, material flow, and financial flow within the supply chain using the "Process Map" designed by MS Visio.

		Process	Code	Description
SCOR PROCESSES	PLAN	Plan	sP1	Plan Supply chain
		Plan	sP2	Plan Source
		Plan	sP3	Plan Make
		Plan	sP4	Plan Deliver
	SOURCE	Source	sS1	Source Stocked Product
	MAKE	Make	sM2	Make-to-Order
	DELIVER	Deliver	sD2	Deliver Make-to-Order

Table 4.1 Extracted Domain Knowledge from SCOR

4.2.2.2.2 Define Supply chain Operations and Processes

The main processes of the SC are defined according to the SCOR reference model. Despite the specific characteristics of the SC entities, there is a set of processes with common characteristics, namely planning, manufacturing, delivery, and sourcing (Millet et al., 2009). To identify the supply chain's operations, we first extracted the operation by observing and recognizing the organization's processes' input and output based on the SCOR model. Each identified operation of SC corresponds to one or more processes of the reference model.

Based on the SCOR reference model (SCC, 2010), to define the process components, SCOR suggests the following symbol: ["Process type," "Policy type," "Process Element"]. For example, sD2.8 indicates that the process type (sD) is "Deliver," number "2" represents the "Make-to-Order" Policy and number "8" represents Process Element, which is "Receive Product from Source or Make."

In this study, we build unique operations by composing consecutive processes belonging to the same process type. For instance, the "Produce Final Product" operation is a result of composing "sM2.3 Produce and test", "sM2.4 Package", "sM2.5 Stage Finished Product", and "sM2.6 Release Finished Product to Deliver" process elements.

Table 4.2 describes the identified processes and operations and their relationship to each SCOR reference model level:

	Identified SC Operations Library	**SCOR Level 1 Process Type**	**SCOR Level 2 Symbol**	**SCOR Level 2 Policy Type**	**SCOR Level 3 Process Element**
1	Material Requirement Planning	Plan	sP2	Plan Source	sP2.1 Balance Product Resources with Product Requirements
2	Delivery Planning	Plan	sP4	Plan Deliver	sP4.4 Establish Delivery Plans
3	Delay to Send Raw Material Supply Order to Suppliers	Source	sS1	Source Stocked Product	sS1.1 Schedule Product Deliveries
4	Supplier Order Confirmation	Source	sS1	Source Stocked Product	sS1.1 Schedule Product Deliveries

	Identified SC Operations Library	SCOR Level 1 Process Type	SCOR Level 2 Symbol	SCOR Level 2 Policy Type	SCOR Level 3 Process Element
5	Providing raw material	Source	sS1	Source Stocked Product	sS1.4 Transfer Product
6	Schedule Shipping from Suppliers	Source	sS1	Source Stocked Product	sS1.1 Schedule Product Deliveries
7	Payment to suppliers	Source	sS1	Source Stocked Product	sS1.5 Authorize Supplier Payment, sS1.3 Verify Product
8	Route Raw Materials to Manufacturing Company	Source	sS1	Source Stocked Product	sS1.4 Transfer Product
9	Production Scheduling	Make	sM2	Make-to-Order	sM2.1 Schedule Production Activities
10	Produce Final Product	Make	sM2	Make-to-Order	sM2.2 Issue In-Process Product, sM2.3 Produce and Test, sM2.4 Package, sM2.5 Staged Finished Product

	Identified SC Operations Library	SCOR Level 1 Process Type	SCOR Level 2 Symbol	SCOR Level 2 Policy Type	SCOR Level 3 Process Element
11	Quality Control	Make	sM2	Make-to-Order	sM2.3 Produce and Test, sM2.6 Release Finished Product to Deliver
12	Payment Agreement and Credit Check	Deliver	sD2	Deliver Make-to-Order Product	sD2.1 Process Inquiry and Quote, sD2.2 Receive, Configure, Enter, and Validate Order
13	Purchase Order Confirmation	Deliver	sD2	Deliver Make-to-Order Product	sD2.1 Process Inquiry and Quote, sD2.2 Receive, Configure, Enter, and Validate Order
14	Providing Shipping documents	Deliver	sD2	Deliver Make-to-Order Product	sD2.11 Load Vehicle and Generate Shipping Document
15	Route Final Product to Customer	Deliver	sD2	Deliver Make-to-Order Product	sD2.8 Receive Product from Source or Makes, D2.9 Pick Product, sD2.10 Pack Product, sD2.12 Ship Product

	Identified SC Operations Library	SCOR Level 1 Process Type	SCOR Level 2 Symbol	SCOR Level 2 Policy Type	SCOR Level 3 Process Element
16	Receive and Verify Product by Retailer	Deliver	sD2	Deliver Make-to-Order Product	sD2.13 Receive and Verify Product By Customer
17	Invoice Issue and Receive Payment	Deliver	sD2	Deliver Make-to-Order Product	sD2.15 Invoice

Table 4.2 Identified SC Operations Extracted from SCOR model extracted from (SCC, 2010)

4.2.2.2.3 Representing Information, Material, and Financial Flows

In this study, the retailers are considered as the final consumer. As presented in Figure 4.7, the information flow begins with the customer sending the first purchase order (PO) to the manufacturing company's sales department. On the one hand, if the retailer has already traded by the manufacturer and is considered as a current customer, the sales department examines the order in terms of order quantity, specification, and expected delivery time. If the PO meets the acceptable threshold, especially in terms of minimum order level, the PO is approved and sent to check for production capacity and raw materials inventory based on the product's BOM.

On the other hand, if the customer is new, the sales department prepares a payment agreement and performs a credit check.

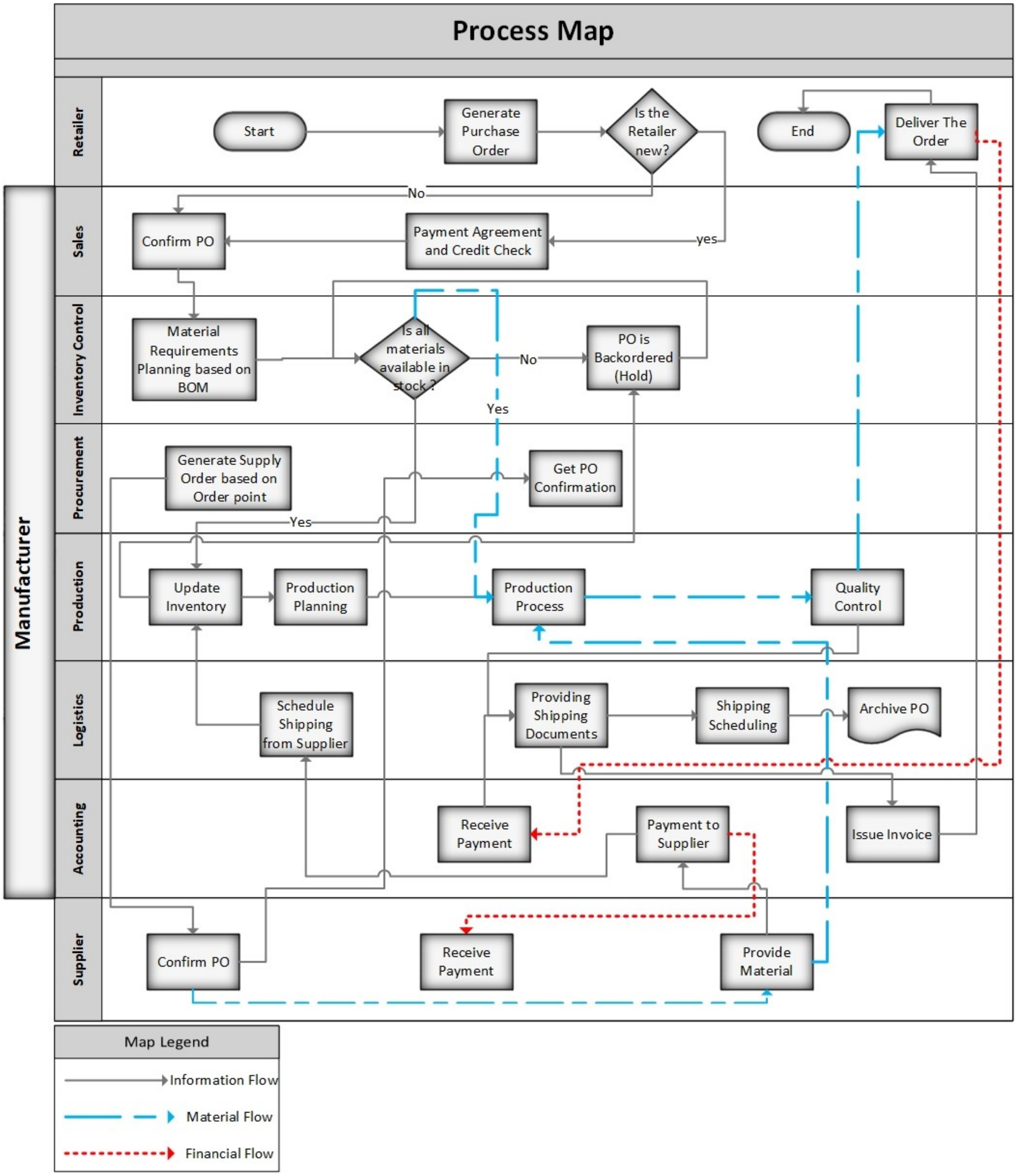

Figure 4.7 The Information, Material, and Financial flow in the SC

In the next step, sales orders are checked based on the BOM. Suppose there is enough quantity of all three raw materials to produce the product and fulfil the PO. The PO is also first sent to the inventory control unit to update the inventory and then sent to the production planning department. If the stock of even one of the raw materials in the warehouse is not enough for that order, the PO is held till the inventory for all raw materials becomes available. The procurement department generates Supply Orders (SO) based on inventory control policy (r, Q) at the order point as large as the order quantity.

After sending the SO to the suppliers, the order is confirmed and announced to the procurement department. The supplier provides raw material and sends the invoice to the accounting department, and the accounting department pays to the supplier after ensuring the approval of the quality of raw materials.

Then the accounting department coordinates with the logistics department to send raw materials from the supplier to the manufacturer. Raw materials are stored in the warehouse, and at the same time, raw materials' inventory level is updated. Consequently, the hold POs are released and sent to be manufactured.

On the other hand, POs whose raw materials were already available are produced with higher priority. Production is continuous, and at the end of production, the final product's quality is controlled. The logistic department then makes the necessary arrangements to transport the final product to the retailer warehouse. The accounting department then sends the final invoice to the retailer. Lastly, after receiving the payment from the retailer, the final products are sent to the retailer.

4.2.2.3 Modelling the SC Risks

As discussed earlier in the first two chapters of this thesis, (Christopher & Lee, 2004) stated a specific risk category that occurs outside of the company but disrupts the entire SC components. Furthermore, this category is divided into two types: increase on the demand side and decrease in supply. This study focuses on a specific type of Low-Frequency High-Impact risk, COVID-19 pandemic outbreak disruption risk. The pandemic outbreak starts small upstream of the supply chain from a shortage in supply and propagates quickly into the SC transportation network to the downstream to manufacturer and retailers as the SC's final customers. In this study, as we discuss earlier, we choose to study essential product's SC. Disruption is doubled due to a rapid increase in downstream demand.

On the one hand, the COVID-19 pandemic outbreak firstly affects the supplier. Suppliers become unable to provide raw materials on time and causing disruption upstream of the supply chain.

However, on the other hand, one of the destructive effects of the COVID-19 pandemic outbreak disruption on the SC in numerous countries, including Canada, is dramatically increasing in demand. The food SCs and most wanted items like toilet papers and paper towels were severely disturbed by a sharp increase in demand due to customers' "Panic Buying" behaviour (Hobbs, 2020). This behaviour causes a sudden increase in the essential items SC demand to serve more customers. This study thoroughly examines changes in supply chain KPI in essential product's SC. We model this type of risk in the supply chain and adapt to our case study in the next chapter, which is the production of essential goods, i.e. toilet paper and paper towel, during the COVID-19 pandemic. We define potential scenarios based on late 2019 and early 2020 available risk data, similar available literature, i.e., (Ivanov, 2020a), official reports (CTV News, 2020), and managerial insights of this specific industry.

This section indicates how a pandemic outbreak disruption risk can overshadow all SC's components. In this study, the rest of the SC's risks are disregarded.

This study demonstrates the impact of the COVID-19 Pandemic outbreak on supply, followed by propagation into the transportation network and downstream echelons, including the manufacturing company and retailers, as the final customers.

Current State Model: Firstly, we preset the SC, which operates normally in Figure 4.8.

Figure 4.8 Normal Operation of SC

Disruption Scenario 1: COVID-19 Pandemic outbreak disturbs the supply of raw materials A resulted in a 100% increase in delivery time for 60 days from February 2020 (Figure 4.9)

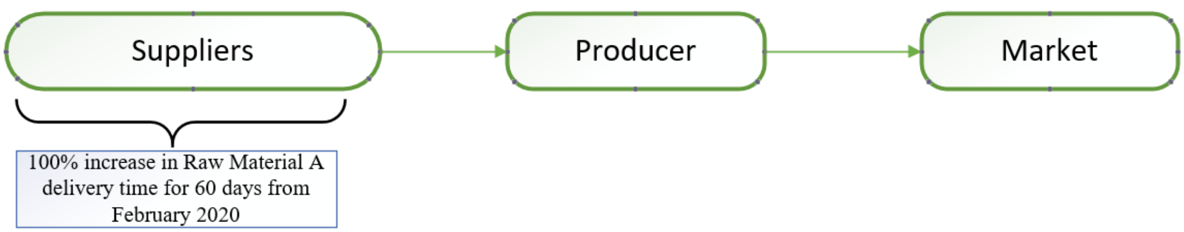

Figure 4.9 The First SC Disruption Scenario

Disruption Scenario 2: In addition to disruption scenario 1, pandemic outbreak disruption propagates into all other suppliers' regions as well as the transportation network by increasing 100% delivery time of raw materials A, B, and C for 60 days immediately after Scenario 1 happening from April 2020 (Figure 4.10).

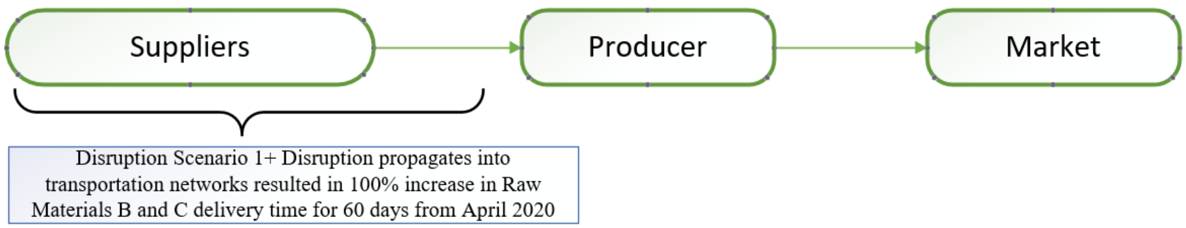

Figure 4.10 The Second SC Disruption Scenario

Disruption Scenario 3: In addition to disruption scenarios 1 and 2, simultaneous disturbances in supply, logistics infrastructure, and market results in a 100% increase in final product demand for 30 days immediately after disruption scenario two occurrence from June 2020 (Figure 4.11)

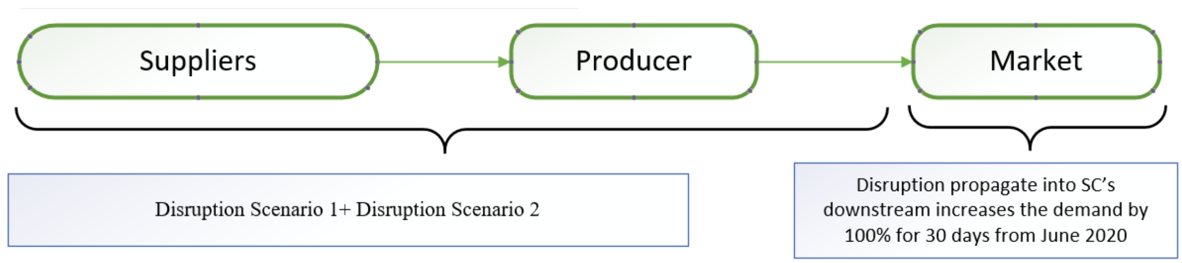

Figure 4.11 The Third SC Disruption Scenario

4.2.2.4 Performance Measures

According to the SCOR reference model, performance attributes are Reliability, Responsiveness, Agility, Supply Chain Cost, and Asset management (SCC, 2010). Based on this study's objectives to compare different disruption scenarios and risk mitigation strategies in terms of resiliency, according to (Karl et al., 2018), we focus on Reliability and Responsiveness attributes. The above attributes result in resiliency during the disruption. As we discussed earlier, during this challenging situation because of the COVID-19 outbreak, the focus should be shifted from maximizing profit to SC survival and satisfying more customer demand and minimizing delivery time. This study focuses on non-financial KPIs (Paul & Chowdhury, 2020b).

4.2.2.4.1 Reliability

According to (SCC, 2010) this attribute contains performance metrics that guarantee reliability by providing the appropriate amount of the goods and at the expected time with the appropriate documents. The reliability attribute describes the ability to execute activities as desired. This attribute assesses the predictability of the processes.

4.2.2.4.1.1 Delivery Performance to Customer Commit Date (RL.2.2)

The following equation calculates the percentage of orders which are delivered within the committed time to the client:

Equation 1: *[Total number of orders delivered on the original commitment date] / [Total number of orders delivered] *100%*

4.2.2.4.2 Responsiveness

The level at which activities are performed is described by this attribute. This characteristic indicates the speed of performing repetitive activities to reach the output. Besides, “Cycle Time” is used to measure the process reaction (SCC, 2010).

4.2.2.4.2.1 Order Fulfillment Cycle Time (RS.1.1)

The estimated real cycle time is continuously achieved to satisfy consumer orders. The cycle time for each individual order begins with the delivery of the order and finishes with the retailer's approval of the order.

Equation 2: *[Sum actual cycle times for all orders delivered] / [Total number of orders delivered] in days*

4.2.2.4.2.2 Source Cycle Time (RS.2.1)

Source CT is the average time associated with Source processes. In this study, Source CT is equalled to the sum of the time needed to send a Supply Order to suppliers and receive it in full.

Equation 3: *Source Cycle Time = Authorize Supplier Payment CT+ Verify Product CT+ Schedule Product Deliveries CT+ Transfer Product CT*

4.2.3 Input Analysis

In this section, based on phase two of the model development framework (Figure 4.12), model parameters and distributions are specified. Based on (Banks et al., 2010; Kelton, 2002), input to the models includes the distributions of demand and lead time for a supply chain simulation. Probability distributions for random inputs should be specified to perform simulation studies. As shown in Figure 4.12, The following three steps should be followed:

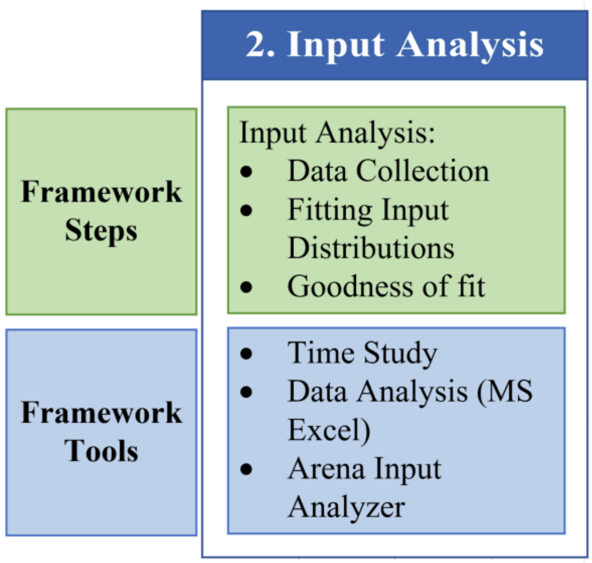

Figure 4.12 Input Analysis Framework

4.2.3.1 Data Collection

This section performs data collection for each defined SC operation and transportation time between SC static actors. For this purpose, SC available historical data is obtained and analyzed.

The historical data has already been stored in the SC database regarding each operation in the specified period. Moreover, for some SC operations, we perform a time study by direct observation. This section includes required input data concerning supply chain structure in terms of the number of SC actors, infrastructure data, inventory data, transportation-related data (both path and means of transportation), and the number of human resources working in each supply chain component. All the above data are reflected as the input to the next chapter's case study simulation model. Also, using Cochran's formula, the number of samples required for each operation is calculated.

4.2.3.1.1 Sample size

Using the Cochran technique (Cochran, 1997), we calculate the sample size to be collected for each SC operation. We assume the maximum variability, which is equal to 50% (p = 0.5) and taking 95% confidence level with ±5% accuracy, the calculation for the required sample size will be as follows (Kr Sarmah et al., 2013; Naing, 2003):

Equation 4:

$$n = \frac{Z^2 pq}{d^2}$$

Selected Critical Value of Desired Confidence Level: Z= 1.96

desired level of accuracy: d = 5%

p=q=0.5

Sample Size = n: 384

4.2.3.2 Fitting Input Distributions Via the Input Analyzer

We enter our data into the input analyzer to generate suitable distributions. The following initial considerations are taken into account to select a suitable distribution for input data:

- The data being analyzed is continuous and consists of positive real numbers.
- All discrete distributions are disregarded.
- All distributions with negative values like normal distribution are disregarded.
- To choose the best distribution, we compare the p-values of the Kolmogorov-Smirnov (KS) test for the remaining distributions and choose the best based on which distribution has the highest p-value > 0.05.

4.2.4 Model Translation

Based on phase three of the developing model framework (Figure 4.13), we translate the SC conceptual model into a simulation model. This section describes Discrete Event System Simulation Components. Secondly, We created a DES algorithm that converts each conceptual model element into a simulation model element. Lastly, Arena software is introduced as the simulation platform for this study.

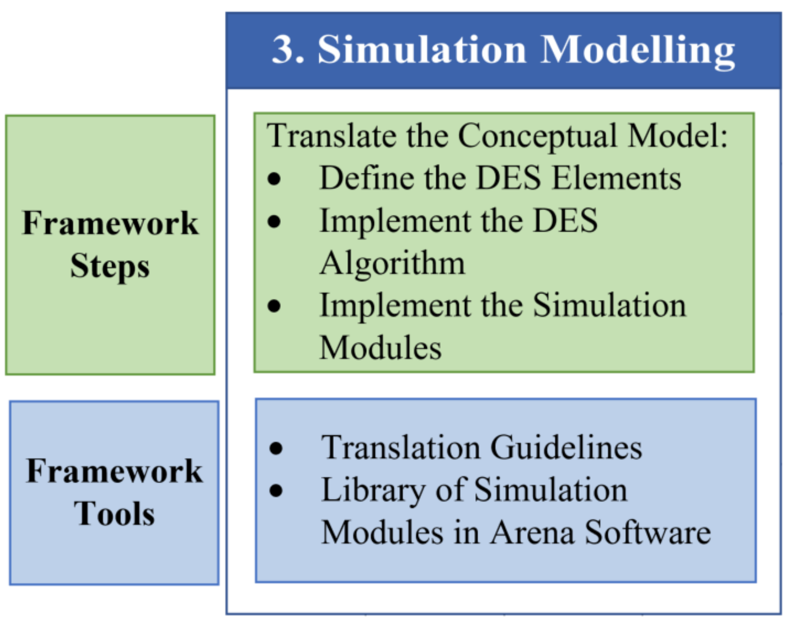

Figure 4.13 Simulation Modeling Framework

4.2.4.1 Discrete Event System Simulation Formalism

DES is selected as a formalism to translate the conceptual model into the simulation model. based on literature, discrete systems, at a separate point in time, "state variables" change immediately. Besides, when an "event" occurs, the "state" will change. At only a countable number of points in time, events occur (Banks et al., 2010; Kelton, 2002). To continue, we explained the component of DES.

4.2.4.1.1 Components of Discrete Event System Simulation

4.2.4.1.1.1 System

According to (Schmidt & Taylor, 1970) a "system is a set of entities working together and collaborating to achieve some logical end." In this study, the system boundaries are limited to a Supply Chain considering echelons, i.e. Retailers, Manufacturers company, Suppliers, and all interactions in terms of information and material flow. As we discussed earlier, the level of details is defined based on level three of the SCOR reference model.

4.2.4.1.1.2 Entities

According to (Kelton, 2002), Entities are objects of interest in the system. In this study, there are four types of entities available. Entities might be only one kind of entity but many realizations. Entities are flowing within the SC. The presented entities in (Table 4.3) are defined in our study:

No.	Entity Name	Definition
1	Purchase Order	PO is generated in the system. PO requested by “Retailer.” Later, it is transformed to “Final Product” by “Manufacturing Event” and be sent to the “Retailer.”
2	Supply Order A	SO is generated in the procurement department. Later, it is transformed to Raw Material A by Supplier and be sent to the Manufacturer.
3	Supply Order B	SO is generated in the procurement department. Later, it is transformed to Raw Material A by Supplier and be sent to the Manufacturer.
4	Supply Order C	SO is generated in the procurement department. Later, it is transformed to Raw Material A by Supplier and be sent to the Manufacturer.
5	Entity S1 Logic	This Entity generates disruption Scenario 1
6	Entity S2 Logic	This Entity generates disruption Scenario 2
7	Entity S3 Logic	This Entity generates disruption Scenario 3

Table 4.3 System Entities

4.2.4.1.1.3 Attributes

Attributes are defined as a common characteristic of all entities. The attribute comes with the specific value that distinguished one entity from another entity (Kelton, 2002) (Table 4.4).

No.	Attributes	Definition
1	PO Arrival Time	Purchase Order Assigned Arrival Time to Each Entity
2	SO Material A Attribute	Unique Serial Number Assigned to Each Supply Order Raw Material A Entity
3	SO Material B Attribute	Unique Serial Number Assigned to Each Supply Order Raw Material B Entity
4	SO Material C Attribute	Unique Serial Number Assigned to Each Supply Order Raw Material C Entity
5	PO Serial Number	Unique Serial Number Assigned to Purchase Order Entity
6	Raw Material A Supply Cycle Time	Raw Material A Supply Order Assigned Creation Time to Each Entity
7	Raw Material B Supply Cycle Time	Raw Material B Supply Order Assigned Creation Time to Each Entity
8	Raw Material C Supply Cycle Time	Raw Material C Supply Order Assigned Creation Time to Each Entity
9	Change Policy Inventory level RM A	Inventory level of Raw Material a which is used in risk mitigation strategy 2, (s, S) inventory control policy
10	Change Policy Inventory level RM B	Inventory level of Raw Material a which is used in risk mitigation strategy 2, (s, S) inventory control policy

No.	Attributes	Definition
11	Change Policy Inventory level RM C	Inventory level of Raw Material a which is used in risk mitigation strategy 2, (s, S) inventory control policy

Table 4.4 Defined Attributes

4.2.4.1.1.4 Activities

The DES activities are the same as defined and extracted operation from the SCOR model, which is already presented in Figure 4.7 and Table 4.2.

4.2.4.1.1.5 State Variables

The variables reflect some characteristics of the whole system, which is presented in Table 4.5.

No.	Variables	Expression
1	WIP	Work In Process
2	RawMaterialCinventory	Inventory Level of Raw Material C
3	RawMaterialBinventory	Inventory Level of Raw Material B
4	RawMaterialAinventory	Inventory Level of Raw Material A
5	ReadytoShipFROMsuplier1	Transfer Permission form Supplier 1 to Manufacturer
6	ReadytoShipFROMsuplier2	Transfer Permission form Supplier 1 to Manufacturer
7	ReadytoShipFROMsuplier3	Transfer Permission form Supplier 1 to Manufacturer

No.	Variables	Expression
8	Variable 18 Scenario 1	Applying Disruption Scenario 1 Variable
9	Variable 19 Scenario 2	Applying Disruption Scenario 2 Variable
10	Variable 20 Scenario 2	Applying Disruption Scenario 2 Variable
11	Variable 21 Scenario 2	Applying Disruption Scenario 2 Variable
12	Delivered Orders In Committed Time	Variable Counts Orders Which are Delivered in Expected Time
13	Delivered POs To Retailers	Variable Counts Orders Which Delivered to Retailer
14	Decision Variable PO Creation 3	Changing Variable Purchase Order Inter Arrival Time Distribution Scenario 3
15	Scenario 3 Decision Variable PO	Changing Variable Purchase Order Inter Arrival Time Distribution for Disruption Scenario 3
16	Sum of Cycle time	Variable Counts Total Cycle Time
17	Maximum Inventory Level RM A	Maximum Inventory Level of Raw Material A
18	Maximum Inventory Level RM B	Maximum Inventory Level of Raw Material B
19	Maximum Inventory Level RM C	Maximum Inventory Level of Raw Material C
20	Supply Order Quantity RM A	Fixed Raw Material A Order Quantity
21	Supply Order Quantity RM B	Fixed Raw Material B Order Quantity
22	Supply Order Quantity RM C	Fixed Raw Material C Order Quantity
23	Variable 40 Inter Arrival time	PO Interarrival Time in Current State Model

No.	Variables	Expression
24	Variable Contingency Plan Policy Change	Changing Variable for Risk Mitigation Strategy 2, Inventory Control Policy Change
25	Supplier A Multiple Sourcing	Changing Variable for Risk Mitigation Strategy 1, Multiple Sourcing

Table 4.5 System Variables

According to (Banks et al., 2010; Kelton, 2002), "State" refers to a set of variables and their values that are required at a specific time to define the systems. Besides, "Event" changes the system state by, i.e., changing the values of some or all of the variable's value. In this study, "Resource," which is another component of DES, is directly translated from a conceptual model that serves entities in all SC components where processing happens. Resources including human resources, machines, operators, etc. Additionally, if an entity requires a resource, but another entity uses the resource or is unavailable, the entity should wait in a "queue" and wait for its turn. In this study, for each process, we have a potential queue.

4.2.4.1.2 DES Algorithm

In this section, a DES Algorithm is developed to play an intermediate role in translating the conceptual model into a simulation model. We include DES components in the algorithm, presented in the following detailed steps:

1. The POs (Purchase Orders) entities are first generated using the "Create" module by Retailer in the system.
2. The arrival time attribute is assigned to each entity using the "Assign" module.
3. The number of arriving entities is recorded in the "Record" module.

4. The “Decide” module in the sales department assesses whether the order comes from the current customer or a new customer. If a new customer orders the PO, the sales department performs a credit check and, if applicable, prepares the payment agreement using the “Process” module.
5. All PO’s are assessed in terms of acceptance criteria, i.e. minimum order quantity, specification, and expected delivery time. Then based on the assessment results, POs are accepted.
6. Then the POs are sent to the inventory control department to be checked in terms of raw material availability based on BOM.

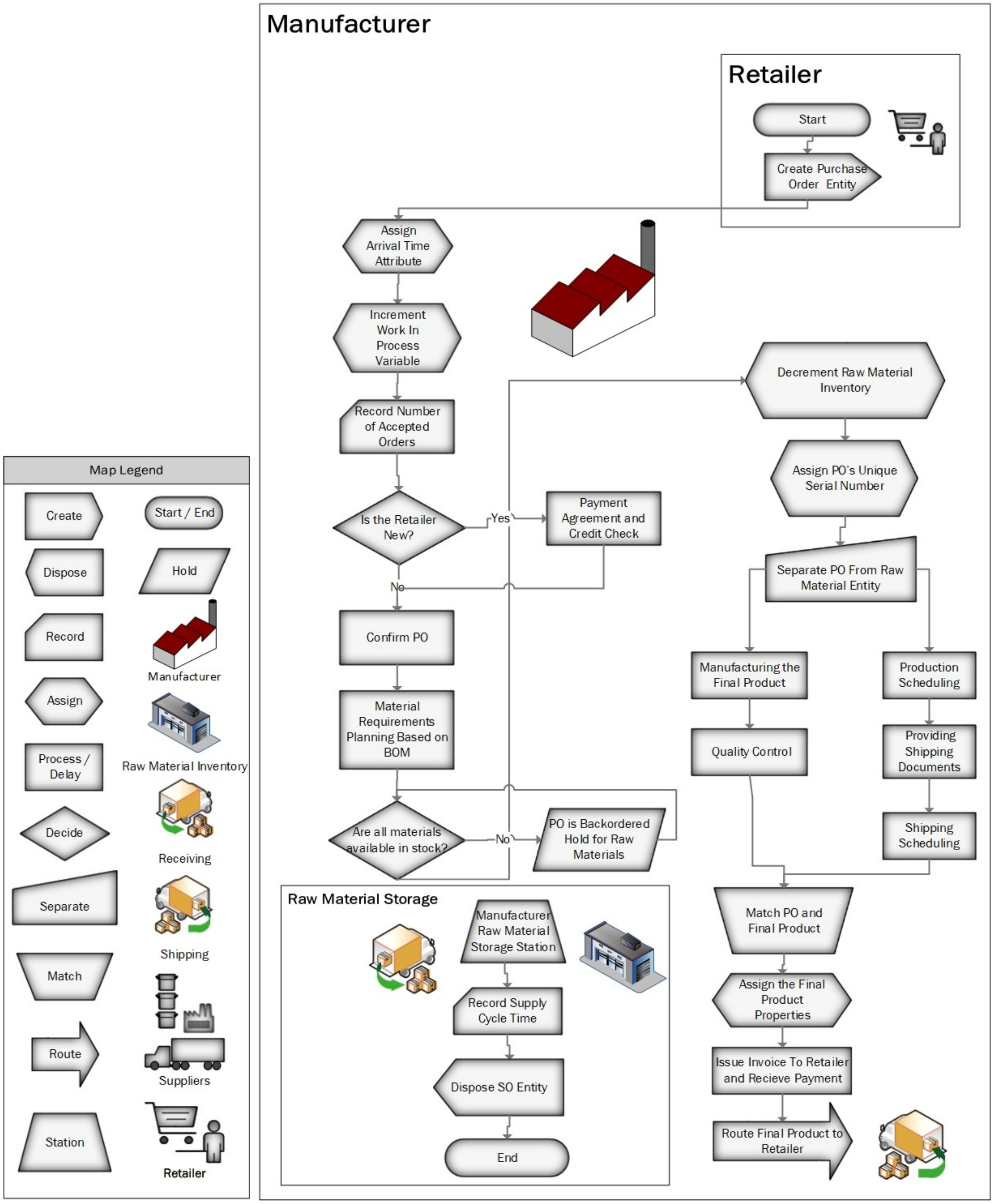

Figure 4.14 Discrete Event Simulation Algorithm (Part 1)

7. PO's are checked based on the available BOM using the "Process" module.

8. Using the "Decide" module, we assess whether the available inventory of all three raw materials is above the "Minimum Raw Material Inventory Level" or not. If the inventory level is above acceptance criteria, raw materials are sent from the raw materials warehouse to the production site. As a result of this "Event," the required amount of raw material A, B, and C, are decremented from corresponding "State Variables," namely "Raw Material A Inventory," "Raw Material B Inventory," and "Raw Material C inventory."
9. If the inventory level of even one raw material type is not enough, the order does not go to the production queue; instead, the POs are held till the raw material reaches the warehouse, and the corresponding "Variable" is changed.

