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Design of a Global Supply Chain for the Unexpected

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by

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Design of a Global Supply Chain for the Unexpected

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research of the author and her supervisor Prof. Waguih ElMaraghy. This joint research has been submitted to Journals and Conferences that are listed below.

I am aware of the University of Windsor Senate Policy on Authorship, and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from Prof. Waguih ElMaraghy to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

This thesis includes four original papers that have been previously published/submitted for publication in peer-reviewed journals and conferences, as follows:

Thesis Chapter	Publication title/full citation	Publication status*
3	Olivares Aguila, J., and W. ElMaraghy. 2018. "Simultaneous global supply chain and product architecture design considering natural hazard exposure and geographical facility location." *Procedia CIRP* 72:533-8. doi: https://doi.org/10.1016/j.procir.2018.03.040.	Conference proceeding (published)
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5	Olivares Aguila, J., and W. ElMaraghy, “Supply chain disruption analysis: A system dynamics approach.”	(to be submitted)

6	Olivares Aguila, J., and W. ElMaraghy, "Supply chain resilience and structure: An evaluation framework." *Procedia Manufacturing*	Conference proceeding (accepted)

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ABSTRACT

Supply chains (SCs) play a crucial role in business operations and economies around the globe. They are in constant change and face challenges such as recurrent risks and disruption risks. The disruptive risks tend to cascade and propagate upstream and downstream of the disruption point. Due to the difficulty of calculating probabilities of disruptions, many decision makers prefer to underestimate disruptive risks. Losses of billions of dollars are accounted for each year due to the disruptive risks. These losses highlight the importance and need of having decision support systems and tools that can aid to design, model and analyze SCs that can cope with disruptions and their effects through all the stages.

This research aims at developing new methods for designing and analyzing SCs that are prepared for unexpected events. It provides new insights into the methods to estimate the impact of possible disruptions during designing and planning stages. It further proposes complexity, robustness and resilience measures which facilitate the comparison between different SC designs in different scenarios. The significance of this research is to provide more stable production environments and develop the capability to prepare for unexpected events.

Particular focus is given to natural disasters due to the magnitude and variety of impacts they could cause. Hence, a mathematical programming model that designs SCs and product architectures is proposed. The objective function is to minimize the disaster risk score of natural disasters (which depends on the geographical location of each SC entity and its associated "World Risk Index"). Also, a goal programming model is derived from the initial model. The goal programming model allows the inclusion of the decision-makers' risk attitudes and costs to balance the decisions. The results obtained from the model showed that the SC and product architecture designs affect each other. Additionally, it was demonstrated that different risk-attitudes could lead to different SC designs.

To achieve harmonious designs between SCs and products while remaining robust and controlling complexity, a novel methodology to assess structural SC complexity and robustness is presented using network analysis. This methodology includes the evaluation of different product architectures. Consequently, managers can choose the SC/product architecture that has a balanced level of complexity and robustness. It is worth noting that complexity and higher costs are needed to protect against disruptions. Moreover, the results demonstrated that the modular architecture is preferable as it has a balanced level of complexity and robustness.

To analyze the dynamic behaviour of the SCs, a system dynamics framework is introduced to evaluate the impacts of disruptions in assembly SCs. Consequently, a pragmatic tool that provides organizational support is proposed. This framework enables the examination of full and partial disruptions and the incorporation of expediting orders after a disturbance. The SC performance indicators are the output of the proposed model. These indicators make the comparison between different scenarios easy. The usage of the framework and the findings can serve to define disruption policies, and assist in the decisions relating to the SC design. After running several scenarios, it was determined that the disruptions happening in the downstream levels have more impacts on the SC performance than the disruptions in the upstream levels. Hence, the disruption policies for the downstream levels should have higher priority. Moreover, it was demonstrated that expediting after disruptions could affect more the already damaged SC performance.

Finally, to evaluate the SC performance and costs when facing disruptions, an index to assess SC resilience cost is provided. The metric considers the fulfilment rate in each period of each SC entity and its associated cost. This index allows comparison between different scenarios in the SC.

DEDICATION

To God

For the privilege of giving me this life

To my Mom and Dad

For their infinite love and support through my life

To my Brother and my Nephews

For their love and endless joy that they have brought to my life

To my Life Partner

For his love, patience and support in this journey

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LIST OF ABBREVIATIONS

CRI	Company Resilience Index
FR	Fulfilment Rate
IDEF0	Function modelling methodology which refers to “Icam DEFinition for Function Modeling" where ICAM is an acronym for "Integrated Computer Aided Manufacturing.”
ILP	Integer Linear Programming
GP	Goal Programming
GSCU	Global Supply Chain for the Unexpected
RDR	Recovery-Dependent Resilience Cost
RE	Recovery effort
SC	Supply Chain
SCRS	Total Supply Chain Risk Score Model
SCC	Total Supply Chain Cost Model
SCSD	Supply Chain System Dynamics Framework
SCRI	Supply Chain Resilience Index
SD	System Dynamics
SSCC	Structural Supply Chain Complexity
SSCR	Structural Supply Chain Robustness
SSCWR	Structural Supply Chain Weighted Robustness
TSP	Target System Performance
WRI	World Risk Index

CHAPTER 1. INTRODUCTION

1.1 Motivation

Customer requirements, global competition and new technologies have created a fast-changing supply chain environment. Hence, companies trying to maximize profits or minimize costs tend to choose strategies like outsourcing, offshoring and reducing the supply base (Nepal, Monplaisir, and Famuyiwa 2012). These globally distributed supply chains (SCs) face new challenges and uncertainties. Events in the SC can range from identified and certain, usually called "known-known" situations, to unidentified and uncertain, usually called "unknown-unknown" situations. These challenges and uncertainties are also reflected in the product design. Consequently, companies select product architectures that allow adaptation to fulfil the needs of different customer segments. As a result, companies are looking to increase robustness and resilience in the SC. However, they are trying ways to devise ways to diminish its complexity as well.

In the literature, many efforts have been devoted to examining SC risks, disruptions and mitigation strategies; just a few of these works, though, are based on quantitative methods. Traditional risk-assessment methods are based on the identification of probabilities and the impact of the disruptions, e.g., (Knemeyer, Zinn, and Eroglu 2009). However, as pointed out by Simchi-Levi et al. (2015), low-probability and high-impact events such as natural disasters are difficult to predict, and historical data is limited or nonexistent. Additionally, decision-makers tend to focus on operational costs and underestimate the impacts of the unexpected events.

Companies trying to reduce their risks look for insurance solutions that can help them to cope with unexpected situations. According to Munich Re (2017), in 2017, there were overall losses of 340 billion dollars due to relevant natural events worldwide. From these losses, 138 billion dollars were insured. Risks are becoming more complex and for that reason, companies buy insurance to provide financial relief (which is expensive and normally designed for non-catastrophic or high-frequency low-impact events) or look ways to minimize possible event impacts.

Due to the fact that disruptions in SC are characterized by different frequencies and impacts, in order to evaluate the SC design and the effects of the disruptive events, robustness reserves (e.g. redundancies like inventories and backup suppliers) and the scale and speed of recovery strategies need to be considered (Sokolov et al. 2016). Hence, the SC structure, as well as dynamics, can be analyzed.

To address the challenges that the SCs face on a daily basis, innovative methodologies that can help to design, model and analyze SCs and the potential disruptions are needed. As a result, managers will be willing to invest in SC designs that support robustness and resilience although the benefits of those investments are not immediate.

This research is motivated by the need for methodological and pragmatic tools that will facilitate the decision-making process of preparation, response and recovery from unexpected events. Even though the literature has attracted researches in the field of SC disruptions, there are still significant gaps in the literature. This research analyzes existing methods and builds on them to provide novel methodologies that can be useful to SC practitioners.

1.2 Supply Chain Network Design

Supply chain network design mainly deals with strategic decisions that are usually long-term such as the number, location and capacities of the SC entities. According to Chopra and Meindl (2007), global network design decisions are carried out in four phases as shown in Figure 1.1.

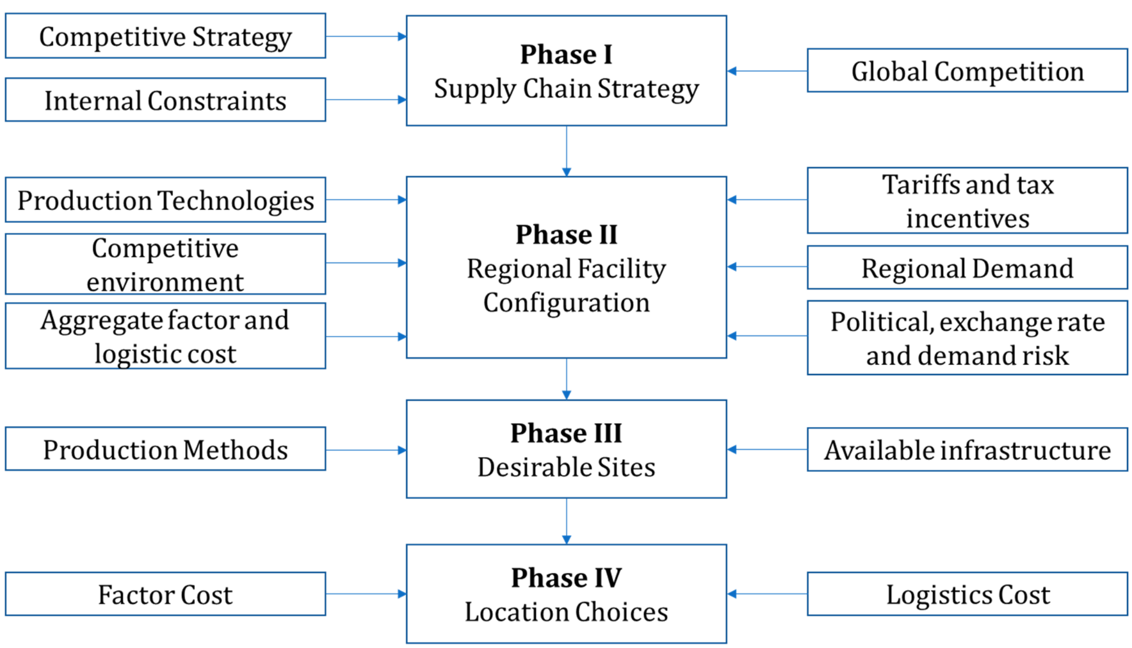


Figure 1.1 Supply chain design framework (Chopra and Meindl 2007).

In the framework presented by Chopra and Meindl (2007), in the first phase, a definition of the supply chain strategy is made. The SC strategy identifies the capabilities that the SC network must have to support the competitive strategy. In the second phase, regions which are going to be considered, their potential roles and approximate capacities are identified. As a result, a list of geographic regions that seem to be promising for consideration for the setup of the SC network is provided. In the third phase, desirable potential sites are selected within each region where facilities are to be located. In the last phase, a precise location and capacity allocation for each facility is decided.

Once the SC network design is fixed, planning is needed to set up policies that maximize the SC surplus that can be generated over the planning horizon given the constraints established during the strategic or design phase. Planning establishes parameters within which a SC will function over a specified period of time. In the planning phase or tactical decision level, companies must include uncertainty in demand, exchange rates and competition over this time horizon in their decision. As a result of the planning phase, companies define a set of operating policies that govern short-term operations (Chopra and Meindl 2007).

1.3 Manufacturing Supply Chains

Manufacturing is concerned with the transformation of materials into items of greater value by processing or assembling. The discrete manufacturing industries produce parts and systems like automobiles, computers, machinery and the component parts from which these products are assembled (Groover 2007). The manufacturing supply chains consist of all the parties involved directly or indirectly in providing the products. These manufacturing SCs are complex infrastructures with various layers of intermediate suppliers that orchestrate the movement of parts and components between those layers. The manufacturing supply chains are usually comprised of geographically dispersed facilities and capabilities. Generally, each product line has its own supply chain, although the same facilities or capabilities are used in multiple product lines, hence multiple supply chains (National Research Council 2000).

1.4 Engineering Problem Statement

Globally distributed manufacturing supply chains are immersed in a fast-changing environment. As a result, unexpected events can occur on a daily basis. While high-frequency low-impact situations could deteriorate supply chain performance, low-frequency high-impact disruptions could damage the supply chain for an indefinite period. Hence, decision management tools to design and analyze supply chains that are prepared to overcome unexpected events are required.

1.5 Research Scope

Supply chains addressed in this dissertation are primarily discrete manufacturing SCs that are globally distributed. Service supply chains and e-supply chains are not studied. The considered supply chains produce mainly assembly products (e.g., auto parts, electronics, appliances, etc.). The supply chain scope of application includes new and existing SC networks. The design level of the dissertation is mainly strategic and tactical. In the strategic design, the setup of SC entities within the supply chain network is limited to regional facility locations (specifically countries). In the strategic level of decision, risk–attitudes of the decision makers are considered to design the supply chain configuration and product architecture. Moreover, product architecture design is considered, but not their product variants. Additionally, natural disasters are analyzed in more detail due to the magnitude of the consequences that they could cause. Through this research, the supply chain configuration is structurally designed. The different suppliers, locations and quantities produced and shipped are determined. Moreover, structural SC complexity and robustness are analyzed.

The dynamic analysis is considered at the tactical level. Analysis of the SC performance when facing a generic shock is represented as a time delay. Operational risks as demand, forecast, lead-time or trade risks are not discussed in this research. Moreover, the representation of an assembly process in the system dynamics model is integrated. However, the implications of this process are not analyzed.

1.6 Research Gaps and Novelty

This subsection briefly highlights the research gaps in the literature depending on the application developed and explains the novelty in each section.

In the first section of this research, a mathematical model to concurrently design the supply chain and the product architecture is proposed. This area of research has been catching interest during the last years. Several mathematical models have been introduced in the literature focusing on this topic, e.g. (Nepal, Monplaisir, and Famuyiwa 2012; Rezapour, Hassani, and Farahani 2015; Gan and Grunow 2016; Baud-Lavigne, Agard, and Penz 2016). However, most of these works disregard the risk that the supply chains face when operating in a global context.

In this research, an integer linear mathematical programming model is proposed to design the supply chain and the product architecture simultaneously. The novelty of this model is the inclusion of the exposure and vulnerability towards natural disasters. Additionally, risk-attitudes of the decision makers are considered.

In the second section of this dissertation, a method to evaluate structural supply chain complexity and robustness is presented. This section intends to identify patterns that could increase complexity and robustness. While several works have been trying to address simultaneously or independently complexity and robustness, these topics have been studied episodically (Ivanov and Sokolov 2013; Bode and Wagner 2015; Sokolov et al. 2016; Monostori 2016). Furthermore, the inclusion of the product architecture in the analysis is mainly disregarded.

In this research, a framework to analyze the structural complexity and robustness of supply chain networks based on product architecture is proposed. The framework facilitates comparison between different supply chain configurations and product architectures.

In the third section of this research, a decision support system based on system dynamics is described to evaluate the impacts of possible disruptions. System dynamics have been widely used to address complex problems. In supply chain, several authors have been using this methodology to evaluate policies and strategic decisions (Mehrjoo and Pasek 2015; Wu, Blackhurst, and O'grady 2007). Moreover, system dynamics has been used to evaluate specific disruptions in a planning period (Wilson 2007; Huang et al. 2012; Bueno-Solano and Cedillo-Campos 2014).

In this research, disruptions are allowed to happen in different supply chain echelons, with different disruption durations, with full and partial disruptions and with the option of production expediting. The proposed pragmatic tool is intended to be used by managers to plan disruption policies and support decision making.

In the fourth section, a new measure to evaluate supply chain resilience is presented to assess different mitigation strategies and their associated cost. While several metrics have been proposed in the literature, e.g. (Barroso, Machado, Carvalho, and Cruz Machado 2015; Spiegler, Naim, and Wikner 2012; Soni, Jain, and Kumar 2014), the available measures only evaluate enablers, performance or cost. In this research, the proposed metric considers the supply chain performance (fulfilment rate) and the associated cost to accomplish that performance in a single metric. The provided supply chain resilience index allows the comparison of different scenarios of different supply chains. For more detailed literature survey, refer to chapter 2.

1.7 Research Plan

This research is presented in seven chapters, in four of the seven chapters different decision tools are introduced. A research map is outlined in Figure 1.2. All the models proposed in this dissertation are intended to be used independently. However, they could be used together as an integral tool.