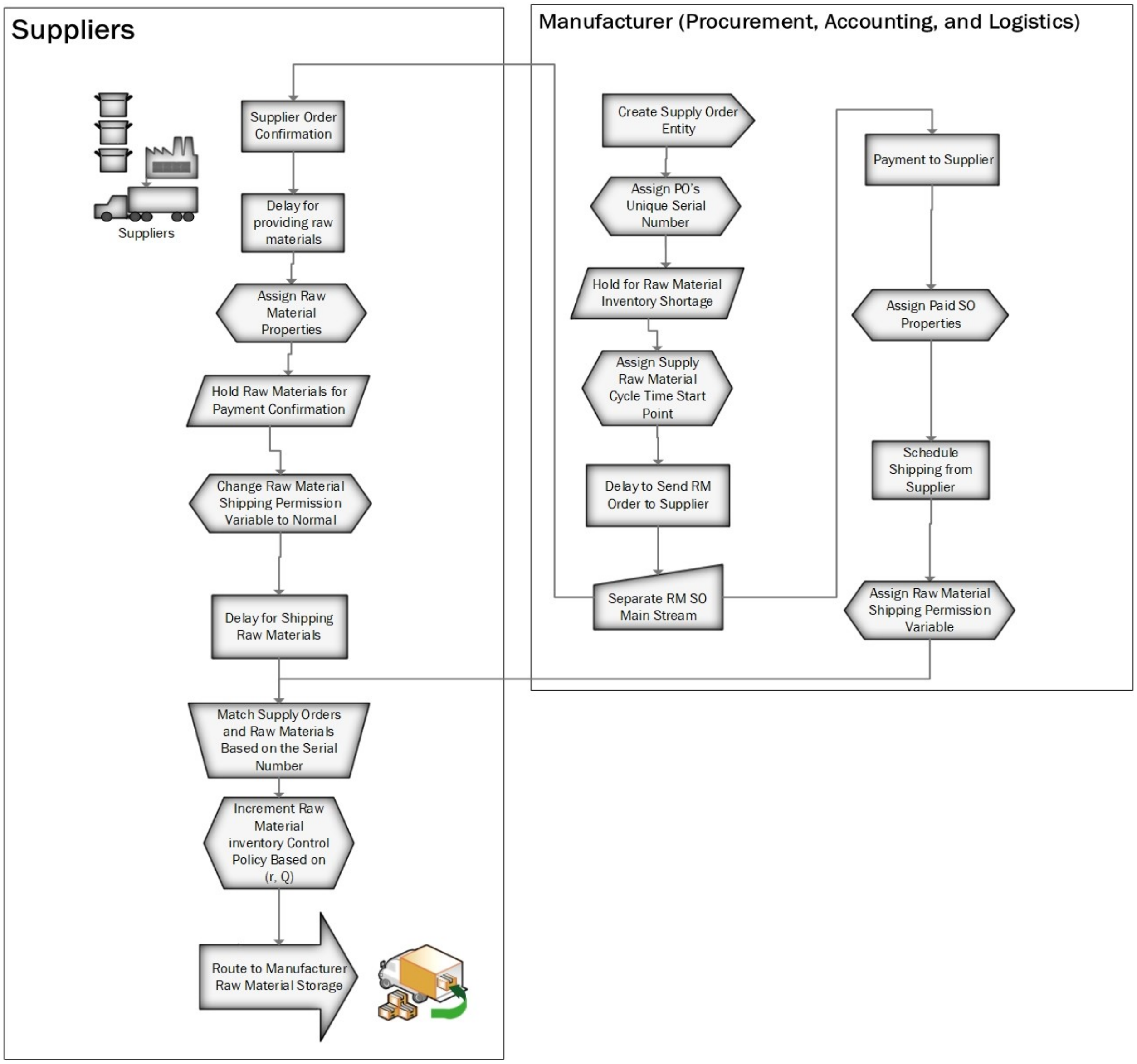

Figure 4.15 Discrete Event Simulation Algorithm (Part 2)

10. On the supply side for each raw material type (A, B, and C), the procurement department generates one Supply Orders entity using the "Create" module.

11. To track each SO and related raw material, using the "Assign" module, the unique serial number is assigned to the SO entity.

12. , the SO entity is waiting for the raw material inventory shortage for each type separately using the "Hold" module. Considering (r, Q) inventory control policy, when the inventory

level reaches the order point based on the given "Safety Stock," the SO is released, and the SO cycle time attribute is assigned to the SO entity.

13. Then procurement department orders as much as Q (fixed Order Quantity) to the concerning supplier. The "Delay" module is used to show the duration of this activity.
14. Then using the "Separate" module, information and material flow are separated by duplication of the mainstream. The information flow, which is the SO, goes to the accounting department in the "Manufacturer" using an integrated management system.
15. The payment to suppliers is performed after ensuring the approval of the quality of raw materials. The accounting department coordinates with the "Logistics" department to reserve means of transportation, i.e., the truck to transfer raw materials from each supplier to the manufacturing company.
16. Using the "assign" module, the "Ready to Ship from Suppliers" variable turns to number one, meaning the permission to send raw materials to the manufacturer.
17. On the other hand, after receiving the SOs from suppliers, the "order confirmation" process is performed. We use a delay module to show the duration to provide raw materials.
18. Raw materials inventory is scanning to receive the payment signal by using the "hold" module. For this reason, if the "payment" event happened, the "Ready to Ship from Suppliers" variable value would change from 0 to 1, and the raw material would send to the manufacturing site.
19. Then SO and raw material are matched based on the unique serial number. Then we utilize the "Route" module to transfer raw materials to corresponding storage in the manufacturer site. Simultaneously, the "Event," which is "receiving raw material" in the production company, occurs, and the "state variable" of the system (Raw Material Inventory) is updated (Figure 4.15).

20. The raw materials are received and stored in raw material storage located in the manufacturing company (Figure 4.14). Then using “Record,” we calculate “Supply Cycle Time,” and using “Dispose,” SO leave the system.
21. On the other hand, the “Hold” module, which contains POs with insufficient raw materials to be produced, releases orders to the manufacturing queue (refer to step 9) (Figure 4.14).
22. On the production site, POs based on FIFO enter the queue. Later, information and material flow are separated by duplication of the mainstream using the “Separate” module. Then, the information flow (Purchase Order) goes to the production planning department to perform the “production scheduling” process.
23. In the material flow stream, the production “Process,” which is continuous, is performed, and raw materials are entered into the production line. Then the quality of the final products is controlled within the “Quality Control” module.
24. Using “Match” modules, the order and final product are matched together based on the PO unique serial number and batch together permanently. In parallel, the “Logistics” department provides shipping documents and performs shipping planning. Moreover, the accounting department then sends the final invoice to the retailer. Also, “Final Product” properties are assigned to PO entities.
25. Lastly, after receiving the retailer's payment, the final product is sent to the retailer “Station” using the “Route” module.
26. The retailer receives the final products, and the number of delivered POs, the total cycle time for each order, are recorded using the related variable, entity, and record module (Figure 4.16).
27. Also, to record orders received on committed time, we first use the “Decide” module to differentiate orders based on given committed time and the record module.

28. Finally, the WIP variable is decremented, and the batch of final product and PO leaves the system using “Dispose” module.

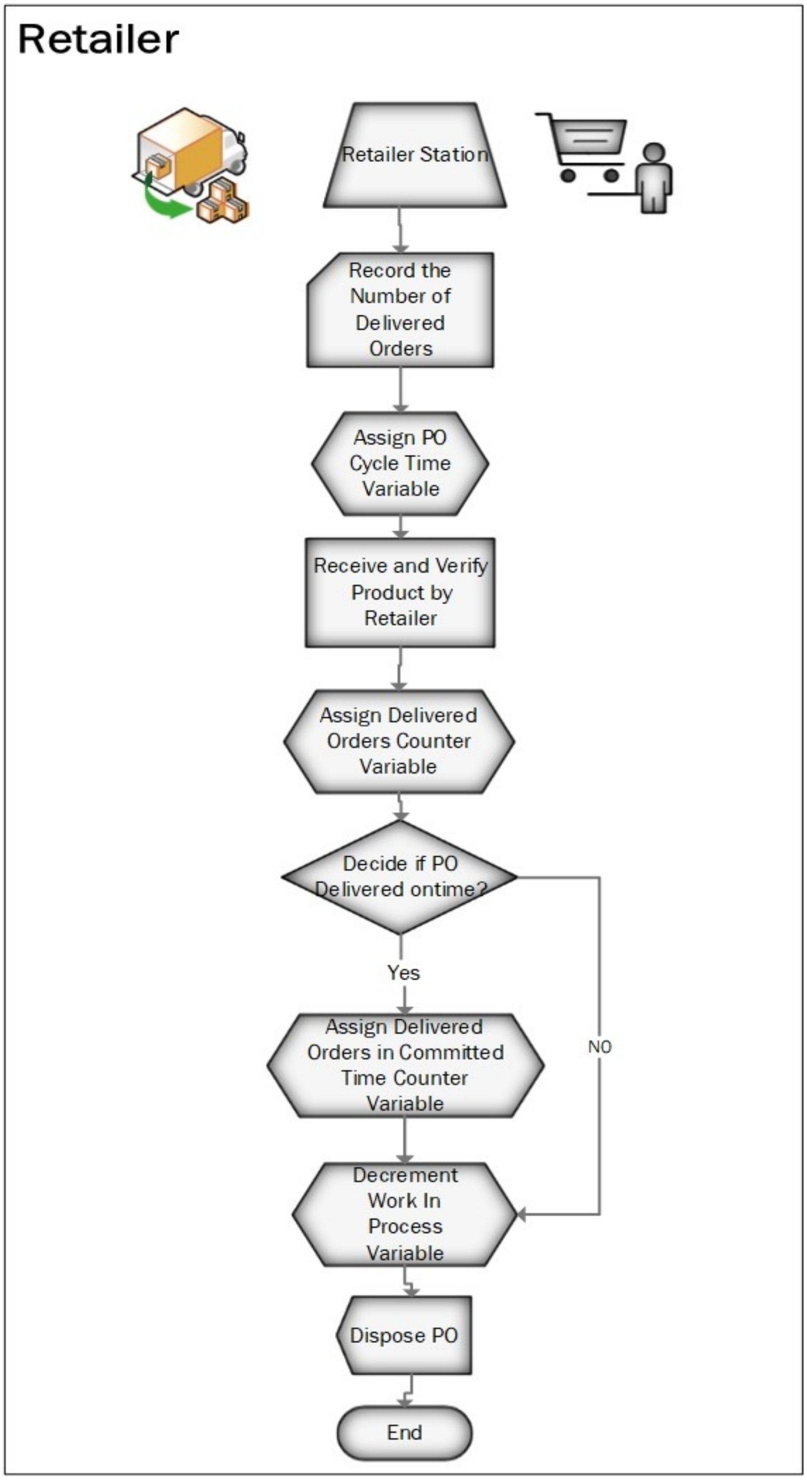

Figure 4.16 Discrete Event Simulation Algorithm (Part 3)

4.2.4.2 Model Development Using ARENA

In this study, Arena simulation software is used to implement the DES algorithm. As compared in Chapter 2, Arena is the high-level "Simulator" and has been used extensively for SCRM. This software has several modules classified in different libraries that give us a wide range of tools enabling us to model complex systems. Chapter 5 describes model development in Arena in detail. Also, the "Arena Output Analyzer," "Input Analyzer," "Process Analyzer," and "OptQuest for Arena" provides us with a bunch of new modelling capabilities. Worth mention, the software is developed in SIMAN simulation language (Kelton, 2002).

4.2.5 Verification and Validation

Figure 4.17 presents the approaches to verify and validate the simulation model.

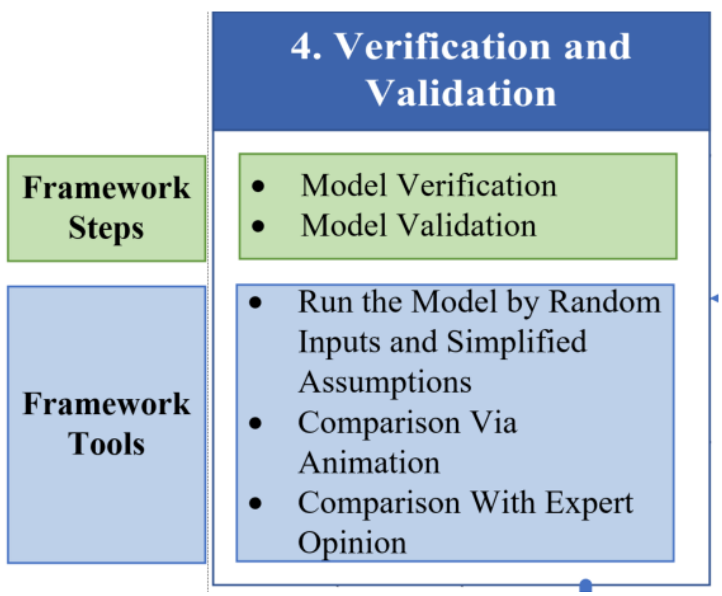

Figure 4.17 Verification and Validation Framework

4.2.5.1 Verification

In this thesis, to verify that the model's details and the assumptions correspond to the real system, we utilize the following methods (Law et al., 2000).

We first start to model the smaller and more superficial parts of the model for each primary SC process and, after finishing each section, run the model by random inputs and simplified assumptions to check the logic of modelling. Additionally, we run the model several times in different circumstances to check different outcomes to assure that our model’s logic is reasonable. We also have several meetings with the SC owner and CEO of the manufacturer to ensure we are on the right track. Additionally, we run the model as many times as possible and follow the attributes, variables and flow of entities visually after each event in the model.

Also, we double-checked all the input data's statistical distributions. Besides the “Input Analyzer,” we do not limit ourselves to the software suggested distribution. We assessed other distributions in terms of squared error, Chi-square P-Value, and Kolmogorov- Smirnov P-Value. We also assured input data statistical reports and re-applied them in the software.

Also, by adding control and response in the output analyzer variables, we verified the model in different conditions by applying changes to the control variables and monitored the model outputs' animation.

4.2.5.2 Validation

According to (Kelton, 2002; Law et al., 2000), we validate the model to ensure that our simulation study meets this study's objectives and is an accurate representation of the real system.

For this purpose, based on the following four methods have been used.

4.2.5.2.1 Numerical Comparison with Existing System

In this method, we make sure that our outputs match the performance metrics' outputs by applying different inputs to the model. This method has tested the whole model with three different input data, and the results are presented in Chapter Six.

4.2.5.2.2 Comparison Via Animation

In this method, we observed the model behaviour visually with a different view of the Verification technique. In this way, our goal is whether the system behaves as expected or not. For instance, assess the resources that are well displayed in the system are all utilized well.

4.2.5.2.3 Comparison With Expert Opinion

Simultaneously, with checking the model to verify it, the model's behaviour was also assessed by the company's CEO to investigate whether the model represents the system's actual behaviour well or not. Examples of comments and comparisons are shown in Chapter Six.

4.2.6 Supply Chain Design for Resilience

Based on phase four of the model development framework, the recent study's primary focus is to propose a model with a combination of several methods that can maintain supply chain performance in three different areas (Figure 4.18).

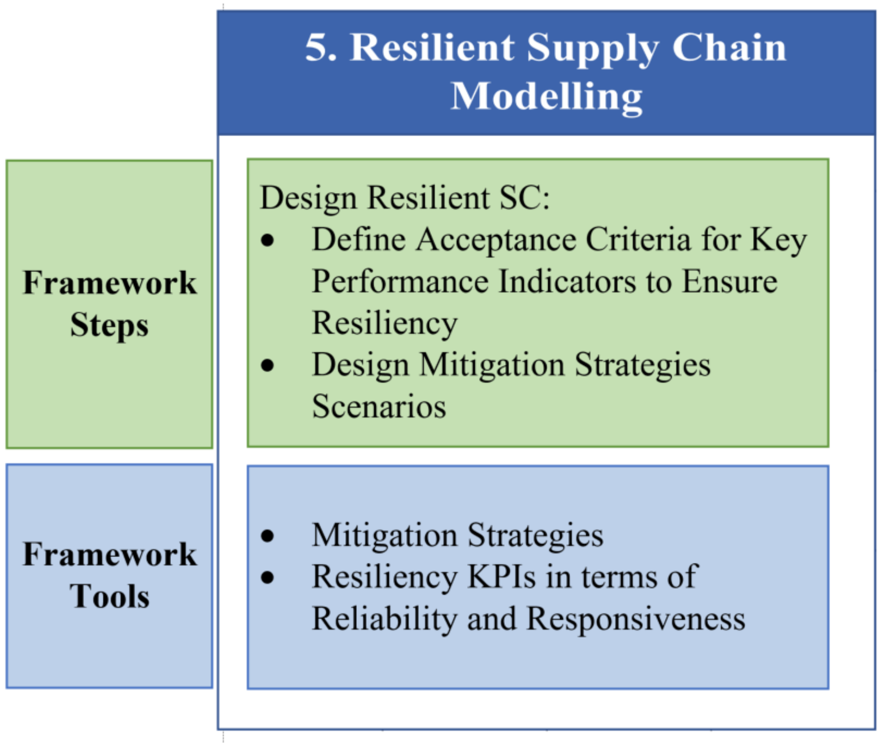

Figure 4.18 Resilient SC Modeling Framework

Based on the SCOR model, we focus on two performance criteria: reliability and responsiveness. Three risk mitigation strategies are applied to make the SC more resistant and reduce the SC's negative impact.

As the first risk mitigation strategy, many authors suggested “Multiple Sourcing” strategies. As an example, (Namdar et al., 2018) proposed a multiple-souring strategy while considering high-impact-low-frequency (HILF) disruptions. Moreover, they mentioned that this strategy as an example of resilient strategies is more effective under HILF disruptions compared to LIHF disruptions. They conclude multiple-sourcing strategy provides a better service level and makes the SC resilient.

We used this approach in coordination with the production company's CEO and available resources, along with the recommendation of one or two alternative raw material A suppliers. These two suppliers already have been audited and are on the Approved Vendor List. As a result, their capability and lead time for supply are known. However, the company has suspended operations with them in order to get the most beneficial value of single- sources suppliers.

In the case that only one supplier is chosen, SOs are split by 50 percent and randomly distributed between two suppliers for ease of measurement. If two additional suppliers are included, there is a chance that 33% of SOs will be spread among three raw material A suppliers.

As the second strategy, we develop the "Buffering" strategy in our DES model, which is one of the most widely employed methods of reduction adopted by the companies. SC managers can ensure that the SC performance is above acceptance criteria in terms of resiliency by maintaining adequate inventory (Chattopadhyay et al., 2001; Mishra et al., 2016). This study utilizes a simplified scenario by increasing the initial inventory level for raw materials by 100%.

The third strategy which is developed in this study is changing inventory control policy from "Continuous review, fixed order quantity policy (Reorder Point, Order Quantity)" to Continuous review, order-up-to policy (Min/Max) or (s, S) (Hopp et al., 1997).

The current inventory control policy is (r, Q). "r" stands for reorder point, and Q is the fixed order quantity. During COVD-19 more flexible policy is preferable. In (s, S), inventory control policy "s" is the reorder point and "S" is the order-up-to level. "(Min, Max) is even more receptive than (r, Q) because it adjusts the order size to take account of how much the inventory has fallen below the Min."(Thomas Willemain, 2019).

In the suggested strategy, instead of using the current constant order quantity (Q), at the order point, the difference between the maximum inventory level of raw materials, which is known, and the exact inventory level of each raw material is ordered up to maximum level is fulfilled. This value is either equal to or greater than the difference between the order point and maximum inventory level.

In Chapter Five, we describe how these strategies are applied in the simulation model.

4.2.6.1 Scenario Design

To Mitigate Disruption Scenario 1: COVID-19 pandemic outbreak disturbs the supply of raw materials A resulted in a 100% increase in delivery time for 60 days from February 2020 (Figure 4.9)

- **Risk Mitigation Strategy 1:** Multiple Sourcing to Supply Raw Material A
    - 50% supplier 1 RM A, 50% 1st Alternative Supplier RM A OR,
    - 33% supplier 1 RM A, 33% 1st Alternative Supplier RM A, 33% 2nd Alternative Supplier RM A
- **Risk Mitigation Strategy 2:** Buffering
    - 100% Increase in Inventory Level RM A and/or RM B and/or RM C
- **Risk Mitigation Strategy 3:** Change the Inventory Control Policy from (r, Q) to (s, S)

To Mitigate Disruption Scenario 2: In addition to disruption scenario 1, pandemic outbreak disruption propagates into all other suppliers' regions as well as the transportation network by increasing 100% delivery time of raw materials A, B, and C for 60 days immediately after Scenario 1 happening from April 2020 (Figure 4.10).

- **Risk Mitigation Strategy 1:** Multiple Sourcing to Supply Raw Material A
    - 50% supplier 1 RM A, 50% 1st Alternative Supplier RM A OR,
    - 33% supplier 1 RM A, 33% 1st Alternative Supplier RM A, 33% 2nd Alternative Supplier RM A
- **Risk Mitigation Strategy 2:** Buffering
    - 100% Increase in Inventory Level RM A and/or RM B and/or RM C
- **Risk Mitigation Strategy 3:** Change the Inventory Control Policy from (r, Q) to (s, S)

To Mitigate Disruption Scenario 3: In addition to disruption scenarios 1 and 2, simultaneous disturbances in supply, logistics infrastructure, and market results in a 100% increase in final product demand for 30 days immediately after disruption scenario two occurrence on day 180

- **Risk Mitigation Strategy 1:** Multiple Sourcing to Supply Raw Material A
  - 50% supplier 1 RM A, 50% 1st Alternative Supplier RM A OR,
  - 33% supplier 1 RM A, 33% 1st Alternative Supplier RM A, 33% 2nd Alternative Supplier RM A
- **Risk Mitigation Strategy 2:** Buffering
  - 100% Increase in Inventory Level RM A and/or RM B and/or RM C
- **Risk Mitigation Strategy 3:** Change the Inventory Control Policy from (r, Q) to (s, S)

4.2.6.2 Acceptance Criteria for Resilient SC

this section defineS KPI's values which is the threshold of having resilient SC.

WIP* =Acceptable Average Work In Process

TAVG* = Acceptable Average Wait Time in Queue (Hold for Raw Materials)

RL.2.2* = Acceptable Average Delivery Performance to Customer in Committed Time

RS.1.1* = Acceptable Average Order Fulfillment Cycle Time

RS.2.1* = Acceptable Average Supply Cycle Time

The value of all above mentioned five performance metrics equals the corresponding values captured in the current state model (No disruption).

Following constraints should be respected to have a resilient SC:

Set of Replications $J = \{1, \ldots, 120\}$

$$\frac{\sum_j WIP_j}{120} \leq WIP^* \quad j \in J \qquad (1)$$

$$\frac{\sum_j \mathrm{TAVG}_j}{120} \leq \mathrm{TAVG}^* \qquad j \in J \qquad (2)$$

$$\frac{\sum_j \mathrm{RL.2.2}_j}{120} \leq \mathrm{RL.2.2}^* \qquad j \in J \qquad (3)$$

$$\frac{\sum_j \mathrm{RS.1.1}_j}{120} \leq \mathrm{RS.1.1}^* \qquad j \in J \qquad (4)$$

$$\frac{\sum_j \mathrm{RS.2.1}_j}{120} \leq \mathrm{RS.2.1}^* \qquad j \in J \qquad (5)$$

4.2.7 Experiment the Model

Figure 4.19 illustrates the steps that should be followed in order to analyze the model in terms of input data and outputs.

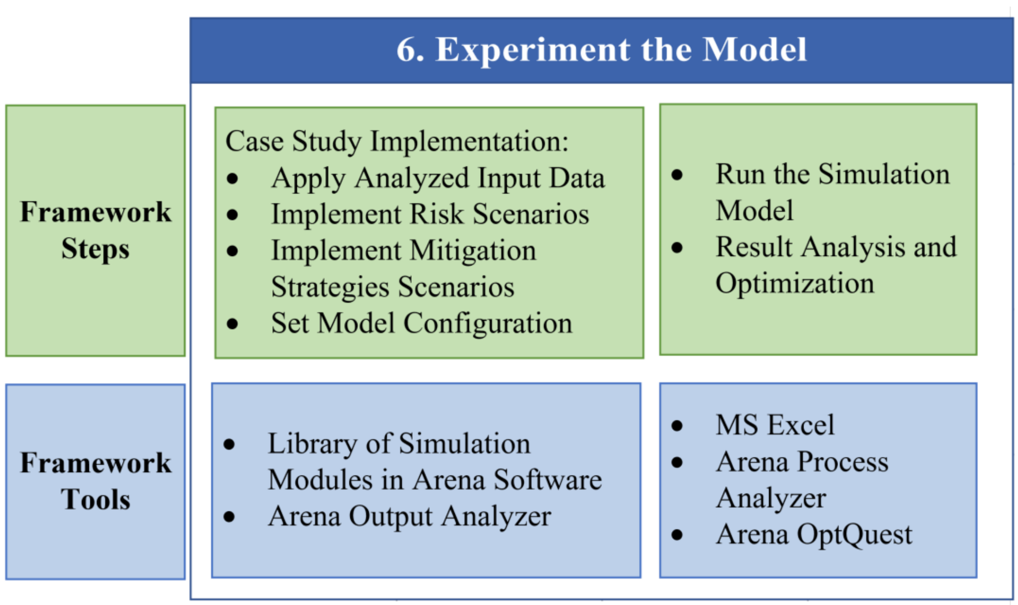

Figure 4.19 Experiment the Model Framework

In the following two chapters, we explain all steps in detail. We first adjust the run setup according to the purpose and scope of our project. The simulation is non-terminating in our study. We calculate the time required as a warm-up period using the output analyzer and drawing the corresponding plot. We also use "Equation 5" to determine the required number of replication.

Equation 5:

$$n \cong n_0 \frac{\beta_0^2}{\beta^2}$$

"120" replications were determined to be suitable to give us our required half-width of 1 day. Then we enter several "Control" and "Response" variables in the process analyzer and apply and execute the strategy for each dispersion and risk mitigation scenario.

To get the optimum solutions, "OptQuest for Arena" is utilized to optimize the objective functions for each KPI. on the one hand, the primary goal of this study is to maximize "delivery performance to customer commit time" and "total numbers of delivered orders in committed time." On the other hand, "order fulfilment cycle time," "total average supply cycle time," and "work in process" should be minimized. These five objective functions are implemented in "OptQuest for Arena," as shown in Table 4.6. (DPO: Delivered POs in customer Commit time)

$$min \frac{\sum_j WIP_j}{120} \qquad (1)$$

$$max \frac{\sum_j \mathrm{DPO}_j}{120} \qquad (2)$$

$$max \frac{\sum_j \mathrm{RL.2.2}_j}{120} \qquad (3)$$

$$min \frac{\sum_j \mathrm{RS.1.1}_j}{120} \qquad (4)$$

$$min \frac{\sum_j \mathrm{RS.2.1}_j}{120} \qquad (5)$$

Set of Replications $J = \{1, \ldots, 120\}$

Objectives Summary

	Included	Name	Goal	Expression
▸	☑	Maximize Delivered Orders On Committed Time	Maximize	[Delivered Ordered Ontime]
	☐	Maximize Delivery Performance	Maximize	[Delivery Performance to Customer Committed Date]
	☐	Minimize Order Fulfillment Cycle Time	Minimize	[Total CT Statistics]
	☐	Minimize Total Supply Cycle time	Minimize	[Total Supply CT Statistics]
	☐	Minimize Work In Process	Minimize	[WIP_Statistics]

Table 4.6 Objective Functions

decision variables are defined as shown in Table 4.7, utilizing three risk mitigation strategies.

Controls

	Included	Name	Element Type	Type
	☑	RawMaterialAinventory	Variable	Discrete
	☑	RawMaterialBinventory	Variable	Discrete
	☑	RawMaterialCinventory	Variable	Discrete
	☑	Supplier A Multiple Sourcing	Variable	Integer
	☑	Variable Contigency Plan Policy ...	Variable	Binary

Table 4.7 Decision Variables (Controls)

The next Chapter presents the model implementation approach in Luxxeen Co.

CHAPTER 5

IMPLEMENTATION (CASE STUDY: LUXXEEN COMPANY)

5.1 Chapter Overview

As discussed in chapter three, we implement our model development framework at Luxxeen Productions Inc., which is the Canadian green disposable products (i.e. Toilet Tissues) manufacturer company. In this section, a brief explanation about the Laxxeen company is provided. Moreover, all the 28-steps of modelling and implementing the DES algorithm to the Arena Simulation Software are described along with the settings in comprehensive detail. Also, we include disruption risk scenarios and three risk mitigation strategies model development translation guide to ensure SC's resiliency.

5.2 Case Study Description

Luxxeen Productions Inc., based in Montreal, Quebec, is a Canadian manufacturer of high-quality branded and private-label facial tissue and toilet paper. (*Luxxeen Production*, 2021).

"Toilet Tissues" is chosen as an example of the essential product during the COVID-19 pandemic outbreak in the current study. According to the CEO of Luxxeen co., the company was faced with an increase of almost 100% in demand in mid-2020 for toilet papers and paper. Moreover, they faced a 100% increase in raw materials supply, which all are single-sourced.

Figure 5.1 Luxxeen Production Inc.

5.3 Model Implementation

5.3.1 SC's Structure

5.3.1.1 SC Actors

There are three suppliers considered in this study. The first supplier, which provides raw material A, is located in South Carolina, U.S.A.The supplier of raw material B is located in Ontario, Canada. Also, the 3rd supplier (for raw material C) is located in Quebec, Canada. Also, information about the logistics and transportation network is provided by Luxxeen Co., including route time from suppliers to Luxxeen Co. and from there to the retailer. In this study, trucks are the only means of transportation either from the supplier to Luxxen Co. and from there to the retailer. To simplify the model, we consider all retailers as one leading retailer located in Montreal, QC, with the cumulative purchase order quantities (Figure 5.2).

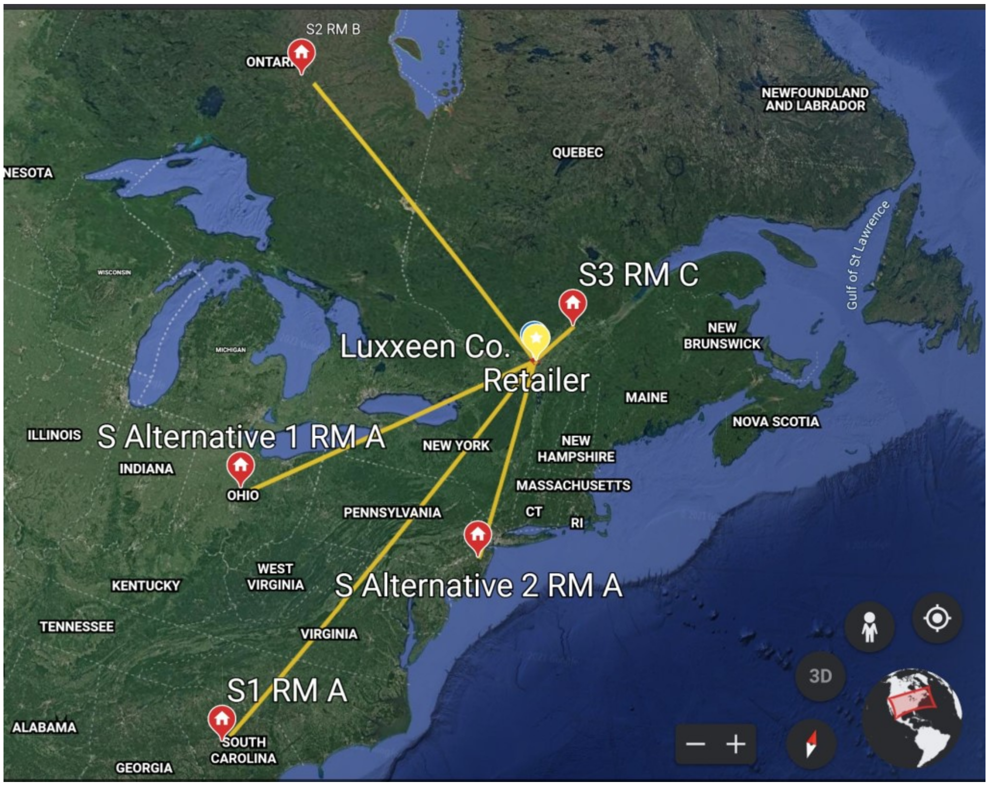

Figure 5.2 Luxxeen Co. SC's Structure

5.3.1.2 Product and Raw Materials

The product reviewed in this thesis is Toilet Paper which is an essential product during the pandemic outbreak. Required raw materials and their consumption coefficient should be identified To produce this product. Figure 5.3 represents the "Bill Of Materials" of the product mentioned above.

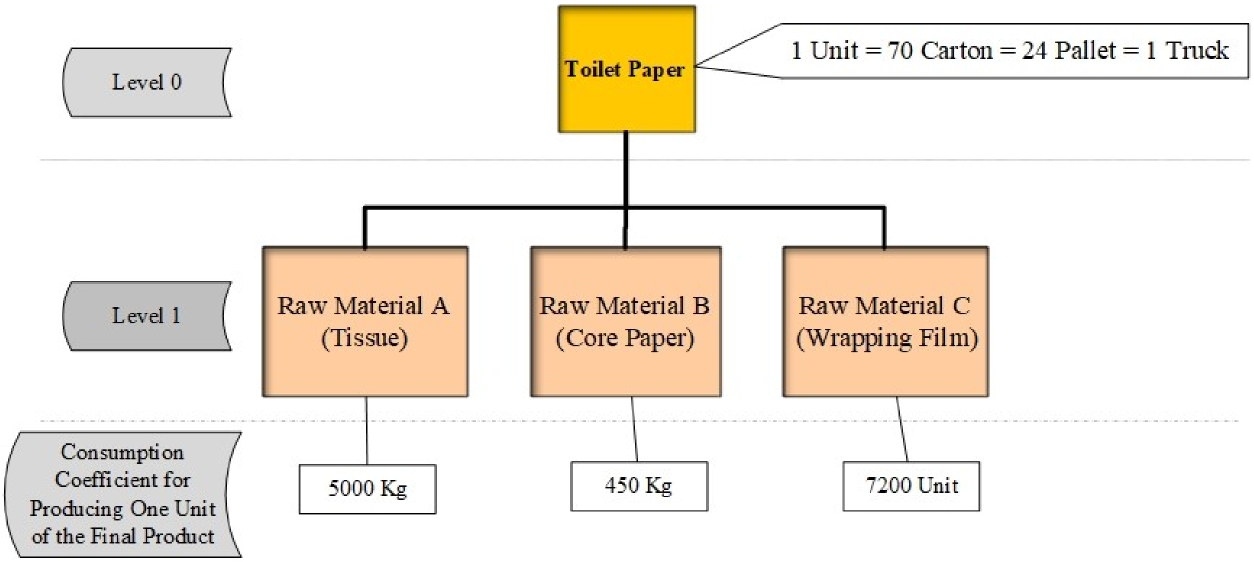

Figure 5.3 Bill of Material

Besides, one unit of the final product is considered 70 cartons, which equals 24 pallets and the total capacity of a Truck. Required raw materials are summarized in BOM date is organized in Table 5.1.

No.	Raw Material Type	Policy	Definition	Consumption Coefficient
1	Raw material A	Single - Sourced	“Tissue Paper” which supplies from the US	5000 Kg is required to produce one unit of the final product
2	Raw Material B	Single - Sourced	The Raw Material B supplies within Canada	450 Kg required to produce one unit of the final product

No.	Raw Material Type	Policy	Definition	Consumption Coefficient
3	Raw Material C	Single - Sourced	The Raw Material C supplies within Canada	7200 units required to produce one unit of the final product

Table 5.1 Required Raw Materials

5.3.2 Input Data

5.3.2.1 Demand data

Based on the historical data provided by Luxxeen Co. in the current state model, the interarrival time to receive an order from a retailer follows Expo (0.8). We assumed each order equals one unit of the final product. Also, the Luxxeen Co. provides a list containing the expected lead time and actual PO cycle time for the past two years. On average, it takes 35 days from receiving a new purchase order to deliver the final product to the retailer.

5.3.2.2 Operations Data

The essential information for conducting a near-reality simulation study is information about each process's activities. In this regard, in one year, the available historical data based on Equation 4, the number 384 samples required. The direction of the investigation was determined.

Table 5.2 presents the best fit distribution in terms of the lowest "Squared Error" and the highest " Kolmogorov-Smirnov P-Value."

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
1	Plan	Material Requirement Planning for Purchase Orders	0.003931	0.097	> 0.15	0.7 + 0.6 * BETA(1.6, 1.57)
2	Plan	Shipping Scheduling	0.003592	0.0169	> 0.15	0.08 + 0.24 * BETA(1.65, 1.62)
3	Source	Delay Send Raw Material A Order to Supplier 1	0.005771	< 0.005	> 0.15	0.17 + 0.64 * BETA(1.7, 1.62)
4	Source	Process Supplier 1 Order Confirmation	0.001206	> 0.75	> 0.15	0.999 + 1 * BETA(0.974, 0.928)
5	Source	Delay for provide raw material A	0.003055	0.153	> 0.15	EXPO (7)

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
6	Source	Delay for provide raw material A From Alternative 1	0.005834	< 0.005	> 0.15	5.3 + 2.4 * BETA(1.46, 1.5)
7	Source	Delay for provide raw material A From Alternative 2	0.005087	< 0.005	> 0.15	6 + 1.65 * BETA(1.23, 1.43)
8	Source	Schedule Shipping from Supplier 1	0.002186	0.422	> 0.15	5 + 2 * BETA(1.06, 0.908)
9	Source	Payment to suppliers 1	0.009790	< 0.005	> 0.15	0.23 + 0.24 * BETA(1.48, 1.5)
10	Source	Route Raw Material A to Manufacturing	0.002920	0.17	> 0.15	2 + 1 * BETA(1.02, 1.03)

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
11	Source	Delay Send Supply Order Raw Material B to Supplier 2	0.007085	< 0.005	> 0.15	0.17 + 0.64 * BETA(1.64, 1.72)
12	Source	Process Supplier 2 Order Confirmation	0.002225	0.364	> 0.15	0.999 + 1 * BETA(0.905, 1.04)
13	Source	Delay for provide raw material B	0.001116	0.0924	> 0.15	3 + 4 * BETA(0.917, 0.952)
14	Source	Payment to supplier 2	0.003677	0.0154	> 0.15	0.999 + 0.551 * BETA(1.17, 1.41)
15	Source	Schedule Shipping from Supplier 2	0.002356	0.385	> 0.15	2 + 2 * BETA(0.962, 0.949)

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
16	Source	Route Raw Material B to Manufacturing	0.005881	< 0.005	> 0.15	1 + 1.64 * BETA(1.25, 1.46)
17	Source	Delay Send Supply Order Raw Material C to Supplier 3	0.002878	0.175	> 0.15	0.999 + 2 * BETA(0.879, 0.88)
18	Source	Process Supplier 3 Order Confirmation	0.003513	0.0664	> 0.15	0.999 + 1 * BETA(0.924, 0.949)
19	Source	Delay for provide raw material C	0.002788	0.324	> 0.15	UNIF(2, 4)
20	Source	Schedule Shipping from Supplier 3	0.001541	> 0.75	> 0.15	3 + 2 * BETA(1.06, 0.985)

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
21	Source	Payment to supplier 3	0.003768	0.00992	> 0.15	0.4 + 1.2 * BETA(1.6, 1.55)
22	Source	Route Raw Material C to Manufacturing	0.002380	0.399	> 0.15	0.999 + 1 * BETA(1.04, 0.999)
23	Make	Production Scheduling	0.005539	< 0.005	> 0.15	0.14 + 0.73 * BETA(1.67, 1.57)
24	Make	Process Manufacture Final Product	0.005144	< 0.005	> 0.15	0.87 + 0.36 * BETA(1.75, 1.66)
25	Make	Quality Control	0.004631	0.00854	> 0.15	1.24 + 0.72 * BETA(1.46, 1.51)
26	Deliver	Purchase Order Inter Arrival Time	0.002475	0.37	> 0.15	2 * BETA(2.49, 2.6)
27	Deliver	Payment Agreement and Credit Check	0.005132	< 0.005	> 0.15	0.54 + 2.46 * BETA(1.43, 1.21)

No.	Operation Type	Data	Squared Error	Chi-Square P-Value	Kolmogorov-Smirnov P-Value	Distribution
28	Deliver	Purchase Order Confirmation	0.004998	< 0.005	> 0.15	0.09 + 1.81 * BETA(1.51, 1.44)
29	Deliver	Providing Shipping Documents	0.004889	< 0.005	> 0.15	0.19 + 0.26 * BETA(1.66, 1.93)
30	Deliver	Average Route Time to Retailers	0.001738	0.692	> 0.15	0.999 + 1 * BETA(1.1, 1.13)
31	Deliver	Receive and Verify Product by Retailer	0.001780	0.639	> 0.15	0.999 + 2 * BETA(1.15, 1.12)
32	Deliver	Invoice Issue and Receive Payment	0.001815	0.637	> 0.15	2 + 3 * BETA(0.903, 0.965)

Table 5.2 Input Analyzer Best Fit Distribution

5.3.2.3 Resources

The critical data on each department's human resources as available capacity was also examined, which is presented in Table 5.3.

No.	Human Resources	Capacity	Work Schedule
1	Sales Clerk	3	Full time 8 hrs./day
2	Warehouse Employee	2	Full time 8 hrs./day
3	Production Operator/Worker	3	Full time 8 hrs./day
4	Logistics Officer	4	Full time 8 hrs./day
5	Production Planning employee	3	Full time 8 hrs./day

Table 5.3 Human Resources Working In Luxxeen Co.

5.3.2.4 DES Input Parameters

5.3.2.4.1 List of Entities

Defined entities for Luxxeen Co. are presented in Table 5.4.

No.	Entity Name	Assumption
1	Purchase Order	The minimum acceptable Order equals One unit of Products
2	Supply Order A	SO A is generated in review intervals based on (r, Q) policy
	Supply Order B	SO B is generated in review intervals based on (r, Q) policy

No.	Entity Name	Assumption
	Supply Order C	SO C is generated in review intervals based on (r, Q) policy
3	Entity S1 Logic	Generates disruption scenario 1
4	Entity S2 Logic	Generates disruption scenario 2
5	Entity S3 Logic	Generates disruption scenario 3

Table 5.4 List of Entities

5.3.2.4.2 List of Variables

Defined entities for Luxxeen Co. are presented in Table 5.5.

No.	Variables	Expression	Initial Value	Condition
1	WIP	Work In Process	0	0
2	Raw Material C Inventory	Inventory Level of Raw Material C (Wrapping Film)	100000	-
3	Raw Material B Inventory	Inventory Level of Raw Material B (Craft Paper)	12000	-
4	Raw Material A Inventory	Inventory Level of Raw Material A (Tissue Paper)	60000	-
5	ReadytoShipFROMsuplier1	Transfer Permission from Supplier 1 to Luxxeen Co.	0	if = 1, Transfer Raw Material A from Supplier 1; otherwise, 0 Hold

No.	Variables	Expression	Initial Value	Condition
6	ReadytoShipFROMsuplier2	Transfer Permission from Supplier 2 to Luxxeen Co.	0	if = 1, Transfer Raw Material B from Supplier 2; otherwise, 0 Hold
7	ReadytoShipFROMsuplier3	Transfer Permission from Supplier 3 to Luxxeen Co.	0	if = 1, Transfer Raw Material C from Supplier 3; otherwise, 0 Hold
8	Variable 18 Scenario 1	Applying Disruption Scenario 1 Variable	2	increase 100% delay in providing Raw Material A
9	Variable 19 Scenario 2	Applying Disruption Scenario 2 Variable	1	increase 100% delay in Shipping Raw Material A
10	Variable 20 Scenario 2	Applying Disruption Scenario 2 Variable	1	increase 100% delay in Shipping Raw Material B
11	Variable 21 Scenario 2	Applying Disruption Scenario 2 Variable	2	increase 100% delay in for

No.	Variables	Expression	Initial Value	Condition
				providing Raw Material C
12	Delivered Orders In Committed Time	Variable Counts Orders Which are Delivered in Expected Time	-	TAVG(Tally Total Cycle Time) <= Average Committed Delivery Time
13	Delivered POs To Retailer	Variable Counts Orders Which Delivered to Retailer	-	-
14	Decision Variable PO Creation	Changing Variable Purchase Order Inter Arrival Time Distribution	100	-
15	Scenario 3 Decision Variable PO	Changing Variable Purchase Order Inter Arrival Time Distribution for Disruption Scenario 3	0	-
16	Sum of Cycle time	Variable Counts Total Cycle Time	-	-
17	Maximum Inventory Level RM A	Maximum Inventory Level of Raw Material A	150000	-

No.	Variables	Expression	Initial Value	Condition
18	Maximum Inventory Level RM B	Maximum Inventory Level of Raw Material B	25000	-
19	Maximum Inventory Level RM C	Maximum Inventory Level of Raw Material C	250000	-
20	Supply Order Quantity RM A	Fixed Raw Material A Order Quantity	100000	-
21	Supply Order Quantity RM B	Fixed Raw Material B Order Quantity	10000	-
22	Supply Order Quantity RM C	Fixed Raw Material C Order Quantity	200000	-
23	Variable Contingency Plan Policy Change	Changing Variable for Risk Mitigation Strategy 2, Inventory Control Policy Change	0	if 0, Follows (r, Q), Otherwise if =1, (s,S)
24	Variable 40 Inter Arrival time	PO Interarrival Time in Current State Model	0.8	-
25	Supplier A Multiple Sourcing	Changing Variable for Risk Mitigation Strategy 1, Multiple Sourcing	0	-

Table 5.5 List of Variables

5.3.2.4.3 List of Expressions

Defined expressions for Luxxeen Co. are presented in Table 5.6.

Number	Expression	Value	Unit
1	Raw Material A Safety Stock Level	50000	KG
2	Raw Material B Safety Stock Level	3000	KG
3	Raw Material C Safety Stock Level	28000	KG
4	Consumption Coefficient Raw Material A	5000	KG
5	Consumption Coefficient Raw Material B	450	KG
6	Consumption Coefficient Raw Material C	7200	KG
7	Minimum Inventory Raw Material A	5000	KG
8	Minimum Inventory Raw Material B	450	KG
9	Minimum Inventory Raw Material C	7200	Unit
10	Average Committed Delivery Time Based On Available Historical Data	45	Days
11	Disruption Rate Scenario 1,2,3	2	-

Table 5.6 List of Expressions

5.4 Model Assumptions

- Inventory control policy: re-order point-based (r, Q)
- The manufacturing factory shows the (r, Q) inventory control policy.
- Retailers are considered as one leading retailer with the same route time and cumulative demand.
- Production is controlled by the parameters of the inventory control policy.
- The production schedule of the orders is based on the First In First Out (FIFO) rule.

- Direct and indirect costs are not considered in the proposed framework.
- Multiple Sourcing is defined as the first risk mitigation strategy in this study. We just considered 1 or 2 alternative supplies with an equal share of order fulfillment.
- Material is not defective.
- Products do not reverse flow.

5.5 Translation of the SC behaviour

In the previous chapter, we thoroughly explained the translation of the conceptual model into DES by a 28-step algorithm. In this section, we explain how to implement the Luxxeen Co. SC model in Arena simulation software. In addition to the modules' connection view of the model, the critical modules' details, conditions, and input data are also displayed.

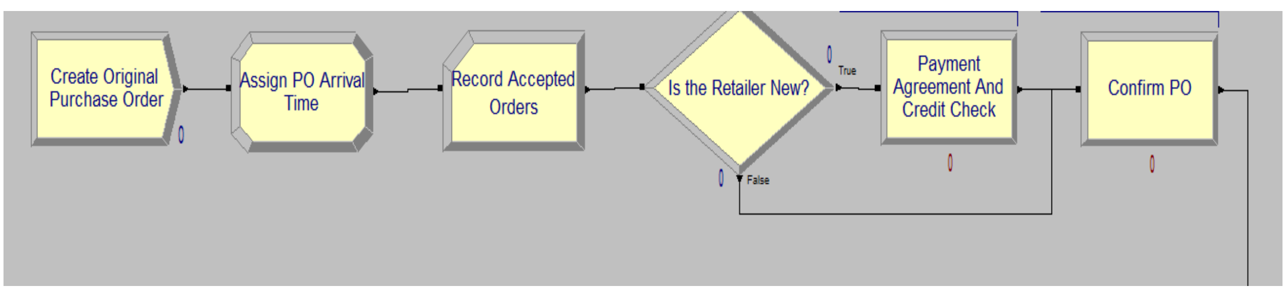

Figure 5.4 Sales Department Operations

Figure 5.4 represents the Luxxeen Co. sales department operations. As shown in Figure 5.5, the " Create" module is used to illustrate the creation of entities in the system. The maximum arrival is set to infinite, and in this study, we assume that each PO contains one unit of the final product. The PO entity is firstly created into the system a little bit after time 0 of simulation.

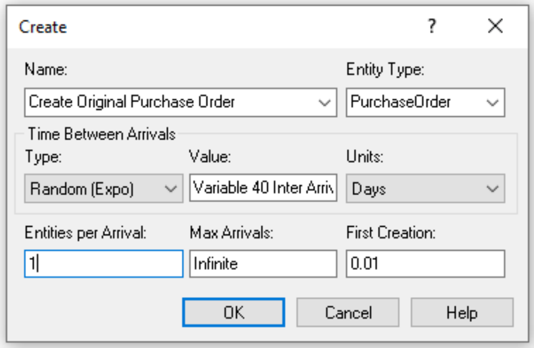

Figure 5.5 Create Purchase Order Module

Using the "Assign" module (Figure 5.6), we set the arrival time attribute equals to TNOW, which is the system's current time. Also, by entering each PO into the system, the "Work In Process" variable is incremented by one unit. Besides, the "Record" module reports the number of PO received from the retailer. Then, PO is checked by the "Decide" module whether the request is new or not. The "Credit Check" would be performed if the order came from a new retailer. Then, All orders are confirmed and be sent to the inventory control department (Figure 5.7).

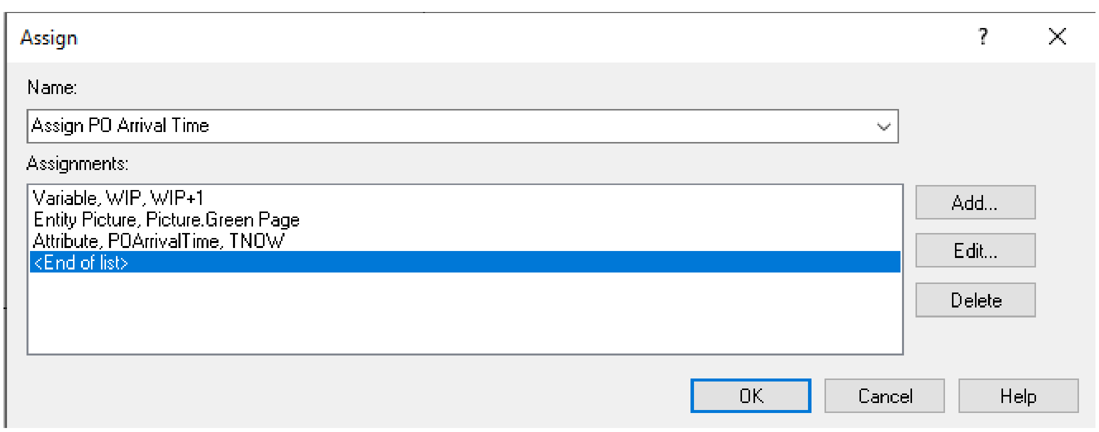

Figure 5.6 Assign Purchase Orders Properties Module

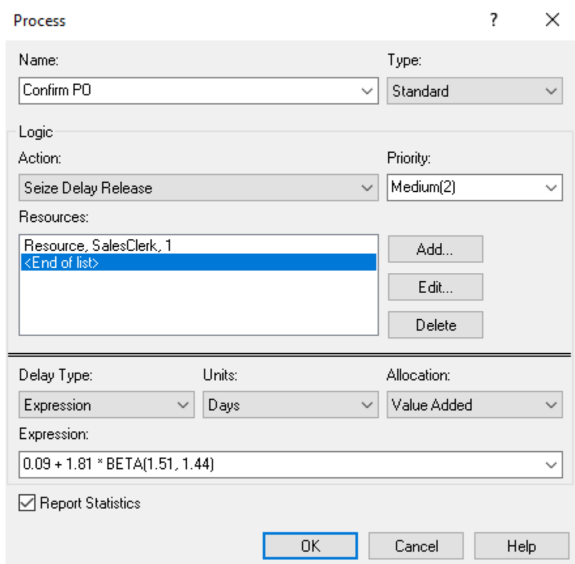

Figure 5.7 Purchase Order Confirmation Process Module

According to Figure 5.8, in the following, the approved POs are sent to the inventory control department, and the Material Requirements Planning operation is done.

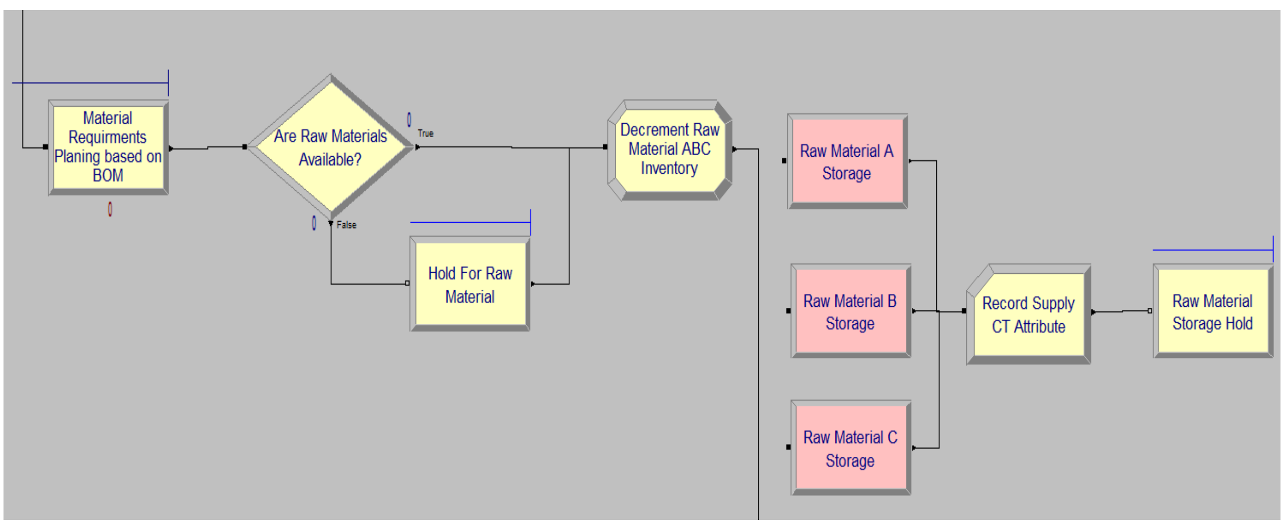

Figure 5.8 Inventory Control Department Operations

Suppose condition <u>" RawMaterialAinventory >= Minimum Inventory RM A && RawMaterialBinventory >= Minimum Inventory RM B&& RawMaterialCinventory >= Minimum Inventory RM C"</u> is met, meaning that the inventory of all three raw material is more than the minimum amount required for production (Figure 5.8). In that case, the entity is transferred to the

“Assign” module. If the condition is not met, the PO waits in the “Hold” module and, according to Figure 5.10, will wait until the condition “Hold: RawMaterialAinventory >= Minimum Inventory RM A&& RawMaterialBinventory >= Minimum Inventory RM B && RawMaterialCinventory >= Minimum Inventory RM C” is established. In that case, the inventory level for raw materials is decremented by the consumption coefficient, which is 5000 Kg for raw material A, 450 Kg for raw material B, and 7200 units for raw material C (Figure 5.11).

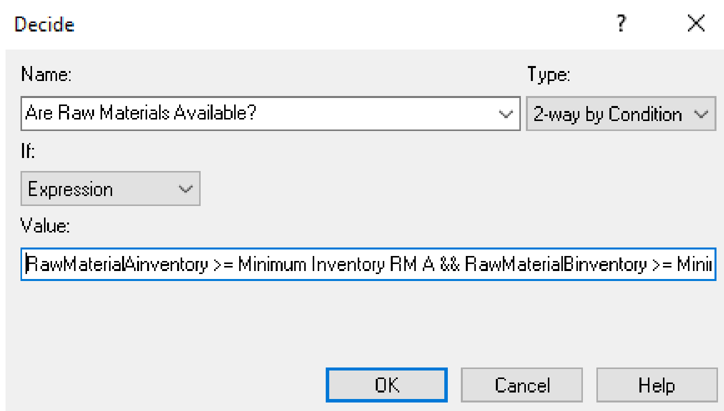

Figure 5.9 Inventory Control Decide Module

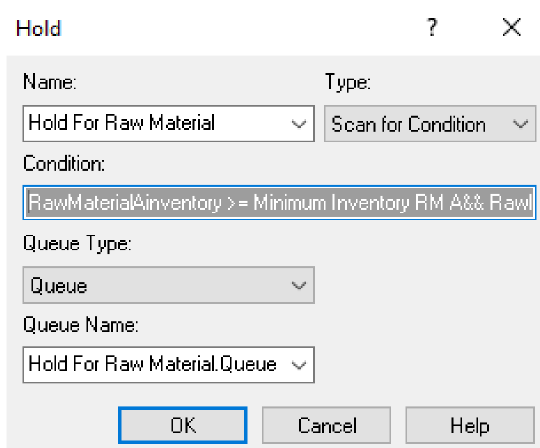

Figure 5.10 Waiting for Raw Material Inventory Hold Module

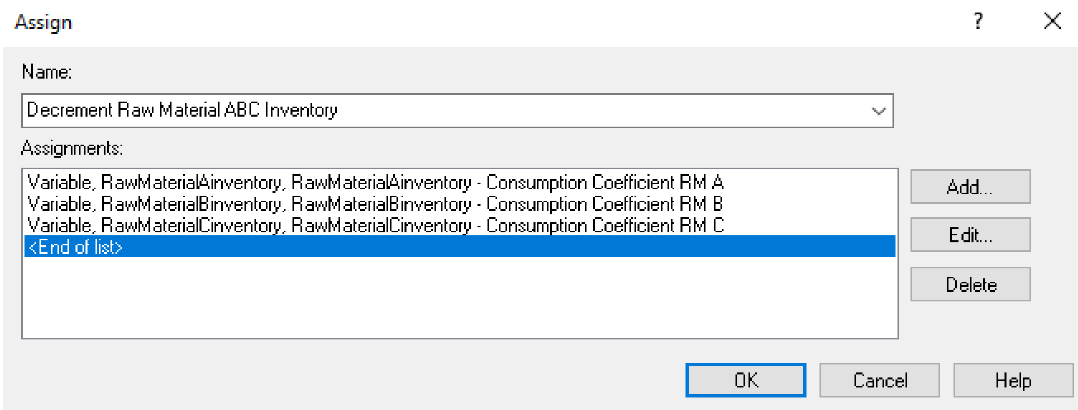

Figure 5.11 Decrement Raw Material Inventory Assign Module

Figure 5.12 presents an overview of the "Supply" process. The SC follows (r, Q) inventory control policy. In this study, we focused on three single-source suppliers that operated similarly and have small variations in terms of operation and routing times. We go over supplier 1's function in supplying raw material A.

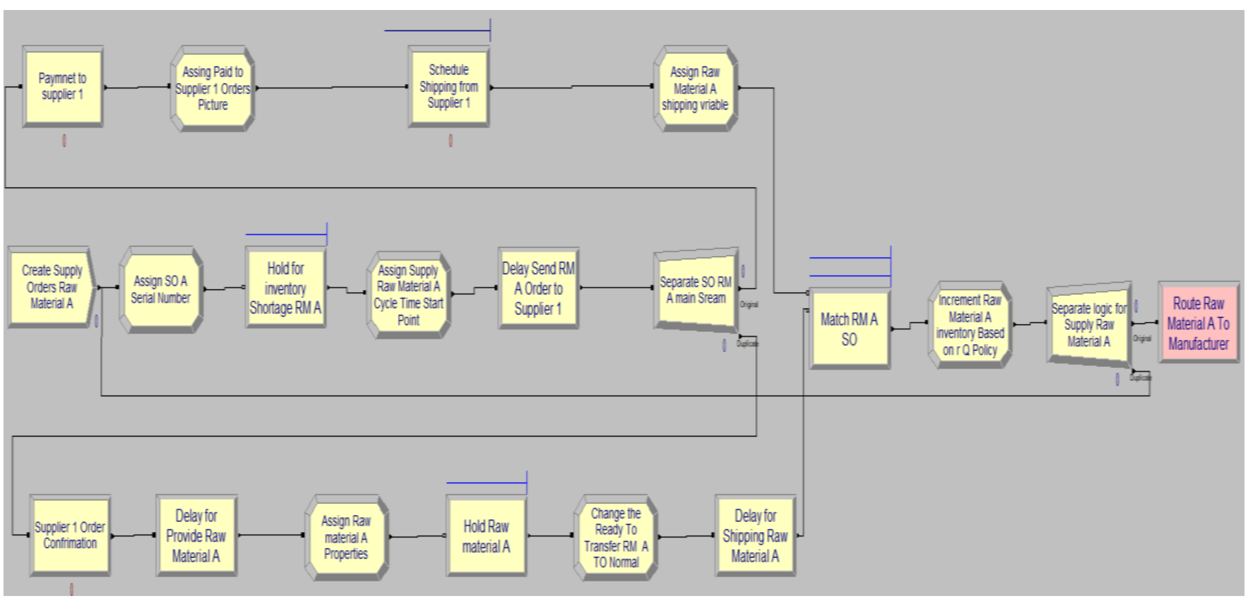

Figure 5.12 Supply Raw Materials Operations

Firstly, the "Supply Order" is created in the system for suppliers 1, 2, and 3 to supply raw materials A, B, and C, respectively. As shown in Figure 5.13, only one SO entity is created at the beginning of the simulation.

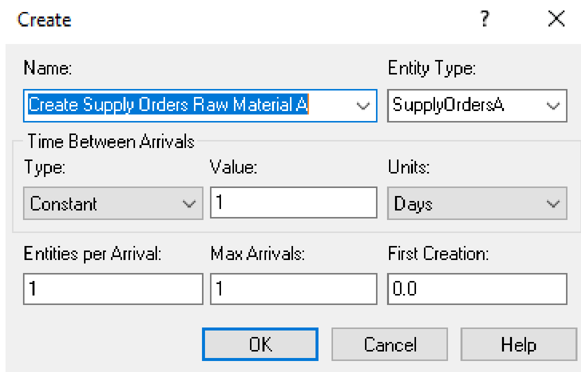

Figure 5.13 Supply Order Create Module

The SO's unique serial number is assigned to the entity, which is shown in Figure 5.14. Then, it is kept in the "Hold" module, waiting for inventory shortage to release the order to the matching supplier if the raw materials inventory level is less than or equal to "Order Point" based on "Safety Stock Level." When the inventory level of raw materials reaches to order point, and the condition "RawMaterialAinventory <= Raw Material A SS" is satisfied, the SO entity is released and sent to the supplier (Figure 5.15).

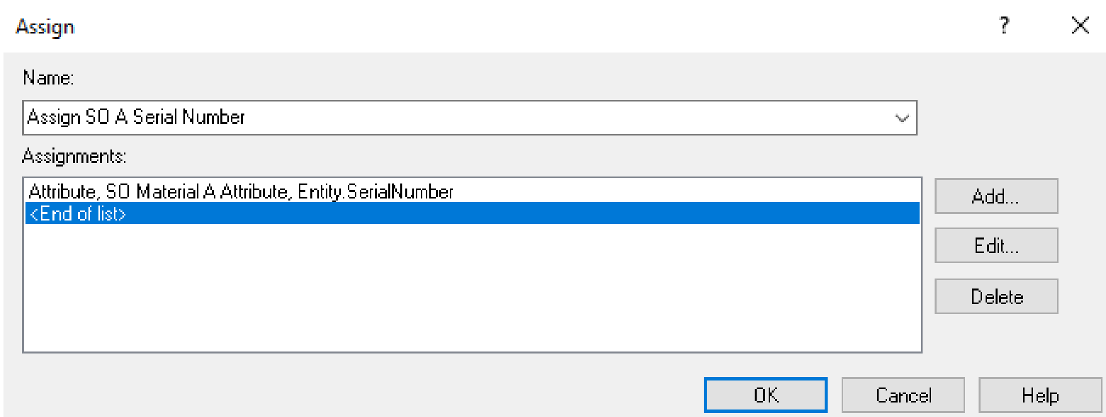

Figure 5.14 Assign Supply Order Serial Number Module

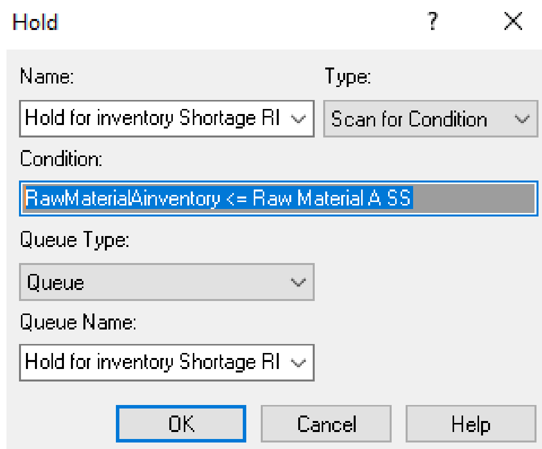

Figure 5.15 Hold for Raw Material Shortage Module

As shown in Figure 5.16, the “Separate” module is used to split the information flow and material flow. The “Separate” module duplicated the number of entities. The original information flow stream goes to the Luxxeen accounting department. After utilizing the “Delay” and” Process” modules to perform payment to the supplier and from there shipping planning from supplier to Luxxeen company in the logistics department, “the Ready to Ship from Supplier” variable is changed from zero to one allowing suppliers to ship raw materials to the Luxxeen company. (Figure 5.17).

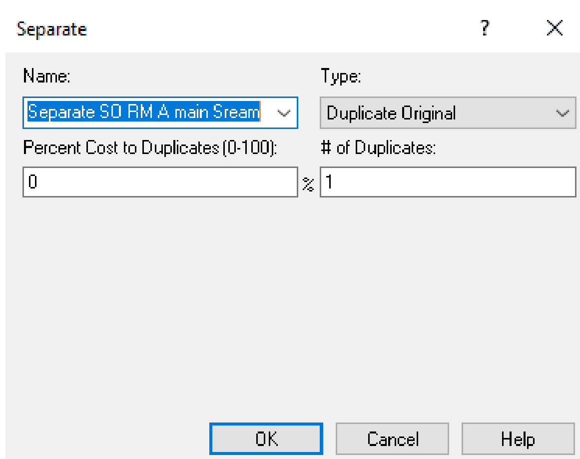

Figure 5.16 Separate Supply Order Main Stream Module

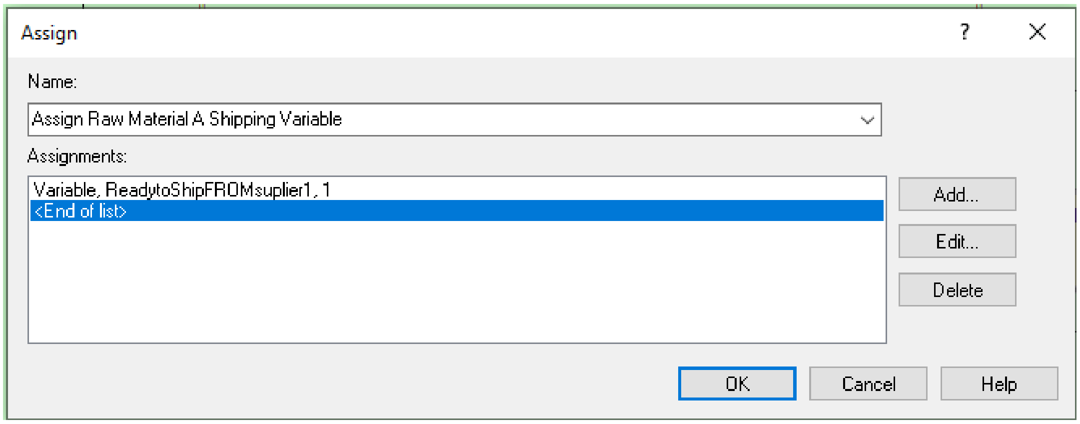

Figure 5.17 Assign Shipping Permission Variable Module

The supplier, on the other hand, collects the supply order and executes the SO confirmation operation. The raw material, as seen in Figure 5.18, requires time for the supplier to be provided. We used a variable time distribution and put initial data to 2. We alter this variable to design the first disruption scenario.

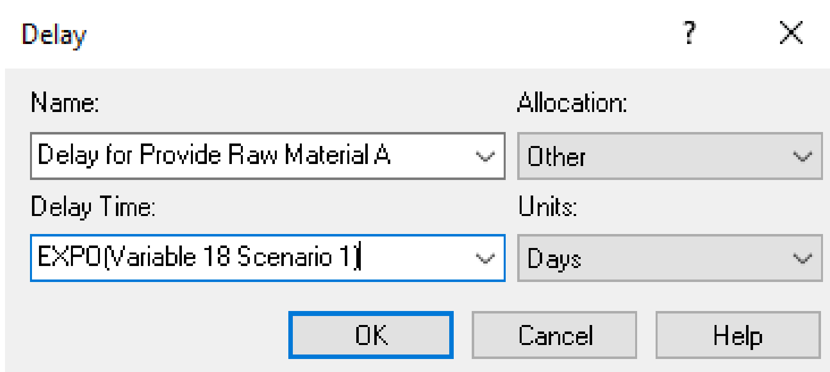

Figure 5.18 Delay to Provide Raw Material Module

Then the entity waits to receive confirmation of payment. If the condition "ReadytoShipFROMsuplier2 == 1" is established, the entity is released from the "Hold" module. After changing the value of the permission variable to normal, it is entered into the "Match" module

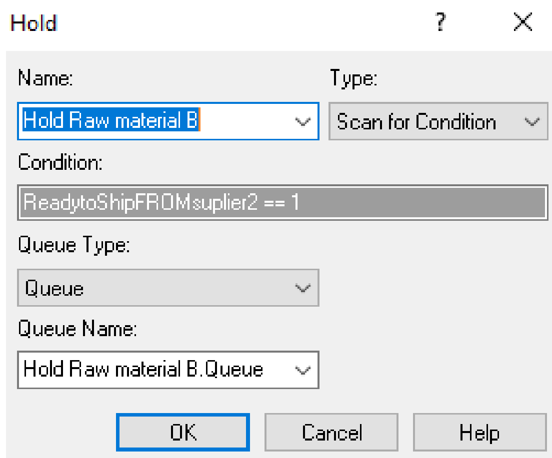

Figure 5.19 Hold for Payment Module

According to Figure 5.20, Both information and material streams are entered into the "Match" module and there, based on SO's serial number attribute, are permanently batched and ready to be sent to the raw material storage in Luxxeen company.

As shown in Figure 5.21, to increment the inventory level for A, B, and C raw materials, the "Assign" module is used. The new inventory level would be equals to "RawMaterialinventory + Supply Order Quantity Raw Material." It is then sent to the raw material storage using the "Route" module. On the other hand, they are received by raw material "Station" and "Supply Cycle Time," which is reported using "Record." In the end, SOs using "Dispose," leave the system (Figure 5.22 and Figure 5.8).

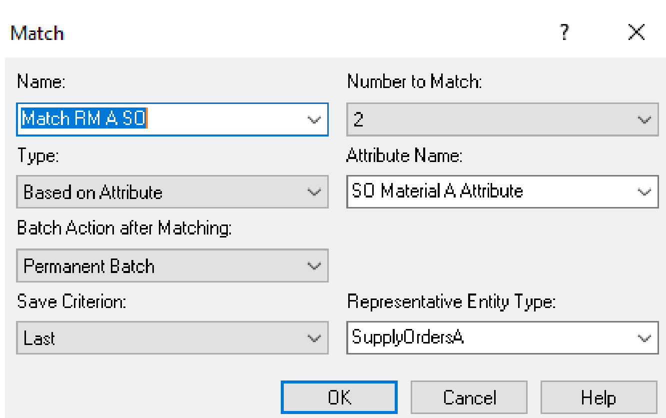

Figure 5.20 Match Supply Order's Material and Information Flow Module

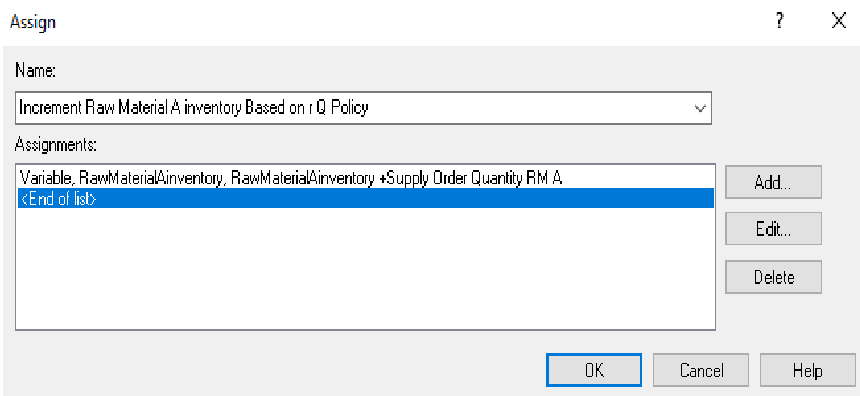

Figure 5.21 Assign Increment Raw Materials Inventory Module

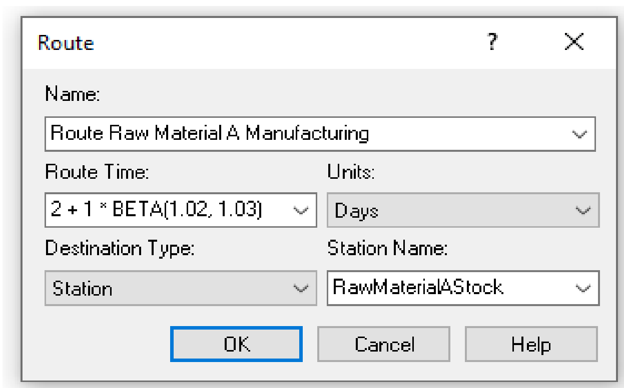

Figure 5.22 Route Module

Figure 5.23 represents the "Make" operations of the "Luxxeen" company. Firstly as shown in Figure 5.24, using the "Assign" module, a unique serial number is assigned to each PO entity and, similar to SO, is divided into two main streams of information and materials flow using the "Separate" module.