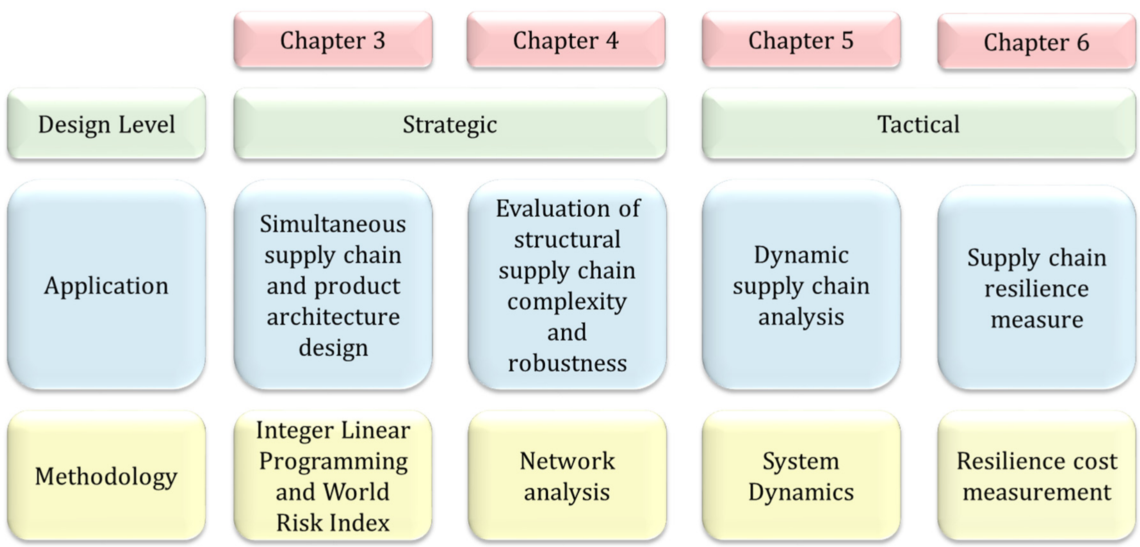


Figure 1.2 Research map.

1.8 Thesis Hypothesis

> *"Concurrently integrating the product architecture with the supply chain design and including conjoint analyses of structural and dynamic characteristics could result in robust supply chains that are prepared for the unexpected"*

In the thesis hypothesis, design refers to the mapping process from the functional domain to the physical domain that satisfies the requirements within identified constraints, as stated by ElMaraghy and ElMaraghy (2014). In this research, the design of a supply chain comprises the decisions regarding the number and location of production facilities and supplier selection for each module, as well as the product module configuration. Analysis, according to Tomiyama et al. (2009), is based on known or given characteristics, where the properties are determined or predicted if the product does not exist. In order to carry out analyses, experiments are needed to be performed using physical models, prototypes or digital simulation tools. In this research, design and analysis are performed.

CHAPTER 2. LITERATURE REVIEW

2.1 Overview

This chapter provides an overview of previous research relevant to the theme of this dissertation: supply chain design for the unexpected. Emphasis is particular given to four subsections. The first relates to the simultaneous design of supply chains and product architectures. The second relates to the structural complexity and robustness of supply chains. The third section refers to the quantification of supply chain disruptions using system dynamics. Finally, the fourth section reviews the literature regarding resilience measures in supply chain. These reviews also identify gaps in the literature that lead to the formulation of this research. Moreover, this chapter defines terms that will be employed in this dissertation.

2.2 Definition of Key Terms

The goal of this section is to provide a quick overview of the terms and definitions that are used in this dissertation.

2.2.1. *Supply chain networks*

Supply chains or supply chain networks are organized firms that their main purpose is to satisfy the customer requirements. They involve all the parties that participate directly or indirectly, from raw material suppliers, producers, distribution centres, retailers, transporters and customers (Chopra and Meindl 2007).

2.2.2. *Risk, uncertainty and unexpected*

Risk: It is defined as the fear of loss or devaluation of an important asset (Heckmann, Comes, and Nickel 2015). Usually, risk is associated with a negative result. According to APICS (2013), supply chain risk is defined as follow: "The variety of possible events and their outcomes that could have a negative effect on the flow of goods, services, funds or information resulting in some level of quantitative or qualitative loss for the supply chain." Some authors consider that risk is purely event-oriented, and therefore it relates to the probability of the disruptive events. Other authors are concentrated on the consequences of possible disruptive events, and how the supply chain performance is affected (Heckmann, Comes, and Nickel 2015). Depending on the perspective, risk can be interpreted in different ways. For our purpose, supply chain risk is considered as defined by Heckmann, Comes, and Nickel (2015): "Supply chain risk is the potential loss for supply chain in terms of its target values of efficiency and effectiveness evoked by uncertain developments of supply chain characteristics whose changes were caused by the occurrence of triggering-events".

Uncertainty: Refers to a situation which involves imperfect or unknown information. The probability of its occurrence is not known, and the results of this situation are unknown. This type of situation in the supply chain can emerge from the global environment.

Unexpected: Refers to the possibility of any triggering event or the miss of any event that could cause any variance in the targeted value of the supply chain. The unexpected is the whole view of uncertainties and risks not depending on their level of impact. Because even when the probabilities of occurrence are available, external factors can change the path of an expected outcome.

2.2.3. *Disruptive events*

In the literature, different terms are used synonymously to refer to triggering events. For instance, disturbances, disruptions, disasters, hazards and crisis (Heckmann, Comes, and Nickel 2015). However, some of these synonyms can be classified according to their impacts and if they are controllable. In this research, these terms are used to describe situations that destabilize the usual performance in the supply chain.

2.2.4. *Classification of risk*

Several classifications of risk have been carried out in the supply chain literature. Generally, supply chain risk is divided in operational risk (e.g., demand disruption, delays, procurement risk, etc.) and disruption risk (e.g., natural disasters, terrorism, etc.) (Kleindorfer and Saads 2005). Similarly, Jüttner, Peck, and Christopher (2003) presented a classification that is related to environmental risk, network-related risk sources and organizational risk sources. The first relates to uncertainties that arise from the interaction in the supply chain (e.g. natural disasters, terrorism). Organizational risk relates to labour and production uncertainties (e.g. machine failure, strikes, etc.). Lastly, network-related risk arises from interactions between organizations within the SC (e.g. lack of ownership, complexity, etc.). Likewise, Chopra and Meindl (2007) classified risk factors in nine categories as disruptions, delays, systems risk, forecast risk, intellectual property risk, procurement risk, receivable risk, inventory risk and capacity risk. In this research, the focus is on low-frequency high-impact events such as natural disasters.

2.2.5. *Global Supply Chain for the Unexpected (GSCU)*

Refers to a holistic concept where the domain of Global Supply Chain considers unexpected situations. As a result, GSCU includes all the problems related to the SC and the activities developed to achieve competitive advantages in different environments even in those where information is not available. The primary goal of this domain is to achieve a strategic fit between customer priorities and capabilities in any supply chain environment. GSCU considers the structural and dynamic perspectives of SCs.

2.2.6. *Risk attitudes*

Risk appetite or attitude reflects the degree that the decision maker is willing to accept in pursuing its objectives (Schlegel and Trent 2016). Risk can be classified according to the utility theory depending on the risk attitude of the decision maker as risk-averse, risk-seeking and risk-neutral. These perspectives may influence decision makers and lead to different solutions (Heckmann, Comes, and Nickel 2015).

2.2.7. *Bullwhip and ripple effect*

Bullwhip effect is related to operational risks, for instance, demand fluctuation where there is a magnification of variability in orders in the SC. The bullwhip effect impacts critical parameters and performance of the SC. The recovery of this effect is usually in the short term. On the other hand, the ripple effect is the propagation of disruptions in the SC, and it is related to disruptive risks, for example, natural disasters. In the ripple effect, structure, critical parameters and output performance are affected in the middle to long-term (Ivanov, Dolgui, and Sokolov 2015).

2.2.8. *Product architecture*

According to Ulrich (1995), SC decisions depend on the architecture of the end product. “The product architecture is the scheme by which the function of a product is allocated to physical components” as defined by Ulrich (1995). Different product architectures can lead to different product characteristics and different SCs. Product architectures can be broadly classified into integral and modular, as per Figure 2.1. Integral architecture is the scheme by which functional elements are shared by physical elements. In contrast, in a modular architecture, each function is delivered by a separate element. Additionally, there is the platform design approach that is considered as an extension of the modular design (Gu 2014).

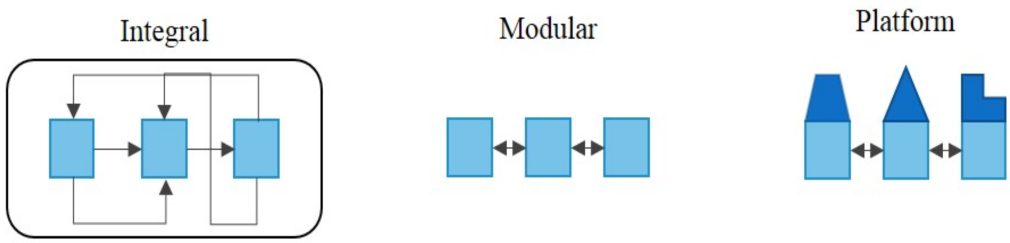


Figure 2.1 Product Architectures.

2.3 Concurrent Product and Supply Chain Design

Concurrent product and supply chain design at the architectural phase focuses on finding the best overall modular design for the product and the SC (Gan and Grunow 2016). Several authors have tried to solve the concurrent design problem with mathematical programming, some of the relevant works are presented as follows: Fine, Golany, and Naseraldin (2005) proposed a goal programming approach that simultaneously designs the product and supply chain. They considered several goals like cost, lead-time, fidelity, partnership and dependency. Moreover, in the paper presented by ElMaraghy and Mahmoudi (2009), a model was proposed to determine the optimal location of SC nodes by simultaneously considering the currency exchange rate and the optimal product structure to be used in order to minimize the total SC cost. Similarly, in the research introduced by Nepal, Monplaisir, and Famuyiwa (2012), an optimization model was formulated as a weighted goal programming model. They considered as objectives the minimization of the supply chain costs and maximization of the supply chain compatibility. The model analyzed two product architectures (modular and integral). Another paper dedicated to the concurrent design of product and supply chain architecture is the one presented by Rezapour, Hassani, and Farahani (2015). They considered two models, one that maximizes profits and the second one is a bi-objective model where the trade-offs are quality vs price. Similarly, the work developed by Baud-Lavigne, Agard, and Penz (2016) proposed a model to minimize total supply chain costs and included module substitution possibilities. Likewise, the paper developed by Chiu and Okudan (2014) studied the impact of different modularity levels, they used minimization of total cost and minimization of lead time as the objective functions.

Case studies that analyze risks and the potentials of the concurrent design to mitigate different risks have been barely studied in the literature. For instance, Khan, Christopher, and Creazza (2012) investigated how product commonality is related to supply chain integration and the risk of technological knowledge leakage. Lau et al. (2010) highlighted the importance of information sharing but also the potential information risk across the supply chain. Hoetker, Swaminathan, and Mitchell (2007) analyzed the benefits of the concurrent design in the presence of supplier failure risk. These case studies showed the need to consider risk at the strategic level of decisions. However, none of them proposed a methodology that includes risk.

Several works have been dealing with the concurrent design of a product and its corresponding SC. In the existing research, common objectives are the minimization of total costs (ElMaraghy and Mahmoudi (2009), Ivanov and Sokolov (2013), Nepal, Monplaisir, and Famuyiwa (2012), Baud-Lavigne, Agard, and Penz (2016), Chiu and Okudan (2014)), maximization of profits (Rezapour, Hassani, and Farahani (2015), Gokhan, Needy, and Norman (2010)), and other aspects.

2.3.1. *Research gap*

Most of the supply chain design mathematical models are looking to minimize the total supply chain cost or maximize profits, as we can observe from Table 2.1. These models, however, disregard the risk that they are exposed to. Hence, there can be a difference in cost between one and another option. However, in the case that disruption occurs, this difference of cost would be smaller compared with the recovery cost. For that reason, managers should not consider just cost.

Table 2.1 Research gap of risk consideration in the concurrent design.

	Objective Function					
Author	**Minimize cost**	**Maximize profit**	**Quality/Price**	**Minimize lead time**	**Risk consideration**	**No risk consideration**
Fine, Golany, and Naseraldin (2005)	X			X		X
ElMaraghy and Mahmoudi (2009)	X				X	
Nepal, Monplaisir, and Famuyiwa (2012)	X					X
Rezapour, Hassani, and Farahani (2015)		X	X			X
Baud-Lavigne, Agard, and Penz (2016)	X					X
Chiu and Okudan (2014)	X			X		X
Gokhan, Needy, and Norman (2010)		X				X

2.4 Structural Complexity and Robustness in SC

In the literature, mainly two approaches have been used to analyze complexity. The first uses information as a measure of uncertainty. Based on this concept, an entropy measure was developed by Shannon (2001). This measure has been widely used in different areas to assess complexity. The second approach uses the information content, and it is based on axiom 2 of the axiomatic design theory, as presented by Suh (1999). Additionally, there are analyses based on empirical methods, heuristics and statistics.

Several authors have analyzed structural SC complexity. For example, Wang et al. (2010) presented a complexity measure for assembly SCs based on Shannon's entropy. They considered the SC structure, product variety level and mix ratios. Allesina et al. (2010) assessed network organization and network complexity using eight ecological entropic indices. Similarly, Arkhipov and Ivanov (2011) proposed a complexity measure based on entropy. Moreover, Isik (2011) used entropy to evaluate structural complexity and operational complexity. Cheng, Chen, and Chen (2014) examined structural complexity considering the degree of order and diversity. Modrak and Bednar (2016) used structural and axiomatic design based measures as well as graphical and numerical correlations.

To establish a systematic analysis of complexity in other domains like engineering design (Kreimeyer 2010), and structural complexity of manufacturing systems (ElMaraghy et al.

2014), several papers have used metrics based on network theory. This approach offers potentials to identify patterns and draw inferences from the entities relationships in the process.

A design is robust if the network is able of providing steady value creation under different scenarios for a specific period (Klibi, Martel, and Guitouni 2010). Several authors have used graph theory to reveal the relationship between robustness and network properties. For example, Basole and Bellamy (2014) and Kim, Chen, and Linderman (2015) analyzed the supply chain network, the impact of disruptions and resilience. They demonstrated a relevant association between network structure and the likelihood of a disruption and risk diffusion. Hearnshaw and Wilson (2013) underlined network properties of efficient SCs. Nair and Vidal (2011) examined how robustness is affected by network topology. Likewise, Zhao et al. (2011) analyzed random and targeted disruptions of supply networks. They studied how supply topologies that come from different growth models affect supply resilience. Brintrup, Ledwoch, and Barros (2016) developed a structural analysis of the network topology and a simulation analysis in disrupted scenarios to get statistical properties. Similarly, Han and Shin (2016) proposed a robustness evaluation method considering disruption propagation. Adenso-Díaz, Mar-Ortiz, and Lozano (2017) analyzed how different design factors affect robustness in targeted and random disruptions.

To mitigate the impacts of a supply chain disruption, Kamalahmadi and Mellat-Parast (2016) developed a two-stage mixed integer programming model for a flexible sourcing strategy under supply and environmental risk. Lin, Huang, and Yeh (2014) proposed a minimal paths algorithm to evaluate network reliability. Lin et al. (2017) evaluated system reliability and the probability that a multistage SC can fulfil the demand. Ivanov, Pavlov, and Sokolov (2016) used the genome method to analyze the reliability of SC structures and identify critical suppliers. Ojha et al. (2018) developed a holistic measurement based on Bayesian networks for predicting risk propagation.

Other research publications focusing on robustness and complexity simultaneously have been presented. For instance, Ivanov and Sokolov (2013) proposed a control framework that includes complexity and robustness as perspectives that SC dynamics should include. Bode and Wagner (2015) investigated horizontal, vertical, and spatial complexity, and their interaction to explain the frequency of disruptions. Sokolov et al. (2016) proposed a multi-criteria approach that considers static and dynamic indicators. The considered static performance indicators included connectivity coefficient as a robustness measure, and complexity as an efficiency measure and others measures. Monostori (2016) evaluated robustness with two measures, betweenness centrality and factor R. Additionally, complexity was estimated with the vertex degree and the network entropy.

2.4.1. *Research gap*

Interest about structural complexity and robustness in SC have increased during the last years. However, most of these studies are carried out separately. There is a lack of literature regarding how structural SC complexity and robustness are affected by the product architecture, as shown in Table 2.2. The need of a practical analysis tool to estimate robustness and complexity has been pointed out by several researchers (Ivanov, Dolgui, et al. (2017); Dolgui, Ivanov, and Sokolov (2018)). Hence, there is the need to develop a methodology that jointly assesses structural SC complexity and robustness and at the same time considers the product architecture.

Table 2.2 Research gap of product architecture in the complexity and robustness analysis.