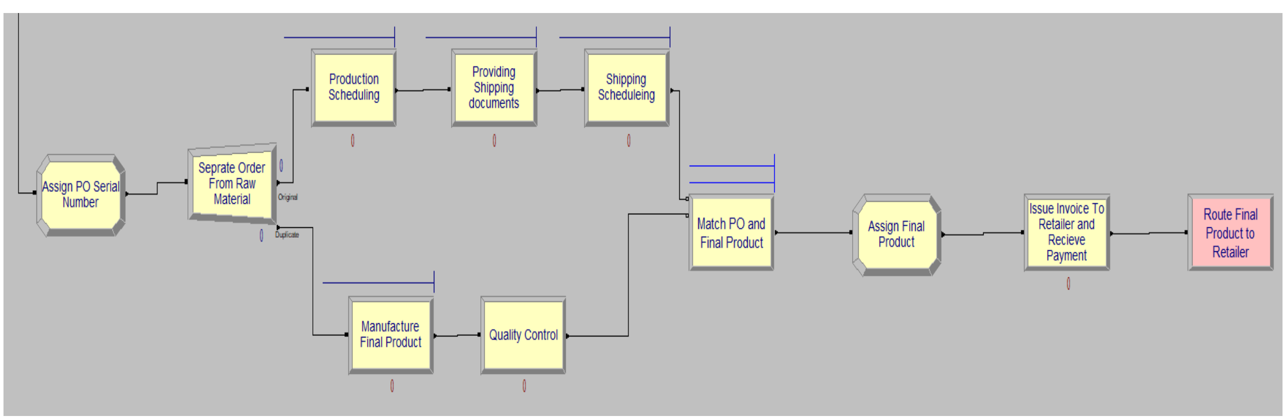

Figure 5.23 Production Department Overview

On the information flow stream, "production planning," "providing shipping documents," and "shipping scheduling" are executed using three consecutive "Process" modules with a specific time distribution. Simultaneously, as it is shown in Figure 5.25, the "production process" is done, followed by the "quality control" process.

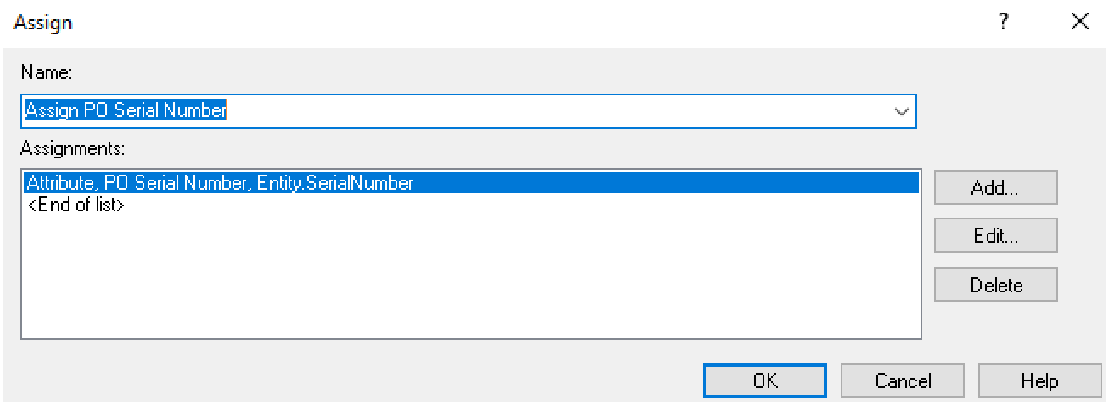

Figure 5.24 Assign Serial Number to Purchase Orders Module

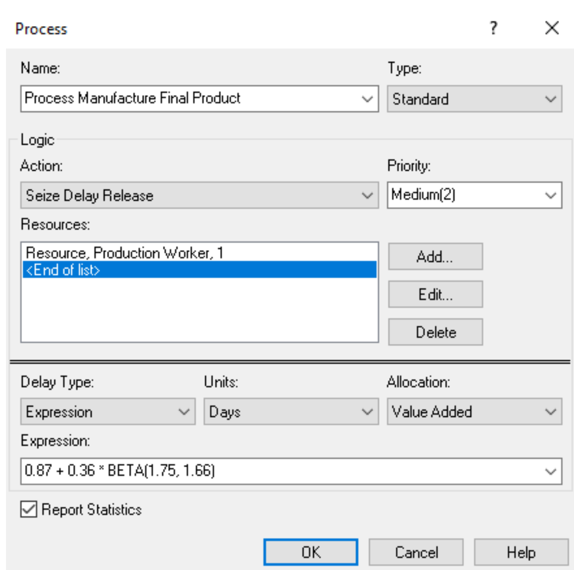

Figure 5.25 Manufacturing Process Module

Then using the “Match” module, PO and Final Product are batched permanently (Figure 5.26). Then, the new properties related to the final product are assigned to the entity.

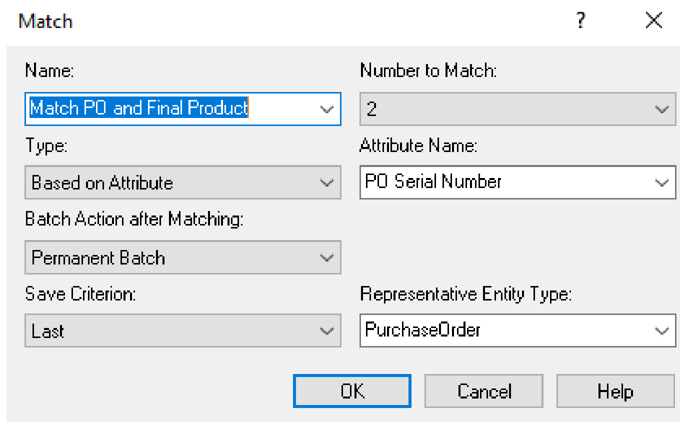

Figure 5.26 Match Information and Material Flows of Purchase Orders Module

Finally, one unit of the final product is sent to retailer “Station” using the “Route” module for each PO which is seen in Figure 5.27.

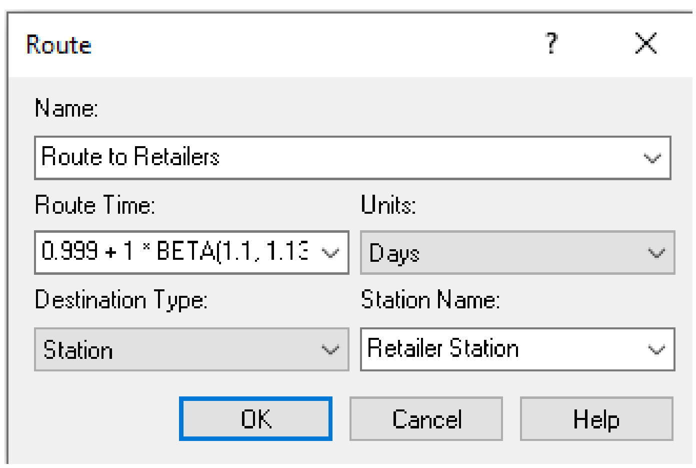

Figure 5.27 Route Final Products to Retailer Module

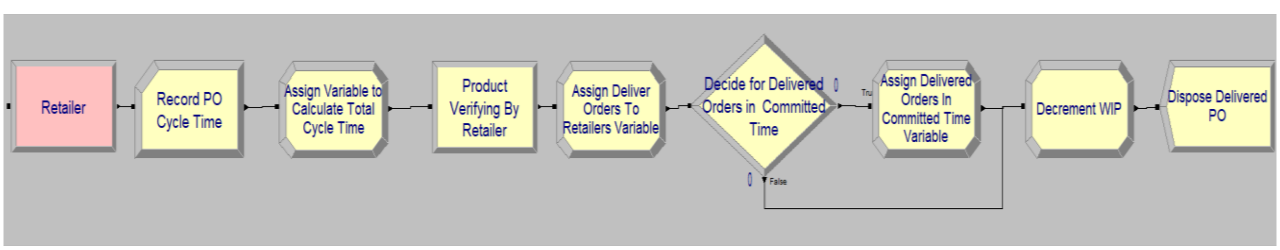

Figure 5.28 Retailer Operations Overview

Figure 5.28 represents the retailer operations. The final product entities are entered into the retailer "Station" module as Figure 5.29. then the number of "Delivered Orders" and the total "Cycle Purchase Order Cycle Time are reported using the "Record" module (Figure 5.30). The customer verifies the final product through the "Process" module, and then the number of delivered orders is counted using the "Assign" module by incrementing the "Delivered Orders" variable (Figure 5.32).

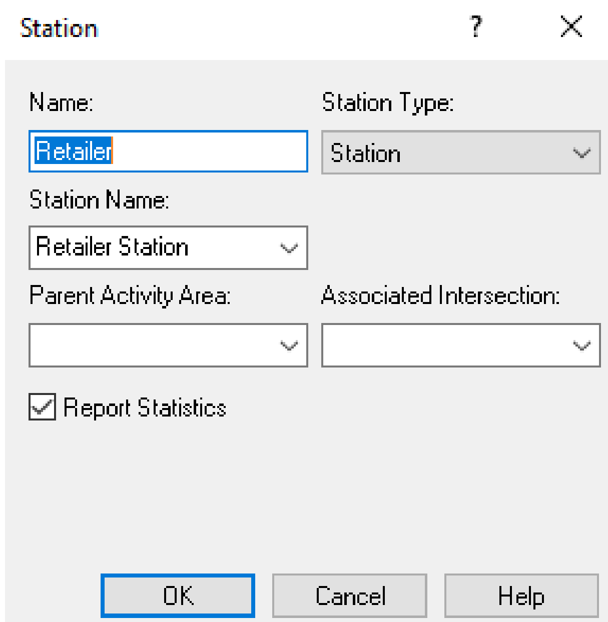

Figure 5.29 Retailer Station Module

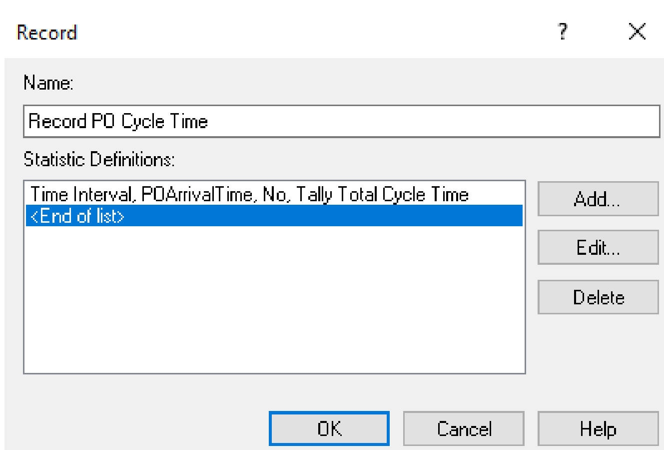

Figure 5.30 Record Purchase Order Cycle Time Module

Also, we need to calculate the summation of the total Cycle Time. We calculate it using the "Sum of Cycle time+TVALUE(Tally Total Cycle Time) expression and store the result in a new variable (Figure 5.31).

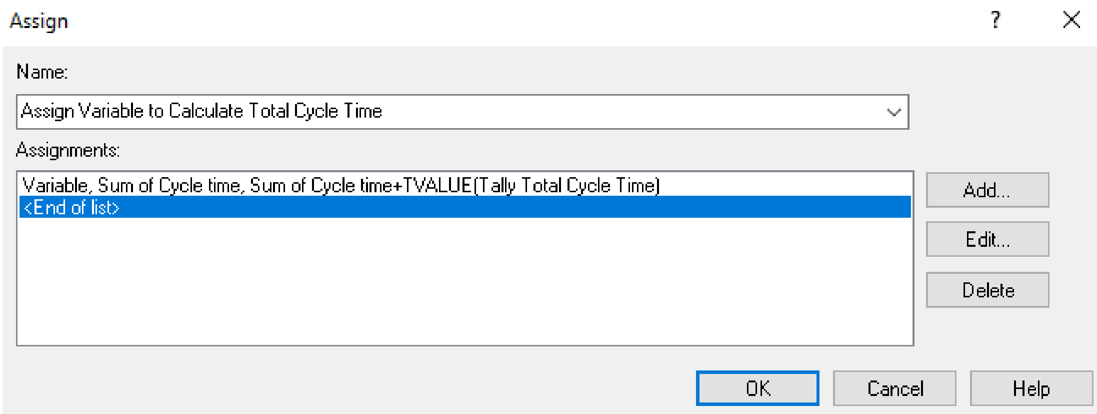

Figure 5.31 Assign Total Cycle Time Variable Module

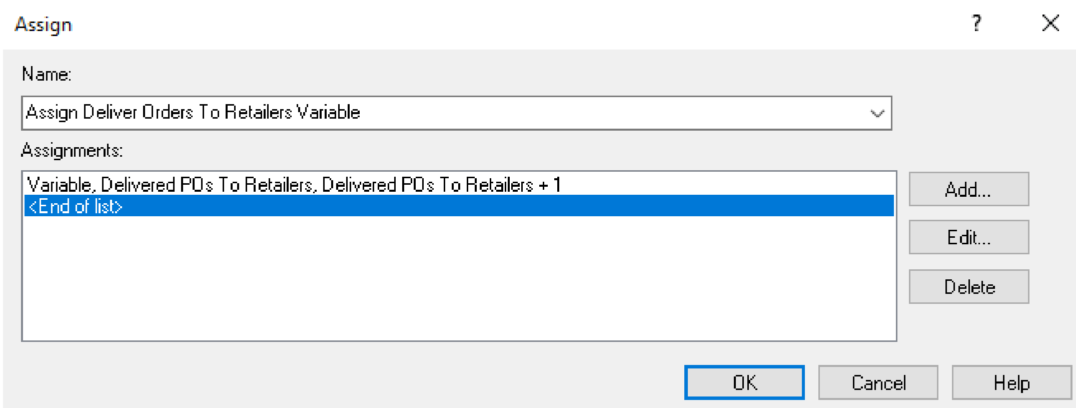

Figure 5.32 Assign Variable to Count Delivered Orders Module

Moreover, to differentiate the delivered orders in committed time, as shown in Figure 5.33, the "Decision" module is used. If the condition "TAVG(Tally Total Cycle Time) <= Average Committed Delivery Time," it increments_delivered orders in committed time" variable (Figure 5.34.)

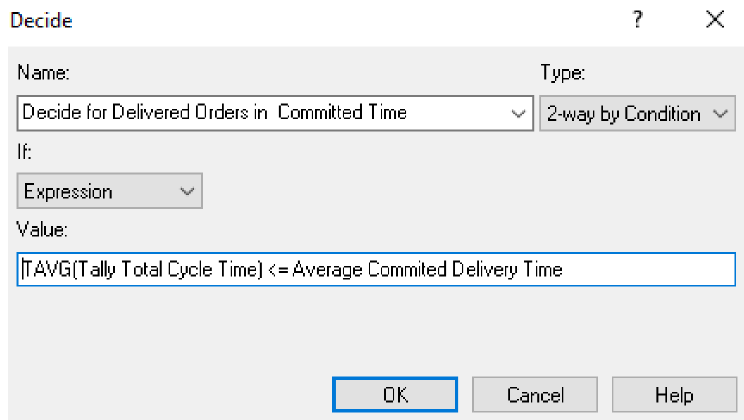

Figure 5.33 Decide Whether Order Delivered on Committed Time

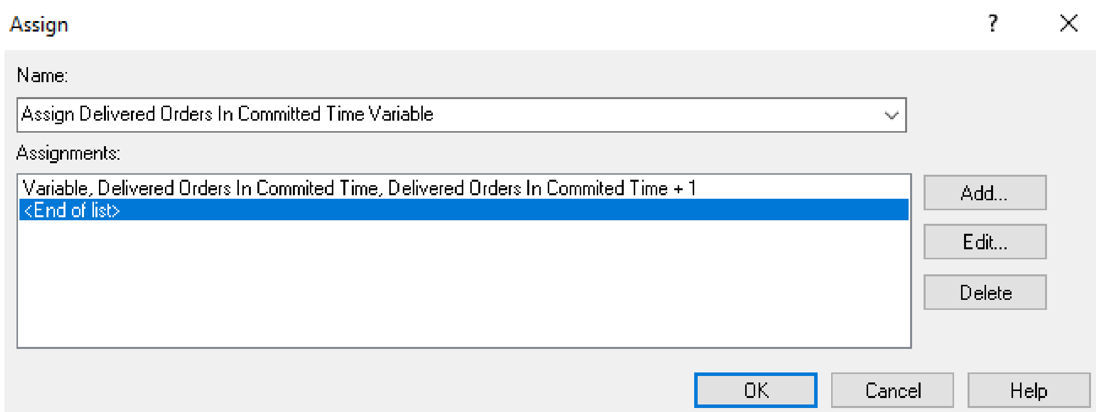

Figure 5.34 Assign Variable to Count Delivered Orders on Committed Time Module

Finally, all entities enter the “Assign” module, and the WIP variable is decremented and using the “Dispose” module, the entities leave the system (Figure 5.35, Figure 5.36).

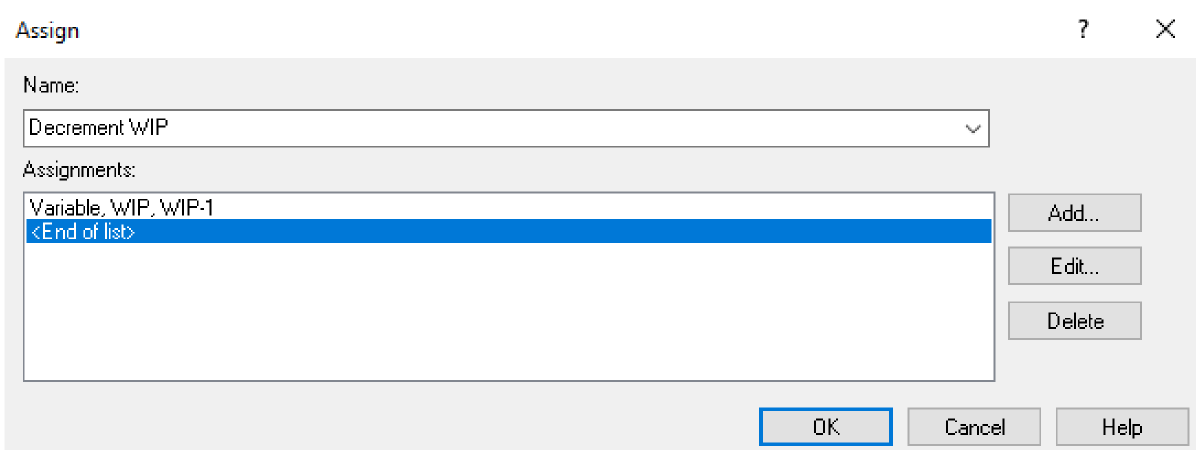

Figure 5.35 Decrement Work In Process Variable

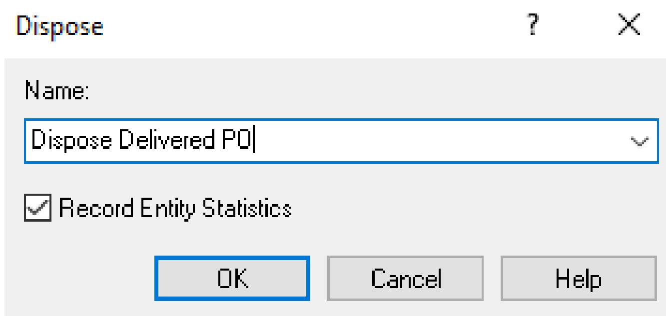

Figure 5.36 Dispose Purchase Order Entity from the System

5.6 Experimentation of the simulation model

5.6.1 Implement Disruption Risk Scenarios in ARENA

5.6.1.1 Disruption Risk Scenario 1

Figure 5.37 represents the first disruption scenario creation operations. As we discussed in chapter 4, the first disruption scenario starts on day 90 of simulation and disturbs SC for 60 days by increasing supply delay time by 100% for raw material A from supplier one located in the U.S.A.

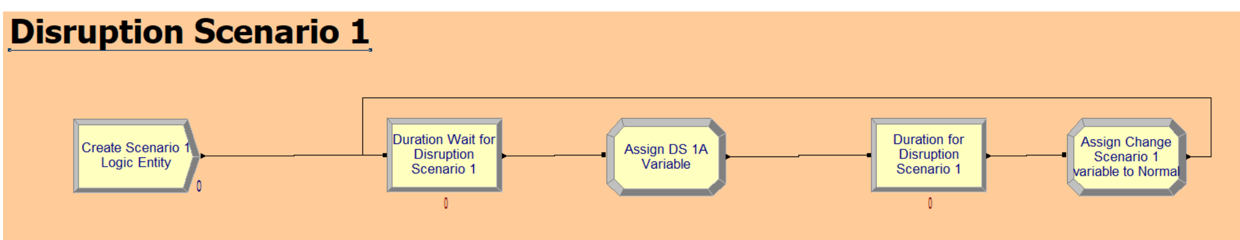

Figure 5.37 Disruption Scenario 1 Overview

According to Figure 5.38, "Entity 1 Logic" is created and entered into the system at the beginning of the simulation. The entity is first created to the system using the "Create" and waited for 30 days using the "Delay" Module (Figure 5.39).

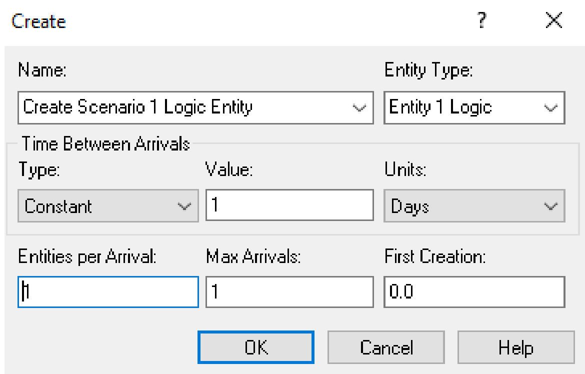

Figure 5.38 Create Disruption Scenario 1 Entity Module

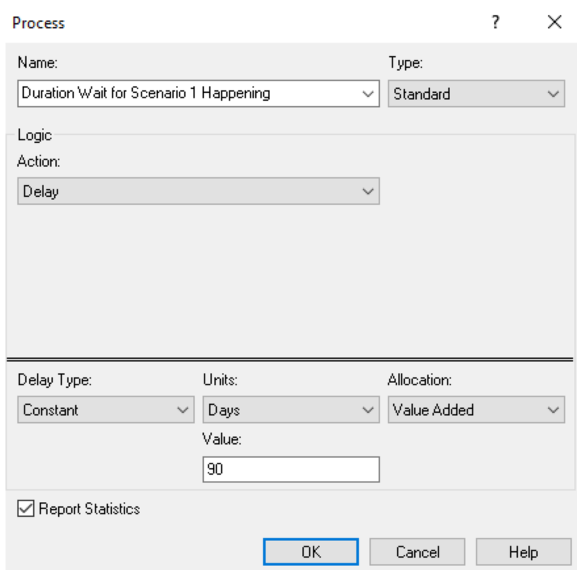

Figure 5.39 Delay for Occurring First Disruption Scenario Module

On the other hand, the statistical distribution for supplying raw Material A follows "EXPO (Variable 18 Scenario 1)". When the "Delay" module releases the entity, using the "Assign" module, the variable value is doubled by "Variable 18 Scenario 1 * Disruption Rate Scenario 1", resulting in a 100% increase in delay for supplying raw material A (Figure 5.40). Afterward, the entity enters the second "Delay" module and waits for the 90 days as a duration of the disruption (Figure 5.41).

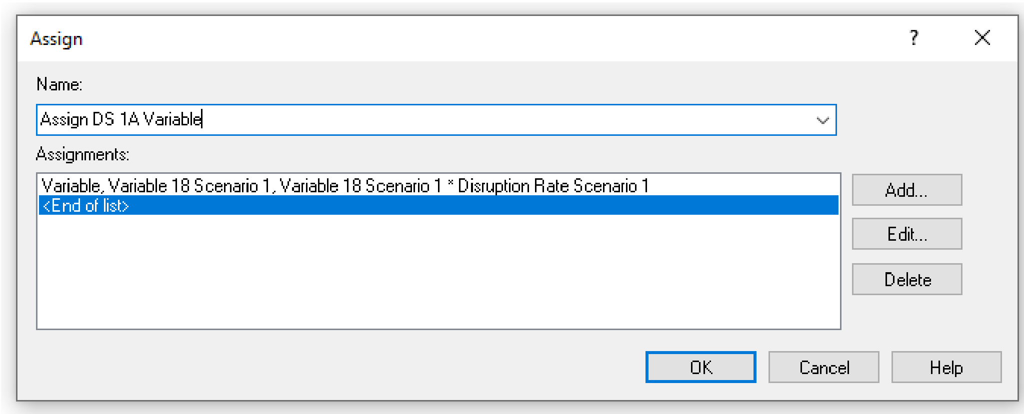

Figure 5.40 Assign Disruption Scenario 1 Variable Module

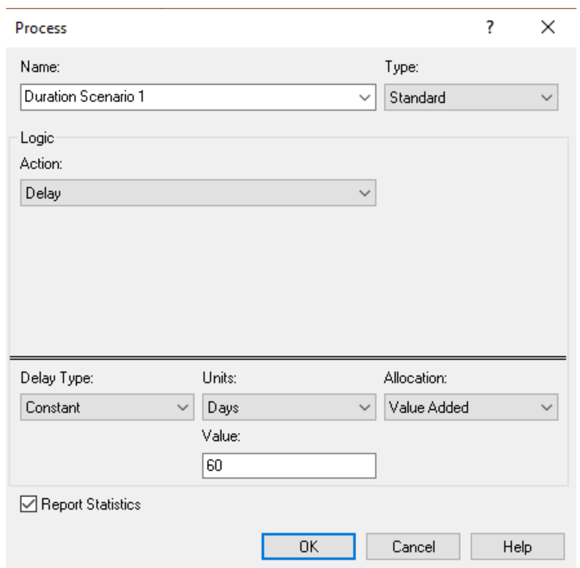

Figure 5.41 Delay for Duration of Disruption Scenario 1

Finally, as it is seen in Figure 5.42, on day 150, the entity transferred to the "Assign" module, which changes the variable to the normal value using the "Variable 18 Scenario 1 / Disruption Rate Scenario 1" expression.

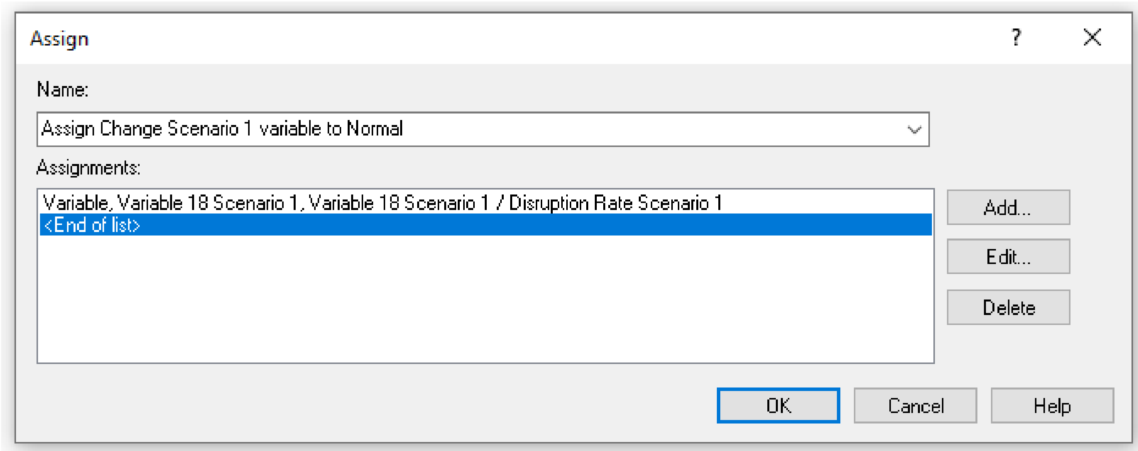

Figure 5.42 Assign Disruption Scenario 1 Variable Back to Normal Module

5.6.1.2 Disruption Risk Scenario 2

Figure 5.43 represents disruption scenario two occurrence operations overview. As we discussed in chapter 4, in addition to disruption scenario 1, pandemic outbreak disruption propagates into all other suppliers and the transportation network.

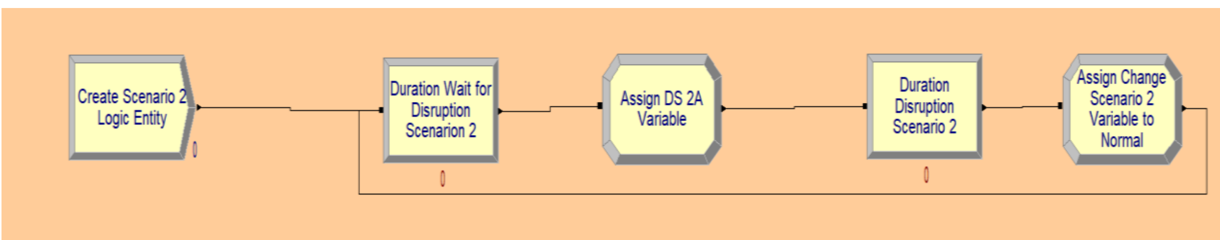

Figure 5.43 Disruption Scenario 2 Occurrence Overview

The logic of creating this disruption scenario is similar to scenario 1, except that this time the waiting time for sending all three raw materials from suplier1, supplier 2, and supplier 3 is 100% delayed for 60 days starting from day 150 of simulation.

For this purpose, three variables have been defined and established in the “Daily” module, represents shipping operations duration for all suppliers instead of having fixed duration distribution during the simulation (Figure 5.44).

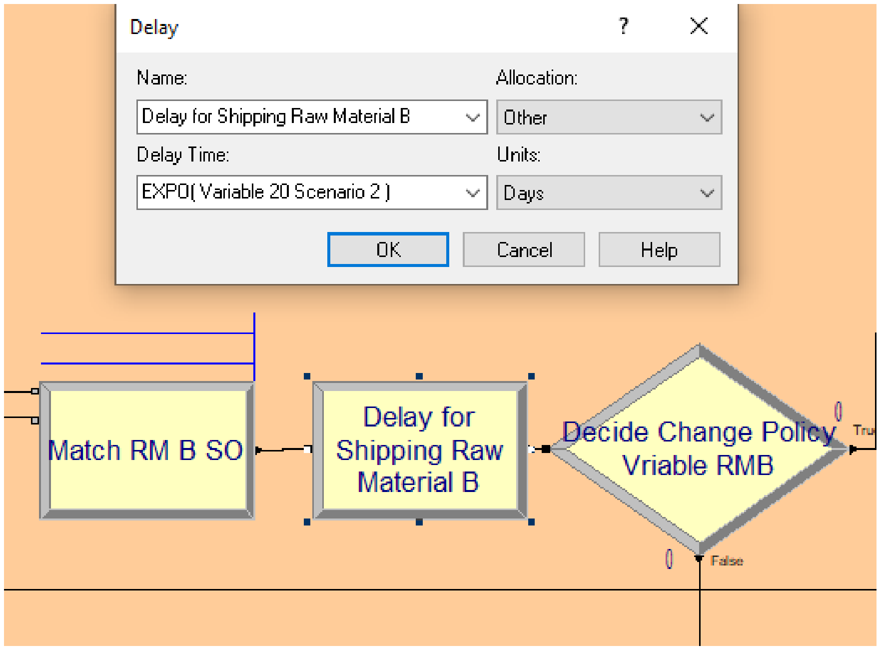

Figure 5.44 Delay Module Which is Affected By Disruption Scenario 2

Afterward, using the “Assign” module by increasing corresponding variables, as shown in Figure 5.45, disruption scenario 2, arises. Moreover, we increase the duration of disruption scenario one to 120 till the end of scenario 2.

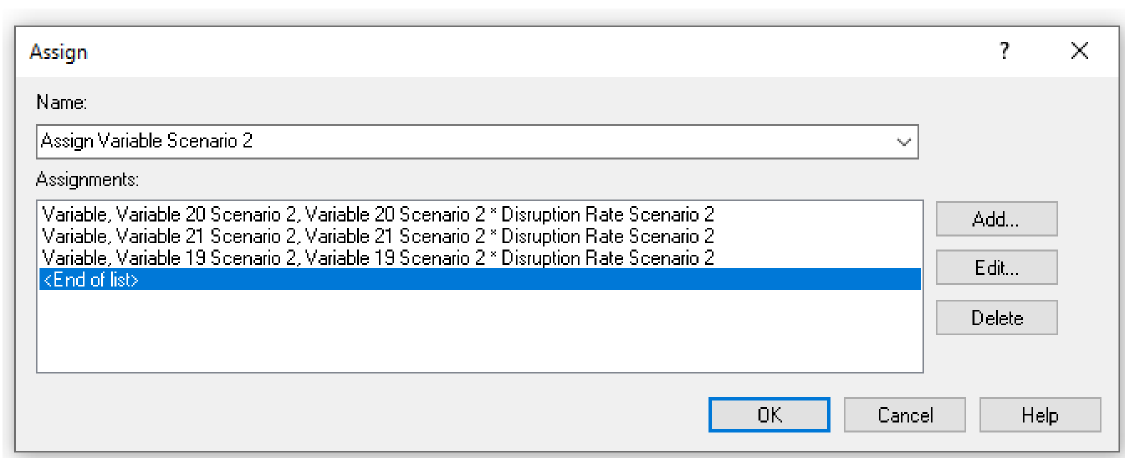

Figure 5.45 Assign Disruption Scenario 2 Variables Module

5.6.1.3 Disruption Risk Scenario 3

Figure 5.46 represents disruption scenario 3, which interrupts SC downstream by increasing 100% in demand due to customers' "Panic Buying" behaviour during the COVID-19 Pandemic outbreak. The disruption is started on day 210 and lasts for 30 days.

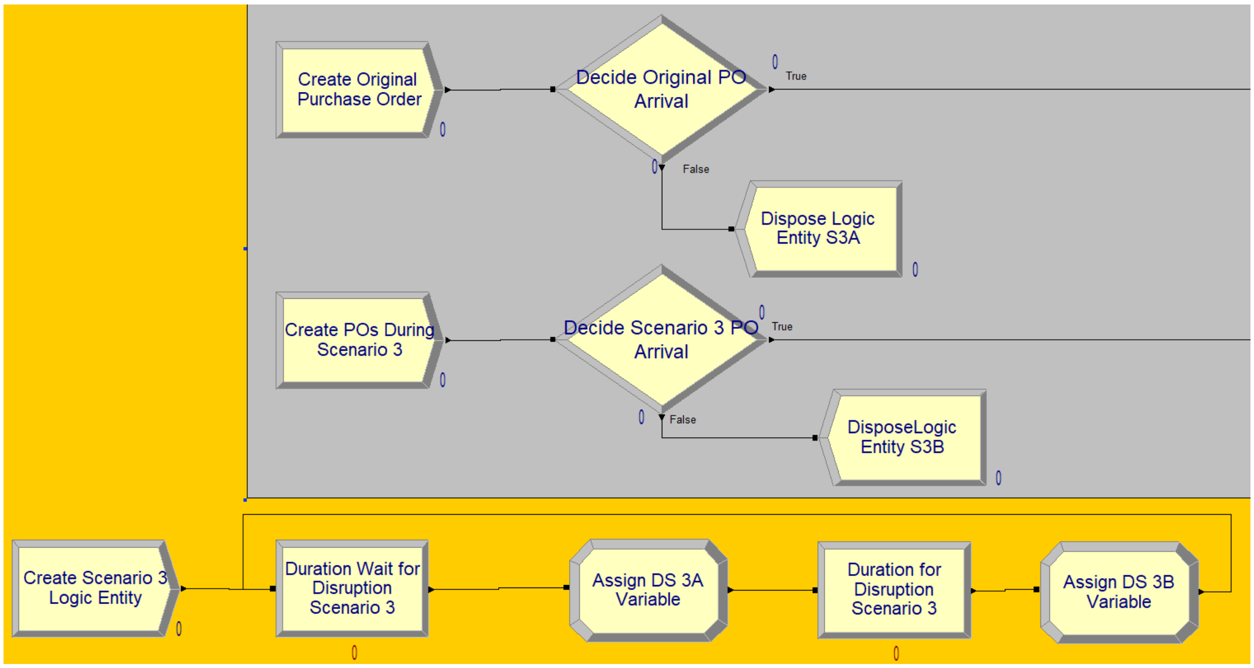

Figure 5.46 Disruption Scenario 3 Occurrence Overview

Initially, "Entity S3 Logic" is generated at the beginning of simulation into the system and waited for 210 days using the "Delay" Module. Afterward, using the "Assign" module, by changing the variable according to Figure 5.48, entities that are created using "Create Original Purchase Order" are disposed from the system as a result of the "Decide" module application.

On the other hand, entities created by "PO orders During Scenario 3" are entered into the system by an interarrival rate based on the "Variable 40 Inter Arrival time * Disruption Rate Scenario 3" expression. (Figure 5.47). The speed of getting POs during the disruption scenario 3 is two times faster than usual.

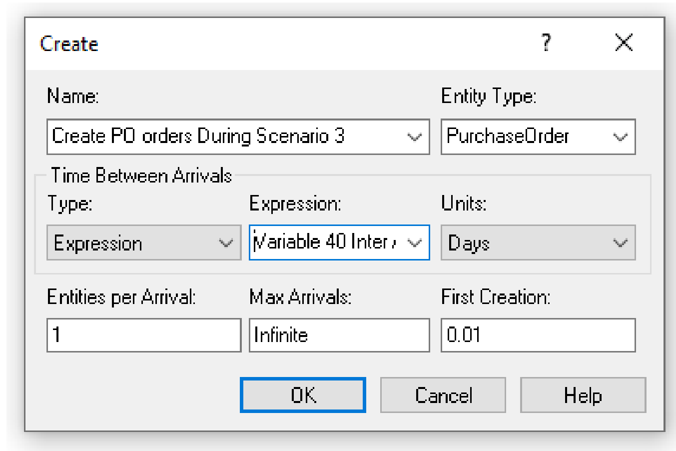

Figure 5.47 Create Disruption Scenario 3 Module

This situation lasts for 30 days up to day 240 of simulation. Finally, using another assign module, the variable's values are changed to normal.

Moreover, the duration of disruption scenarios 1 and 2 are changed to 150 days and 90 days, respectively.

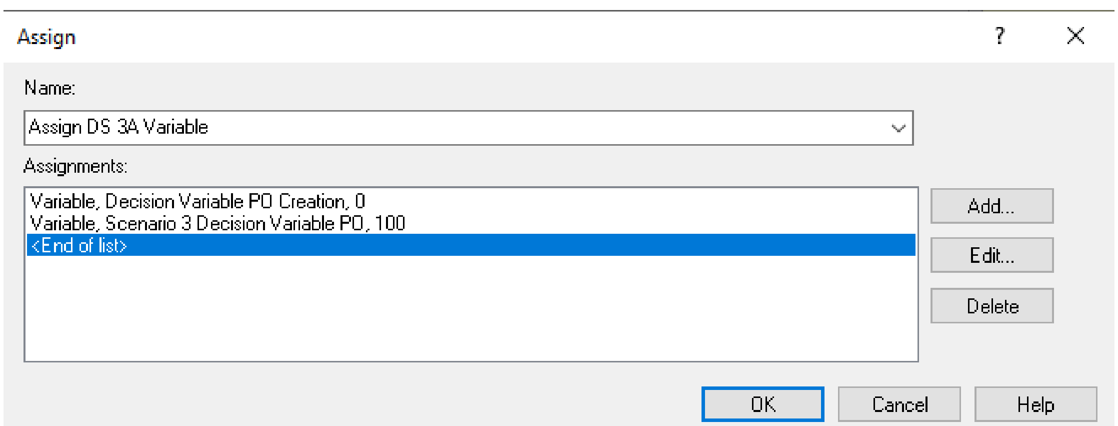

Figure 5.48 Assign Disruption Scenario 3 Variables Module

5.6.2 Implement Resiliency Scenarios in ARENA

As discussed in the previous chapter, "Multiple Sourcing," "Changing Inventory Control Policy," and "adding buffer by 100% increase in raw material storage" are three risk mitigation strategies are used to make the supply chain resilient in this study.

5.6.2.1 Risk Mitigation Strategy 1

In the “Supply” operations, as shown in Figure 5.49, two alternative suppliers are suggested in the model. To distribute supply orders among these three suppliers (including the current supplier), we use the three “Decide” modules consecutively, as presented in Figure 5.50, Figure 5.51, and Figure 5.52. We utilize “Supplier A selection Variable” for each alternative raw material A supplier.

We use the process analyzer tool to apply the “Multiple Sourcing” strategy to find the best distribution combination of SOs among these suppliers. The results are reflected in the next chapter.

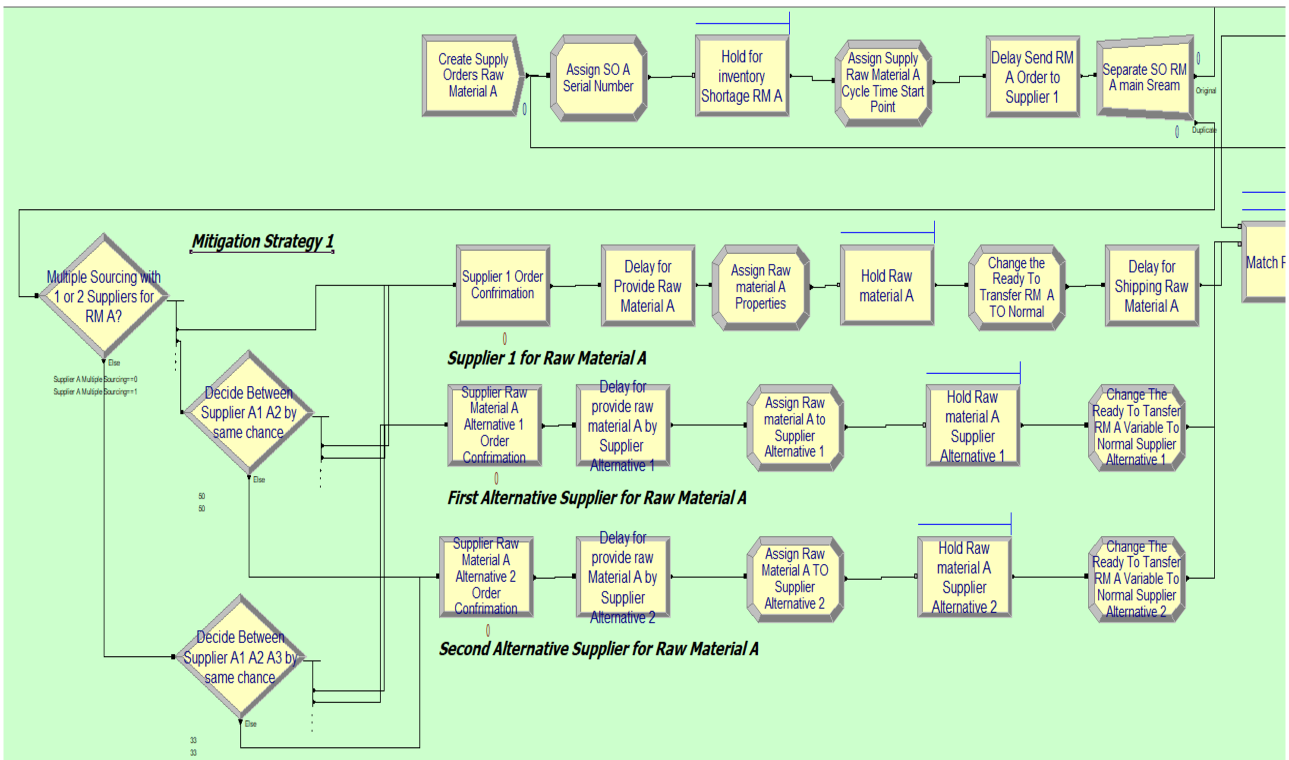

Figure 5.49 Risk Mitigation Strategy 1 Overview – Multiple Sourcing

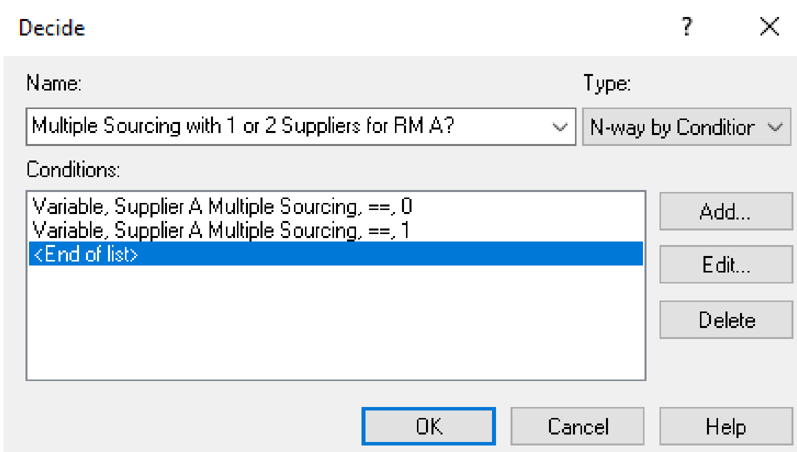

Figure 5.50 Decide Among Alternative Supplier in First Risk Mitigation Strategy

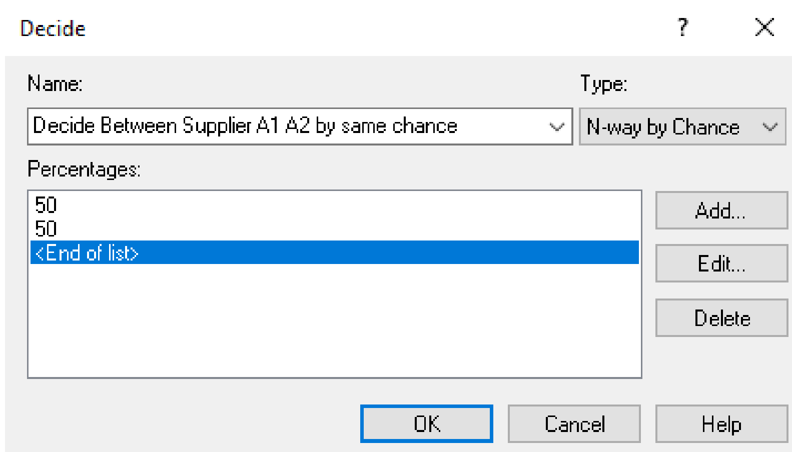

Figure 5.51 Decide for Current and 1st Alternative Supplier in First Risk Mitigation Strategy

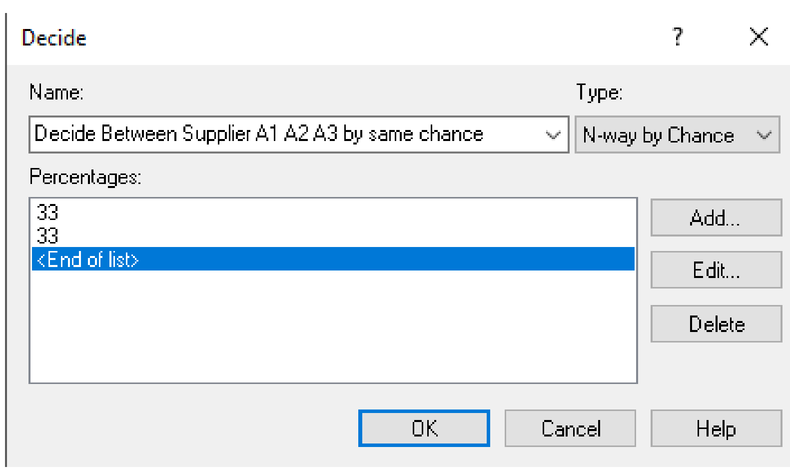

Figure 5.52 Decide Among Current and Two Alternatives Supplier

5.6.2.2 Risk Mitigation Strategy 2

Figure 5.53 represents risk mitigation strategy two logic overview. To design this strategy, we first define the maximum inventory level of each raw material A, B, and C variable Table 5.5.

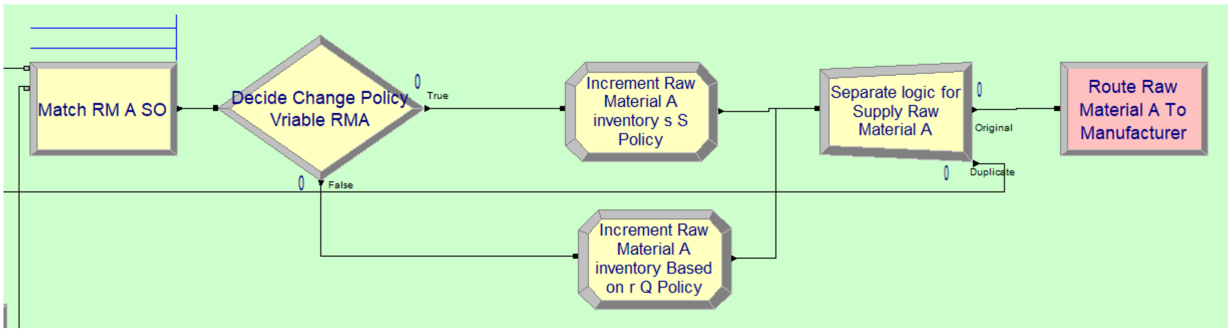

Figure 5.53 Risk Mitigation Strategy 2 Overview – Change inventory Control Policy to (s, S)

Later, to capture the inventory level in order point (which can be equal to or less than the order point) as shown in Figure 5.55, we assign "Change Policy Inventory level RM A" attribute right after generation of new SO as a result of a shortage in raw materials inventory. According to Figure 5.54, we define the "Decide" module utilizing (s, S) inventory control policy variable for each raw material entity. If "Variable Contingency Plan Policy Change" changed to 1, "RawMaterialAinventory + ABS(Maximum Inventory Level RM A -Change Policy Inventory level RM A) equation is used to increment raw materials inventory up to maximum level (Figure 5.56).

The same equation is used for raw materials B and C. In the next chapter, the results using "Process Analyzer" are reflected.

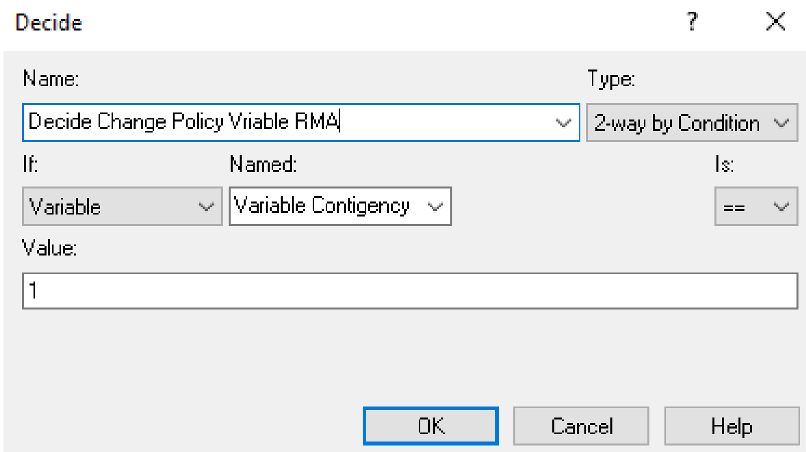

Figure 5.54 Decide Module to Change Inventory Control Policy

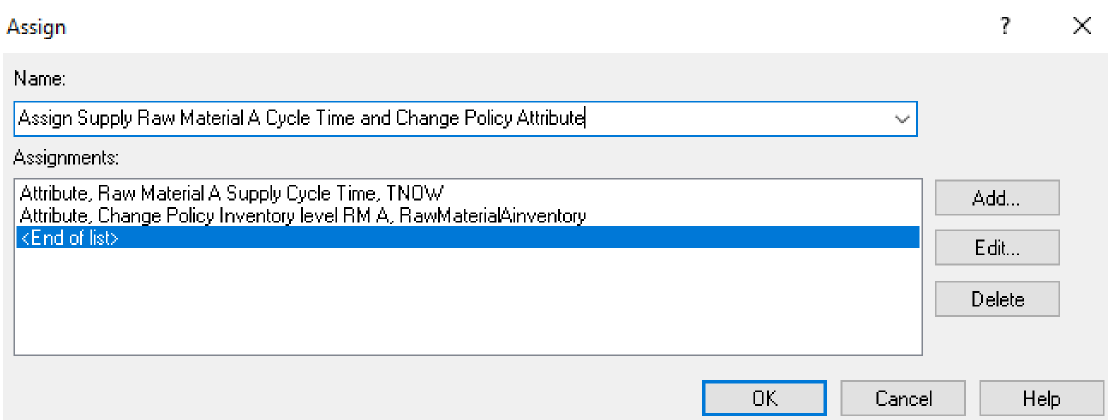

Figure 5.55 Assign Change Inventory Control Policy Attribute

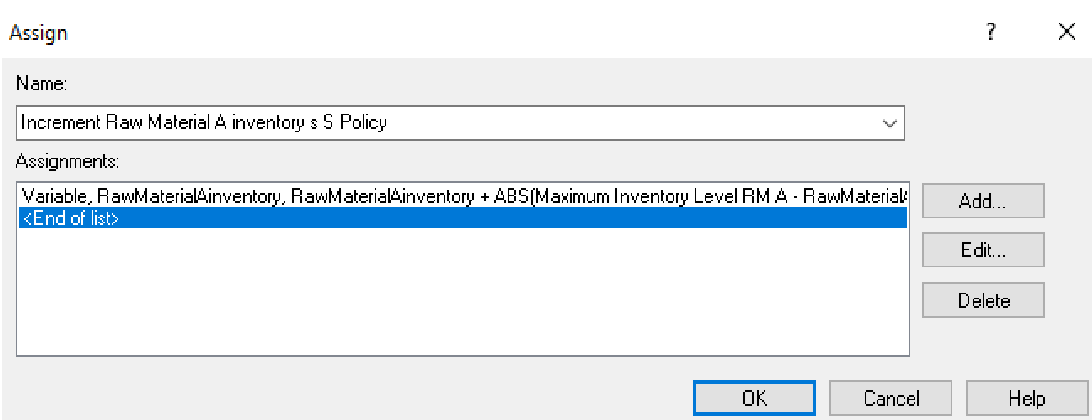

Figure 5.56 Assign (s, S) Inventory Control Policy

5.6.2.3 Risk Mitigation Strategy 3

We increase the initial value of raw material A, B, and C inventory levels by 100% to implement this strategy. In this scenario, we do not modify the model. We utilize "Process Analyzer" and add raw material inventory level as the control variables and observe the response variables. We increase the current value of the control variable in each disruption scenario.

5.6.3 Statistics Collection

Table 5.7 illustrates variables and equations used to measure performance metrics in our thesis. Later the results are reported in Chapter 6.

Statistic - Advanced Process

	Name	Type	Expression	Report Label
1	Delivered Ordered	Output	Delivered POs To Retailer	Delivered Ordered
2	Delivered Ordered Ontime	Output	Delivered Orders In Committed Time	Delivered Ordered Ontime
3	WIP_Statistics	Output	WIP	WIP_Statistics
4	Raw Material A Cycle Time	Time-Persistent	TAVG(RawMaterialASupplyCycleTime)	Raw Material A Cycle Time
5	Raw Material B Cycle Time	Time-Persistent	TAVG(RawMaterialBSupplyCycleTime)	Raw Material B Cycle Time
6	Raw Material C Cycle Time	Time-Persistent	TAVG(RawMaterial CSupplyCycleTime)	Raw Material C Cycle Time
7	Average Supply Cycle Time Statistics	Time-Persistent	TAVG(RawMaterial CSupplyCycleTime) + TAVG(RawMaterialASupplyCycleTime) + TAVG(RawMaterialBSupplyCycleTime)	Average Supply Cycle Time Statistics
8	Delivery Performance to Customer Committed Date	Output	(Delivered Orders In Committed Time / Delivered POs To Retailer) * 100	Delivery Performance to Customer Committed Date
9	Order Fulfillment Cycle Time	Output	Sum of Cycle time / Delivered POs To Retailer	Order Fulfillment Cycle Time
10	Total CT Statistics	Time-Persistent	TAVG(Tally Total Cycle Time)	Total CT Statistics
11	Total Supply CT Statistics	Time-Persistent	DAVG(Average Supply Cycle Time Statistics)	Total Supply CT Statistics

Table 5.7 Statistics Collection

5.6.4 Model Run Control

As shown in Figure 5.57 and Figure 5.58, the SC model created for Luxxeen's SC is a non-terminating simulation running for 8 hours a day for two years starting from December 2019. A pilot test simulation with 50 replications was run. Using the Equation 6:

$$n \cong n_0 \frac{\beta_0^2}{\beta^2}$$

"120" replications were determined to be suitable to give us our required half-width of 1 day. This half-width was selected based on the application.

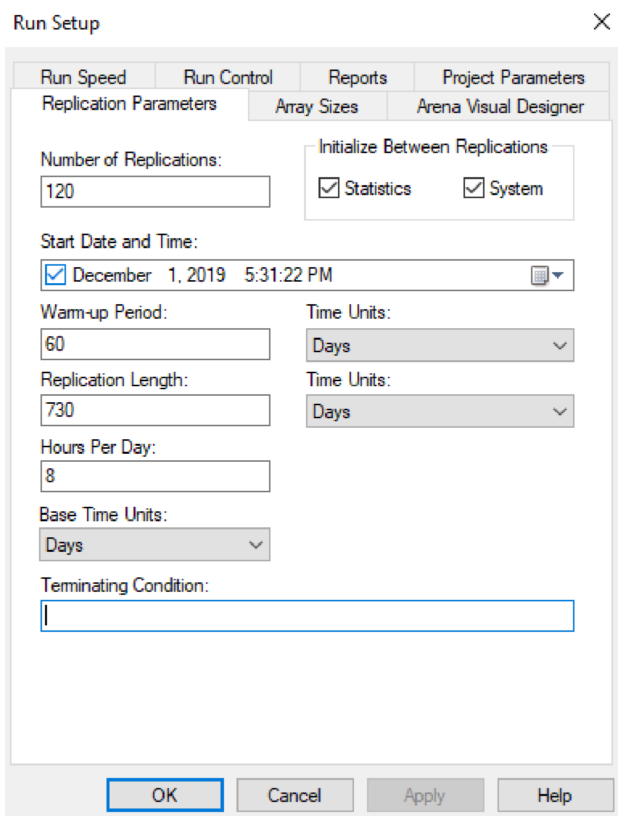

Figure 5.57 Run Setup View

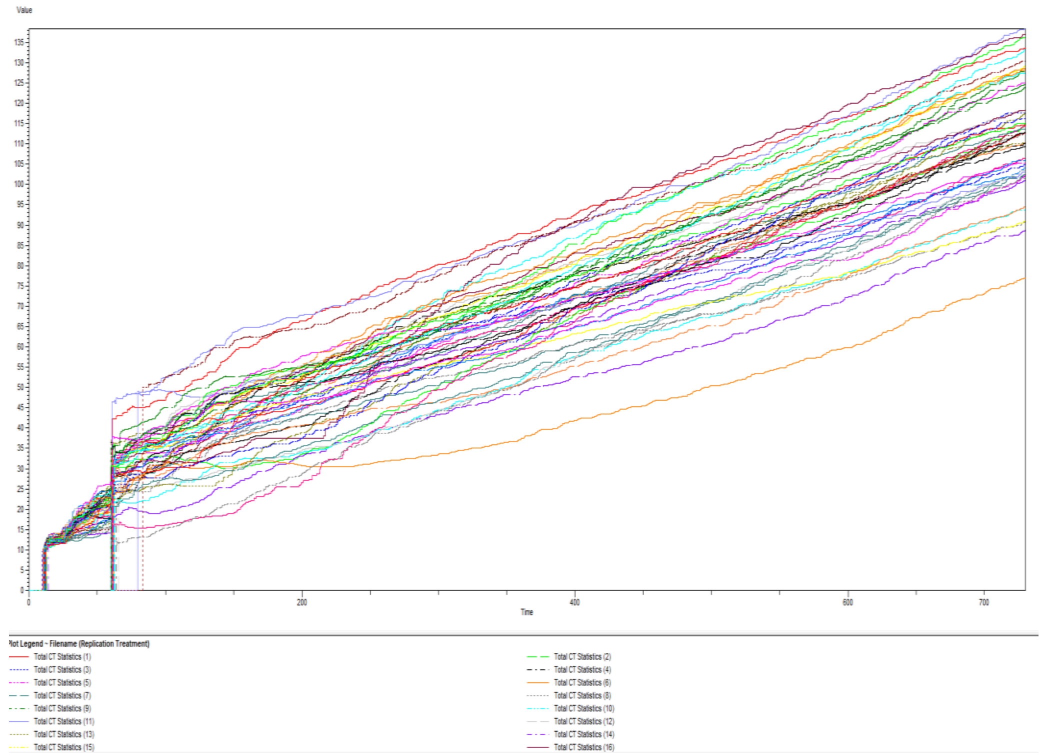

Figure 5.58 Total PO Cycle Time Plot by Output Analyzer

CHAPTER 6

RESULTS AND ANALYSIS

6.1 Chapter Overview

In this section, the Arena Simulation Software results are presented for the current state model and values obtained due to disruption scenarios. Then three risk mitigation strategies are applied in each of the disruption scenario steps, and using “Process Analyzer” and “OptQuest for Arena,” obtained results are compared with the disrupted values. Finally, the best combination of strategies to have a resilient supply chain is presented for each disruption scenario.

6.2 Output Analysis

Based on the results obtained in Chapter 5, we ran the model for 720 days and considered 60 days as the warmup period, and to obtain half-width under one day, we considered the number of replications to be 120.

According to Table 6.1, the following primary results are obtained by the “Arena Process Analyzer” of the current model and the destructive effects of the COVID-19 pandemic outbreak disruption risk on the selected performance metrics.

	Scenario Properties			Responses							
	S	Name	Reps	Delivery Performance to Customer Committed Date (RL.2.2)	Order Fulfillment Cycle Time (RS.1.1)	Average Purchase Order Cycle Time	Total Number Of Delivered Orders in Committed Time	Total Number Of Delivered Orders	Work In Process	Total Number of Accepted Purchase Orders	Average Supply Orders Cycle Time
1		Current State Model - NO DISRUPTION	120	74.10	38.29	29.54	623.64	836.37	80.57	841.23	292.98
2		Disruption Scenario 1	120	46.37	65.78	43.70	359.99	763.68	149.63	837.61	291.85
3		Disruption Scenario 2	120	38.65	81.27	51.12	285.81	726.06	185.63	835.99	290.24
4		Disruption Scenario 3	120	31.40	107.67	62.87	218.82	692.13	334.88	952.00	289.50

Table 6.1 Process Analyzer Initial Results

In the current state model, the average percentage of fulfilled orders on the customer's committed date is 74.10 percent. It also takes an average of 38.29 days for a PO to be sent by a retailer, be produced by the Luxxeen Co., and again received and approved by the customer.

Out of 841 requests received, 836 are delivered to the retailer. Also, 623 POs are delivered in committed time to the customer. The average Work In Process (WIP) is 80.57 POs, and the total average supply time of raw materials A, B, and C is about 293 days.

First, by the first disruption scenario from day 90 till day 150 of the simulation, performance indicators are significantly disrupted. The Delivery Performance to Customer Commit Date (RL.2.2) is reduced to 46.37%. This decrease is due to the delay in the supply of raw material A. Also, the Order Fulfillment Cycle Time (RS.1.1) is increased to 65.76 days, which presents an almost 70% increase compared to the current state model. With about the same number of requests, this time, compared to the current state model, the average “Total Number of Delivered Orders” drops 763.68 and only 360 requests reach the customer on committed time on average. The number of WIP has also increased significantly and reaches 149.63 POs on average. Additionally, the total average supply time is 291.85 days.

Later, on day 150 of the simulation, the supply chain is disrupted 100% increase in delivery time of all raw materials, including type A, B, and C. In this case, the first disruption scenario is still active. In this case, the RL.2.2 drops significantly to 38.65%, which is only 52% of the initial value. Also, the RS.1.1 is increased to 81.27, which presents an almost 24% increase compared to the first disruption scenario and 110% compared to the current state model. Nearly 85% (726 out of 836) of received POs are delivered to the retailer. On average, only 285.81 POs reach the customer on committed time. WIP is also recorded on average 185.63 POs, and the total average supply time fluctuates slightly around 290 days.

Finally, the third scenario is considered as the worst-case scenario due to the simultaneous decrease in raw material supply on the one hand and sharply increase by 100% in demand on the other and. As a result, RL.2.2 declines to 31.40%, which puts the supply chain in danger of collapse. Also, the RS.1.1 is increased to 107.67 days, which illustrates a 180% increase compared to the current state model. Particularly in this scenario, the number of accepted orders is almost 952 on average. 692.13 of received POs are delivered to the retailer. Only 218.82 POs reach the customer on the committed time, which is less than 25% of accepted orders. WIP shows a considerable surge to 334.88 on average, almost four times more than the current state model. The total average supply cycle time is recorded as 290 days.

6.2.1 Resilient Supply Chain

To create a resilient supply chain, we first examine each of the risk mitigation strategies individually during each of the disruption scenarios. For this purpose, we first used the "process analyzer," and by selecting control variables, we examined their effect on response value. Later

“OptQuest for Arena” is utilized to get the optimal solutions by combining risk mitigation strategies. To do this, firstly, the optimal values are calculated for each decision variable, considering the constraints. Secondly, we select the best combination of strategies by comparing the software's feasible solutions and a meeting with Luxxeen’s CEO.

Finally, we rerun the combination of strategies as the optimal answer in Process Analyzer and obtain the best approach for each disruption stage. As a reminder, the initially suggested risk mitigation strategies are as follows:

- **Risk Mitigation Strategy 1:** Multiple Sourcing to Supply Raw Material A
    - 50% supplier 1 RM A, 50% 1st Alternative Supplier RM A OR,
    - 33% supplier 1 RM A, 33% 1st Alternative Supplier RM A, 33% 2nd Alternative Supplier RM A
- **Risk Mitigation Strategy 2:** Buffering
    - 100% Increase in Inventory Level RM A and/or RM B and/or RM C
- **Risk Mitigation Strategy 3:** Change the Inventory Control Policy from (r, Q) to (s, S)

6.2.2 Solution Optimization

To get the optimum solutions, “OptQuest for Arena” is utilized to optimize the objective functions for each KPI. on the one hand, the primary goal of this study is to maximize “delivery performance to customer commit time” and “total numbers of delivered orders in committed time.” On the other hand, “order fulfilment cycle time,” “total average supply cycle time,” and “work in process” are minimized (Table 6.2).

Objectives Summary

	Included	Name	Goal	Expression
▶	☑	Maximize Delivered Orders On Committed Time	Maximize	[Delivered Ordered Ontime]
	☐	Maximize Delivery Performance	Maximize	[Delivery Performance to Customer Committed Date]
	☐	Minimize Order Fulfillment Cycle Time	Minimize	[Total CT Statistics]
	☐	Minimize Total Supply Cycle time	Minimize	[Total Supply CT Statistics]
	☐	Minimize Work In Process	Minimize	[WIP_Statistics]

Table 6.2 Objective Functions

Based on the current state model output, available historical data in the Luxxeen company and particularly consult with Luxxeen's CEO, the following constraints are considered to make the resilient supply chain (Table 6.3).

Constraints

Included	Name	Expression
☑	Reliability	[Delivery Performance to Customer Committed Date] >= 80
☑	Responsiveness	[Order Fulfillment Cycle Time] <= 35
☑	Supply Cycle Time	[Total Supply CT Statistics] <= 295
☑	WIP	[WIP_Statistics] <= 65
☑	Average Waiting Time in Queue	[Hold For Raw Material.Queue.WaitingTime] <= 37

Table 6.3 Constraints

Five decision variables are defined as "Control" variables as presented in OptQuest, presented in Table 6.4.

Controls

Included	Name	Element Type	Type	Low	Suggested	High	
☑	RawMaterialAinventory	Variable	Discrete	60000	120000	120000	60000
☑	RawMaterialBinventory	Variable	Discrete	12000	24000	24000	12000
☑	RawMaterialCinventory	Variable	Discrete	100000	200000	200000	100000
☑	Supplier A Multiple Sourcing	Variable	Integer	0	1	2	1
☑	Variable Contigency Plan Policy ...	Variable	Binary	0	1	1	N/A

Table 6.4 Control Variables in OptQuest

In the following, the software has suggested 25 feasible responses for each objective function, combining the proposed risk mitigation strategies presented in tables followed by the corresponding diagram and the optimum solution. To be concise, we include detailed “OptQuest for Arena” analysis for disruption scenario one and disruption scenario three as examples. In between, we also include results obtained from analysis for disruption scenario 2. The details are included in the appendix.

6.2.2.1 Analysis for Disruption Scenario 1

COVID-19 Pandemic outbreak disturbs the supply of raw materials A resulted in a 100% increase in delivery time for 60 days (from day 90 to 150).

Number	Disruption Scenario	Mitigation Strategy	Responses						
			Delivery Performance to Customer Commit Date (RL.2.2)	Order Fulfillment Cycle Time (RS.1.1)	Total Number Of Delivered Orders in Committed Time	Total Number Of Delivered Orders	Work In Process	Total Number of Accepted Purchase Orders	Average Supply Orders Cycle Time
1	Current State Model No Disruption	-	74.1	38.29	623.64	836.37	80.57	841.23	292.98
2	Disruption Scenario 1	-	46.37	65.78	359.99	763.68	149.6	837.61	291.85
3	Disruption Scenario 1	Multiple Sourcing - 50% supplier 1 RM A- 50% 1st Alternative Supplier RM A -0% 2nd Alternative Supplier RM A	79.59	32.88	678.89	849.77	60.19	835.29	293.51
4	Disruption Scenario 1	Multiple Sourcing - 33% supplier 1 RM A- 33% 1st Alternative Supplier RM A - 33% 2nd Alternative Supplier RM A	90.49	26.53	786.87	867.2	46.52	837.59	292.52
5	Disruption Scenario 1	Changing the Inventory Control Policy from (r, Q) to (s, S)	83.31	28.04	722.43	866.83	41.7	831.58	291.79
6	Disruption Scenario 1	Buffering Raw Materials Inventory by 100% Increase in Inventory Level	54.18	59.96	428.52	776.83	137.6	838.31	293.7

Table 6.5 Disruption Scenario 1 and Three Risk Mitigation Strategies

As presented in Table 6.5, the first set of strategies is tested at the disruption scenario one duration. We initially tested the results on five performance metrics by adding an alternative supplier previously on Luxxeen's approved vendor list. By applying this strategy, as shown in Table 6.5, 50% of SOs are provided by the current supplier of raw material A and the rest 50% SOs are fulfilled by the 1st alternative raw material A supplier. As is seen, in this case, the RL.2.2 rise significantly to 79.59%, which was decreased to 46.37 % due to disruption scenario 1 to 48.37. furthermore, the RS.1.1 drops to 32.88, which is even shorter than the current state model, 38.29 days. Besides, the total number of delivered orders in committed time shoots up to 678.89 from only 359.99 POs. Likewise, WIP is also shown to drop to 60.19 POs considerably. Although, the total average supply cycle time slightly increases to 293.51 days on average due to adding sourcing operations and routing time.

Secondly, If we added two alternative suppliers when each fulfils 33% of SOs, the best results would be achieved. For instance, RL.2.2 and total numbers of delivered orders in committed time would reach, on average to 90.49% and 786.87 POs, respectively. Moreover, RS.1.1 and WIP would drop to 26.53 days and 46.52 POs o average. Even though the total average supply cycle time slightly rises to 292.52 days on average.

Thirdly, by changing the inventory control policy to (s, S), RS.1.1 and WIP decrease to 28.53 days and 41.7 POs, respectively, which are better results than the current state model. Besides, as a result, RL.2.2 and total numbers of delivered orders in committed time rise to 83.31% and 722.43 POs on average, respectively. This strategy is considered the second-best strategy during the first disruption scenario. The total average supply cycle time almost remains the same as the current state model and fluctuates around 292 days on average.