Author	**Complexity**	**Robustness**	**Product architecture**
Wang et al. (2010)	X		
Allesina et al. (2010)	X		
Arkhipov and Ivanov (2011)	X		
Isik (2011)	X		
Cheng, Chen, and Chen (2014)	X		
Modrak and Bednar (2016)	X		
Basole and Bellamy (2014)		X	
Kim, Chen, and Linderman (2015)		X	
Nair and Vidal (2011)		X	
Zhao et al. (2011)		X	
Han and Shin (2016)		X	
Ivanov and Sokolov (2013)	X	X	
Bode and Wagner (2015)	X	X	
Sokolov et al. (2016)	X	X	
Monostori (2016)	X	X	

2.5 Supply Chain Disruption Analysis using System Dynamics

Supply chains are dynamic and complex systems because of the number of entities involved and the interactions between them. While mathematical models are not able to accommodate the dynamics of the supply chain, simulation has been used to support supply chain decisions.

A typical method to analyze dynamic systems from the viewpoint of the whole systems is System Dynamics (SD). SD methodology is a modelling method presented by Jay Forrester in 1950. This modelling allows complex system analysis to design more effective policies and organizations (Sterman 2000). SD is based on the system thinking, where decisions are not affected in a linear manner. Contrary, a circular effect will occur. SD uses feedback loops, called causal loops as the heart of the methodology. These causal loops identify and display processes and the interaction between them. So, the behaviour of the whole system is recognized. It is important to mention that this kind of methodology is ideal at the strategic level of decisions. It is not suitable for optimization or to get a match point-by-point to the actual system. The relationships between variables define the system structure.

Several works have used SD to design policies and analyze SC behaviour when it faces different uncertainties and the bullwhip effect. For instance, Özbayrak, Papadopoulou, and Akgun (2007) investigated the supply chain performance under different scenarios, i.e., demand uncertainty, unreliable suppliers, different lead times and information sharing. They pointed out that the supply chain that manages enriched information observes reductions in inventory levels through all the echelons. Cheng, Chiou, and Tai (2008) analyzed the effect of disruptions in a three-echelon TFT-LCD industry and determined that this industry is sensitive to capacity planning and they pointed out the need of sharing information instantly, completely and correctly to diminish the risk of over-production. Campuzano, Mula, and Peidro (2010) used fuzzy estimations of demand in a two-stage system dynamic simulation model, showing the bullwhip effect and the amplification of the inventory variance.

Several authors have proposed system-dynamic frameworks to evaluate different disruptions in the supply chain. For example, Spiegler, Naim, and Wikner (2012) used a system-dynamic framework for assessing supply chain resilience under different control policies in a one-echelon supply chain. This study found that highly resilient systems have the disadvantage of high production costs. Additionally, they found that the supply chain is more resilient when it has shorter lead times. A system dynamic approach to analyze different risk with specified probabilities was presented by Ghadge et al. (2013). That research provided the predicted impact regarding cost and time according to specified input conditions. Mehrjoo and Pasek (2015) presented a framework to analyze managerial policies for perishable products in a three-echelon SC under three different kind of risks: risk of delays, forecast and inventory. Additionally, they used the Conditional Value at Risk (CVaR) to measure the risk of the supply chain. As a conclusion, they stated that the supply chain risk is more sensitive to scenarios where the lead time of all SC stages changes at the same time.

Another work, dedicated mainly to the bullwhip effect analysis was the one presented by Langroodi and Amiri (2016). This work analyzed oscillation in demand, variation in price, changes in costs and the simultaneous occurrence of them in a five-echelon supply chain. Their primary objective was the minimization of cost to choose the policy. They stated that this could lead to having a considerable lead time.

Other research publications focus specifically on disruptions. For instance, Wilson (2007) evaluated the impact of transportation disruption between two-echelon in a five-echelon supply chain. This study demonstrated that the disruptions that are closer to the consumer have a more significant impact on the supply chain performance. A two-echelon supply chain is used to analyze the use of backup suppliers when facing a disruption (Huang et al. 2012). They observed the inventory amplification after disruption, and they concluded that the longer the supply disruption is, the heavier the inventory fluctuation is. Bueno-Solano and Cedillo-Campos (2014) used system dynamics to study the effects of terrorist acts on the performance of a global supply chain. They highlighted the increase in inventory as a result of increased security measures on international borders. Ivanov, Pavlov, et al. (2017) presented a hybrid linear programming – system dynamics model for reconfiguration plans in a closed loop supply chain that is affected by gradual deterioration and variable recovery cost and time. They showed that the consideration of gradual capacity recovery leads to a minimization of return flows.

Several studies have analyzed disruptions using system dynamics, but they included different perspectives that may determine the disruption impact. For example, Lorentz and Hilmola (2012) analyzed the decision makers expectations and concluded that the supply chain disruption profile is the result of prior expectations. The value of information sharing when facing a disruption in a three-echelon supply chain was analyzed by Li et al. (2017). That work concluded that information sharing helps to improve supply chain resilience regarding backlog and duration.

Some studies have used other simulation paradigms to analyze supply chain disruptions. For instance, Schmitt et al. (2017) examined and considered disruptions in multi-echelon SCs using agent-based modelling. This analysis was focused on the first echelon and last echelon in the SC, and the impact of strategies like expediting and adaptive ordering. On the one hand, they concluded that expediting could hurt the already damaged system. This phenomenon occurs due to the increment in the inventory because of variation in order quantity and frequency of the orders. On the other hand, they advised that adapting ordering with order-up-to policies are a promising mitigation tool. Discrete-event simulation has also been used in several works in the supply chain disruption context. For example, Carvalho et al. (2012) presented a simulation study for a three-echelon assembly SC that considered a disturbance that affects transportation of material between two SC entities. They used flexibility and redundancy as mitigation strategies and observed the disruption impact on lead time ratio and total cost.

2.5.1. *Research gap*

Previous works that modelled and analyzed supply chain disruptions, usually represent the last echelons of the supply chain (e.g. retailer, distribution centre and manufacturer) and they have ignored beyond Tier 1 suppliers. While the justification of the omission could be because of disruptions closer to the consumer seem to be more relevant (Schmitt et al. 2017), more analysis needs to be performed. Additionally, the inclusion of assembly echelons in the SC are not represented. However, in assembly environments, when one material is not supplied the SC could halt its production. Moreover, there is no model that allows partial degradation/recovery and at the same time enables expediting after the disruption. Hence there was the need to develop a methodology that makes possible to holistically evaluate the mentioned research gaps as shown in Table 2.3.

Table 2.3 Research gap in the system-dynamic analysis for supply chain disruptions.

Author	Full disruption	Partial disruption	Expediting	Assembly echelon	Simulation paradigm	Disruption type
Özbayrak, Papadopoulou, and Akgun (2007)					SD	Demand, supply & lead time
Cheng, Chiou, and Tai (2008)					SD	Demand
Campuzano, Mula, and Peidro (2010)					SD	Demand
Spiegler, Naim, and Wikner (2012)	X				SD	Generic disruption
Ghadge et al. (2013)	X				SD	Generic disruption
Mehrjoo and Pasek (2015)					SD	Lead time, forecast & inventory
Langroodi and Amiri (2016)					SD	Demand, price & cost
Wilson (2007)	X				SD	Transportation
Huang et al. (2012)	X				SD	Generic disruption
Bueno-Solano and Cedillo-Campos (2014)	X				SD	Border disruption
Ivanov, Pavlov, et al. (2017)	X	X			SD	Capacity disruption
Schmitt et al. (2017)	X		X	X	AB	Generic disruption
Carvalho et al. (2012)	X			X	DE	Transportation

2.6 Supply Chain Resilience Measures

Resilience is a concept that has been used in ecology, sociology, psychology and economy to denote the ability to absorb changes. In SC, it was defined by Ponomarov and Holcomb (2009) as the adaptive capability of the SC to be prepared for unexpected events, to respond and to recover to its original state. Similarly, Pettit, Fiksel, and Croxton (2010) defined supply chain resilience. They not just considered the ability to survive, but they also considered the ability to grow in the face of turbulent change. Tierney and Bruneau (2007) presented the resilience triangle for critical infrastructure systems. It represents the loss of functionality from damage and disruption, as well as the restoration and recovery pattern over time.

According to Barroso, Machado, and Machado (2011), the recovery pattern can change depending on the mitigation strategy available. In other words, when a disruption occurs, there is a performance decrement, and it takes some time to recover to the previous level. In case that it is available a mitigation strategy, the impacts on the SC performance are less. Additionally, the time to recover from the disruption is shortened, and the performance level is reached as before the disruption or even higher.

Some approaches to quantify the resilience in the supply chain are available in the SC literature. Soni, Jain, and Kumar (2014) proposed a supply chain resilience index that is modelled using graph theory. They considered resilience enablers (agility, collaboration, information sharing, etc.) and their interrelationships. In that approach, the included enablers are subjective to the survey respondent firms. Another method to assess the resilience and the 'greenness' in the supply chain was presented by Azevedo et al. (2013). They proposed an index that evaluates the company green behaviour and the company resilient behaviour (sourcing strategies, strategic stock, flexible transportation, etc.).

Supply chain performance measures have been used as a proxy to evaluate resilience in SC. For instance, Carvalho et al. (2011) used the fulfilment rate. Barroso, Machado, and Machado (2011) and Carvalho et al. (2012) used a lead-time ratio and SC total cost. Cardoso et al. (2015) proposed eleven indicators to assess supply chain resilience. Four of them about network design indicators, four related to network centralization and three related to operational indicators (net present value, customer service level and investment).

A resilience metric that captures individual metrics of recovery, impact, profile length and the time-dependent deviation-weighted sum was proposed by Munoz and Dunbar (2015). They presented a linear weighted-sum aggregate index. Additionally, they used structural equation modelling to calculate the weights for each metric. In that research, they left aside the performance loss because it is highly correlated with the other metrics.

Spiegler, Naim, and Wikner (2012) considered as a SC resilience measure the integral of time multiplied by the absolute error (ITAE). The latter measure is commonly used in control engineering and corresponds to the best response and recovery with the lowest deviation from the target (readiness).

In the research presented by Barroso, Machado, Carvalho, and Machado (2015), quantification of the SC resilience was done using each company delivery performance. Individual indices for companies were used as a proxy to assess the individual companies' resilience. Additionally, they proposed four approaches (an additive model, a reliability model, a network model and a constrained approach) to create a composite SC resilience index. In the existing measures of resilience presented by Barroso, Machado, Carvalho, and Machado (2015), they considered just the performance impact. However, there could be the case where two systems have the same impact but not the same recovery effort.

Additionally, Vugrin et al. (2010) proposed the resilience costs for infrastructure and economic systems. They defined the resilience costs as a function of the sum of the system impact (SI) plus the total recovery effort (TRE) multiplied by a weighting factor, α, to assign relative significance. It is relevant to mention that system performance during the disruption in the SC will depend on the recovery strategy chosen. If a mitigation strategy is available, the system impact will be smaller. Conversely, if there is a reactive strategy, the system impact will be more significant.

2.6.1. *Research gap*

Uncertainties in SC will always exist. Hence, we have to learn to handle this kind of situations. However, we need to balance the desired performance and the cost to achieve this resilient supply chain within specified limits. The available approaches for measuring resilience in SC are directly evaluating the SC performance and its enablers. However, some of these approaches are not considering the economic system impact and the economic recovery effort (SC resilience cost), as shown in Table 2.4. For that reason, in this research, a supply chain resilience index is presented to evaluate the SC resilience cost.

Table 2.4 Research gap in resilience measures.

Author	Qualitative measure	Quantitative measure	SC performance	SC resilience cost	Measure
Soni, Jain, and Kumar (2014)	X				Agility, collaboration, information sharing, etc.
Azevedo et al. (2013)	X				Resilient behaviour
Carvalho et al. (2011)		X	X		Fulfilment rate
Barroso, Machado, and Machado (2011)		X	X		Lead time and SC total cost
Carvalho et al. (2012)		X	X		Lead time and SC total cost
Cardoso et al. (2015)		X	X		NPV, customer service level and investment
Spiegler, Naim, and Wikner (2012)		X	X		ITAE

CHAPTER 3. SIMULTANEOUS GLOBAL SUPPLY CHAIN AND PRODUCT ARCHITECTURE DESIGN

3.1 Overview

In this section, an integer linear programming model is presented to simultaneously design the supply chain and product architecture. Figure 3.1 provides an overview of the mathematical model. The main expected outputs are the SC structure and the product architecture and the quantities produced and shipped from each SC entity as shown in Figure 3.1. The distinctive characteristic of our model is the inclusion of natural hazard exposure and vulnerability depending on geographical facility location. Additionally, the decision maker's risk-attitudes are considered as presented in the model of section 3.7.

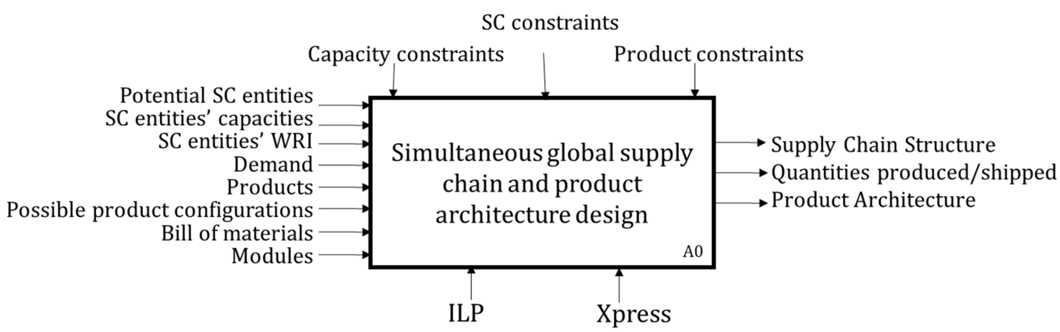


Figure 3.1 IDEF0 of the mathematical model for the simultaneous design.

3.2 Introduction

Globalization and competitive markets have forced many firms to extend their supply chain boundaries globally. Hence, companies trying to reduce costs and maximize profits tend to choose strategies such as outsourcing, offshoring and reducing supply base. Usually, companies overlook the increased risk exposure and consider it a business cost. The cost of damage of natural disasters has been rising during the last years. According to Munich Re (2017), overall losses due to natural disasters have increased from approximately \$50 billions of dollars in 1980 to more than \$350 billions of dollars in 2011. This effect could be present due to the interconnection of businesses. As a result of a domino effect that causes halting operations not just in the disrupted area.

Product and supply chain designs have been under study for decades. Both designs usually have been carried out as a sequential process. However, to achieve harmonious designs, matching both processes is needed.

During the last years, the concurrent design of product architecture and supply chain networks has started to attract attention. Several mathematical models have been presented. However, there is a scarcity of models that consider the geographical location of the supply chain and their risk of natural disasters. Zones that have increased exposure and vulnerability towards natural disasters will be prone to more significant impact. Additionally, if the location zone of the disrupted supplier does not have recovery capabilities, the effects of those disruptions can be worsened.

In this paper, natural disasters are considered because they can cause facility disruption, transportation disruption, supply disruption and maybe information system disruption. These situations justify the necessity of including the natural disaster risk of the geographical location of the SC facilities at the strategic decision level. The incorporation of a risk factor when designing the supply chain should be done without overlooking the product configuration. Since the product architecture selected will affect the number of suppliers and production centres.

Low-probability and high-impact events such as natural disasters are difficult to predict (Simchi-Levi et al. 2015), hence analytics to enable decisions should be carried out with the available information. For instance, humanitarian supply chains can operate in disrupted areas. They use available information to be aware of the exposure and vulnerability of specific regions or countries. Starting with this idea, we believe that SCs can be designed using information about exposure and vulnerability towards natural disasters to decrease their risk.

In this paper, a mathematical model for decision making is developed to design the supply chain and product configurations concurrently. We achieve this by reformulating the integer linear programming model (ILP) proposed by ElMaraghy and Mahmoudi (2009) to include geographical location information of each facility and its corresponding risk.

The remainder of this chapter is organized as follows: section 3.3 reviews the related work regarding the assessment of exposure and vulnerability towards natural disasters. Section 3.4 presents a mathematical model to simultaneously design the product and supply chain considering natural hazards risk. Section 3.5 contemplates a case study; it discusses the results and the managerial implications of the results. Section 3.6 describes decision-maker risk attitudes and the conflict of costs. Section 3.7 presents a goal programming model that considers risk attitudes and cost. Section 3.8 analyzes a case study and shows the results. Section 3.9 presents managerial insights. Finally, section 3.10 summarizes this chapter and proposes future research avenues.

3.3 Natural Disaster Risk Assessment

There have been a few attempts to assess risk and vulnerability towards natural hazards on a global scale. One of them was the Disaster Risk Index (DRI). The DRI was developed by the United Nations Development Program (Peduzzi et al. 2009). It was created focusing on disaster mortality. As a result, the classification of countries was provided. A second attempt to assess natural hazard risk was the Natural Disaster Hotspots (Dilley 2005) that was developed by the World Bank. It was focused on disaster mortality and economic losses. Another attempt to assess risk and vulnerability on a global scale was the World Risk Index (WRI) (Welle and Birkmann 2015). The WRI considered exposure and vulnerability of societies towards natural hazards (cyclones, droughts, earthquakes, floods and sea-level rise). The WRI was developed as collaborative research between members of the University of Stuttgart for the Bündnis Entwicklung Hilft (The Alliance Development Works) and with the collaboration of the Institute for Environment and Human Security of the United Nations University (UNU-EHS). This index calculated the risk for 171 countries considering exposure, vulnerability, coping capacities and adapting capacities. It ranks the countries according to the disaster risk as per Figure 3.2. The WRI has been used in politics, science and civil society to draw attention to the importance of disaster preparedness (Welle and Birkmann 2015).

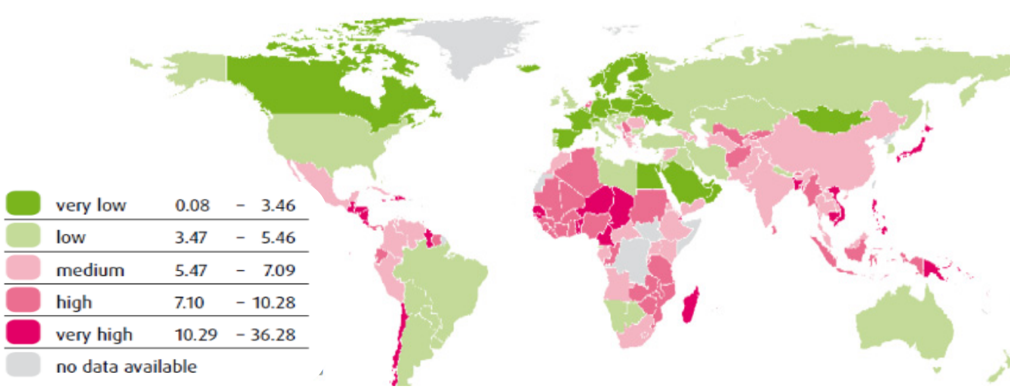


Figure 3.2 World Risk Index Map 2016 (Comes et al. 2016).

The WRI highlights the risk of becoming a victim of a disaster. Each country is rated according to the disaster risk. The disaster risk refers to a combination of potential prone countries and the social, economic and ecological conditions within the respective countries. The WRI calculates the disaster risk by multiplying vulnerability with exposure to natural hazards (Welle and Birkmann 2015).

3.4 Simultaneous Design of Global Supply Chains and Product Architecture under Natural Disaster Risk

As mentioned by Simchi-Levi, Schmidt, and Wei (2014), it is almost impossible to determine the probability of black-swan events. However, we can examine the exposure and vulnerability of specific regions that will potentiate the impact of this kind of events.

In this research, the information provided by the WRI is used to design the supply chain and product architectures simultaneously. The use of the WRI is intended to plan for disasters and to minimize their impacts. It is important to mention that the usage of the WRI is not designed to avoid the establishment of facilities in riskier countries. It is intended to make adequate preparation and consider in advance possible mitigation strategies.

The WRI is considered to design the supply chain and the product architecture. The reason we included the WRI is that in the presence of a natural disaster, not just the factories will not be available to produce. Also, facilities and infrastructures will be most probably affected. As a result, people in the affected areas will not be able to attend to work, roads will be closed, and perhaps IT systems and electricity will not be available.

3.4.1. *The model for the minimization of the total supply chain risk score (SCRS)*

This model addresses the supply chain network design and product architecture design. The objective is to select the suppliers, assemblers, plants and distribution centres, as well as the product architecture simultaneously. Additionally, the model determines the production and shipment quantities. The best supply chain and product configuration minimize the risk of natural disasters in the supply chain. The model is intended to identify regions that should be considered for setting up the supply chain as well as the product configuration. Usually, the models consider quantitative criteria as transportation costs, building costs, rental costs, material costs and so on. Conversely, the approach used in this model is based on measurable characteristics of qualitative criteria (Infrastructure and natural disaster risks), specifically the World Risk Index. The WRI is used to weight the location of a facility in each country in the supply chain.

An ILP model is presented to be used as a tool for decision making at the strategic level. All the notations used in this model are compiled in Table 3.1. The assumptions considered are the following:

- The network consists of a four supply chain echelons (supplier, manufacturer, distributor centre and customer).
- The model is considered as a single period because at the strategic level managers are targeted to cover a particular market share, they are not interested in tactical design as the level of inventory.
- All the model parameters can be estimated.
- Multiple products are considered. Possible product architectures are predetermined in advance.
- Potential location of suppliers, assemblers, plants and distribution centres are predetermined depending on production capabilities.
- Products move to the next echelon as soon as they are produced.
- Lead times and transportation time are not considered.
- Costs are not considered.
- Demand for all customers is always fulfilled.
- The World risk index is available for the considered country.

Table 3.1 Notations and definitions for the model.

Notation	Definition
Indices	
i	Modules ($i = 1, \dots, I$)
n	Products ($n = 1, \dots, N$)
s	Potential suppliers upstream ($s = 1, \dots, S$)
p	Potential plants ($p = 1, \dots, P$)
k	Potential distribution centres ($k = 1, \dots, K$)
c	Customers ($c = 1, \dots, C$)
m	Potential product configurations ($m = 1, \dots, M$)
Parameters	
I	Number of modules
N	Number of products
S	Number of potential suppliers
P	Number of potential plants

K	Number of potential distribution centres
C	Number of customers
M	Number of potential product configurations
D_{cn}	Demand of customer c of product n
B_{1si}	Capacity of supplier s to send module i
B_{2pn}	Capacity of plant p to produce product n
B_{3k}	Capacity of distribution centre k
R_{1s}	World risk index of supplier s
R_{2p}	World risk index of plant p
R_{3k}	World risk index of distribution centre k
O_{pnmi}	Quantity of module i needed at plant p to produce product n with configuration m
Variables	
W_{pnmsi}	Quantity of module i purchased from supplier s to produce product n with configuration m at plant p
x'_{pnmi}	Quantity of product n that can be produced at plant p with configuration m with module i
X_{pnm}	Quantity produced at plant p of product n with configuration m
Y_{pnk}	Quantity shipped from plant p of product n to distribution centre k
E_{kcn}	Quantity of units shipped from distribution centre k to customer c of product n
Q_{1s}	$\in \{0,1\}$ Binary variable that indicates that the supplier s is closed or opened
Q_{2p}	$\in \{0,1\}$ Binary variable that indicates if the plant p is closed or opened
Q_{3k}	$\in \{0,1\}$ Binary variable that indicates if the distribution centre k is closed or opened

$$min \sum_{s=1}^{S} R_{1s} * Q_{1s} + \sum_{p=1}^{P} R_{2p} * Q_{2p} + \sum_{k=1}^{K} R_{3k} * Q_{3k} \tag{3.1}$$

$$\sum_{p=1}^{P}\sum_{n=1}^{N}\sum_{m=1}^{M} W_{pnmsi} \leq B_{1si} * Q_{1s} \qquad \forall\ s, i \tag{3.2}$$

$$x'_{pnmi} = \frac{1}{O_{pnmi}} \sum_{s=1}^{S} W_{pnmsi} \qquad \forall\ p, n,\ m, i \tag{3.3}$$

$$X_{pnm} \leq x'_{pnmi} \qquad \forall\ p, n,\ m, i \tag{3.4}$$

$$\sum_{m=1}^{M} X_{pnm} \leq B_{2pn} * Q_{2p} \qquad \forall\ p, n \tag{3.5}$$

$$\sum_{m=1}^{M} X_{pnm} = \sum_{k=1}^{K} Y_{pnk} \qquad \forall\ p, n \tag{3.6}$$

$$\sum_{p=1}^{P}\sum_{n=1}^{N} Y_{pnk} \leq B_{3k} * Q_{3k} \qquad \forall\ k \tag{3.7}$$

$$\sum_{p=1}^{P} Y_{pnk} = \sum_{c=1}^{C} E_{kcn} \qquad \forall\, n,\ k \tag{3.8}$$

$$D_{cn} = \sum_{k=1}^{K} E_{kcn} \qquad \forall\ c, n \tag{3.9}$$

$$Q_{1s} \in \{0,1\} \quad \forall \ s \tag{3.10}$$

$$Q_{2p} \in \{0,1\} \quad \forall \ p \tag{3.11}$$

$$Q_{3k} \in \{0,1\} \quad \forall \ k \tag{3.12}$$

$$W_{pnmsi}, x'_{pnmi} \in \mathbb{Z}_{\geq 0} \quad \forall \ p, n, \ m, i \tag{3.13}$$

$$X_{pnm} \in \mathbb{Z}_{\geq 0} \quad \forall \ p, n, \ m \tag{3.14}$$

$$Y_{pnk} \in \mathbb{Z}_{\geq 0} \ \forall \ p, n, \ k \tag{3.15}$$

$$E_{pnk} \in \mathbb{Z}_{\geq 0} \ \forall \ p, n, \ k \tag{3.16}$$

The objective function (3.1) minimizes the total supply chain risk score of natural disaster depending on the geographical location of the SC facilities. Equations (3.2), (3.5) and (3.7) are capacity constraints for suppliers, plants and distribution centres respectively. Equation (3.3) calculates how much can be produced at each plant for each product for each configuration with the available module i. Equation (3.4) calculates how much can be produced in each plant depending on the availability of all the modules for each product configuration. Equation (3.6) is a flow constraint; it ensures that what is produced at the plant is sent to the distribution centres. Equation (3.8) makes sure that what enter to the distribution centres is equal to what is sent to the customers. Equation (3.9) states that what is sent from the distribution centres to the customers satisfies the demand. Equations (3.10), (3.11) and (3.12) enforce that each facility is either opened or closed for the suppliers, assemblers, plants and distribution centres respectively. Equations (3.13), (3.14), (3.15) and (3.16) constrain the quantity purchased from suppliers, the amount produced and the amount shipped from plants and distribution centers to be integers respectively.

The ILP models tend to increase in size significantly as the number of variables increases, making the solution procedure very time consuming for large instances. Due to this computational limitation, the model can be solved for small- to medium-size instances. For bigger ones, heuristics can be adapted to find a solution in a reasonable period. However, an optimal solution, in this case, is not guaranteed.

3.5 Case Study

The case study is designed to be as simple as possible yet providing useful insights for larger cases. Three scenarios are analyzed, a base case (BC), scenario 1 (S1) and scenario 2 (S2). We consider as the base case study a four-stage SC that comprises ten potential suppliers of modules, three potential locations for plants, two possible distribution centres (DCs) and one customer. The SC design structure with the possible facilities is shown in Figure 3.3. Additionally, we consider one generic product called ABC. This product has three possible product architecture configurations for the base case scenario, as shown in Figure 3.4. For example, If we assume that product ABC has three functions (A', B' and C'), and each function is mapped to an individual module, a fully modular architecture is obtained as presented in Figure 3.4 (configuration 3).

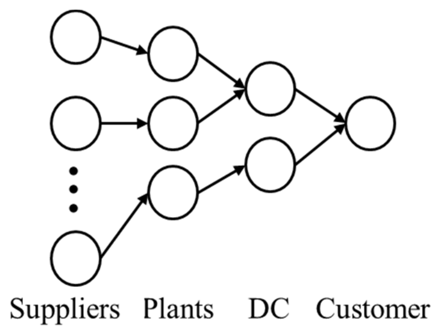


Figure 3.3 Potential supply chain structure.

Each SC entity (suppliers, plants and distribution centres) is located in a different country. Each entity has a different capacity as shown in Table 3.2 and Table 3.3. The product configurations in each plant are according to Table 3.4. The WRI for each country is specified in Table 3.5. The required demand by the customer is 100 units of product ABC.

Table 3.2 Modules and supplier data for base case.

Module	Module No.	Supplier No.	Potential Location	Base Capacity
A	1	1	China	50
		2	India	100
B	2	3	Mexico	100
		4	US	100
C	3	5	Canada	100
		6	US	50
AB	4	7	Bangladesh	100
		8	Brazil	50
BC	5	9	Japan	50
		10	Germany	100

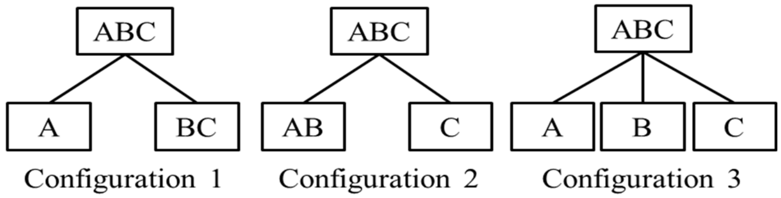


Figure 3.4 Different configurations for a modular product architecture.

Table 3.3 Plants and DC data.

Plant Number	Potential Location	Capacity	DC Number	Potential Location	Capacity
1	US	25	1	India	100
2	China	100	2	Mexico	100
3	Canada	75			

Table 3.4 Bill of materials of each product architecture in each plant for base case.

Plant (p)	Product (n)	Configuration (m)	Module (i)	O_{pnmi}
1	1	1	1	1
1	1	1	5	1
1	1	2	4	1
1	1	2	3	1
1	1	3	1	1
1	1	3	2	1
1	1	3	3	1
2	1	1	1	1
2	1	1	5	1
2	1	2	4	1
2	1	2	3	1
2	1	3	1	1
2	1	3	2	1
2	1	3	3	1
3	1	1	1	1
3	1	1	5	1
3	1	2	4	1
3	1	2	3	1
3	1	3	1	1
3	1	3	2	1
3	1	3	3	1

Table 3.5 WRI for each country from (Comes et al. 2016).

Country	WRI
Bangladesh	19.17
Brazil	4.09
Canada	3.01
China	6.39
Germany	2.95
India	6.64
Japan	12.99
Mexico	5.97
United States of America	3.76

Scenario 1 (S1) uses the same three architectures presented in the base case study, as per Figure 3.4. Additionally, S1 considers different capacities for the suppliers as shown in Table 3.6. The capacities for potential plants and potential distribution centers remain as in the base case. Hence, Table 3.3 and Table 3.4 are used to solve the problem in S1. The WRI for each country is specified in Table 3.5. Customer demand is 100 units of product ABC.

Table 3.6 Modules and supplier data for Scenario 1 (S1).

Module	Module No.	Supplier No.	Potential Location	Capacity S1
A	1	1	China	100
		2	India	50
B	2	3	Mexico	50
		4	US	50
C	3	5	Canada	100
		6	US	50
AB	4	7	Bangladesh	50
		8	Brazil	50
BC	5	9	Japan	50
		10	Germany	50

Scenario 2 (S2) considers an integral architecture where the three functions (A', B' and C') are performed by a single module called abc, as shown in Figure 3.5. In this scenario, all the suppliers can supply the integral module abc, as shown in Table 3.7. The capacities for potential plants and potential distribution centers remain as in the base case. Product configurations in each plant are according to Table 3.8. Customer demand is 100 units of product ABC.

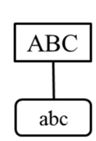


Figure 3.5 Product configuration for scenario 2.

Table 3.7 Module and supplier data for S2.

Module	Module No.	Supplier No.	Potential Location	Capacity S2
abc	1	1	China	100
		2	India	50
abc	1	3	Mexico	50
		4	US	50
abc	1	5	Canada	100
		6	US	50
abc	1	7	Bangladesh	50
		8	Brazil	50
abc	1	9	Japan	50
		10	Germany	50

Table 3.8 Bill of materials of each product architecture in each plant for S2.

Plant (p)	Product (n)	Configuration (m)	Module (i)	O_{pnmi}
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1

3.5.1. *Case study results*

The Xpress-IVE optimization tool is used to find the optimal supply chain configuration and product architecture for the presented example. For the base case study, the optimal solution selects the product architecture of configuration 1 and the supply chain configuration with a total risk score of 21.95, as shown in Figure 3.6. Quantities of production and shipments are shown in Table 3.9.

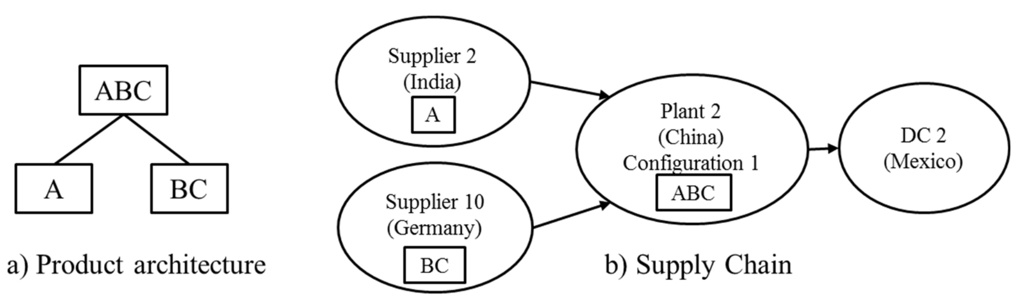


Figure 3.6 Optimal product architecture and supply chain configuration.