Finally, buffering raw materials inventory by a 100% increase in inventory level is tested on disrupted performance metrics due to disruption scenario 1. RL.2.2 and total numbers of delivered orders in committed time are raised to 54.18% and 428.83 POs, respectively on average. Furthermore, RS.1.1 and WIP are 59.96 days and 137.61 POs on average, respectively. This strategy fails to make the SC resilient during the COVID-19 pandemic outbreak first disruption scenario.

6.2.2.1.1 Minimize Work in Process

As shown in Table 6.6, all 25 solutions are feasible and meet the constraints set for having a resilient supply chain. Among these objective values, the worst WIP value in the system is 39 POs, which results from doubling the inventory level of raw materials C and using one alternative supplier to supply raw material A. Although the optimal solution is 13 POs for the WIP performance metric, to achieve this value, in addition to the strategies mentioned, the inventory control policy must be changed to (s, S) (Figure 6.1).

Best Solutions **Optimal solution found.**

Best Solutions

	Included	Simulation	Objective Value	Status	awMaterialAinvento	awMaterialBinvento	awMaterialCinvento	Supplier A Multiple	Variable
▸	☑	8	13	Feasible	60000	12000	200000	1	1
	☐	40	13	Feasible	60000	24000	100000	0	1
	☐	5	15	Feasible	60000	24000	100000	1	1
	☐	23	15	Feasible	120000	12000	200000	2	1
	☐	39	15	Feasible	120000	24000	100000	1	1
	☐	15	16	Feasible	120000	12000	100000	1	1
	☐	47	16	Feasible	120000	12000	100000	2	1
	☐	12	18	Feasible	60000	12000	100000	2	1
	☐	31	18	Feasible	60000	12000	200000	2	1
	☐	32	18	Feasible	120000	12000	200000	1	1
	☐	6	20	Feasible	60000	24000	200000	1	0
	☐	48	21	Feasible	60000	24000	100000	2	1
	☐	24	22	Feasible	120000	24000	100000	2	1
	☐	1	23	Feasible	120000	24000	200000	1	1
	☐	4	23	Feasible	60000	12000	100000	1	0
	☐	13	24	Feasible	60000	24000	100000	2	0
	☐	42	25	Feasible	60000	12000	200000	2	0
	☐	45	25	Feasible	120000	12000	100000	2	0
	☐	2	27	Feasible	60000	12000	100000	0	0
	☐	11	28	Feasible	60000	24000	200000	0	1
	☐	34	31	Feasible	60000	12000	100000	2	0
	☐	27	32	Feasible	60000	24000	200000	1	1
	☐	17	35	Feasible	60000	12000	200000	0	0
	☐	18	39	Feasible	60000	12000	100000	1	1
	☐	26	39	Feasible	60000	12000	200000	1	0

Table 6.6 Best Strategies Minimize WIP in Disruption Scenario 1

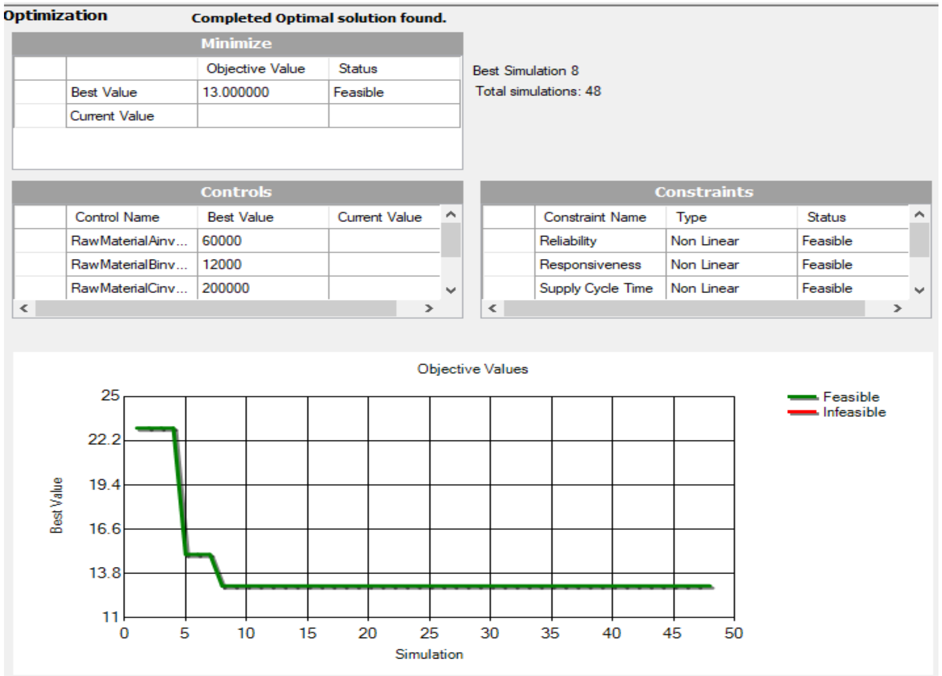

Figure 6.1 Optimal Solution to Minimize WIP in Disruption Scenario 1

6.2.2.1.2 Maximize Total Number of Delivered Orders in Committed Time

As shown in Table 6.7, for this KPI also all 25 solutions are feasible. Among these objective values, the worst value is 850 POs, which results from changing the inventory control policy to (s, S). However, the optimal solution is 916 POs. To achieve this value, in addition to the strategies mentioned, the two alternative suppliers are considered for raw material A and the inventory level of raw materials A and C are doubled. (Figure 6.2).

Best Solutions **Optimal solution found.**

Included	Simulation	Objective Value	Status	awMaterialAinventoı	awMaterialBinventoı	awMaterialCinventoı	Supplier A Multiple	Variable
☑	38	916	Feasible	120000	12000	200000	2	1
☐	4	902	Feasible	60000	12000	100000	1	0
☐	32	894	Feasible	120000	12000	100000	2	0
☐	33	894	Feasible	60000	12000	200000	1	0
☐	2	892	Feasible	60000	12000	100000	0	0
☐	30	892	Feasible	60000	12000	200000	2	0
☐	14	891	Feasible	60000	24000	100000	2	0
☐	12	887	Feasible	60000	24000	200000	0	1
☐	6	885	Feasible	60000	24000	100000	1	1
☐	13	884	Feasible	60000	12000	100000	2	1
☐	36	878	Feasible	60000	24000	100000	0	1
☐	43	876	Feasible	120000	24000	200000	2	0
☐	1	874	Feasible	120000	24000	200000	1	1
☐	9	870	Feasible	60000	12000	200000	1	1
☐	21	870	Feasible	60000	12000	200000	2	1
☐	19	866	Feasible	60000	12000	100000	1	1
☐	41	866	Feasible	120000	24000	100000	2	1
☐	17	864	Feasible	120000	12000	200000	2	0
☐	44	862	Feasible	120000	12000	200000	1	1
☐	3	861	Feasible	120000	24000	200000	2	1
☐	16	860	Feasible	120000	12000	100000	1	1
☐	22	858	Feasible	120000	12000	100000	2	1
☐	35	857	Feasible	120000	12000	200000	0	1
☐	37	857	Feasible	120000	24000	100000	1	1
☐	45	850	Feasible	60000	12000	100000	0	1

Table 6.7 Best Strategies to Maximize Delivered Orders in Disruption Scenario 1

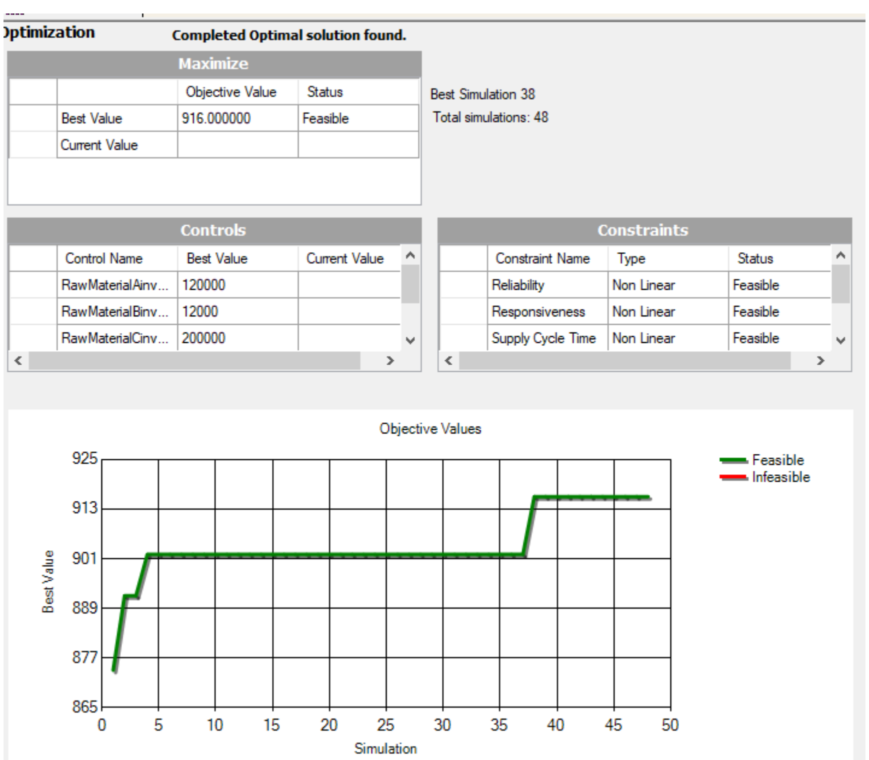

Figure 6.2 Optimal Solution to Maximize Delivered Orders in Disruption Scenario 1

6.2.2.1.3 Maximize Delivery Performance to Customer Commit Date (RL.2.2)

As shown in Table 6.7, all responses are feasible and represent the optimal result which is 100%. Raw material C inventory level is doubled, and the inventory control policy is changed to (s, S), to achieve this value (Figure 6.3).

Best Solutions **Optimal solution found.**

Best Solutions

	Included	Simulation	Objective Value	Status	awMaterialAinventor	awMaterialBinventor	awMaterialCinventor	Supplier A Multiple	Variable
▸	☑	11	100	Feasible	60000	24000	200000	0	1
	☐	1	100	Feasible	120000	24000	200000	1	1
	☐	2	100	Feasible	60000	12000	100000	0	0
	☐	3	100	Feasible	120000	24000	200000	2	1
	☐	4	100	Feasible	60000	12000	100000	1	0
	☐	5	100	Feasible	60000	24000	100000	1	1
	☐	6	100	Feasible	60000	24000	200000	1	0
	☐	8	100	Feasible	60000	12000	200000	1	1
	☐	12	100	Feasible	60000	12000	100000	2	1
	☐	13	100	Feasible	60000	24000	100000	2	0
	☐	15	100	Feasible	120000	12000	100000	1	1
	☐	16	100	Feasible	120000	12000	200000	2	0
	☐	18	100	Feasible	120000	24000	200000	2	0
	☐	20	100	Feasible	60000	12000	200000	2	1
	☐	21	100	Feasible	120000	12000	100000	2	1
	☐	22	100	Feasible	60000	12000	200000	0	0
	☐	24	100	Feasible	60000	24000	200000	1	1
	☐	25	100	Feasible	120000	24000	200000	1	0
	☐	28	100	Feasible	60000	12000	200000	2	0
	☐	30	100	Feasible	60000	12000	200000	1	0
	☐	31	100	Feasible	120000	12000	100000	2	0
	☐	33	100	Feasible	120000	12000	200000	0	1
	☐	34	100	Feasible	60000	12000	100000	2	0
	☐	36	100	Feasible	60000	24000	100000	0	1

Table 6.8 Best Strategies to Maximize RL.2.2 Performance in Disruption Scenario 1

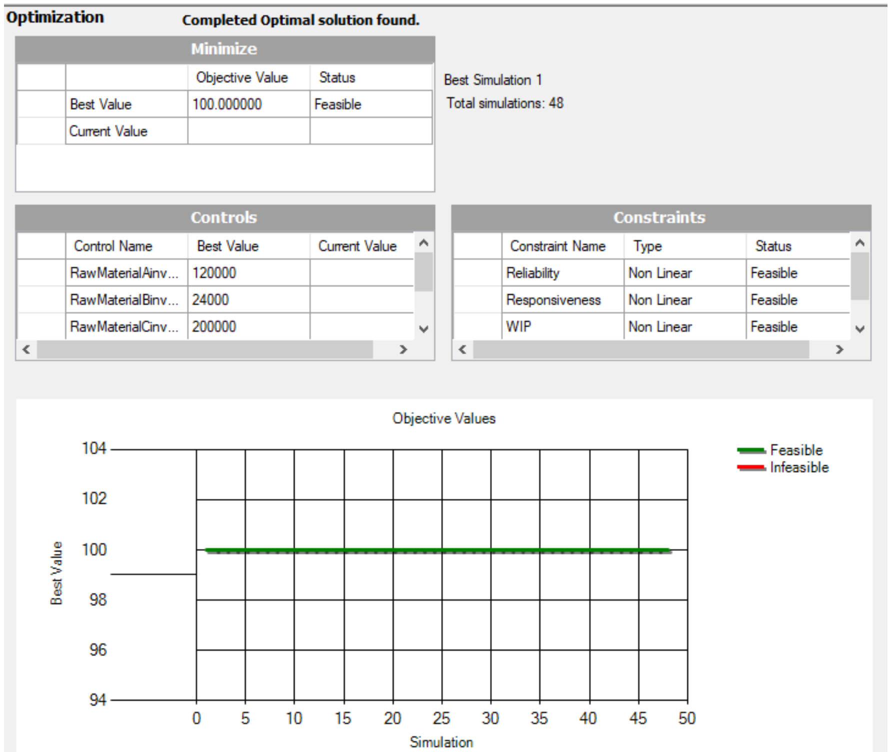

Figure 6.3 Optimal Solution to Maximize RL.2.2 Performance in Disruption Scenario 1

6.2.2.1.4 Minimize Order Fulfillment Cycle Time (RS.1.1)

As shown in Table 6.9, for RS.1.1 out of 25 feasible results, the optimal value is 11.41 days. To achieve this value, the inventory control policy is changed to (s, S), an alternative supplier is considered for raw material A, and the inventory level of raw materials A and is increased by 100% (Figure 6.4).

Best Solutions **Optimal solution found.**

Included	Simulation	Objective Value	Status	awMaterialAinvento	awMaterialBinvento	awMaterialCinvento	Supplier A Multiple	Variable
☑	15	11.41932	Feasible	120000	12000	100000	1	1
☐	30	11.994236	Feasible	60000	12000	200000	2	1
☐	16	12.539374	Feasible	120000	12000	100000	2	1
☐	12	12.616999	Feasible	60000	12000	100000	2	1
☐	3	13.000708	Feasible	120000	24000	200000	2	1
☐	29	13.044749	Feasible	60000	12000	100000	1	1
☐	37	13.129797	Feasible	120000	24000	100000	1	1
☐	8	13.163963	Feasible	60000	12000	200000	1	1
☐	13	13.367963	Feasible	60000	24000	100000	2	0
☐	33	13.891859	Feasible	120000	24000	200000	1	0
☐	48	14.116716	Feasible	120000	24000	100000	2	1
☐	28	14.327087	Feasible	60000	24000	200000	1	1
☐	6	14.547284	Feasible	60000	24000	200000	1	0
☐	5	15.382604	Feasible	60000	24000	100000	1	1
☐	21	15.728195	Feasible	60000	12000	100000	2	0
☐	32	15.872802	Feasible	60000	24000	100000	0	1
☐	25	16.363566	Feasible	120000	12000	200000	2	1
☐	35	16.53828	Feasible	120000	12000	200000	1	1
☐	36	17.066994	Feasible	60000	12000	200000	2	0
☐	1	18.235098	Feasible	120000	24000	200000	1	1
☐	17	19.314813	Feasible	120000	12000	200000	2	0
☐	40	19.467617	Feasible	120000	12000	100000	2	0
☐	4	19.577191	Feasible	60000	12000	100000	1	0
☐	43	19.800438	Feasible	60000	12000	100000	0	1
☐	42	20.242672	Feasible	120000	12000	200000	0	1

Table 6.9 Best Strategies to Minimize Order Fulfillment Cycle Time in Scenario 1

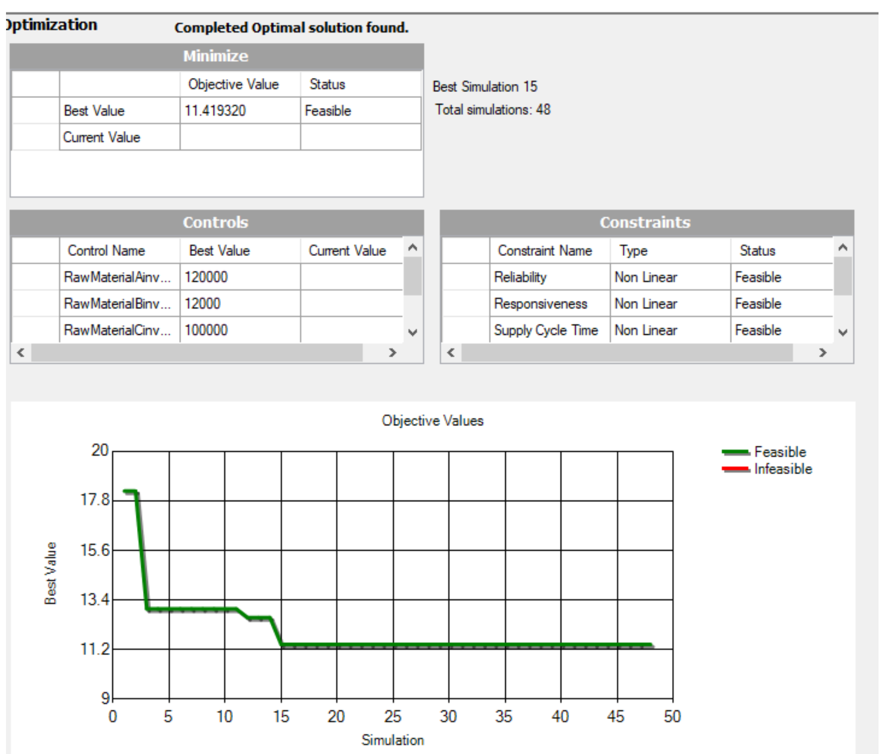

Figure 6.4 Optimal Solution to Minimize Order Fulfillment Cycle Time in Scenario 1

6.2.2.1.5 Minimize Average Supply Orders Cycle Time

As shown in Table 6.10, the optimal value is 278.07 days out of all feasible results to minimize the average supply cycle time. To achieve this value, in addition to the change inventory control policy to (s, S), the inventory level of raw materials A and C are increased by 100% (Figure 6.5).

Best Solutions — Optimal solution found.

Included	Simulation	Objective Value	Status	awMaterialAinventor	awMaterialBinventor	awMaterialCinventor	Supplier A Multiple	Variable
☑	28	278.077136	Feasible	120000	12000	200000	0	1
☐	31	282.115487	Feasible	120000	12000	200000	1	1
☐	5	286.416356	Feasible	60000	24000	100000	1	1
☐	30	286.570418	Feasible	120000	12000	100000	2	0
☐	34	287.570782	Feasible	120000	12000	100000	2	1
☐	15	287.662434	Feasible	120000	12000	100000	1	1
☐	11	288.417939	Feasible	60000	24000	200000	0	1
☐	22	288.683909	Feasible	120000	24000	100000	2	1
☐	1	288.768504	Feasible	120000	24000	200000	1	1
☐	12	288.901087	Feasible	60000	12000	100000	2	1
☐	4	289.350697	Feasible	60000	12000	100000	1	0
☐	33	289.458206	Feasible	60000	24000	100000	0	1
☐	3	291.057327	Feasible	120000	24000	200000	2	1
☐	41	291.074528	Feasible	60000	12000	200000	2	0
☐	46	291.091524	Feasible	60000	12000	100000	0	1
☐	44	291.341889	Feasible	60000	12000	200000	0	0
☐	8	291.506849	Feasible	60000	12000	200000	1	1
☐	17	291.7262	Feasible	60000	24000	100000	2	1
☐	21	291.792979	Feasible	60000	12000	200000	2	1
☐	18	292.311707	Feasible	60000	24000	200000	1	1
☐	37	292.598516	Feasible	120000	12000	200000	2	1
☐	36	292.820865	Feasible	60000	12000	100000	2	0
☐	13	292.877752	Feasible	60000	24000	100000	2	0
☐	32	293.148331	Feasible	60000	12000	100000	1	1
☐	19	293.304264	Feasible	120000	24000	100000	1	1

Table 6.10 Best Strategies to Minimize Supply Cycle Time in Disruption Scenario 1

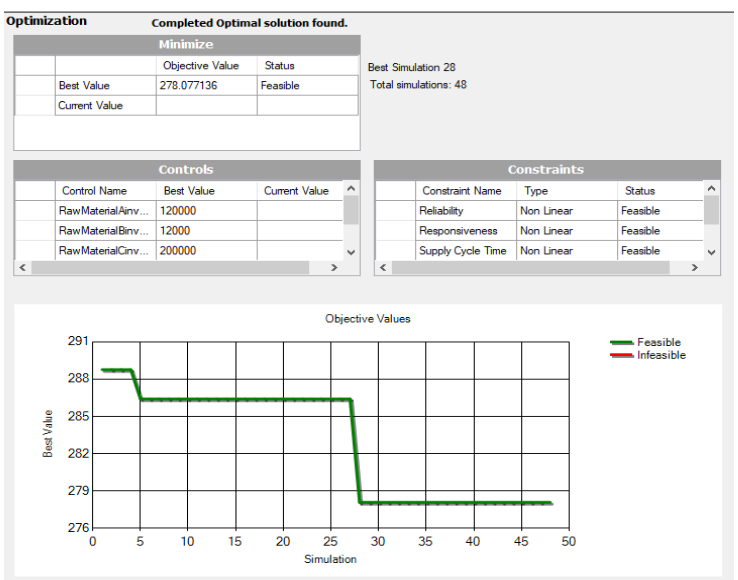

Figure 6.5 Optimal Solution to Minimize Supply Cycle Time in Disruption Scenario 1

6.2.2.1.6 Summary for Disruption Scenario 1 Analysis

Table 6.11 represents the summary of the best solutions based on optimal values of each objective function. The CEO of Luxxeen reviews this table, and considering managerial aspects, the following combination of risk mitigation strategies are selected to make a resilient supply chain during disruption scenario 1.

Key Performance Indicator	Objective Value	Raw Material A Inventory level	Raw Material B Inventory Level	Raw Material C Inventory Level	Multiple Sourcing (0 or 1 or 2) Alternatives	Inventory Control Policy (r, Q) = 0 (s, S) = 1
Work In Process	13	60000	12000	200000	1	1
Total Number Of Delivered Orders in Committed Time	902	60000	12000	100000	1	0
Delivery Performance to Customer Committed Date (RL.2.2)	100	60000	12000	100000	0	0
Order Fulfillment Cycle Time (RS.1.1)	11.41932	120000	12000	100000	1	1
Average Supply Orders Cycle Time	278.077136	120000	12000	200000	0	1

Table 6.11 Optimized Values for Disruption Scenario 1

Based on the analysis, the best solution is to apply the following combination of risk mitigation strategies to make the resilient SC during the first disruption scenario:

1. Multiple Sourcing with one alternative Supplier:
    - 50% supplier 1 for Raw Material A (Current Supplier)
    - 50% 1st Alternative Supplier for Raw Material A

2. Change Inventory Control Policy to (s, S)
3. Buffering:
    - Raw Material A Inventory Level: 100% Increase
    - Raw Material B Inventory Level: Same
    - Raw Material C Inventory Level: 100% Increase

6.2.2.2 Analysis for Disruption Scenario 2:

COVID-19 Pandemic outbreak propagates into transportation network resulted in 100% increase in delivery time from raw material A, B, and C suppliers.

Number	Disruption Scenario	Mitigation Strategy	Responses						
			Delivery Performance to Customer Commit Date (RL.2.2)	Order Fulfillment Cycle Time (RS.1.1)	Total Number Of Delivered Orders in Committed Time	Total Number Of Delivered Orders	Work In Process	Total Number of Accepted Purchase Orders	Average Supply Orders Cycle Time
1	Current State Model No Disruption	-	74.1	38.29	623.64	836.37	80.57	841.23	292.98
2	Disruption Scenario 2	-	38.65	81.27	285.81	726.06	185.6	835.99	290.24
3	Disruption Scenario 2	Multiple Sourcing - 50% supplier 1 RM A- 50% 1st Alternative Supplier RM A -0% 2nd Alternative Supplier RM A	63.51	46.03	522.45	815.23	95.46	836.02	292.37
4	Disruption Scenario 2	Multiple Sourcing - 33% supplier 1 RM A- 33% 1st Alternative Supplier RM A - 33% 2nd Alternative Supplier RM A	81.45	32.64	698.98	851.69	61.23	836.78	292.58
5	Disruption Scenario 2	Changing the Inventory Control Policy from (r, Q) to (s, S)	70.5	37.25	606.67	853.98	59.39	836.42	291.92
6	Disruption Scenario 2	Buffering Raw Materials Inventory by 100% Increase in Inventory Level	40.44	77.64	299.08	733.05	179.7	836.63	291.99

Table 6.12 Disruption Scenario 2 and Three Risk Mitigation Strategies

As presented in Table 6.12, risk mitigation strategies are tested in disruption scenarios 2. The optimum results are achieved by adding two suppliers when each fulfils 33% of SOs. For instance, RL.2.2 and total numbers of delivered orders in committed time would reach, on average to 81.45% and 698.98 POs, respectively. Moreover, RS.1.1 and WIP are fallen to 32.64 days and 61.23 POs on average.

Changing control policy to (s, S) is considered as the second-best strategy during the 2nd disruption scenario. For instance, RS.1.1 and WIP decrease to 37.25 days and 59.39 purchase orders, respectively. Likewise, as a result, RL.2.2 and total numbers of delivered orders in committed time rise to 70.5% and 606.67 POs on average, respectively. However, other contingency plans (i.e., add one alternative source and buffering) cannot meet resilient SC acceptance criteria. As the same as risk mitigation strategies in disruption scenario 1, using only one strategy at a time is not the optimized solution, and it should be combined with other strategies to make resilient SC. Lastly, after doing analysis using "OptQuest for Arena," optimal objective values and corresponding selected strategies are presented.

6.2.2.2.1 Summary for Disruption Scenario 2 Analysis

Table 6.13 is reviewed by the CEO of Luxxeen, and considering managerial aspects, the following combination of risk mitigation strategies are selected to make a resilient supply chain during disruption scenario 2.

Key Performance Indicator	Objective Value	Raw Material A Inventory level	Raw Material B Inventory Level	Raw Material C Inventory Level	Multiple Sourcing (0 or 1 or 2) Alternatives	Inventory Control Policy (r, Q) = 0 (s, S) = 1
Total Number Of Delivered Orders in Committed Time	942	120000	12000	200000	1	1
Order Fulfillment Cycle Time (RS.1.1)	12.295817	60000	12000	200000	1	1
Work In Process	13	120000	12000	100000	1	1
Average Supply Orders Cycle Time	278.738631	120000	12000	200000	0	1
Delivery Performance to Customer Committed Date (RL.2.2)	100	60000	12000	100000	0	1

Table 6.13 Optimized Values for Disruption Scenario 2

Based on the analysis, the best solution is to apply the following combination of risk mitigation strategies to make the resilient SC during the 2nd disruption scenario:

1. Change Inventory Control Policy to (s, S)
2. Multiple Sourcing with one alternative Supplier:
    - 50% supplier 1 RM A
    - 50% 1st Alternative Supplier RM A
3. Buffering
    - Raw Material A Inventory Level: 100% Increase
    - Raw Material B Inventory Level: Same
    - Raw Material C Inventory Level: 100% Increase

6.2.2.3 Analysis for Disruption Scenario 3

In this scenario, in addition to disruption scenarios 1 and 2, simultaneous disturbances in supply, logistics infrastructure, and market results in a 100% increase in final product demand for 30 days immediately after disruption scenario two occurrence on day 180.

Number	Disruption Scenario	Mitigation Strategy	Responses						
			Delivery Performance to Customer Commit Date (RL.2.2)	Order Fulfillment Cycle Time (RS.1.1)	Total Number Of Delivered Orders in Committed Time	Total Number Of Delivered Orders	Work In Process	Total Number of Accepted Purchase Orders	Average Supply Orders Cycle Time
1	Current State Model No Disruption	-	74.1	38.29	623.64	836.37	80.57	841.23	292.98
2	Disruption Scenario 3	-	31.4	107.67	218.82	692.13	334.9	952	289.5
3	Disruption Scenario 3	Multiple Sourcing - 50% supplier 1 RM A- 50% 1st Alternative Supplier RM A -0% 2nd Alternative Supplier RM A	50.25	65.85	415.38	814.45	212.6	952	291.39
4	Disruption Scenario 3	Multiple Sourcing - 33% supplier 1 RM A- 33% 1st Alternative Supplier RM A - 33% 2nd Alternative Supplier RM A	63.78	51.9	561.07	867.27	159.7	952	291.72
5	Disruption Scenario 3	Changing the Inventory Control Policy from (r, Q) to (s, S)	52.09	62.74	447.11	839.9	187.1	952	292.12
6	Disruption Scenario 3	Buffering Raw Materials Inventory by 100% Increase in Inventory Level	37.21	100.11	261.37	699.44	327.6	952	289.91

Table 6.14 Disruption Scenario 3 and Three Risk Mitigation Strategies

As presented in Table 6.14, the same risk mitigation strategies are tested in disruption scenarios 3 in the same way as scenarios 1 and 2. This scenario is considered the worst-case scenario, and each contingency plan cannot individually mitigate the disruption effects. The best results are achieved when two alternative suppliers fulfil 66% of SOs for raw material A. Moreover, work in process is decreased by 47% to 159.72 POs, but this value is two times greater than the acceptance criteria. Besides, the order fulfillment cycle time decreased to 32.66 days. Delivery performance to customer commit date is increased only to 63.78%, which is not acceptable. Lastly, the total number of delivered orders in committed time reaches 561.07 out of 952 accepted orders which is almost 60%.

6.2.2.3.1 Minimize Work in Process

As shown in Table 6.15, the software can only suggest five solutions considered feasible out of 25 possible solutions for a resilient supply chain. As shown in Figure 6.6, the optimal value is 41 POs on average for the WIP performance metric. To attain this value, the inventory control policy must be changed to (s, S), two alternative suppliers are considered for raw material A and the inventory level of raw materials A and C are doubled.

Best Solutions **Optimal solution found.**

Included	Simulation	Objective Value	Status	awMaterialAinventor	awMaterialBinventor	awMaterialCinventor	Supplier A Multiple	Variable
☑	37	41	Feasible	60000	24000	200000	2	1
☐	21	52	Feasible	120000	12000	200000	2	1
☐	12	55	Feasible	60000	12000	100000	2	1
☐	35	63	Feasible	120000	24000	100000	2	1
☐	38	63	Feasible	60000	12000	100000	1	1
☐	44	55	Infeasible	60000	12000	200000	2	0
☐	17	44	Infeasible	60000	24000	200000	1	1
☐	3	63	Infeasible	120000	24000	200000	2	1
☐	1	57	Infeasible	120000	24000	200000	1	1
☐	11	57	Infeasible	60000	24000	200000	0	1
☐	32	73	Infeasible	120000	12000	100000	1	1
☐	40	77	Infeasible	120000	12000	100000	2	1
☐	26	88	Infeasible	60000	12000	200000	2	1
☐	31	93	Infeasible	60000	12000	200000	1	0
☐	41	56	Infeasible	120000	12000	200000	1	1
☐	23	98	Infeasible	120000	24000	100000	1	1
☐	15	109	Infeasible	60000	24000	100000	2	1
☐	8	48	Infeasible	60000	12000	200000	1	1
☐	4	135	Infeasible	60000	12000	100000	1	0
☐	24	152	Infeasible	120000	24000	200000	0	1
☐	5	132	Infeasible	60000	24000	100000	1	1
☐	18	94	Infeasible	120000	24000	200000	1	0
☐	33	135	Infeasible	60000	12000	100000	0	1
☐	28	130	Infeasible	120000	24000	200000	2	0
☐	43	121	Infeasible	60000	12000	100000	2	0

Table 6.15 Best Strategies Minimize WIP in Disruption Scenario 3

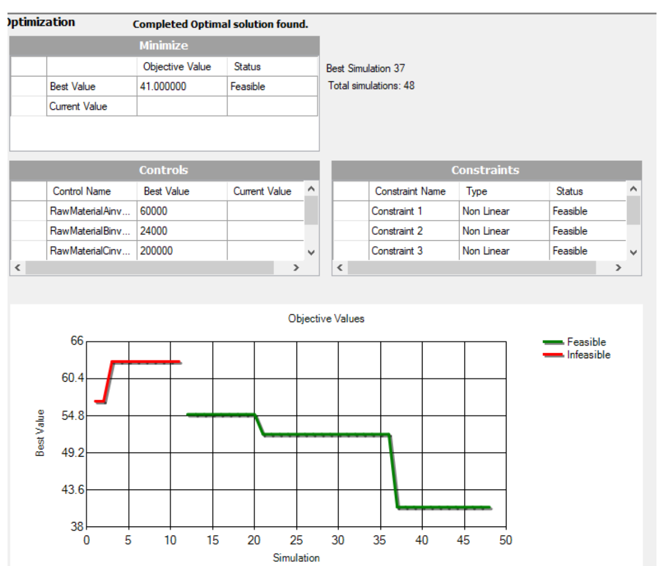

Figure 6.6 Optimal Solution to Minimize WIP in Disruption Scenario 3

6.2.2.3.2 Minimize Average Supply Orders Cycle Time

As shown in Table 6.16Table 6.10, to minimize average supply cycle time, out of 5 feasible results, the optimal value is 291.36 days. To attain this value, the inventory control policy must be changed to (s, S), two alternative suppliers are considered for raw material A and the inventory level of raw materials B and C are doubled (Figure 6.7).

Best Solutions **Optimal solution found.**

Best Solutions								
Included	Simulation	Objective Value	Status	awMaterialAinventor	awMaterialBinventor	awMaterialCinventor	Supplier A Multiple	Variable
☑	38	291.369883	Feasible	60000	24000	200000	2	1
☐	12	292.555927	Feasible	60000	12000	100000	2	1
☐	43	292.710495	Feasible	120000	24000	100000	2	1
☐	16	293.796972	Feasible	60000	12000	100000	1	1
☐	20	294.449623	Feasible	120000	12000	200000	2	1
☐	47	295.235532	Infeasible	60000	12000	200000	2	0
☐	17	295.6237	Infeasible	60000	24000	200000	1	1
☐	3	296.511655	Infeasible	120000	24000	200000	2	1
☐	1	297.9007	Infeasible	120000	24000	200000	1	1
☐	11	298.828722	Infeasible	60000	24000	200000	0	1
☐	44	290.281522	Infeasible	120000	12000	100000	1	1
☐	29	290.418028	Infeasible	120000	12000	100000	2	1
☐	30	293.995989	Infeasible	60000	12000	200000	2	1
☐	21	297.929217	Infeasible	60000	12000	200000	1	0
☐	33	291.860007	Infeasible	120000	12000	200000	1	1
☐	34	293.826758	Infeasible	120000	24000	100000	1	1
☐	15	292.659428	Infeasible	60000	24000	100000	2	1
☐	8	288.625214	Infeasible	60000	12000	200000	1	1
☐	4	295.154114	Infeasible	60000	12000	100000	1	0
☐	27	294.858348	Infeasible	120000	24000	200000	0	1
☐	5	294.696984	Infeasible	60000	24000	100000	1	1
☐	46	297.450508	Infeasible	120000	24000	200000	1	0
☐	40	292.215582	Infeasible	60000	12000	100000	0	1
☐	42	299.710655	Infeasible	120000	24000	200000	2	0
☐	26	294.080676	Infeasible	60000	12000	100000	2	0

Table 6.16 Best Strategies to Minimize Supply Cycle Time in Disruption Scenario 3

Figure 6.7 Optimal Solution to Minimize Supply Cycle Time in Disruption Scenario 3

6.2.2.3.3 Maximize Total Number of Delivered Orders in Committed Time

As shown in Table 6.17, the optimal value as the "Total Number of Delivered Orders in Committed Time" is 986 POs, resulting from changing inventory control policy to (s, S). To attain this value, the inventory control policy is changed to (s, S), two alternative suppliers are considered for raw material A and the inventory level of raw materials B and C are increased by 100% (Figure 6.8).

Best Solutions Optimal solution found.