Table 3.9 Results for base case scenario.

SC Echelon	SC Echelon No.	Quantity produced/shipped	Country	WRI
Supplier	2	Module A=100	India	6.64
Supplier	10	Module BC= 100	Germany	2.95
Plant	2	ABC=100	China	6.39
DC	2	100	Mexico	5.97
			Total Risk	21.95

In scenario 1, different capacities are assigned to the suppliers. As a result, S1 chooses two different product configurations (configurations 1 and 3) as shown in Figure 3.7. The resulting SC structure has a risk score of 28.47 as presented in Table 3.10.

Table 3.10 Results for scenario 1.

SC Echelon	SC Echelon No.	Quantity produced/shipped	Country	WRI
Supplier	1	Module A=100	China	6.39
Supplier	4	Module B= 50	US	3.76
Supplier	5	Module C=50	Canada	3.01
Supplier	10	Module BC= 50	Germany	2.95
Plant	2	ABC=100	China	6.39
DC	2	100	Mexico	5.97
			Total Risk	28.47

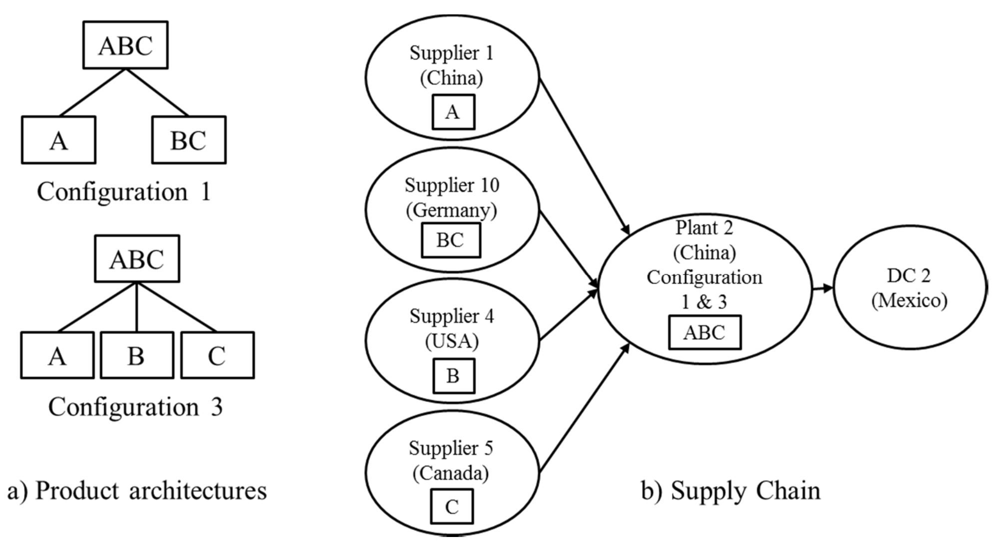


Figure 3.7 Optimal configuration for scenario 1.

For scenario 2, the integral product architecture yields a simple supply chain structure that includes just one entity in each echelon as presented in Figure 3.8. This structure has a total risk score of 15.37 as shown in Table 3.11.

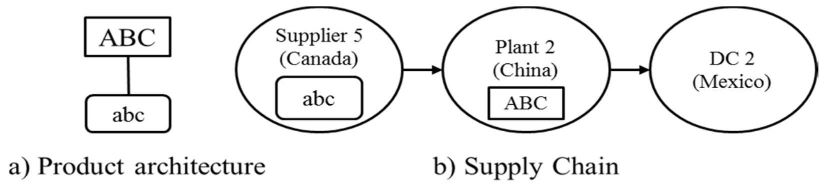


Figure 3.8 Product configuration and optimal SC for S2.

Table 3.11 Results for scenario 2.

SC Echelon	SC Echelon No.	Quantity produced/shipped	Country	WRI
Supplier	5	Module abc=100	Canada	3.01
Plant	2	ABC=100	China	6.39
DC	2	100	Mexico	5.97
			Total Risk	15.37

The results from S2 suggest that an integral architecture leads to a reduced risk towards natural disasters. The fact of having fewer facilities is the reason for the reduced risk.

3.6 Risk-Attitudes and Cost Considerations

Risk can be classified according to the utility theory depending on the risk attitude of the decision maker as risk-averse, risk-seeking and risk-neutral. These attitudes may influence decision makers and lead to different solutions (Heckmann, Comes, and Nickel 2015). For that reason, goal programming will be used to design the SC and product architecture. On one side, reduction of exposure and vulnerability is considered for the risk-averse decision maker. On the other hand, the minimization of the cost is considered for the risk-seeking decision maker.

3.7 Goal Programming Formulation

Goal programming (GP) has been used as an approach to optimize multiple objectives simultaneously. There are two methods to solve goal programming models. The first method is the weights method that forms a single objective function with the weighted sum of the goals. The second method, the pre-emptive method, prioritizes the goals in order of importance. In this research, the weighted method is used. Additional notations to formulate this model are described in Table 3.12.

Table 3.12 Notations for the goal programming model.

Notation	Definition
Parameters	
L_{1s}	Cost of opening supplier s
L_{2p}	Cost of opening plant p
L_{3k}	Cost of opening distribution centre k
G_{1psi}	Cost of producing and shipping from supplier s to plant p one unit of module i
G_{2pkn}	Cost of producing and shipping from plant p to distribution center k one unit of product n
G_{3kcn}	Cost of shipping from distribution centre k to customer c one unit of product n
Wt_R	Weight for the goal of minimization of total supply chain risk score
Wt_C	Weight for the goal of minimization of total supply chain cost
λ_R	Target risk score
λ_C	Target cost
Variables	
Δ_R	Deviation of the total supply chain risk score from its target
Δ_C	Deviation of the total supply chain cost from its target

The goals of the goal programming model are the minimization of the total supply chain risk score (Equation (3.1)) and the minimization of the total supply chain cost (Equation (3.17)).

First, the model presented in section 3.4.1 will be solved independently for the minimization of the total supply chain risk score (SCRS)(using Equation 3.1 as the objective function) and for the minimization of total supply chain cost (SCC) (using Equation 3.17 as the objective function). The optimal risk score for the SC obtained when solving for SCRS is assigned to the parameter λ_R. Similarly, the optimal cost for the SC obtained when solving (SCC) is assigned to the parameter λ_C. The lambda values represent the targets for each goal. Then, the goal programming objective function is formulated as presented in Equation (3.18). The new objective function minimizes the deviations from the target values λ_R and λ_C.

$$min \sum_{s=1}^{S} L_{1s} * Q_{1s} + \sum_{p=1}^{P} L_{2p} * Q_{2p} + \sum_{k=1}^{K} L_{3k} * Q_{3k} + \sum_{s,p,i=1}^{S,P,I} \left(G_{1psi} * \sum_{n,m=1}^{N,M} W_{pnmsi} \right) + \sum_{p,k,n=1}^{P,K,N} G_{2pkn} * Y_{pnk} + \sum_{k,c,n=1}^{K,C,N} G_{3kcn} * E_{kcn} \tag{3.17}$$

$$min \quad Wt_R\left(\frac{\Delta_R}{\lambda_R}\right) + Wt_C\left(\frac{\Delta_C}{\lambda_C}\right) \tag{3.18}$$

Where Wt_R and Wt_C represent the weights or assigned priorities of each goal. The determination of specific values of the weights is subjective. The weights are positive values and reflect the decision makers' preferences regarding the relative importance of each goal. In the model, the weights are related to the decision makers' risk-attitudes. For instance, if $Wt_R = 200$ and $Wt_C = 100$, it means that the minimization of the total risk score is more important than the cost.

Additionally, Δ_R represents the deviation of the total supply chain risk score from its target λ_R. And Δ_C represents the deviation of the total supply chain cost from its target λ_C. Furthermore, two additional constraints are added to our initial set of constraints, e.g., Equation (3.19) and Equation (3.20). The extra restrictions ensure that the deviation of both total supply chain risk score and total supply chain cost are not greater than their target values.

$$\left(\sum_{s=1}^{S} R_{1s} * Q_{1s} + \sum_{p=1}^{P} R_{2p} * Q_{2p} + \sum_{k=1}^{K} R_{3k} * Q_{3k}\right) - \Delta_R \leq \lambda_R \tag{3.19}$$

$$\begin{aligned}\Bigg(\sum_{s=1}^{S} L_{1s} * Q_{1s} &+ \sum_{p=1}^{P} L_{2p} * Q_{2p} + \sum_{k=1}^{K} L_{3k} * Q_{3k} \\ &+ \sum_{s,p,i=1}^{S,P,I}\left(G_{1psi} * \sum_{n,m=1}^{N,M} W_{pnmsi}\right) + \sum_{p,k,n=1}^{P,K,N} G_{2pkn} * Y_{pnk} \\ &+ \sum_{k,c,n=1}^{K,C,N} G_{3kcn} * E_{kcn}\Bigg) - \boldsymbol{\Delta_C} \leq \boldsymbol{\lambda_C}\end{aligned} \tag{3.20}$$

3.8 Case Study with Risk-Attitudes and Cost Considerations

The same case study used in section 3.5 is used to show the applicability of the extended model. The assumption that a risk-seeker decision maker prioritizes the total cost is made. Contrary, the assumption that the risk-averse decision maker prioritizes the reduction of risk is made. Finally, the assumption that for the risk-neutral decision maker both goals are equally important is established. The weights assigned to each risk perspective are shown in

Table 3.13. Moreover, the related cost of producing and shipping are as presented in Table 3.14, Table 3.15 and Table 3.16. Additionally, the costs of opening facilities are stipulated in Table 3.17.

Table 3.13 Scenarios and weights for the goal programming model.

Wt_R	Wt_C	Risk perspective	Risk code
100	200	Risk-seeker	A
100	100	Risk-neutral	B
200	100	Risk-averse	C

Table 3.14 Cost of producing and shipping from suppliers.

G_{psi}			
Plant (p)	**Supplier (s)**	**Module (i)**	**$**
1	1	1	2
1	2	1	2.5
1	3	2	0.5
1	4	2	0.25
1	5	3	0.5
1	6	3	0.25
1	7	4	4.5
1	8	4	4
1	9	5	4.5
1	10	5	4
2	1	1	0.25
2	2	1	1
2	3	2	2
2	4	2	2.5
2	5	3	2.5
2	6	3	2.5
2	7	4	4.5
2	8	4	5
2	9	5	3.5
2	10	5	4.5
3	1	1	2.5
3	2	1	2.5
3	3	2	1
3	4	2	0.5
3	5	3	0.25
3	6	3	0.5
3	7	4	2.5
3	8	4	2
3	9	5	2.5
3	10	5	2.5

Table 3.15 Cost of shipping from distribution centres.

G_{kcn}			
DC (k)	**Customer (c)**	**Product (n)**	**$**
1	1	1	0.5
2	1	1	1

Table 3.16 Cost of producing and shipping from plants.

G_{pkn}			
Plant (p)	**DC (k)**	**Product (n)**	**$**
1	1	1	1
1	2	1	0.5
2	1	1	0.5
2	2	1	1
3	1	1	1
3	2	1	0.7

Table 3.17 Cost of opening facilities.

Facility #	L_{1s}	L_{2p}	L_{3k}
1	100	300	100
2	200	100	150
3	100	250	
4	200		
5	200		
6	200		
7	100		
8	150		
9	150		
10	200		

3.8.1. *Goal programming results*

Each scenario in the case study (base case scenario, scenario 1 and scenario 2) is solved under three different risk-attitudes, as per Table 3.13. That is, the base case scenario (BC) is solved three times. The first time it is solved with a risk-seeker perspective (BC-A). The second time it is solved with a risk-neutral attitude (BC-B). Moreover, the third time it is solved considering the risk-averse position (BC-C). Similarly, for scenario 1 (S1) and scenario 2 (S2), the three perspectives are implemented.

The results of the nine runs are presented in Table 3.18. As we can observe from the table, in the base case scenario, the three risk perspectives lead to the same result.

Table 3.18 Results of different scenarios under different risk-attitudes.

Scenario Code	Weighted Goal	Total risk score	Total SC cost	Suppliers	Plants	DC	Product Configuration
BC-A	3.05	22.62	1250	2 , 10	2	1	1
BC-B	3.05	22.62	1250	2 , 10	2	1	1
BC-C	6.1	22.62	1250	2 , 10	2	1	1
S1-A	24.2	35.36	1175	1,9,10	2	1	1
S1-B	24.2	35.36	1175	1,9,10	2	1	1
S1-C	32.36	29.14	1500	1,4,5,10	2	1	1,3
S2-A	26.35	19.42	400	1	2	1	1
S2-B	26.35	19.42	400	1	2	1	1
S2-C	33.71	16.04	500	5	2	1	1

For scenario 1, the results under different risk attitudes are shown in Table 3.19. The fact that the weighted goal is not zero indicates that at least one of the goals is not met.

For the risk-seeker (S1-A) and risk-neutral (S1-B) decision maker, the supply chain produces one product configuration (Configuration 1), as per Figure 3.9.

Table 3.19 Results of scenario 1 under different risk-attitudes.

Scenario Code	Weighted Goal	Total risk score	Target risk score	Total SC cost	Target cost
S1-A	24.2	35.36	28.47	1,175	1175
S1-B	24.2	35.36	28.47	1,175	1175
S1-C	32.36	29.14	28.47	1,500	1175

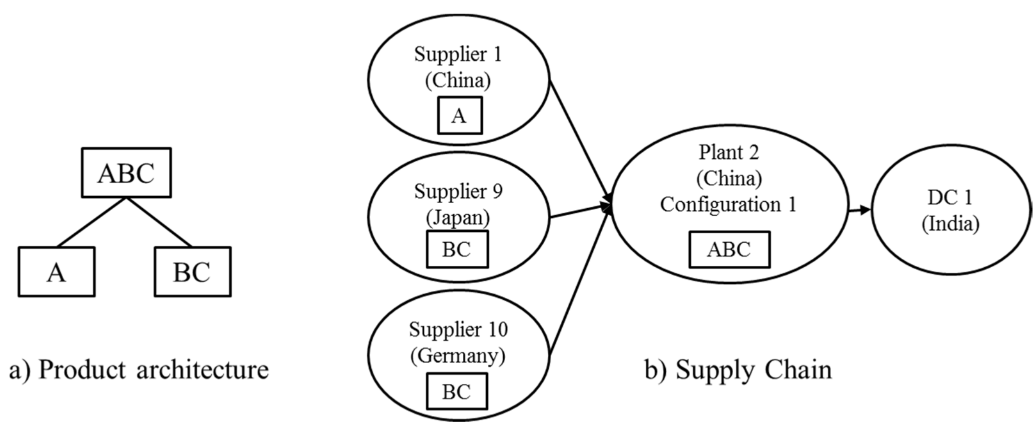


Figure 3.9 Product configuration and SC for scenarios S1-A and S1-B.

For the risk-averse (S1-C) decision maker, the supply chain produces two product configurations (Configurations 1 and 3). Moreover, the supply chain configuration has more suppliers as per Figure 3.10. Comparing the goal programming results with the model that only minimizes the total supply chain risk score (SCRS), the produced product architectures are the same, and the supply chain configuration is different. In the goal programming, distribution centre 1 is chosen, while in the model that minimizes the risk, distribution centre 2 is selected.

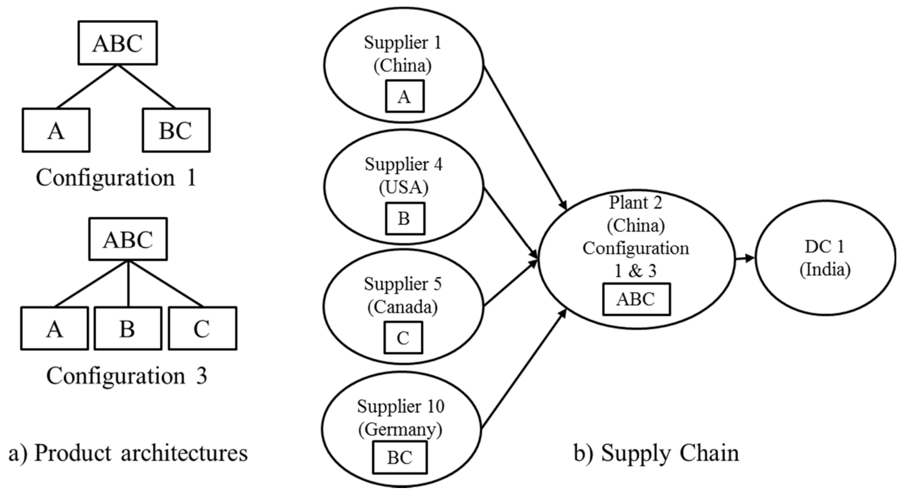


Figure 3.10 Product configuration and SC for scenario S1-C.

For scenario 2, the results from the risk-seeker attitude and the risk-neutral attitude lead to the same product architecture and supply chain. In contrast, changing to a risk-averse perspective, the supply chain structure is modified.

As we can observe from the results, depending on product architecture, available suppliers, costs and risk perspectives, different supply chains can be designed for the same product. While this model solves a part of the complex problem of the supply chain design, it brings awareness of the need to include this kind of risk at the strategic level of decisions. Additionally, it guides decision-makers to choose the "best" product architecture and supply chain design according to their specified objectives (risk vs cost).

3.9 Strategic Insights

The results from the scenarios show that the product architecture impacts directly on the configuration of the supply chain design. For that, it is needed that both designs are carried out concurrently. As a result, reduced vulnerability and exposure can be achieved. Additionally, different facility capacities could lead to consider more than one product architecture which gives flexibility to the SC. This result can be beneficial in case that a damaged supplier of a product architecture cannot supply, then the second product architecture can be produced if the modules are not provided by the same supplier. However, the trade-offs of having two architectures for the same product need to be analyzed in more detail.

Moreover, different capacities could also lead to having modules that are double-sourced. As a result, having more than one supplier for a module could be beneficial as there will be a backup. However, there is needed a supplier segmentation to restrict which modules can have double sourcing. For example, a critical module can be the one that has a redundant supplier.

The model can be used as a guideline to evaluate different strategic decisions in the development of product architectures and the corresponding supply chain. For instance, it can be used to analyze how the number of facilities changes according to the product architecture. The model can also help managers to explore different architectural strategies. Furthermore, the model can be used to identify where resources should be allocated in case of a potential natural disaster. That is, after the model has produced the results, the facility with the highest WRI should prepare mitigation strategies.

3.10 Summary

This research deals with the concurrent product architecture and supply chain design problem. A model that simultaneously decides the module configuration and the supply chain structure is presented. The model is planned for use at the strategic level of decisions to set up the regional facility locations. The relevant characteristic of the introduced model is the incorporation of the World Risk Index as a determinant to minimize exposure and vulnerability in the SC and product architecture. Moreover, risk-attitudes and costs were included in the model to balance the decisions.

This approach intends to look for product and SC configurations that have less exposure and vulnerability towards natural disasters. Additionally, it is designed to draw attention to the importance of disaster preparedness in the SC. So, events of significant impact are considered in advance.

The advantage of this approach is that the decisions are not just reduced to business costs. This benefit is relevant because a difference of thousands of dollars can mitigate the losses of billions of dollars in case of a natural disruption. As a result, cost no longer overrides geographical location risk.

The disadvantage of this approach is that the score has no real meaning. Additionally, due to the granularity of the WRI values (indices per country), the results can be controversial. Furthermore, the risk-attitudes are subjective and could change depending on the situation and decision maker.

The models presented in this chapter have limitations on the computational level. The ILP (SCRS) model (section 3.4.1) can be solved for small problems sizes such as the base case, scenario 1 and scenario 2. The base case scenario and scenario 1, have 103 constraints and 263 variables. Scenario 2 has 27 constraints and 59 variables. The computational time for these scenarios is approximately 1 second in a PC with an AMD at a 2.20 GHz processor and 8 GB of RAM. On the same computer configuration, the computational time increases to 47 seconds when solving a problem size of 20 suppliers, 20 plants, 20 distribution centres, 20 customers, 20 products, 20 configurations per product and 20 modules. This problem has 48,220 constraints and 509,160 variables.

The ILP could not provide an optimal solution after running the model for 23,816 seconds for a problem size of 40 suppliers, 40 plants, 40 distribution centres, 40 customers, 40 products, 40 configurations per product and 40 modules. This problem has 384,760 constraints and 7,914,880 variables.

Similarly, the GP model can be solved for small problems sizes such as the scenarios BC-A, BC-B, BC-C, S1-A, S1-B, S1-C, S2-A, S2-B, and S2-C. In the goal programming process, first, the SCRS and SCC models are solved. Hence, all scenarios have the same number of constraints and variables as per base case, scenario 1 and scenario 2 respectively. The GP model, the base case scenario and scenario 1 under all the risk attitudes have 105 constraints and 265 variables. Similarly, the GP model in scenario 2 has 29 constraints and 61 variables. The computational time for all these scenarios is approximately 1 second in a PC with an AMD at a 2.20 GHz processor and 8 GB of RAM. On the same computer configuration, the computational time increases to 70 seconds when solving for a problem size of 10 suppliers, 10 plants, 10 distribution centres, 10 customers, 10 products, 10 configurations per product and 10 modules. The SCRS and SCC models have 6,070 constraints and 33,610 variables. The GP model has 6,072 constraints 33,612 variables.

The GP model could not provide an optimal solution after running 5,383 seconds for a problem size of 20 suppliers, 20 plants, 20 distribution centres, 20 customers, 20 products, 20 configurations per product and 20 modules. This problem has 48,220 constraints and 509,160 variables for each of the SCRS and SCC, and 48,222 constraints and 509,162 variables for the GP model.

CHAPTER 4. STRUCTURAL COMPLEXITY AND ROBUSTNESS OF SUPPLY CHAIN NETWORKS BASED ON PRODUCT ARCHITECTURE

4.1 Overview

In this chapter, a framework to evaluate the structural complexity and robustness of supply chains is developed considering the product architecture of the product that they are supplying.

4.2 Introduction

One of the most significant disruptions in automotive supply chains was the 2011 Japan earthquake. The impact caused to Japanese automakers cost roughly $200 million a day and shutdowns extended for several months (Kurtenbach and Karty 2011). For that, supply chains (SCs) need to be prepared to overcome unexpected events that happen in the SC entities and in the environment that involves the SCs. Therefore, one of the main challenges at the early design stage is the process of selecting and putting together the right suppliers, wholesalers, manufacturers and distributors in the SC. This process plays a vital role in the SC design. If managers can understand, measure and compare SC complexity and robustness, they will be able to identify and select less complex and more robust SCs. Thus, unexpected events will affect the SC operations with less intensity.

Complexity and robustness have been discussed in several papers when considering the SC design. Supply chain complexity is characterized by static and dynamic complexity (Bode and Wagner 2015). Static complexity is triggered by SC structure, the number of components and interactions between them. In contrast, dynamic complexity is related to uncertainty concerning randomness and time. The SC design has also been approached by analyzing product complexity that can be defined as the number of components to build a product (Inman and Blumenfeld 2014). While product complexity could influence the SC design, it is not the determinant of it. In this study, the structural complexity of SC is analyzed.

Robustness, resilience and reliability have been used in the SC context as a characteristic of supply chain resistance against disruptions (Ivanov 2018). Generally, robustness is defined as the ability to cope with errors during execution. In contrast, resilience is considered as the ability to return to the original state or a better state after disruption (Christopher and Peck 2004). Some authors consider that robustness comes back to an inferior level after disruption (Asbjørnslett (2009); Spiegler, Naim, and Wikner (2012)). According to Ivanov (2018), robustness is related to the creation of resource excessiveness in order to prevent failures and deviations in the process. This redundancy of resources will allow flexibility of decisions in future scenarios. Similarly, resilience is related to flexibility. But, the flexibility in terms of resilience will allow adaptation of the SC to change structurally and functionally in a quick manner. For that reason, these concepts are interconnected. Hence the discussion of their differences and similarities, whether they are trying to reduce vulnerabilities or remain robust in order to maintain value creation.

Several models and metrics have been developed to assess topological characteristics of complexity and robustness in SC networks. There is also a need of identification of structural network properties and patterns in SC design that relate to complexity and robustness as pointed out by Dolgui, Ivanov, and Sokolov (2018). In addition, there is a scarcity of articles that consider, in parallel, the product architecture embedded in the SC networks. Considering this mentioned research gap, the objective of this study is to identify characteristics of the SC network that increase complexity and robustness, and consider how complexity and robustness depend on the SC structure and product architecture. As a result, the identified SC network features are quantitatively evaluated and presented as overall metrics. Different product architectures are used to evaluate and choose the best network configuration. Moreover, transit times between suppliers are used to assess SC network robustness. Also, a cost analysis is presented to evaluate the trade-offs between cost and complexity and robustness. Therefore, a framework that facilitates the complexity and robustness comparison between possible product architectures/supply chains is presented.

This chapter is organized as follows: section 4.3 proposes a framework to follow for calculating the complexity and robustness measures. Section 4.7 presents a cost analysis. Section 4.8 examines a case study with different SC configurations according to its product architecture. Section 4.9 discusses the results. Section 4.10 presents the summary of this chapter.

4.3 Supply Chain Topological Complexity and Robustness Framework

SCs are graphically represented as networks, where nodes represent entities (e.g., suppliers, manufacturers, etc.), and links represent the flow of material, information or money. The importance of analyzing the network structure was pointed out by Strogatz (2001). This paper mentioned that the network anatomy is important to characterize because it always affects function. For that, graph representation offers the opportunity to analyze the complexity and robustness of the SC networks. In this study, nodes are considered as points where decisions regarding material flow direction and destination are made. Additionally, the directed links are a representation of the connection and direction of material flow.

The inclusion of product architecture in the analysis is justified because changes in product structure influence the dynamic and design of SCs (Inman and Blumenfeld 2014). According to Ulrich (1995) also, SC decisions depend on the structure of the end product. Changes caused by a modification of the product architecture can result in outsourcing, consolidation of suppliers, the formation of strategic alliances, etc. (Nepal, Monplaisir, and Famuyiwa 2012). Hence the importance of considering the product architecture.

The procedure to assess the best SC configuration according to its structural complexity and structural robustness is outlined below. All the notations used in this chapter are compiled in Table 4.1.

Table 4.1 Definition of notations.

Notation	Definition
n	Number of entities in the SC
$\boldsymbol{A}_{i\times j}$	Adjacency matrix of the relationships between SC entities, where i=1,…,n, j=1,…,n
$\boldsymbol{vi}$	Vector of input nodes
$\boldsymbol{vo}$	Vector of output nodes
e	Number of edges in the SC
SI	Size index
PT	Theoretical number of potential edges in the SC
DI	Density index
c	Number of cycles in the SC
MC	Theoretical maximum number of cycles
CI	Cycle index
p	Minimum theoretical number of paths
EP	Number of paths in the SC
PI	Path index
sp	Number of suppliers on the shortest path
lp	Number of suppliers on the longest path
DPI	Decision points index

ID and MID	In-degree and maximum in-degree between all the SC entities
OD and MOD	Out-degree and maximum out-degree between all the SC entities
i, j and k	Indices of SC entities i=1,…,n, j=1,…,n and k=1,…,n
N_i and N_j	SC entity i, and SC entity j
a_{ij}	Element of matrix $\boldsymbol{A}_{i\times j}$ where i=1,…,n, j=1,…,n
MIC	Maximum In-closeness between all the SC entities
$MWIC$	Maximum weighted in-closeness between all the SC entities
MOC	Maximum out-closeness between all the SC entities
$MWOC$	Maximum weighted out- closeness
$d(Ni, Nj)$	Geodesic distance between node Ni and node Nj
g_{jk}	Number of geodesic paths between node j and k
$g_{jk}(N_i)$	Number of geodesic paths between j and k that contains node (N_i)
MB	Maximum betweenness between all the SC entities
MWB	Maximum weighted betweenness between all the SC entities
$SSCC$	Structural supply chain complexity
$SSCR$ and $SSCWR$	Structural supply chain robustness and the weighted version of SSCR
h	Individual evaluating index
H	Total number of evaluating indices to calculate SSCC, SSCR, and SSCWR
Z	Generic overall measure
e_{ji}	Number of incoming edges for node j
e_{ij}	Number of outgoing edges for node j
f_n	Cost of having a node in the SC
f_e	Cost of having an edge in the SC
f_{ji}	Cost of having an incoming edge for node j in the SC
f_{ij}	Cost of having an outgoing edge for node j in the SC
$Cost$	Total cost

Step 0. Information acquisition for the product and SC design. In this step, schematic product design is carried out. In parallel, the SC strategy is drawn according to the scope that is envisioned. Consequently, a delimitation of product architecture options and SC network designs is proposed. Note that this step is not carried out in this study.

Step 1. Select feasible product architecture strategies and the corresponding SC that need to be analyzed. Mainly three SC structures are analyzed: integral, modular and modular customized (platform).

Step 2. For a given SC, construct its corresponding adjacency matrix $\boldsymbol{A}_{i\times j}$ that captures the supply relationships and the SC network configuration. Each matrix element $\boldsymbol{a}_{ij}$ is equal to 0 or 1, where 1 corresponds to a directed relationship from one supplier to another, 0 otherwise. The adjacency matrix has i number of rows and j number of columns, where $i, j = 1, \dots, n$. The square matrix with n number of columns and rows, represents that the SC has n number of entities (suppliers, manufacturers, etc.). Additionally, create two vectors $\boldsymbol{vi}$ and $\boldsymbol{vo}$ that correspond to input and output nodes of the SC. Input nodes are SC entities that initiate an outgoing flow but do not receive an incoming flow. Contrary, output nodes are SC entities that receive an incoming flow but do not initiate an outgoing flow. For instance, a generic SC is presented in Figure 4.1 a). This supply chain is represented with the adjacency matrix as in Figure 4.1 b). In the SC network, the input and output nodes are identified to form the input vector and output vector as per Figure 4.1 c) and d) respectively.

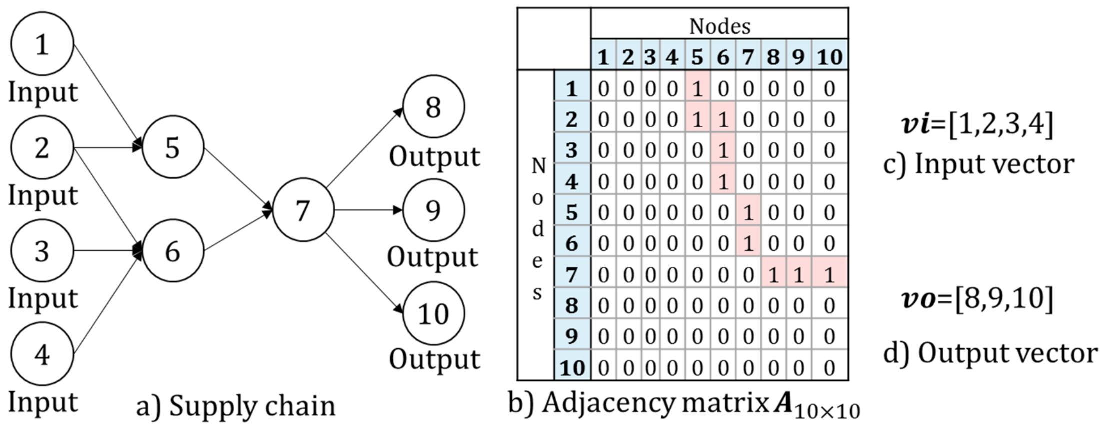


Figure 4.1 SC Matrix and vectors representation.

The adjacency matrix, the input vector and output vector are used for the algorithms described in the pseudocodes in Appendix A to calculate the characteristics related to the proposed indices in the next step.

Step 3. Calculate indices of robustness and complexity of the proposed supply networks as mentioned in section 4.4 and 4.5 respectively.

Step 4. Calculate overall robustness and complexity measures as mentioned in section 4.6.

Step 5. Draw a decision matrix with the results of step 3 and step 4. Additionally, calculate the structural cost of each SC as mentioned in section 4.7.

Step 6. Select the product architecture / SC structure.

4.4 Network Complexity Indicators

A definition of SC network characteristics and material flow patterns that add complexity to the structure of the SC network is carried out. This kind of assessment was used in the evaluation of manufacturing systems as presented by ElMaraghy et al. (2014). They analyzed the occurrence of relevant patterns among their entities and relationships and suggested that the information content acquired from these metrics can be used to assess structural complexity. For that building on that work, in this research structural complexity in SCs is evaluated using graph theory measures. Five complexity indices that measure information content regarding the material flow in the structure of the SC are presented. These indices are derived from structural characteristics of the graphs as a basic representation of the SC. Moreover, they evaluate features as size, connectivity, cycles, paths and decision points.