Included	Simulation	Objective Value	Status	awMaterialAinventoı	awMaterialBinventoı	awMaterialCinventoı	Supplier A Multiple	Variable
☑	17	986	Feasible	60000	24000	200000	2	1
☐	22	975	Feasible	120000	12000	200000	2	1
☐	12	972	Feasible	60000	12000	100000	2	1
☐	16	964	Feasible	60000	12000	100000	1	1
☐	48	964	Feasible	120000	24000	100000	2	1
☐	44	972	Infeasible	60000	12000	200000	2	0
☐	18	983	Infeasible	60000	24000	200000	1	1
☐	3	964	Infeasible	120000	24000	200000	2	1
☐	1	970	Infeasible	120000	24000	200000	1	1
☐	11	970	Infeasible	60000	24000	200000	0	1
☐	43	954	Infeasible	120000	12000	100000	1	1
☐	36	950	Infeasible	120000	12000	100000	2	1
☐	30	939	Infeasible	60000	12000	200000	2	1
☐	20	934	Infeasible	60000	12000	200000	1	0
☐	32	373	Infeasible	120000	12000	200000	1	1
☐	21	929	Infeasible	120000	24000	100000	1	1
☐	15	918	Infeasible	60000	24000	100000	2	1
☐	8	324	Infeasible	60000	12000	200000	1	1
☐	4	772	Infeasible	60000	12000	100000	1	0
☐	25	875	Infeasible	120000	24000	200000	0	1
☐	5	673	Infeasible	60000	24000	100000	1	1
☐	34	351	Infeasible	120000	24000	200000	1	0
☐	35	667	Infeasible	60000	12000	100000	0	1
☐	23	329	Infeasible	120000	24000	200000	2	0
☐	26	426	Infeasible	60000	12000	100000	2	0

Table 6.17 Best Strategies to Maximize Delivered Orders in Disruption Scenario 3

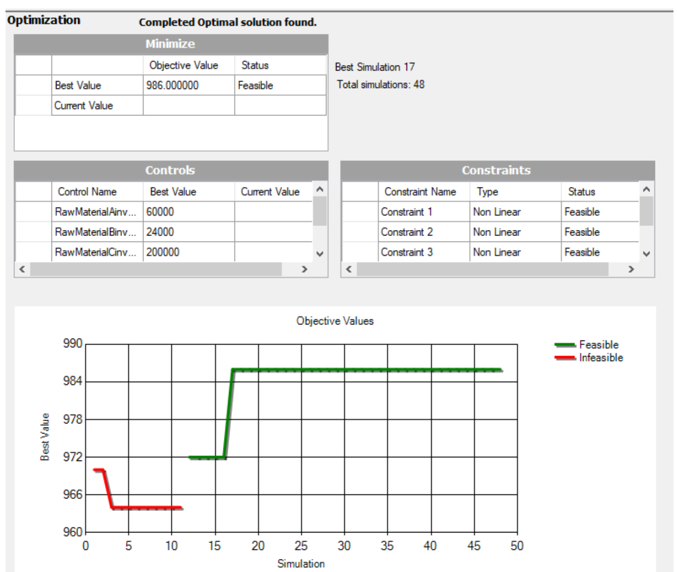

Figure 6.8 Optimal Solution to Maximize Delivered Orders in Disruption Scenario 3

6.2.2.3.4 Minimize Order Fulfillment Cycle Time (RS.1.1)

As shown in Table 6.18, the minimum order fulfillment cycle time equals 14.23 days on average. To get this vale, the inventory control policy is changed to (s, S), two alternative suppliers are considered for raw material A and inventory level of raw materials A, B, and C is increased by 100% (Figure 6.9).

Best Solutions Optimal solution found.

Included	Simulation	Objective Value	Status	awMaterialAinventoı	awMaterialBinventoı	awMaterialCinventoı	Supplier A Multiple	Variable
☑	24	14.239196	Feasible	120000	12000	200000	2	1
☐	16	15.235684	Feasible	60000	12000	100000	1	1
☐	12	19.916773	Feasible	60000	12000	100000	2	1
☐	39	22.462482	Feasible	120000	24000	100000	2	1
☐	23	23.990467	Feasible	60000	24000	200000	2	1
☐	37	23.37982	Infeasible	60000	12000	200000	2	0
☐	17	24.505876	Infeasible	60000	24000	200000	1	1
☐	3	16.465276	Infeasible	120000	24000	200000	2	1
☐	1	20.113296	Infeasible	120000	24000	200000	1	1
☐	11	31.112153	Infeasible	60000	24000	200000	0	1
☐	27	23.110817	Infeasible	120000	12000	100000	1	1
☐	34	16.238844	Infeasible	120000	12000	100000	2	1
☐	31	18.097001	Infeasible	60000	12000	200000	2	1
☐	40	25.643462	Infeasible	60000	12000	200000	1	0
☐	43	34.000201	Infeasible	120000	12000	200000	1	1
☐	30	26.894	Infeasible	120000	24000	100000	1	1
☐	15	24.255487	Infeasible	60000	24000	100000	2	1
☐	8	48.409929	Infeasible	60000	12000	200000	1	1
☐	4	37.925135	Infeasible	60000	12000	100000	1	0
☐	36	29.863947	Infeasible	120000	24000	200000	0	1
☐	5	47.156589	Infeasible	60000	24000	100000	1	1
☐	29	49.328834	Infeasible	120000	24000	200000	1	0
☐	18	47.104224	Infeasible	60000	12000	100000	0	1
☐	19	44.442665	Infeasible	120000	24000	200000	2	0
☐	26	50.640525	Infeasible	60000	12000	100000	2	0

Table 6.18 Best Strategies to Minimize Order Fulfillment Cycle Time in Scenario 3

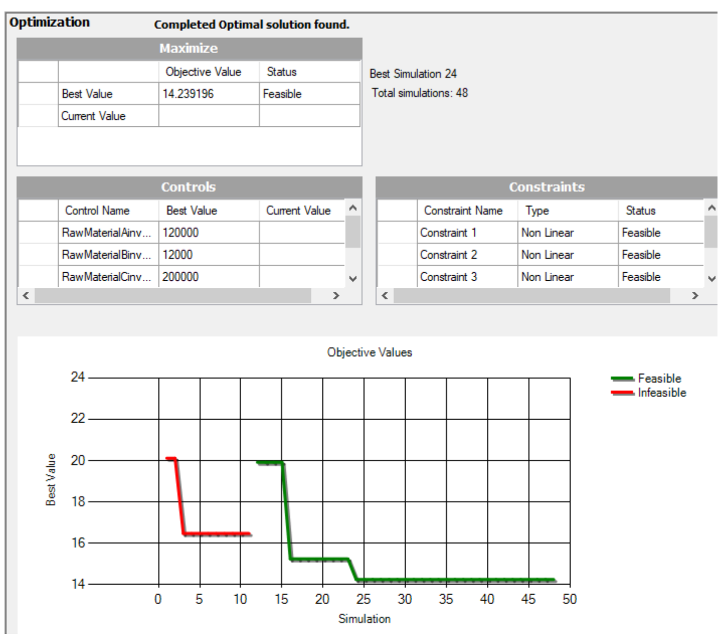

Figure 6.9 Optimal Solution to Minimize Order Fulfillment Cycle Time in Scenario 3

6.2.2.3.5 Maximize Delivery Performance to Customer Commit Date (RL.2.2)

As shown in Table 6.19, to maximize “Delivery Performance to Customer Commit Date” and get the optimal value (100%), the inventory control policy is changed to (s, S), two alternative suppliers are considered for raw material A and inventory level of raw materials B and C are increased by 100% (Figure 6.10).

Best Solutions **Optimal solution found.**

Best Solutions

	Included	Simulation	Objective Value	Status	awMaterialAinventor	awMaterialBinventor	awMaterialCinventor	Supplier A Multiple	Variable
	☐	12	100	Feasible	60000	12000	100000	2	1
▸	☑	16	100	Feasible	60000	12000	100000	1	1
	☐	24	100	Feasible	60000	24000	200000	2	1
	☐	25	100	Feasible	120000	12000	200000	2	1
	☐	40	100	Feasible	120000	24000	100000	2	1
	☐	38	100	Infeasible	60000	12000	200000	2	0
	☐	18	100	Infeasible	60000	24000	200000	1	1
	☐	3	100	Infeasible	120000	24000	200000	2	1
	☐	1	100	Infeasible	120000	24000	200000	1	1
	☐	11	100	Infeasible	60000	24000	200000	0	1
	☐	28	100	Infeasible	120000	12000	100000	1	1
	☐	35	100	Infeasible	120000	12000	100000	2	1
	☐	32	100	Infeasible	60000	12000	200000	2	1
	☐	41	100	Infeasible	60000	12000	200000	1	0
	☐	45	38.414006	Infeasible	120000	12000	200000	1	1
	☐	31	100	Infeasible	120000	24000	100000	1	1
	☐	15	100	Infeasible	60000	24000	100000	2	1
	☐	8	33.094995	Infeasible	60000	12000	200000	1	1
	☐	4	86.547085	Infeasible	60000	12000	100000	1	0
	☐	37	100	Infeasible	120000	24000	200000	0	1
	☐	5	75.195531	Infeasible	60000	24000	100000	1	1
	☐	30	37.620579	Infeasible	120000	24000	200000	1	0
	☐	19	74.775785	Infeasible	60000	12000	100000	0	1
	☐	20	36.677815	Infeasible	120000	24000	200000	2	0
	☐	27	47.019868	Infeasible	60000	12000	100000	2	0

Table 6.19 Best Strategies to Maximize Delivery Performance in Disruption Scenario 3

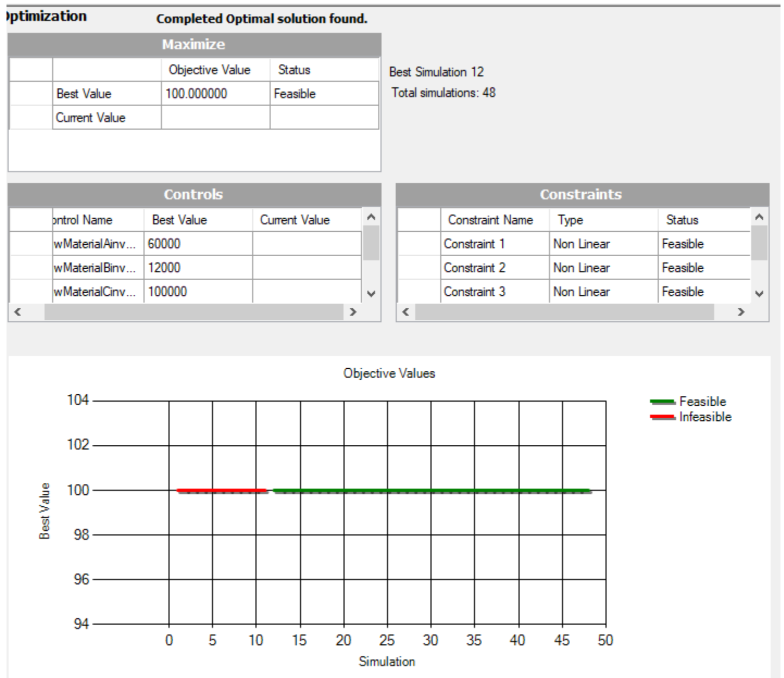

Figure 6.10 Optimal Solution to Maximize RL.2.2 Performance in Disruption Scenario 3

6.2.2.3.6 Summary for Disruption Scenario 3 Analysis

Table 6.20 also reviewed by the CEO of Luxxeen co. the following risk mitigation strategies are selected to make a resilient supply chain during disruption scenario 3 considering managerial aspects.

Key Performance Indicator	Objective Value	Raw Material A Inventory level	Raw Material B Inventory Level	Raw Material C Inventory Level	Multiple Sourcing (0 or 1 or 2) Alternatives	Inventory Control Policy (r, Q) = 0 (s, S) = 1
Work in Process	41	60000	24000	200000	2	1
Total Number Of Delivered Orders in Committed Time	986	60000	24000	200000	2	1
Delivery Performance to Customer Committed Date (RL.2.2)	100	60000	12000	100000	2	1
Order Fulfillment Cycle Time (RS.1.1)	15.235684	60000	12000	100000	1	1
Average Supply Orders Cycle Time	291.369883	60000	24000	200000	2	1

Table 6.20 Optimized Values for Disruption Scenario 3

Based on the analysis, the best solution is to apply the following combination of risk mitigation strategies to make the resilient SC during the 3rd disruption scenario:

1. Change Inventory Control Policy to (s, S)
2. Multiple Sourcing with two alternative Suppliers:
    - 33% supplier 1 RM A
    - 33% 1st Alternative Supplier RM A
    - 33% 2nd Alternative Supplier RM A
3. Buffering
    - Raw Material A Inventory Level: Same
    - Raw Material B Inventory Level: 100% Increase
    - Raw Material C Inventory Level: 100% Increase

6.3 Best Solution

Finally, the best combination of strategies is selected based on the optimal answer, defined constraints, and final meeting with the CEO of Luxxeen co. Then using the process analyzer, these three selected scenarios are combined, and the optimal answer of each section is obtained (Table 6.21).

Number	Disruption Scenario	Mitigation Strategy	Responses						
			Delivery Performance to Customer Committed Date (RL.2.2)	Order Fulfillment Cycle Time (RS.1.1)	Total Number Of Delivered Orders in Committed Time	Total Number Of Delivered Orders	Work In Process	Total Number of Accepted Purchase Orders	Average Supply Orders Cycle Time
1	Current State Model - No Disruption	-	74.1	38.29	623.64	836.37	80.57	841.23	292.98
2	Disruption Scenario 1 Best Mitigation Strategies	**Multiple Sourcing** 50% supplier 1 RM A 50% 1st Alternative Supplier RM A **Buffering** 100% Increase in Inventory Level RM A Same Inventory Level RM B 100% Increase in Inventory Level RM C **Change the Inventory Control Policy** from (r, Q) to (s, S)	95.73	17.93	847.16	884.99	24.45	833.85	291.84
3	Disruption Scenario 2 Best Mitigation Strategies	**Multiple Sourcing** 50% supplier 1 RM A 50% 1st Alternative Supplier RM A **Buffering** 100% Increase in Inventory Level RM A Same Inventory Level RM B 100% Increase in Inventory Level RM C **Change the Inventory Control Policy** from (r, Q) to (s, S)	92.43	22.03	818.98	886.92	25.85	837.18	292.25
4	Disruption Scenario 3 Best Mitigation Strategies	**Multiple Sourcing** 33% supplier 1 RM A 33% 1st Alternative Supplier RM A 33% 2nd Alternative Supplier RM A **Buffering** Same Inventory Level RM A 100% Increase in Inventory Level RM B 100% Increase in Inventory Level RM C **Change the Inventory Control Policy** from (r, Q) to (s, S)	91.57	23.59	879.46	959.59	67.41	952	293.74

Table 6.21 The Best Risk Mitigation Strategies

Figure 6.11 presents the RL.2.2 key performance indicator values in various cases, including applying three disruption scenarios and then implementing risk mitigation strategies to create resiliency. As it is shown, the optimized values of this KPI in all three risk scenarios after implementing the best combination of the proposed solution scenarios (obtained from Table 6.21), for disruption scenarios 1, 2, and 3, are 95.73%, 92.43%, and 91.57% respectively, which all are more optimal than the initial value of 74.1%.

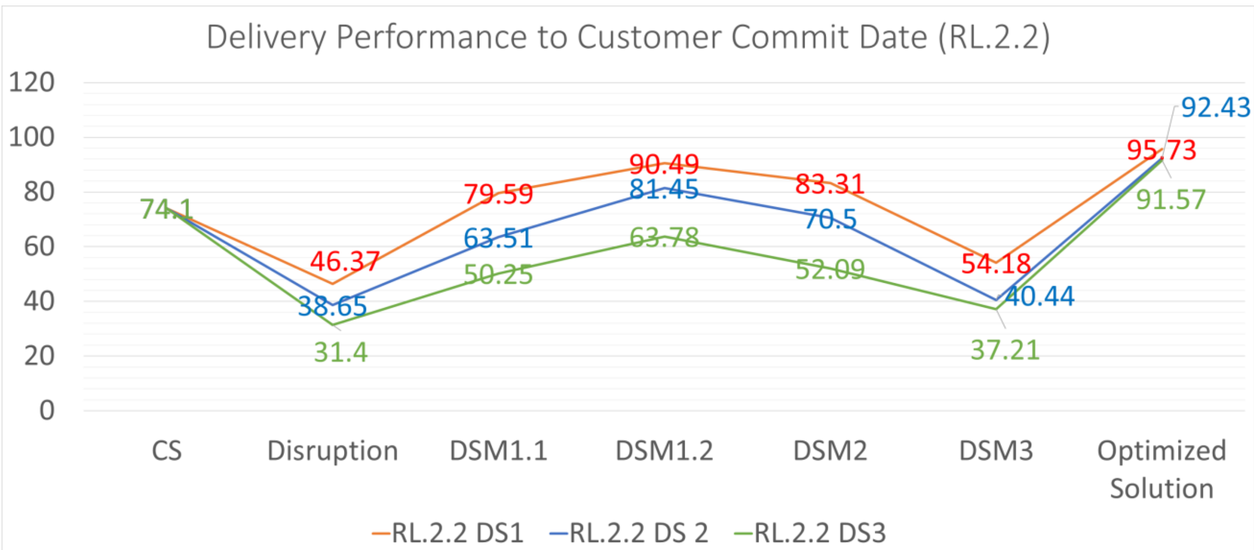

Figure 6.11 Delivery Performance to Customer Commit Date (RL.2.2) Line Chart

Figure 6.12 presents the RS.1.1 key performance indicator values in various cases, including applying three disruption scenarios and then implementing risk mitigation strategies to create resiliency. As is shown, the optimized values of this KPI in all three risk scenarios after implementing the best combination of the proposed solution scenarios (obtained from Table 6.21), for disruption scenarios 1, 2, and 3, are 17.93 days, 22.03 days, and 23.59 days in average respectively, which all are more optimal than the initial value of 38.29 days.

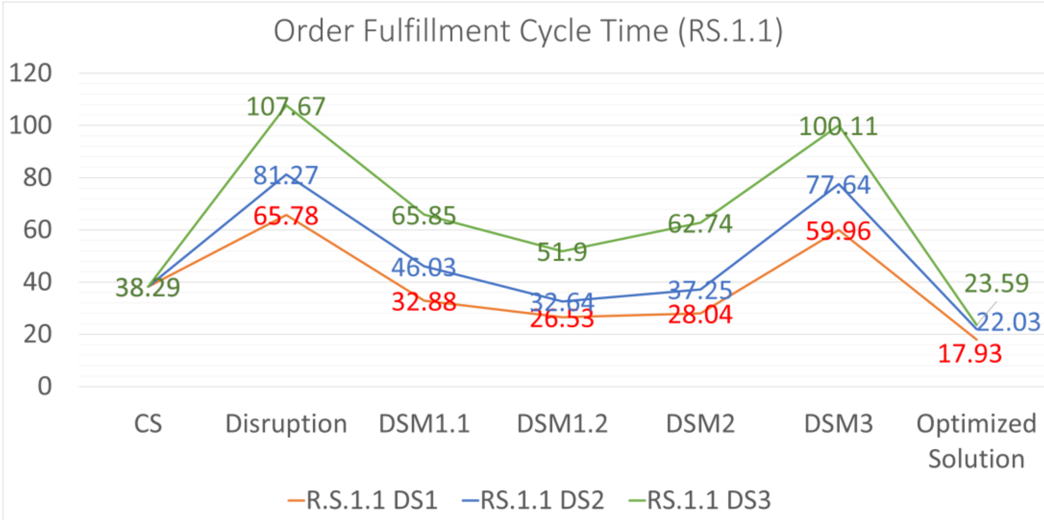

Figure 6.12 Order Fulfillment Cycle Time (RS.1.1) Line Chart

Figure 6.13 presents the total number of delivered orders in committed time values. As is shown, the optimized values of this KPI in all three risk scenarios after implementing the best combination of the proposed solution scenarios for disruption scenarios 1, 2, and 3 are 847.16 units, 818.98 units and 879.46 units on average, respectively, which all are more optimal than the initial value of 623.64 units.

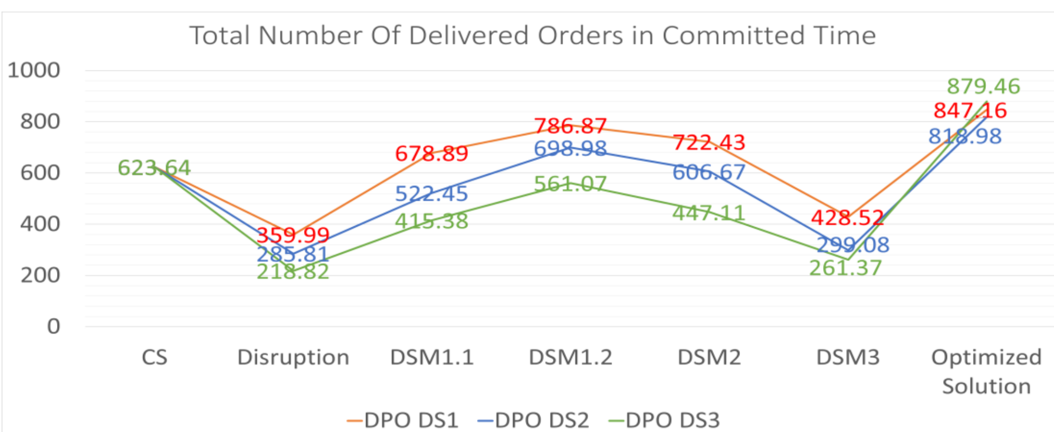

Figure 6.13 Total Number Of Delivered Orders in Committed Time Line Chart

Figure 6.14 presents the work in process performance metric values. As is shown, the optimized values of this KPI in all three risk scenarios after implementing the best combination of the proposed solution scenarios for disruption scenarios 1, 2, and 3 are 24.45 units, 25.85 units and 67.41 units on average, respectively, which all are more optimal than the initial value of 80.57 units.

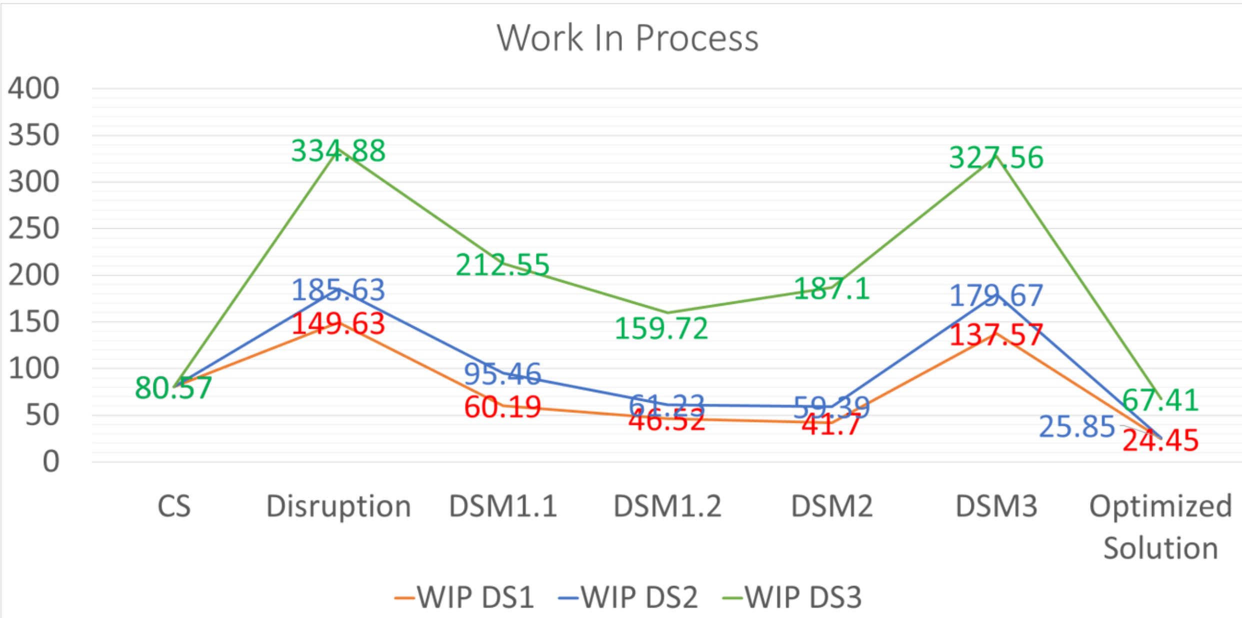

Figure 6.14 Work in Process Line Chart

Finally, the optimized solutions for each disruption scenarios are as followed:

Optimized Solution in Disruption Scenario 1:

- Multiple Sourcing
    - 50% supplier 1 RM A
    - 50% 1st Alternative Supplier RM A
- Buffering
    - 100% Increase in Inventory Level RM A
    - Same Inventory Level RM B

- 100% Increase in Inventory Level RM C

- Change the Inventory Control Policy
  - from (r, Q) to (s, S)

Optimized Solution in Disruption Scenario 2:

1. Multiple Sourcing
   - 50% supplier 1 RM A
   - 50% 1st Alternative Supplier RM A
2. Buffering
   - 100% Increase in Inventory Level RM A
   - Same Inventory Level RM B
   - 100% Increase in Inventory Level RM C
3. Change the Inventory Control Policy
   - from (r, Q) to (s, S)

Optimized Solution in Disruption Scenario 3:

1. Multiple Sourcing
   - 33% supplier 1 RM A
   - 33% 1st Alternative Supplier RM A
   - 33% 2nd Alternative Supplier RM A
2. Buffering
   - Same Inventory Level RM A
   - 100% Increase in Inventory Level RM B
   - 100% Increase in Inventory Level RM C
3. Change the Inventory Control Policy
   - from (r, Q) to (s, S)

6.4 System Verification and Validation

We started by modelling the fundamental processes of the Luxxeen company, after which, for every revision we created, we added other aspects of SC to the model. After the 14th revision, we were able to obtain a model that fully represented the current state of the Luxxeen company's SC.

Additionally, for every revision that was created, it was reviewed by the CEO of Luxxeen company. As our model was running, we observed the animations to detect errors and faulty logic in order to ensure that the model was working according to our expectations. Besides, PO and SO flows in SC can be easily tracked thanks to the graphical representation (Figure 6.15).

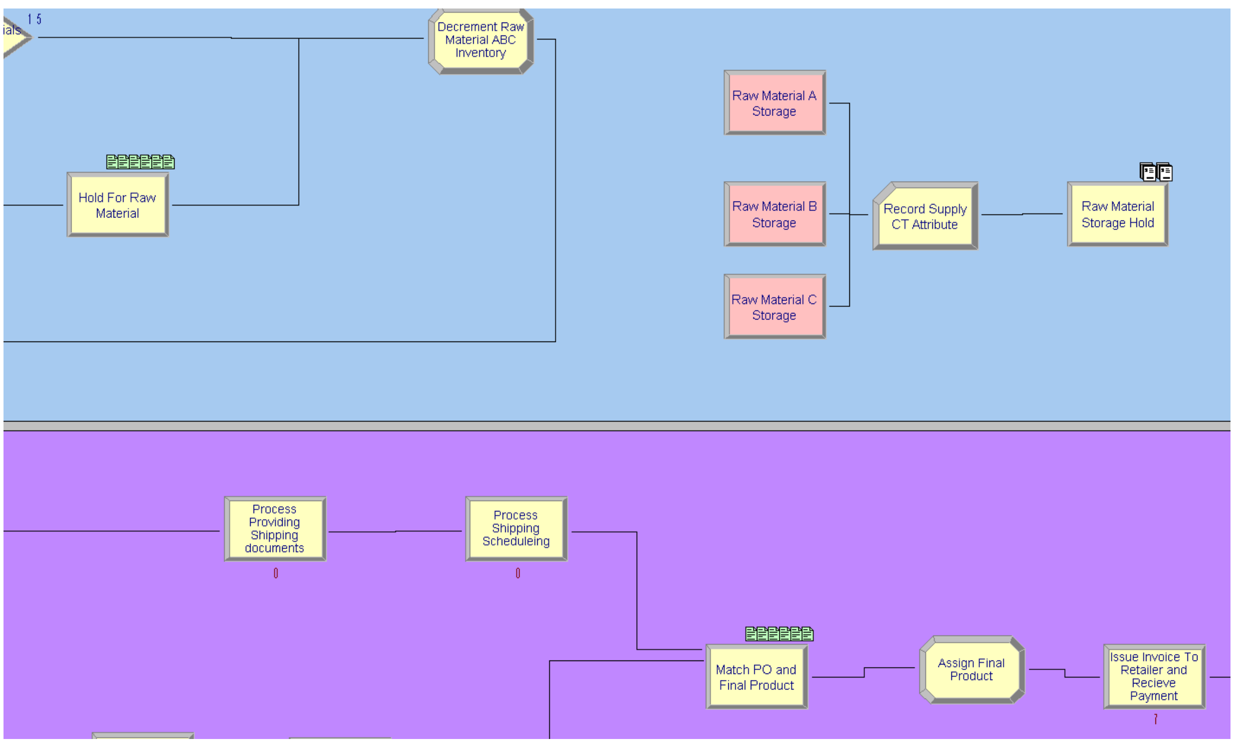

Figure 6.15 Verification by Graphical Representation

The case study outcomes analysis entails verifying that each Operation module execution's outputs match the values determined analytically. For example, we compared the average Order Fulfillment

Cycle Time using the Arena process analyzer and compared it with historical data provided by Luxxeen company and found the metric to be consistent and behaves as expected. Besides, as shown in Table 6.22, we applied different controls and checked responses accordingly.

No.	Scenarios	Replications	Order Fulfillment Cycle Time (Days)	Expectation	Verified?
1	Current State Model - NO DISRUPTION	120	37.7	Based on available historical data, the average expected time is almost 35 days	Yes
2	Current State Model - Doubled RM C inventory Level	120	31.56	By increasing in hand inventory, we expect the cycle time to decrease	Yes
3	Current State Model - Add Alternative Supplier 1	120	22.67	we expect the cycle time to drop	Yes

No.	Scenarios	Replications	Order Fulfillment Cycle Time (Days)	Expectation	Verified?
4	Current State Model - Change Inventory Control Policy	120	17.96	we expect the cycle time to decrease significantly	Yes
5	Disruption Scenario 1	120	65.78	we expect the cycle time to increase by almost 100%	Yes
6	Disruption Scenario 2	120	81.27	we expect the cycle time to increase by almost 100%	Yes
7	Disruption Scenario 3	120	107.67	we expect the cycle time to increase significantly due to double disruption	Yes

Table 6.22 Model Verification and Validation

We presented Luxxeen’s SC current state and alternative state models, including disruption scenarios and appropriate risk mitigation strategies, to Luxxeeen’s CEO and showed him our simulation study findings. We also observed the SC model's animations. He confirmed it behaves as expected and agreed that our outputs were valid and representative of reality considering assumptions and simplifications.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

The demand for a resilient supply chain has been growing in the last few years. The financial advantages of reduced stock levels and inventory buffers have made SCs more vulnerable to global LFHI disruption risk. Notably, by propagating the COVID-19 pandemic outbreak worldwide, numerous SCs, particularly essential products' SCs, have been put in danger of breakdown because of a sharp increase in demand and delay in raw materials supply. According to (Ivanov, 2020a) due to the COVID-19 pandemic, 94% of Fortune 1000 companies were severely disrupted.

This study introduced the methodological SC simulation modelling framework to make the resilient SC during disruption risk by visualizing the SC and facilitating SC managers make decisions in near real-time. The solution approach was applied in the Luxxeen Co., a Canadian manufacturer of green disposable products, i.e., Toilet Tissues.

In the first step, a detailed literature review was conducted to investigate current approaches to address global SC issues in terms of resiliency. We assessed different approaches for the four stages of SCRM: risk identification, risk assessment, risk mitigation, and risk monitoring. Later we reviewed recent literature on disruption risk, including the COVID-19 pandemic outbreak. We also studied SC descriptive and quantitative approaches. Afterward, the SCOR model's description and its application in SCRM as the descriptive approach are presented in detail. Also, current simulation techniques and their application in SCRM were investigated.

Additionally, we investigated resilient SC modelling studies in-depth and identified key performance for RSCs. Besides, the digital SC twins approach in recent literature is reviewed. Gaps and limitations of the current research were illustrated to highlight the need for a methodological SC simulation modelling framework to create resiliency in SCs.

Later, a detailed explanation of the solution approach was provided. To do so, we developed a methodological framework including six phases, namely, model conceptualization, input analysis, simulation modelling, verification and validation, resilient SC modelling, and experiment the model.

First, we developed SC's structural and behavioural conceptual model by customizing the SCOR reference model. We identify the SC operation based on the plan, source, make, and deliver standard SCOR model processes. We also adapt the SCOR performance library to get the proper performance metrics to ensure resiliency in terms of reliability and responsiveness. Afterward, we included the COVID-19 pandemic outbreak disruption risk in the conceptual model and designed three scenarios accordingly for suppliers, transportation networks, and retailers.

Second, we performed input analysis in terms of data collection and fit input distribution using arena input analyzer and MS excel. Afterward, we translated the conceptual model to Discrete Event Simulation formalist by providing a step-by-step translation algorithm and implementing it using the "Arena simulation software" platform. Furthermore, we ran the model by random inputs and simplified assumptions and compared each time using animation in order to verify the model. Likewise, each step of the project's findings was reviewed by the Luxeen' CEO and compared with the company's available historical data to validate the model. Later the acceptance criteria to ensure resiliency were defined. Besides, "Multiple Sourcing," "Changing Inventory Control Policy," and "Buffering" are suggested as the risk mitigation strategies to have the resilient SC.

Third, we applied the duration distribution for each SC operation and implemented risk scenarios by modifying the main model. Also, we implemented three risk mitigation strategies by modifying the model as well. Then we ran the model for two years with 120 replications and considering 60 days as the warmup period. Finally, using the “Process Analyzer” and “OptQuest for Arena” tools, we conduct the comparison analysis to get the optimal solution during each disruption scenario. Based on the analysis, the optimal solutions and our recommendations to Luxxeen Co. are as follows:

To mitigate the first disruption scenario:

- A new alternative supplier should be added in order to fulfill 50% of raw material A supply orders. Additionally, inventory control policy must be changed to (s, S), and raw materials A and C inventory level must be increased as the buffer.

To mitigate the second disruption scenario:

- Similar to scenario 1, a new alternative supplier should be added to fulfill 50% of raw material A supply orders. Additionally, inventory control policy should be changed to (s, S), and raw materials A and C inventory level must be increased as the buffer.

To mitigate the third disruption scenario:

two new alternative suppliers should be added, and each alternative supplier should fulfill 33% of raw material A supply orders. Additionally, inventory control policy should be changed to (s, S), and raw materials B and C inventory level should be increased as the buffer.

Moreover, based on the literature, the other approaches should be considered.

According to (Harvard Business Review, 2020) SC practitioners would re-design SC structure and considered backup suppliers locally. Also, to maximize demand satisfaction, (Paul & Chowdhury, 2020b) suggested changing the packing and quality of products. The company can replace other products with toilet paper and decrease the minimum order quantity for retailers. Additionally, another framework can visualize the simulation and enable the SC practitioner to monitor the SC. Moreover, as a part of social responsibility, other products can e replace by mask production line.

7.2 Research Contributions

Key contributions of the research are:

- We established a methodological framework for SC simulation modelling to make the resilient digital SC twin during the COVID-19 pandemic outbreak disruption risk specifically for essential and most wanted products in 6 steps.
- The COVID-19 pandemic outbreak risk is new to the literature and recently defined as the specific kind of disruption risk which starts small, slowly and slightly but propagates all over the supply chain and lasts for a long time, disrupting performance metrics significantly. It is considered as the 2nd contribution in this study.
- This study's primary focus is on non-financial performance metrics, and due to the emergency situation, the point of view is to survive during the COVID-19 outbreak and do our best to support end-users and customers by satisfying the maximum demand on time and do our social responsibility.

7.3 Research Limitations

The limitation of the proposed framework can be summarized in the following points:

- Due to lack of access to licensed version of "Anylogic" simulation software, we utilized discrete event simulation formalist and Arena simulation software. Although the platform is preferred by numerous researchers, hybrid modelling and the use of a combination of agent-based simulation modelling, system dynamics, and DES would contribute to more reliable and practical findings, particularly to study COVID-19 pandemic outbreak SC disruption risk.
- Due to limited resources, utilizing digital technologies, e.g., RFID sensors to transmit real-time data, the model's input was impossible.

- The risk scenarios are designed based on historical data available in the Luxxeen company, which should not be generalized for all industries and all supply chains.
- Multiple Sourcing is defined as the first risk mitigation strategy in this study. We just considered 1 or 2 alternative supplies with an equal share of order fulfillment.
- For the SC structure design, we considered the retailers all in one with the cumulative data in terms of demand.