The normalized indices range from 0 to 1. Having 0 as the characteristic that makes least complex SC and 1 as the most complex. After calculating the five indices, the overall complexity measure is calculated as shown in section 4.6. In order to give validity to the proposed overall measure, a comparison with another method to assess supply chain complexity is given in Appendix A.

4.4.1. *Supply chain size*

Size refers to the number of nodes or entities in the SC and the interrelations between them. As the number of nodes and relationships between nodes increase, the complexity of the SC will increase as shown in Figure 4.2 (a). Size index is included because there is a consensus that numerousness increases complexity (Cheng, Chen, and Chen (2014); Isik (2011); Bode and Wagner (2015)). Size index is calculated as shown in Equation (4.1), where n is the number of SC entities and e is the number of edges.

$$SI = 1 - \frac{n-1}{e} \tag{4.1}$$

4.4.2. *Supply chain density*

Density refers to the spacing of the nodes in the SC, Figure 4.2 (b). Edges in the SC represent the presence of the material flow between suppliers. A highly dense SC has more connections between nodes, hence a more complex SC structure. Density index is defined as the ratio of the number of edges e to the theoretical number of potential edges PT. Density represents interdependence or connectedness between the entities, complexity increases as the interdependence increases (Isik 2011). Density index is determined as shown in Equation (4.2).

$$DI = \frac{e}{PT} \tag{4.2}$$

4.4.3. *Supply chain cycles*

Cycles are loops of nodes that start and end at the same node. Cycles in SCs are interpreted as outsourcing entities that need to perform an activity over the flow of materials and return it to the sender, as shown in Figure 4.2 (c). For example, subassemblies or processes that are outsourced to another SC entity and then are returned to the initial SC entity for an additional process. Complexity increases as the number of cycles increases. Cycles can be related to horizontal complexity where there are linkages inter-tier (Bode and Wagner 2015). Cycle index is calculated as the ratio between the number of cycles, c, and the theoretical maximum number of cycles, MC, as shown in Equation (4.3). MC is the sum of $i = 2, \dots, n$ of the combination of n nodes taken i at a time. The parameters c and MC can be obtained following the pseudocode for calculating cycles as presented in Appendix A.

$$CI = \frac{c}{MC} \tag{4.3}$$

4.4.4. *Supply chain paths*

A path is any sequence of nodes such that every consecutive pair of nodes in the sequence is connected by an edge in the network (Newman 2010), as shown in Figure 4.2 (d). Path index considers the number of paths in the SC and compares it with the minimum theoretical number of paths as presented in (ElMaraghy et al. 2012). Structural SC complexity increases as the number of possible routes in the SC increases. This measure is related to process variation in the SC that leads to an increase in complexity (Isik 2011). Path index can be calculated as shown in Equation (4.4), where p is the minimum theoretical number of paths and EP is the actual number of paths in the SC. The parameters p and EP can be obtained following the pseudocode for calculating paths as presented in Appendix A.

$$PI = 1 - \frac{p}{EP} \tag{4.4}$$

4.4.5. *Supply chain decision points*

Decision points index as defined by ElMaraghy et al. (2014) characterizes the cumulative complexity of decision making. That is, as the number of nodes in a path increases, the complexity increases, as per Figure 4.2 (e). As the decisions to be made for each supplier increase, the potential for more errors exists. Decision points index can be computed as presented in Equation (4.5), where sp is the number of suppliers in the shortest path of the SC and lp is the number of suppliers on the longest path. SCs with more levels or longer paths exhibit greater complexity (Bode and Wagner 2015). The parameters sp and lp can be obtained following the pseudocode for calculating paths as presented in Appendix A.

$$DPI = 1 - \frac{sp}{lp} \tag{4.5}$$

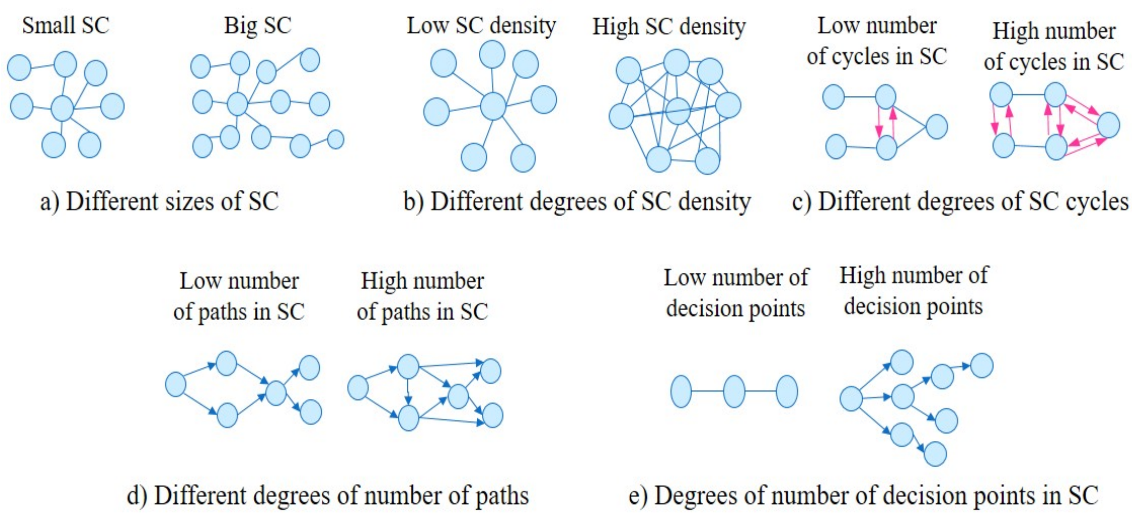


Figure 4.2 Network Complexity Indicators.

4.5 Network Robustness Indicators

Structural SC robustness depends on different factors and characteristics that may position a SC in a more vulnerable situation. Between the characteristics that will increase vulnerability, we consider that the following three are the most important: direct diffusion after disruption, the speed of disruption propagation and intermediaries that control the SC. These characteristics are matched with available network centrality metrics and are used as network robustness indicators. Then an overall robustness measure that quantifies the worst-case scenario in each indicator is derived. That is, the maximum value for each indicator between all the nodes is selected to calculate the overall robustness measure. In order to validate the proposed overall structural supply chain robustness, a comparison with another method is carried out in Appendix A.

4.5.1. *Maximum direct diffusion after disruption*

According to Valente (2010), the degree centrality is an indicator that is highly associated with accelerating direct diffusion. Degree centrality is a nodal measure where only direct paths are considered. As the supply relationships are analyzed, directed networks are used. For that, the in-degree and out-degree centrality are used to evaluate the maximum direct diffusion in the SC. The in-degree centrality of a node accounts for the flows received from other nodes. Contrary, the out-degree centrality is the number of flows initiated. In-degree and out-degree centrality indicate how many suppliers will be affected downstream (to send) and upstream (to receive) the disrupted node, as shown in Figure 4.3 (a). In-degree and out-degree centrality for each node are normalized to allow comparison between networks of different sizes. Normalized in-degree (ID) and out-degree (OD) centrality can be determined as shown in Equation (4.6) and Equation (4.7) where a_{ij} corresponds to the element (ith and jth) of the adjacency matrix A_{ij}. Hence, the sum in i for ID represents the number of inflows for node j and the sum in j for OD represents the number of outflows for node i, where $i, j = 1,\ldots,n$.

$$ID(N_j) = \frac{\sum_{i=1}^{n} a_{ij}}{n-1} \tag{4.6}$$

$$OD(N_i) = \frac{\sum_{j=1}^{n} a_{ij}}{n-1} \tag{4.7}$$

If there are less affected nodes, the SC will be more robust. So, in and out-degree centrality tend to 0 when the SC is more robust. In and out-degree are calculated for each node, then the maximum value of in-degree (MID) centrality and out-degree (MOD) centrality in all the network are used for the overall robustness measure.

4.5.2. *Maximum speed of disruption propagation*

Closeness was introduced as a measure of speed of disruption in the context of SC by Ledwoch et al. (2016). Closeness has been used for undirected supply networks or contractual relationships. But, we consider that in-closeness (IC) centrality and out-closeness (OC) can be used to directed SC networks. In and out –closeness can be used to measure how the disruption is propagated upstream and downstream (receiving and sending), as shown in Figure 4.3 (b). Additionally, we are considering these two measures because the distance between two nodes can be different if there are intermediate suppliers in one of the flows. Closeness is calculated as shown in Equation (4.8), where $d(Ni, Nj)$ is the geodesic distance between nodes Ni and Nj.

$$C(N_i) = \frac{1}{\left[\sum_{j=1}^{n} d(Ni, Nj)\right]} (i \neq j) \tag{4.8}$$

This measure is normalized by multiplying $C(N_i)$ by $(n-1)$. A low result of closeness is desirable in order to contain the disruption. If the results tend to 1, the disruption will spread more quickly, so the network becomes more vulnerable. After calculating in- and out-closeness for all the nodes, the maximum values of in-closeness (MIC) and out-closeness (MOC) are selected to assess the overall network robustness.

Two versions of each index are used, an unweighted and a weighted version. Consequently, the maximum of the weighted values of in-closeness (MWIC) and out-closeness (MWOC) centrality are analyzed. It is important to mention that speed is considered as the number of steps that products follow in the SC, it is not related to time. So in a high speed of dispersion, suppliers that are closer would have the higher speed. In the weighted version, transit times between nodes are used. According to Dong and Chen (2007), transit times describe the links' robustness. The assumption is that larger transit times increase the probability of disruptions. In order to calculate the weighted version, the elements in the matrix $\boldsymbol{A}_{i \times j}$ are replaced with the transit time to traverse from one node to another, instead of 1.

4.5.3. *Maximum high-risk intermediary*

Betweenness centrality has been used to identify high-risk suppliers as presented by Ledwoch et al. (2016). Additionally, it was used to assess robustness as proposed by

Monostori (2016). This measure concerns how other actors mediate the relations between nodes that are not directly connected (Kim et al. 2011), as shown in Figure 4.3 (c). A high value of betweenness means that the evaluated node is an intermediary between a high number of relationships in the network. If there are more intermediaries the probability of disruption is higher, or if the intermediary that regulates most relationships is damaged, the disruption will affect the SC more; so the network becomes more vulnerable. A low result of betweenness is desirable in order to be a more robust network. Betweenness is calculated as shown in Equation (4.9), where g_{jk} is the number of geodesic paths between node j and node k, where j, k =1,…,n. And $g_{jk}(N_i)$ is the number of geodesic paths that contains the node(N_i).

$$B(N_i) = \sum_{j<k} \frac{g_{jk}(N_i)}{g_{jk}} \tag{4.9}$$

Betweenness is normalized dividing $B(N_i)$ by $(n-1)(n-2)$. Betweenness tends to 1 when a node intermediates all the relations in the network, resulting in less robust network. The maximum value of betweenness (MB) is used to compute the overall robustness.

For the weighted version, elements in the matrix $\boldsymbol{A}_{i \times j}$ are replaced by the inversed transit times. The maximum value of the weighted betweenness (MWB) is employed to calculate the overall weighted robustness.

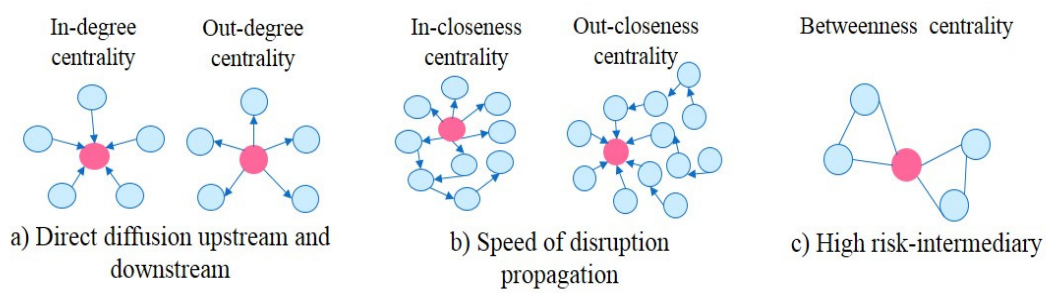


Figure 4.3 Network Robustness Indicators.

4.6 Overall Network Measures: Complexity and Robustness

Looking for measures that capture the complexity and robustness embedded in SCs, indices to evaluate structural supply chain complexity (SSCC) and structural supply chain robustness (SSCR) are hereby derived using the indicators explored in sections 4.4 and 4.5. Additionally, a weighted version of structural supply chain robustness (SSCWR) is presented. SSCC, SSCR, and SSCWR are introduced to ease comparison between different SC network configurations.

Due to the fact that the indicators presented in this research are correlated, methods of aggregation that include vector summation are not suited. For that, a method based on radar charts as presented by ElMaraghy et al. (2014) is used. The generic formula to calculate the overall indices is presented in Equation (4.10). Z is the aggregated measure of all individual indices, z_h. H is the total number of evaluating indices. Following the same formula to calculate Z; SSCC, SSCR, and SSCWR are derived.

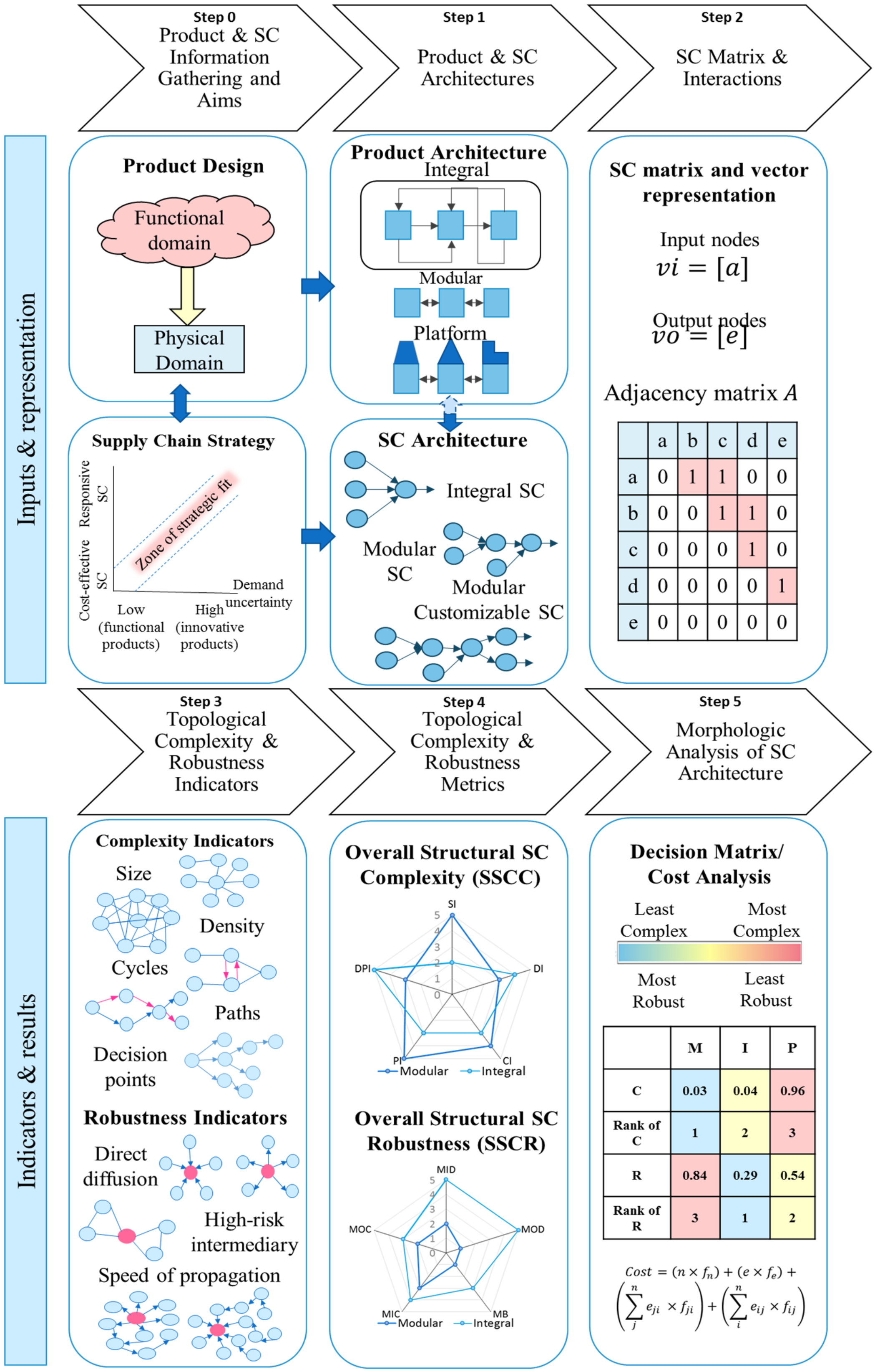
$$Z = \left(\sum_{h=1}^{H} z_h\right)^2 - \sum_{h=1}^{H} z_h^2 \tag{4.10}$$

Once the overall complexity and robustness metrics are calculated, a decision matrix is used to analyze and decide the best product/SC architecture. The summarized methodology to assess topological complexity and robustness is presented in Figure 4.4.