7.4 Future Work and Recommendations

The following future work areas and recommendations are presented based on the above-mentioned research limitation.

- Each stage in the framework can be further detailed.
- More effort should be put into financial performance metrics, e.g., "Costs to Mitigate Supply Chain Risk" and "Total Supply Chain Management Cost."
- The framework can be implemented in other essential product SCs, e.g., hand sanitizers, canned foods, masks, etc. and/ or customized for non-essential products.
- The hybrid simulation modelling study should be conducted using the Anylogic simulation software.
- Most efforts should be taken into account to study each area for risk mitigation strategies.

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Appendices

Appendix A: SCOR Processes and Performance Metrics (Hanus, 2015; "Quick Reference Guide," 1999; SCC, 2010)

sP - Plan

sP1 Plan Supply Chain	sP2 Plan Source	sP3 Plan Make	sP4 Plan Deliver	sP5 Plan Return
sP1.1: Identify, Prioritize and Aggregate Supply Chain Requirements **sP1.2:** Identify, Prioritize and Aggregate Supply Chain Resources **sP1.3:** Balance Supply Chain Resources with SC Requirements **sP1.4:** Establish and Communicate Supply Chain Plans	**sP2.1:** Identify, Prioritize and Aggregate Product Requirements **sP2.2:** Identify, Assess and Aggregate Product Resources **sP2.3:** Balance Product Resources with Product Requirements **sP2.4:** Establish Sourcing Plans	**sP3.1:** Identify, Prioritize and Aggregate Production Requirements **sP3.2:** Identify, Assess and Aggregate Production Resources **sP3.3:** Balance Production Resources with Production Requirements **sP3.4:** Establish Production Plans	**sP4.1:** Identify, Prioritize and Aggregate Delivery Requirements **sP4.2:** Identify, Assess and Aggregate Delivery Resources **sP4.3:** Balance Delivery Resources and Capabilities with Delivery Requirements **sP4.4:** Establish Delivery Plans	**sP5.1:** Assess and Aggregate Return Requirements **sP5.2:** Identify, Assess and Aggregate Return Resources **sP5.3:** Balance Return Resources with Return Requirements **sP5.4:** Establish and Communicate Return Plans

sS - Source

sS1 Source Stocked Product	sS2 Source Make-to-Order Product	sS3 Source Engineer-to-Order Product
sS1.1: Schedule Product Deliveries **sS1.2:** Receive Product **sS1.3:** Verify Product **sS1.4:** Transfer Product **sS1.5:** Authorize Supplier Payment	**sS2.1:** Schedule Product Deliveries **sS2.2:** Receive Product **sS2.3:** Verify Product **sS2.4:** Transfer Product **sS2.5:** Authorize Supplier Payment	**sS3.1:** Identify Sources of Supply **sS3.2:** Select Final Supplier and Negotiate **sS3.3:** Schedule Product Deliveries **sS3.4:** Receive Product **sS3.5:** Verify Product **sS3.6:** Transfer Product **sS3.7:** Authorize Supplier Payment

sM - Make

sM1 Make-to-Stock	sM2 Make-to-Order	sM3 Engineer-to-Order
sM1.1: Schedule Production Activities **sM1.2:** Issue Material **sM1.3:** Produce and Test **sM1.4:** Package **sM1.5:** Stage Product **sM1.6:** Release Product to Deliver **sM1.7:** Waste Disposal	**sM2.1:** Schedule Production Activities **sM2.2:** Issue Sourced/In-Process Product **sM2.3:** Produce and Test **sM2.4:** Package **sM2.5:** Stage Finished Product **sM2.6:** Release Finished Product to Deliver **sM2.7:** Waste Disposal	**sM3.1:** Finalize Production Engineering **sM3.2:** Schedule Production Activities **sM3.3:** Issue Sourced/In-Process Product **sM3.4:** Produce and Test **sM3.5:** Package **sM3.6:** Stage Finished Product **sM3.7:** Release Product to Deliver **sM3.8:** Waste Disposal

sD - Deliver

sD1 Deliver Stocked Product	sD2 Deliver Make-to-Order Product	sD3 Deliver Engineer-to-Order Product	sD4 Deliver Retail Product
sD1.1: Process Inquiry and Quote **sD1.2:** Receive, Enter, and Validate Order **sD1.3:** Reserve Inventory and Determine Delivery Date **sD1.4:** Consolidate Orders **sD1.5:** Build Loads **sD1.6:** Route Shipments **sD1.7:** Select Carriers and Rate Shipments **sD1.8:** Receive Product from Source or Make **sD1.9:** Pick Product **sD1.10:** Pack Product **sD1.11:** Load Vehicle & Generate Shipping Docs **sD1.12:** Ship Product **sD1.13:** Receive and Verify Product by Customer **sD1.14:** Install Product **sD1.15:** Invoice	**sD2.1:** Process Inquiry and Quote **sD2.2:** Receive, Configure, Enter and Validate Order **sD2.3:** Reserve Inventory and Determine Delivery Date **sD2.4:** Consolidate Orders **sD2.5:** Build Loads **sD2.6:** Route Shipments **sD2.7:** Select Carriers and Rate Shipments **sD2.8:** Receive Product from Source or Make **sD2.9:** Pick Product **sD2.10:** Pack Product **sD2.11:** Load Product & Generate Shipping Docs **sD2.12:** Ship Product **sD2.13:** Receive and Verify Product by Customer **sD2.14:** Install Product **sD2.15:** Invoice	**sD3.1:** Obtain and Respond to RFP/RFQ **sD3.2:** Negotiate and Receive Contract **sD3.3:** Enter Order, Commit Resources & Launch Program **sD3.4:** Schedule Installation **sD3.5:** Build Loads **sD3.6:** Route Shipments **sD3.7:** Select Carriers & Rate Shipments **sD3.8:** Receive Product from Source or Make **sD3.9:** Pick Product **sD3.10:** Pack Product **sD3.11:** Load Product & Generate Shipping Docs **sD3.12:** Ship Product **sD3.13:** Receive and Verify Product by Customer **sD3.14:** Install Product **sD3.15:** Invoice	**sD4.1:** Generate Stocking Schedule **sD4.2:** Receive Product at Store **sD4.3:** Pick Product from backroom **sD4.4:** Stock Shelf **sD4.5:** Fill Shopping Cart **sD4.6:** Checkout **sD4.7:** Deliver and/or install

sR - Return

sSR1 Source Return Defective Product	sSR2 Source Return MRO Product	sSR3 Source Return Excess Product	sDR1 Deliver Return Defective Product	sDR2 Deliver Return MRO Product	sDR3 Deliver Return Excess Product
sSR1.1: Identify Defective Product Condition **sSR1.2:** Disposition Defective Product **sSR1.3:** Request Defective Product Return Authorization **sSR1.4:** Schedule Defective Product Shipment **sSR1.5:** Return Defective Product	**sSR2.1:** Identify MRO Product Condition **sSR2.2:** Disposition MRO Product **sSR2.3:** Request MRO Return Authorization **sSR2.4:** Schedule MRO Shipment **sSR2.5:** Return MRO Product	**sSR3.1:** Identify Excess Product Condition **sSR3.2:** Disposition Excess Product **sSR3.3:** Request Excess Product Return Authorization **sSR3.4:** Schedule Excess Product Shipment **sSR3.5:** Return Excess Product	**sDR1.1:** Authorize Defective Product Return **sDR1.2:** Schedule Defective Return Receipt **sDR1.3:** Receive Defective Product (includes verify) **sDR1.4:** Transfer Defective Product	**sDR2.1:** Authorize MRO Product Return **sDR2.2:** Schedule MRO Return Receipt **sDR2.3:** Receive MRO Product **sDR2.4:** Transfer MRO Product	**sDR3.1:** Authorize Excess Product Return **sDR3.2:** Schedule Excess Return Receipt **sDR3.3:** Receive Excess Product **sDR3.4:** Transfer Excess Product

sE - Enable

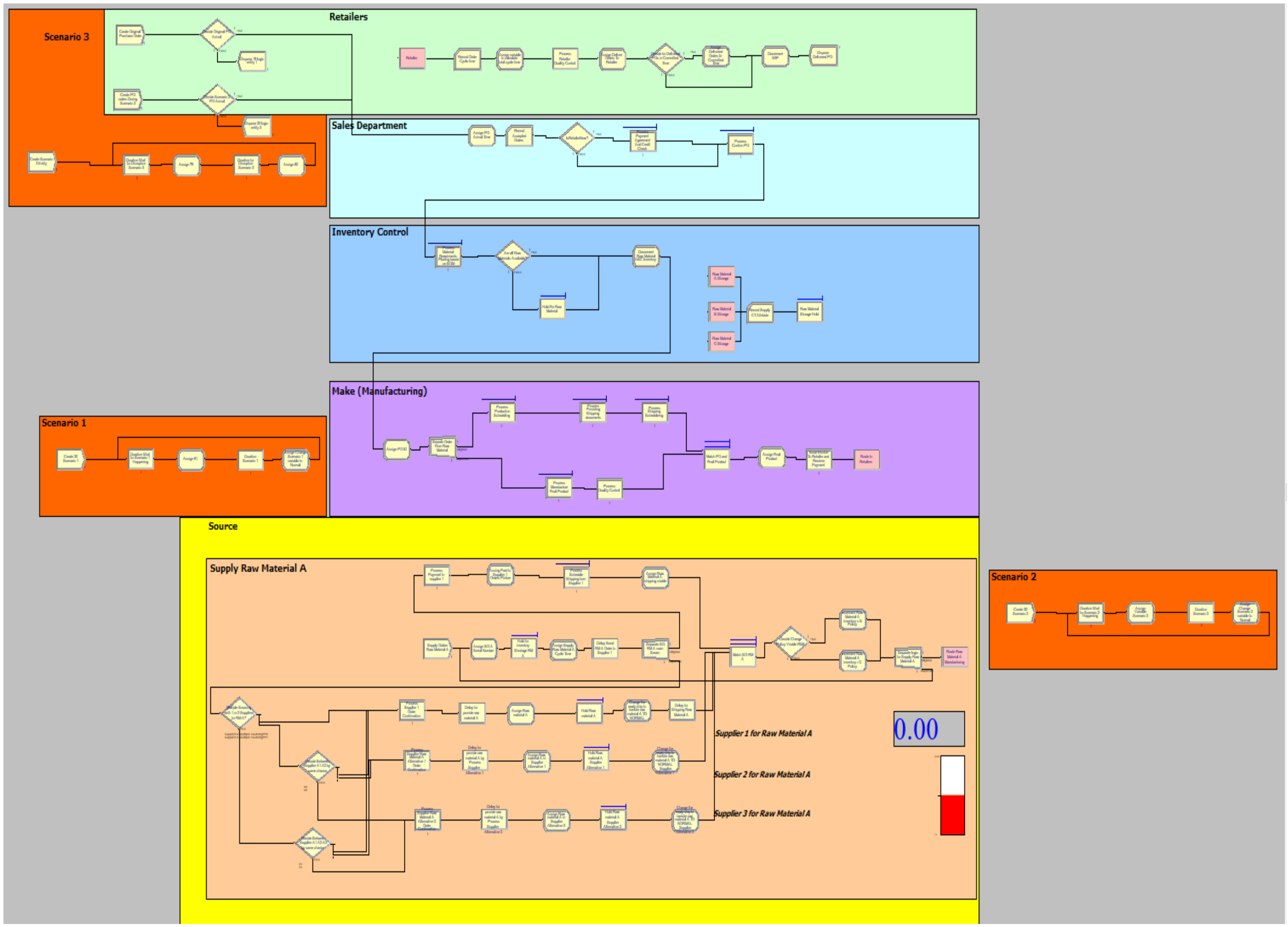
sE1 Manage Supply Chain Business Rules	sE2 Manage Supply Chain Performance	sE3 Manage Supply Chain Data and Information	sE4 Manage Supply Chain Human Resources	sE5 Manage Supply Chain Assets	sE6 Manage Supply Chain Contracts
sE1.1: Gather Business Rule Requirements **sE1.2:** Interpret Business Rule Requirement **sE1.3:** Document Business Rule **sE1.4:** Communicate Business Rule **sE1.5:** Release/Publish Business Rule **sE1.6:** Retire Business Rule	**sE2.1:** Initiate Reporting **sE2.2:** Analyze Reports **sE2.3:** Find Root Causes **sE2.4:** Prioritize Root Causes **sE2.5:** Develop Corrective Actions **sE2.6:** Approve & Launch	**sE3.1:** Receive Maintenance Request **sE3.2:** Determine/Scope Work **sE3.3:** Maintain Content/Code **sE3.4:** Maintain Access **sE3.5:** Publish Information **sE3.6:** Verify Information	**sE4.1:** Identify Skills/ Resource Requirement **sE4.2:** Identify Available Skills/Resources **sE4.3:** Match Skills/ Resources **sE4.4:** Determine Hiring/ Redeployment **sE4.5:** Determine Training/Education **sE4.6:** Approve, Prioritize and Launch	**sE5.1:** Schedule Asset Management Activities **sE5.2:** Take Asset Off-line **sE5.3:** Inspect and Troubleshoot **sE5.4:** Install and Configure **sE5.5:** Clean, Maintain and Repair **sE5.6:** Decommission and Dispose **sE5.7:** Inspect Maintenance **sE5.8:** Reinstate Asset	**sE6.1:** Receive Contract/ Contract Updates **sE6.2:** Enter and Distribute Contract **sE6.3:** Activate/Archive Contract **sE6.4:** Review Contractual Performance **sE6.5:** Identify Performance Issues/ Opportunities **sE6.6:** Identify Resolutions/ Improvements **sE6.7:** Select, Prioritize and Distribute Resolutions

sE7 Manage Supply Chain Network	sE8 Manage Supply Chain Regulatory Compliance	sE9 Manage Supply Chain Risk	sE10 Manage Supply Chain Procurement	sE11 Manage Supply Chain Technology
sE7.1: Select Scope and Organization **sE7.2:** Gather Input and Data **sE7.3:** Develop Scenarios **sE7.4:** Model/Simulate Scenarios **sE7.5:** Project Impact **sE7.6:** Select and Approve **sE7.7:** Develop Change Program **sE7.8:** Launch Change Program	**sE8.1:** Monitor Regulatory Entities **sE8.2:** Assess Regulatory Publications **sE8.3:** Identify Regulatory Deficiencies **sE8.4:** Define Remediation **sE8.5:** Verify/Obtain License **sE8.6:** Publish Remediation	**sE9.1:** Establish Context **sE9.2:** Identify Risk Events **sE9.3:** Quantify Risks **sE9.4:** Evaluate Risks **sE9.5:** Mitigate Risk	**sE10.1:** Develop Strategy and Plan **sE10.2:** Pre-Procurement / Market Test and Market Engagement **sE10.3:** Develop Procurement Documentation **sE10.4:** Supplier Selection to Participate **sE10.5:** Issue ITT / RFQ **sE10.6:** Bid / Tender Evaluation and Validation **sE10.7:** Contract Award and Implementation	**sE11.1:** Define Supply Chain Technology Requirements **sE11.2:** Identify Technology Solution Alternatives **sE11.3:** Define/Update Supply Chain Technology Roadmap **sE11.4:** Select Technology Solution **sE11.5:** Define and Deploy Technology Solution **sE11.6:** Maintain and Improve Technology Solution **sE11.7:** Retire Technology Solution

Appendix B: SCOR Model Performance Metrics Library (Hanus, 2015; "Quick Reference Guide," 1999; SCC, 2010)

Reliability	Responsiveness	Agility	Cost	Asset Management Efficiency
RL.1.1 - Perfect Order Fulfillment	RS.1.1 - Order Fulfillment Cycle Time	AG.1.1 - Upside Supply Chain Adaptability	CO.1.1 - Total Supply Chain Management Costs	AM.1.1 - Cash-to-Cash Cycle Time
RL.2.1 - % of Orders Delivered In Full	RS.2.1 - Source Cycle Time	AG.2.1 - Upside Adaptability (Source)	CO.2.1 - Cost to Plan	AM.2.1 - Days Sales Outstanding
RL.3.33 - Delivery Item Accuracy	RS.3.8 - Authorize Supplier Payment Cycle Time	AG.2.2 - Upside Adaptability (Make)	CO.3.1 - Cost to Plan Supply Chain	AM.2.2 - Inventory Days of Supply
RL.3.35 - Delivery Quantity Accuracy	RS.3.35 - Identify Sources of Supply Cycle Time	AG.2.3 - Upside Adaptability (Deliver)	CO.3.2 - Cost to Plan (Source)	AM.3.16 - Inventory Days of Supply (Raw Material)
RL.2.2 - Delivery Performance to Customer Commit Date	RS.3.107 - Receive Product Cycle Time	AG.2.4 - Upside Return Adaptability (Source)	CO.3.3 - Cost to Plan (Make)	AM.3.17 - Inventory Days of Supply (WIP)
RL.3.32 - Customer Commit Date Achievement Time Customer Receiving	RS.3.122 - Schedule Product Deliveries Cycle Time	AG.2.5 - Upside Return Adaptability (Deliver)	CO.3.4 - Cost to Plan (Deliver)	AM.3.23 - Recycle Days of Supply
RL.3.34 - Delivery Location Accuracy	RS.3.125 - Select Supplier and Negotiate Cycle Time	AG.1.2 - Downside Supply Chain Adaptability	CO.3.5 - Cost to Plan (Return)	AM.3.28 - Percentage Defective Inventory
RL.2.3 - Documentation Accuracy	RS.3.139 - Transfer Product Cycle Time	AG.2.6 - Downside Adaptability (Source)	CO.2.2 - Cost to Source	AM.3.37 - Percentage Excess Inventory
RL.3.31 - Compliance Documentation Accuracy	RS.3.140 - Verify Product Cycle Time	AG.2.7 - Downside Adaptability (Make)	CO.3.6 - Cost to Authorize Supplier Payment	AM.3.44 - Percentage Unserviceable MRO Inventory
RL.3.43 - Other Required Documentation Accuracy	RS.2.2 - Make Cycle Time	AG.2.8 - Downside Adaptability (Deliver)	CO.3.7 - Cost to Receive Product	AM.3.45 - Inventory Days of Supply (Finished Goods)
RL.3.45 - Payment Documentation Accuracy	RS.3.33 - Finalize Production Engineering Cycle Time	AG.1.3 - Overall Value at Risk (VAR)	CO.3.8 - Cost to Schedule Product Deliveries	AM.2.3 - Days Payable Outstanding
RL.3.50 - Shipping Documentation Accuracy	RS.3.49 - Issue Material Cycle Time	AG.2.9 - Supplier's/Customer's/ Product's Risk Rating	CO.3.9 - Cost to Transfer Product	AM.1.2 - Return on Supply Chain Fixed Assets
RL.2.4 - Perfect Condition	RS.3.101 - Produce and Test Cycle Time	AG.2.10 - Value at Risk (Plan)	CO.3.10 - Cost to Verify Product	AM.2.4 - Supply Chain Revenue
RL.3.12 - % Of Faultless Installations	RS.3.114 - Release Finished Product to Deliver Cycle Time	AG.2.11 - Value at Risk (Source)	CO.2.3 - Cost to Make	AM.2.5 - Supply Chain Fixed Assets
RL.3.24 - % Orders/Lines Received Damage Free	RS.3.123 - Schedule Production Activities Cycle Time	AG.2.12 - Value at Risk (Make)	CO.3.11 - Direct Material Cost	AM.3.11 - Fixed Asset Value (Deliver)
RL.3.41 - Orders Delivered Damage Free Conformance	RS.3.128 - Stage Finished Product Cycle Time	AG.2.13 - Value at Risk (Deliver)	CO.3.12 - Indirect Cost Related to Production	AM.3.18 - Fixed Asset Value (Make)
RL.3.42 - Orders Delivered Defect Free Conformance	RS.3.142 - Package Cycle Time	AG.2.14 - Value at Risk (Return)	CO.3.13 - Direct Labor Cost	AM.3.20 - Fixed Asset Value (Plan)
RL.3.55 - Warranty and Returns	RS.2.3 - Deliver Cycle Time	AG.2.15 - Time to Recovery (TTR)	CO.2.4 - Cost to Deliver	AM.3.24 - Fixed Asset Value (Return)
	RS.3.16 - Build Loads Cycle Time		CO.3.14 - Order Management Costs	AM.3.27 - Fixed Asset Value (Source)
	RS.3.18 - Consolidate Orders Cycle Time		CO.3.15 - Order Delivery and / or Install Costs	AM.1.3 - Return on Working Capital
	RS.3.46 - Install Product Cycle Time		CO.2.5 - Cost to Return	AM.2.6 - Accounts Payable (Payables Outstanding)
	RS.3.51 - Load Product & Generate Shipping Documentation Cycle Time		CO.3.16 - Cost to Source Return	AM.2.7 - Accounts Receivable (Sales Outstanding)
	RS.3.102 - Receive & Verify Product by Customer Cycle Time		CO.3.17 - Cost to Deliver Return	AM.2.8 - Inventory
	RS.3.110 - Receive Product from Source or Make Cycle Time		CO.2.6 - Mitigation Costs	
	RS.3.111 - Receive, Configure, Enter, & Validate Order Cycle Time		CO.3.18 - Risk Mitigation Costs (Plan)	
	RS.3.116 - Reserve Resources and Determine Delivery Date Cycle Time		CO.3.19 - Risk Mitigation Costs (Source)	
	RS.3.117 - Route Shipments Cycle Time		CO.3.20 - Risk Mitigation Costs (Make)	
	RS.3.120 - Schedule Installation Cycle Time		CO.3.21 - Risk Mitigation Costs (Deliver)	
	RS.3.124 - Select Carriers & Rate Shipments Cycle Time		CO.3.22 - Risk Mitigation Costs (Return)	
	RS.3.126 - Ship Product Cycle Time		CO.1.2 - Costs of Goods Sold	
	RS.2.4 - Delivery Retail Cycle Time		CO.2.7 - Direct Labor Cost	
	RS.3.17 - Checkout Cycle Time		CO.2.8 - Direct Material Cost	
	RS.3.32 - Fill Shopping Cart Cycle Time		CO.2.9 - Indirect Cost Related to Production	
	RS.3.34 - Generate Stocking Schedule Cycle Time			
	RS.3.97 - Pick Product from Backroom Cycle Time			
	RS.3.109 - Receive Product at Store Cycle Time			
	RS.3.129 - Stock Shelf Cycle Time			
	RS.2.5 - Return Cycle Time			

Appendix C: Overview of the Arena simulation model



Appendix D: Process Analyzer View

	Scenario Properties				Controls					Responses							
	S	Name	Reps	Supplier A Multiple Sourcing	Variable Contigency Plan Policy Change	RawMaterialA inventory	RawMaterialB inventory	RawMaterial Cinventory	Delivery Performance to Customer Committed Date	Order Fulfillment Cycle Time	Total CT Statistics	Delivered Ordered Ontime	Delivered Ordered	WIP_Statistics	AcceptedOrdersCounter	Total Supply CT Statistics
1		Current State Model - NO DISRUPTION	120	0	0	60000	12000	100000	74.10	38.29	29.54	623.64	836.37	80.57	841.23	292.98
2		Disruption Scenario 1	120	0	0	60000	12000	100000	46.37	65.78	43.70	359.99	763.68	149.63	837.61	291.85
3		Disruption Scenario 1 - Mitigation Strategy 1- Multiple Sourcing - 50% supplier 1- 50% Supplier 1 Alternative 1	120	1	0	60000	12000	100000	79.59	32.88	26.57	678.89	849.77	60.19	835.29	293.51
4		Disruption Scenario 1 - Mitigation Strategy 1- Multiple Sourcing - 33% supplier 1- 33% Supplier 1 Alternative 1- 33% Supplier 1 Alternative 2	120	2	0	60000	12000	100000	90.49	26.53	22.00	786.87	867.20	46.52	837.59	292.52
5		Disruption Scenario 1 - Mitigation Strategy 2- Change inventory control policy from (r, Q) to (s, S)	120	0	1	60000	12000	100000	83.31	28.04	24.55	722.43	866.83	41.70	831.58	291.79
6		Disruption Scenario 1 - Mitigation Strategy 3- Add a buffer for raw material inventory by 100% increase in inventory level	120	0	0	60000	12000	100000	46.37	65.78	43.70	359.99	763.68	149.63	837.61	291.85
7		Disruption Scenario 2	120	0	0	60000	12000	100000	38.65	81.27	51.12	285.81	726.06	185.63	835.99	290.24
8		Disruption Scenario 2 - Mitigation Strategy 1- Multiple Sourcing - 50% supplier 1- 50% Supplier 1 Alternative 1	120	1	0	60000	12000	100000	63.51	46.03	32.69	522.45	815.23	95.46	836.02	292.37
9		Disruption Scenario 2 - Mitigation Strategy 1- Multiple Sourcing - 33% supplier 1- 33% Supplier 1 Alternative 1- 33% Supplier 1 Alternative 2	120	2	0	60000	12000	100000	81.45	32.64	25.57	698.98	851.69	61.23	836.78	292.58
10		Disruption Scenario 2 - Mitigation Strategy 2- Change inventory control policy from (r, Q) to (s, S)	120	0	1	60000	12000	100000	70.50	37.25	29.84	606.67	853.98	59.39	836.42	291.92
11		Disruption Scenario 2 - Mitigation Strategy 3- Add a buffer for raw material inventory by 100% increase in inventory level	120	0	0	60000	12000	100000	38.65	81.27	51.12	285.81	726.06	185.63	835.99	290.24
12		Disruption Scenario 3	120	0	0	60000	12000	100000	31.40	107.67	62.87	218.82	692.13	334.88	952.00	289.50
13		Disruption Scenario 3 - Mitigation Strategy 1- Multiple Sourcing - 50% supplier 1- 50% Supplier 1 Alternative 1	120	1	0	60000	12000	100000	50.25	65.85	40.38	415.38	814.45	212.55	952.00	291.39
14		Disruption Scenario 3 - Mitigation Strategy 1- Multiple Sourcing - 33% supplier 1- 33% Supplier 1 Alternative 1- 33% Supplier 1 Alternative 2	120	2	0	60000	12000	100000	63.78	51.90	32.66	561.07	867.27	159.72	952.00	291.72
15		Disruption Scenario 3 - Mitigation Strategy 2- Change inventory control policy from (r, Q) to (s, S)	120	0	1	60000	12000	100000	52.09	62.74	40.49	447.11	839.90	187.10	952.00	292.12
16		Disruption Scenario 3 - Mitigation Strategy 3- Add a buffer for raw material inventory by 100% increase in maximum inventory level	120	0	0	60000	12000	100000	31.40	107.67	62.87	218.82	692.13	334.88	952.00	289.50
17		Disruption Scenario 1 - Best Solution	120	1	1	120000	12000	200000	95.73	17.93	16.96	847.16	884.99	24.45	833.85	291.84
18		Disruption Scenario 2 - Best Solution	120	1	1	120000	12000	200000	92.43	22.03	19.66	818.98	886.92	25.85	837.18	292.25
19		Disruption Scenario 3 - Best Solution	120	2	1	60000	24000	200000	91.57	23.59	19.56	879.46	959.59	67.41	952.00	293.74

Appendix E: The example of collected data

No.	InterArrival Time	Process Manufacture Final Product	Average Route time to Retailer	Delay for providing RM A	Route RM A to Luxxeen	…	Delay for providing RM B	Route RM B to Luxxeen	Delay for providing RM C
1	0.551	0.97	1.75	15.8	2.13	….	5.71	1.19	2.28
2	0.868	1.03	1.14	16.2	2.14	….	3.11	1.16	2.31
3	0.571	1.08	1.80	14	2.65	….	5.13	2.08	2.90
4	0.95	0.92	1.39	17.5	2.98	….	6.85	1.96	2.60
5	0.714	1.16	1.44	16.9	2.99	….	5.33	2.40	2.40
6	1.07	1.15	1.54	19	2.37	…	4.47	2.47	2.63
7	1.031	1.11	1.78	15	2.14	….	6.88	1.71	3.10
8	0.878	1.12	1.43	18.9	2.74	….	4.48	1.84	3.93
9	0.685	1.00	1.67	18.5	2.92	….	5.68	2.41	2.42
10	0.855	0.93	1.49	19.8	2.04	….	6.67	1.55	2.37
11	1.025	1.14	1.77	17.6	2.32	….	4.84	1.60	3.98

No.	InterArrival Time	Process Manufacture Final Product	Average Route time to Retailer	Delay for providing RM A	Route RM A to Luxxeen	…	Delay for providing RM B	Route RM B to Luxxeen	Delay for providing RM C
12	0.553	1.10	1.61	19.5	2.91	…	5.56	1.83	2.14
13	0.731	1.10	1.72	14.6	2.61	….	3.46	1.91	3.47
14	0.707	1.11	1.49	14.7	2.14	….	6.03	1.46	3.88
15	1.136	0.97	1.26	20.6	2.37	….	5.32	1.53	2.35
16	1.018	0.90	1.35	18.5	2.97	….	3.31	1.94	2.58
17	0.888	1.09	1.34	15.3	2.22	….	6.10	1.79	2.99
18	1.078	0.93	1.73	18.6	2.32	…	3.92	1.19	2.99
19	0.685	1.06	1.22	19.1	2.84	….	3.17	2.40	2.12
20	0.925	1.18	1.58	16.2	2.74	….	5.14	1.32	3.25
21	1.198	1.15	1.08	17.2	2.64	….	5.06	2.37	2.15
22	1.117	1.03	1.44	17.3	2.10	….	3.92	1.39	3.83
23	0.585	0.90	1.16	18.1	2.92	….	5.41	2.10	2.63

No.	InterArrival Time	Process Manufacture Final Product	Average Route time to Retailer	Delay for providing RM A	Route RM A to Luxxeen	…	Delay for providing RM B	Route RM B to Luxxeen	Delay for providing RM C
24	0.562	1.01	1.38	14	2.45	….	3.85	1.96	3.79
25	1.018	1.00	1.55	18	2.38	….	6.46	1.73	3.56
26	1.083	1.11	1.39	19.9	2.30	….	5.98	1.31	3.33
27	0.714	1.19	1.50	15.7	2.59	….	6.54	2.03	2.63
28	0.818	1.14	1.39	20.3	2.71	….	3.82	2.25	2.31
29	0.667	0.95	1.41	14.3	2.72	…	6.26	2.28	3.85
30	.	.	.	.	.	….	.	.	.
31	.	.	.	.	.	….	.	.	.
32	.	.	.	.	.	….	.	.	.
33	.	.	.	.	.	….	.	.	.
98	0.844	1.18	1.18	18.7	2.71	….	6.50	1.13	2.09
99	0.744	1.01	1.23	19.9	2.24	…	5.29	2.21	3.31

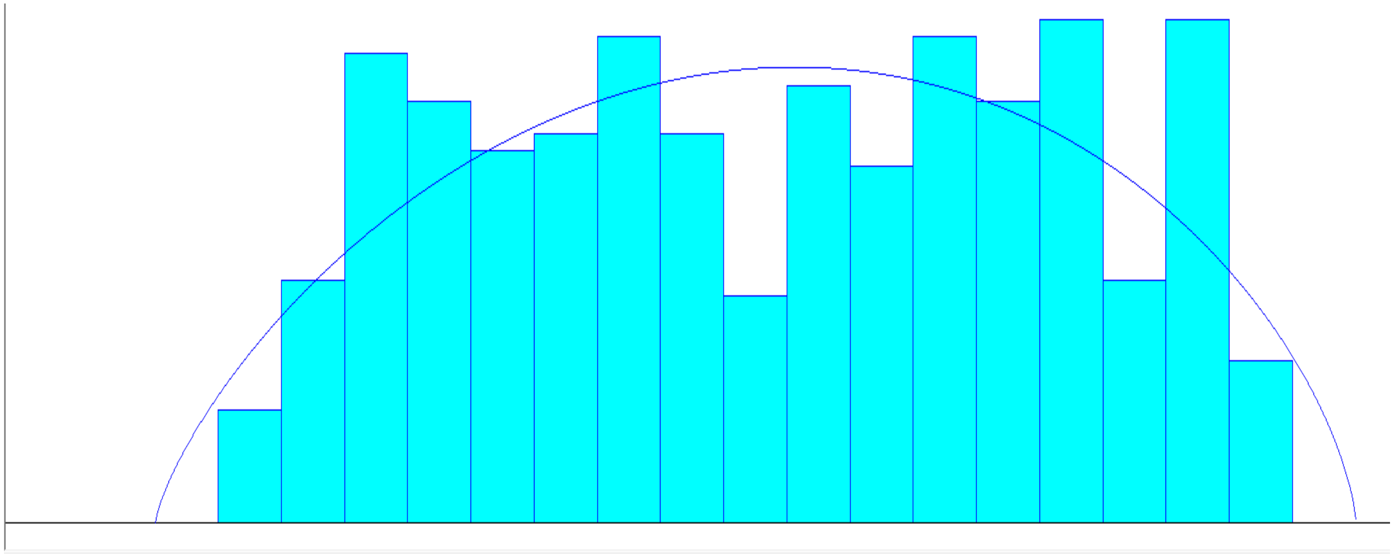
No.	InterArrival Time	Process Manufacture Final Product	Average Route time to Retailer	Delay for providing RM A	Route RM A to Luxxeen	…	Delay for providing RM B	Route RM B to Luxxeen	Delay for providing RM C
100	0.613	1.04	1.68	14.4	2.88	….	3.23	2.42	3.00
101	1.033	1.10	1.26	18.8	2.57	….	4.28	1.68	2.17
102	0.835	1.06	1.28	17.9	2.79	….	3.72	1.37	2.85
.	.	.	.	.	.	….	.	.	.
.	.	.	.	.	.	….	.	.	.
.	.	.	.	.	.	….	.	.	.
						…			
366	1.025	0.91	1.40	15	2.38	….	4.47	1.57	3.20
367	0.522	1.11	1.91	20	2.36	….	6.06	2.07	3.36
368	0.921	1.07	1.19	19.5	2.75	….	6.63	1.42	2.17
369	1.16	1.12	1.71	20.8	2.92	….	5.61	1.72	3.53
370	0.615	1.15	1.84	15.9	2.01	….	5.97	2.22	3.05
371	0.575	0.92	1.58	18.1	2.39	…	3.09	1.63	3.94

No.	InterArrival Time	Process Manufacture Final Product	Average Route time to Retailer	Delay for providing RM A	Route RM A to Luxxeen	…	Delay for providing RM B	Route RM B to Luxxeen	Delay for providing RM C
372	0.825	1.01	1.55	19.3	2.29	….	3.07	1.53	3.69
373	0.83	1.04	1.31	20.3	2.84	….	3.55	2.33	3.49
374	0.698	0.98	1.49	18	2.87	….	6.81	2.18	2.10
375	0.632	1.18	1.94	20.9	2.09	….	3.52	1.97	3.57
376	0.706	0.91	1.02	17.6	2.37	….	3.06	2.18	3.35
377	1.007	0.99	1.33	18.6	2.74	…	4.09	1.49	3.75
378	1.146	1.01	1.40	15.3	2.67	….	4.31	1.20	3.01
379	1.094	1.01	1.69	15.8	2.86	….	5.16	1.66	3.65
380	0.904	1.11	1.11	15.1	2.11	….	6.29	1.24	3.75
381	1.127	1.18	1.64	14.5	2.58	….	5.65	1.23	2.77
382	0.643	1.00	1.36	17.3	2.19	….	4.86	2.18	2.69
383	0.915	1.03	1.11	16	2.54	…	3.60	1.70	3.06
384	0.906	1.02	1.68	16.4	2.71	…..	3.28	2.10	3.50

Appendix F: Sample of fitting input data distribution with Input Analyzer

Operation: "Manufacturing the Final Product"

Function	Sq Error
Beta	0.00514
Weibull	0.00956
Normal	0.0105
Gamma	0.0108
Triangular	0.0113
Erlang	0.0116
Uniform	0.0125
Lognormal	0.0131
Exponential	0.0314



Distribution Summary

Distribution: Beta
Expression: 0.87 + 0.36 * BETA(1.75, 1.66)
Square Error: 0.005144

Chi Square Test
Number of intervals = 17
Degrees of freedom = 14
Test Statistic = 40.9
Corresponding p-value < 0.005

Kolmogorov-Smirnov Test
Test Statistic = 0.0491
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 384
Min Data Value = 0.9
Max Data Value = 1.2
Sample Mean = 1.05
Sample Std Dev = 0.0857

Histogram Summary

Histogram Range = 0.87 to 1.23
Number of Intervals = 19