4.7 Cost Analysis

A common objective when designing the SC is cost minimization. So in order to compare the trade-offs between cost and robustness and complexity of the different product architectures / SC structures, a cost analysis is carried out as performed by Ivanov, Pavlov, and Sokolov (2016). The total cost of the SC network is calculated as shown in Equation (4.11), where $Cost$ is the total cost. e_{ji} is the number of incoming edges for node j and f_{ji} its associated cost. e_{ij} is the number of outgoing edges for node j and f_{ij} its associated cost. f_n is the cost of having a node in the SC and f_e is the cost of having an edge in the SC.

$$Cost = (n \times f_n) + (e \times f_e) + \left(\sum_{j}^{n} e_{ji} \times f_{ji}\right) + \left(\sum_{i}^{n} e_{ij} \times f_{ij}\right) \tag{4.11}$$



	a	b	c	d	e
a	0	1	1	0	0
b	0	0	1	1	0
c	0	0	0	1	0
d	0	0	0	0	1
e	0	0	0	0	0

	M	I	P
C	0.03	0.04	0.96
Rank of C	1	2	3
R	0.84	0.29	0.54
Rank of R	3	1	2

$$Cost = (n \times f_n) + (e \times f_e) + \left(\sum_j^n e_{ji} \times f_{ji}\right) + \left(\sum_i^n e_{ij} \times f_{ij}\right)$$

Figure 4.4 SC topological complexity and robustness framework.

4.8 Case Study

A case study based on the SC for a bulldozer as presented by Graves and Willems (2003) is used to evaluate complexity and robustness in integral, modular and modular customized SC configurations. Integral and modular architectures for the bulldozer are used as presented by Nepal, Monplaisir, and Famuyiwa (2012), as per Figure 4.5. Additionally, modular-customized architecture is included for the bulldozer as shown in Figure 4.6. The corresponding SCs for integral, modular and modular-customized architectures are presented in Figure 4.7, Figure 4.9 and Figure 4.11 respectively. Due to the integral and modular SC configurations (convergent supply chains) are more likely to happen in an assembly environment, two other configurations with modular and integral structure, but with outsourcing entities and alternative routes, are presented for each architecture (Figure 4.8 and Figure 4.10). Additionally, modular-customized SC configuration includes two manufacturers that produce a semi-finished product that is sent to several manufacturers that can finish the product in different locations as per Figure 4.12.

The SC configurations are identified as: integral (I1), integral with interchange of materials between suppliers (I2), modular (M1), modular with three final assemblers and interchange of material between them (M2), modular customized with two semi-final assemblers and four final assemblers (MC1), and modular customized with two semi-final assemblers, four final assemblers and interchange of material between suppliers (MC2). Additionally, the weighted version of each configuration is identified as follows: I1W, I2W, M1W, M2W, MC1W, and MC2W.

Each configuration is evaluated for complexity and robustness. Complexity evaluation is the same for the weighted and unweighted SC. For robustness evaluation, there are differences in closeness and betweenness for the unweighted and weighted versions. Transit times are assigned to each edge in each configuration. Table 4.2, Table 4.3, Table 4.4 and Table 4.5 show the edges in each configuration and the weight of each edge. For the unweighted versions, 1 is assigned as weight in all existing edges. From these tables, adjacency matrices and vectors $\boldsymbol{vi}$ and $\boldsymbol{vo}$ are constructed as shown in Table 4.6. Functions in Matlab to compute complexity and robustness were developed to speed up the calculation process.

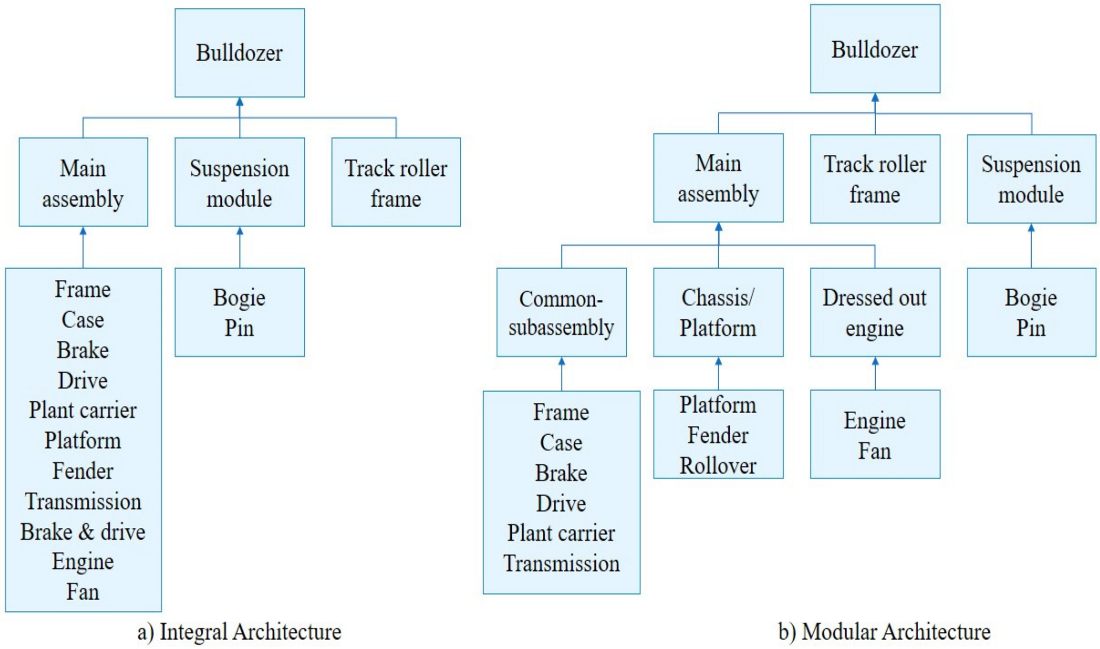


Figure 4.5 Integral and modular product architecture for bulldozer. Adapted from (Nepal, Monplaisir, and Famuyiwa 2012).

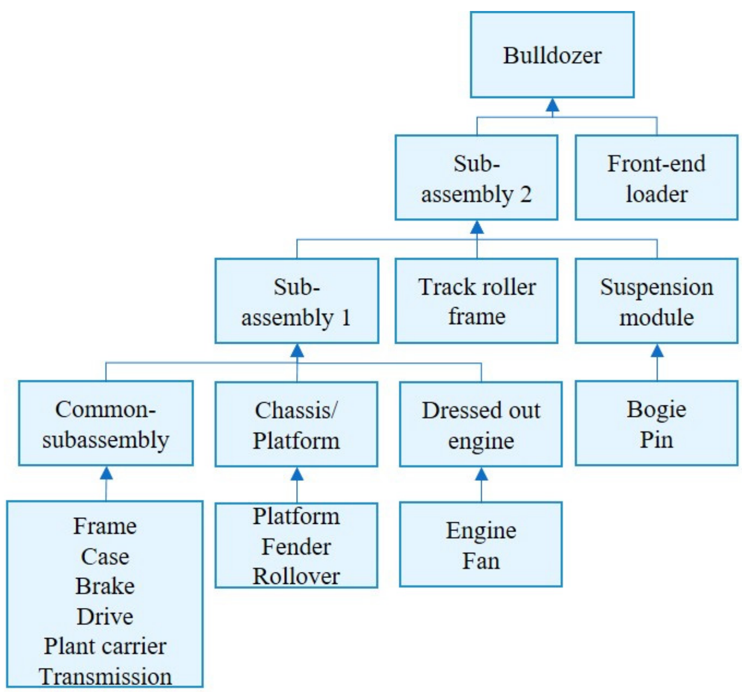


Figure 4.6 Modular-customized product architecture for bulldozer.

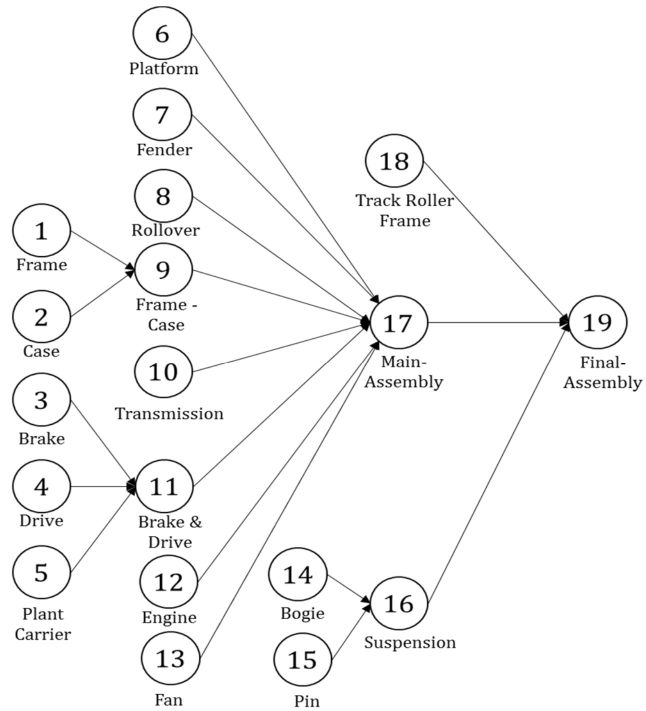


Figure 4.7 SC configuration for integral (I1).

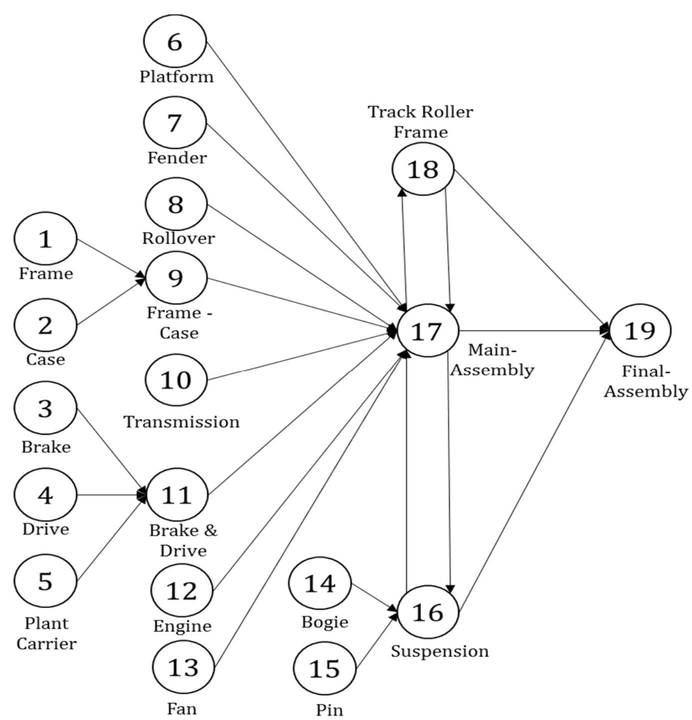


Figure 4.8 SC configuration for integral (I2).

Table 4.2 Edge table of I1W & I2W configurations.

		I1W		I2W					
From		**To**	**Weight**	**To**	**Weight**	**To**	**Weight**	**To**	**Weight**
1	Frame	9	10	9	10				
2	Case	9	10	9	10				
3	Brake	11	10	11	10				
4	Drive	11	10	11	10				
5	Plant Carrier	11	10	11	10				
6	Platform	17	5	17	5				
7	Fender	17	5	17	5				
8	Rollover	17	5	17	5				
9	Frame-Case	17	5	17	5				
10	Transmission	17	5	17	5				
11	Brake & Drive	17	5	17	5				
12	Engine	17	5	17	5				
13	Fan	17	5	17	5				
14	Bogie	16	10	16	10				
15	Pin	16	10	16	10				
16	Suspension	19	2	17	1	19	2		
17	Main-Assembly	19	2	16	10	18	10	19	10
18	Track Roller Frame	19	2	17	1	19	2		
19	Final-Assembly								

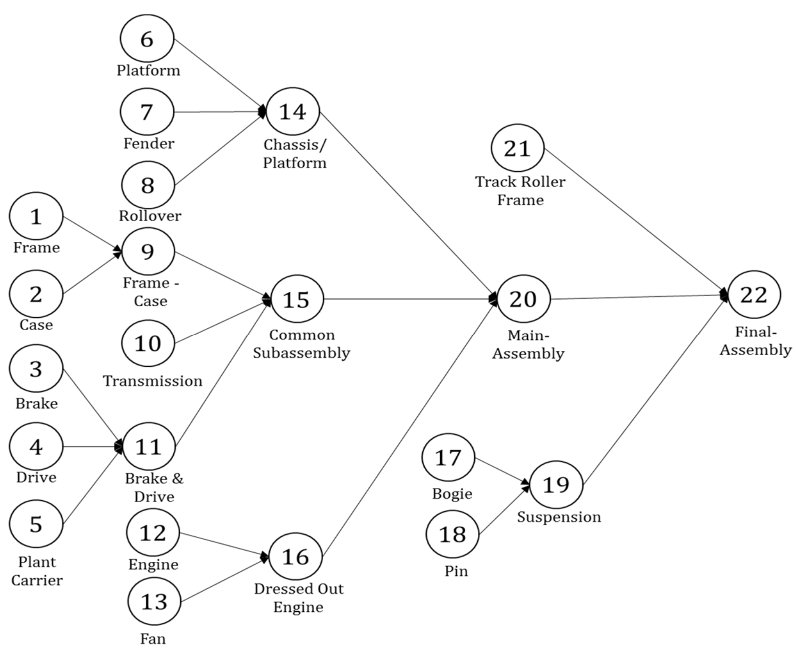


Figure 4.9 SC configuration for modular (M1).

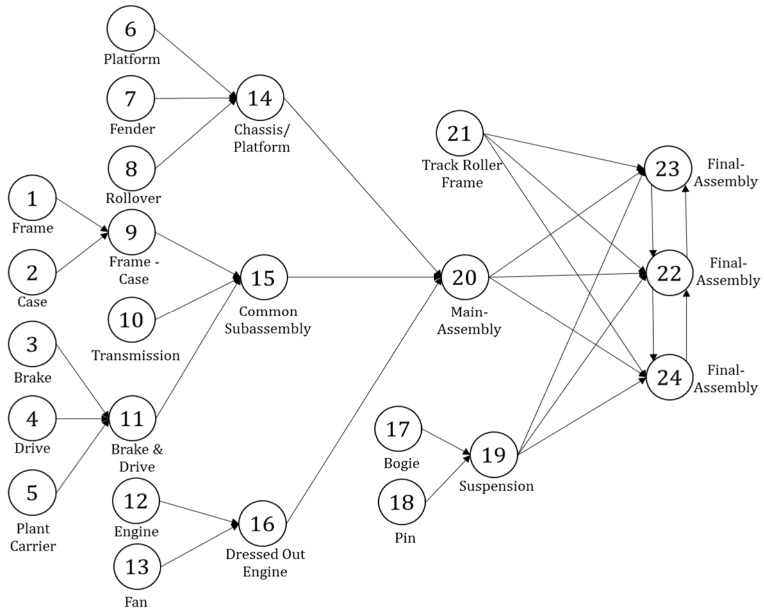


Figure 4.10 SC configuration for modular (M2).

Table 4.3 Edge table of M1W & M2W configurations.

		M1W		M2W					
From		**To**	**Weight**	**To**	**Weight**	**To**	**Weight**	**To**	**Weight**
1	Frame	9	10	9	10				
2	Case	9	10	9	10				
3	Brake	11	10	11	10				
4	Drive	11	10	11	10				
5	Plant Carrier	11	10	11	10				
6	Platform	14	10	14	10				
7	Fender	14	10	14	10				
8	Rollover	14	10	14	10				
9	Frame-Case	15	5	15	5				
10	Transmission	15	5	15	5				
11	Brake & Drive	15	5	15	5				
12	Engine	16	10	16	10				
13	Fan	16	10	16	10				
14	Chassis/Platform	20	5	20	5				
15	Common Subassembly	20	5	20	5				
16	Dressed Out Engine	20	5	20	5				
17	Bogie	19	5	19	5				
18	Pin	19	5	19	5				
19	Suspension	22	2	22	2	23	2	24	2
20	Main-Assembly	22	2	22	2	23	2	24	2
21	Track Roller Frame	22	2	22	2	23	2	24	2
22	Final-Assembly	-	-	23	1	24	1		
23	Final-Assembly	N/A	N/A	22	1				
24	Final-Assembly	N/A	N/A	22	1				

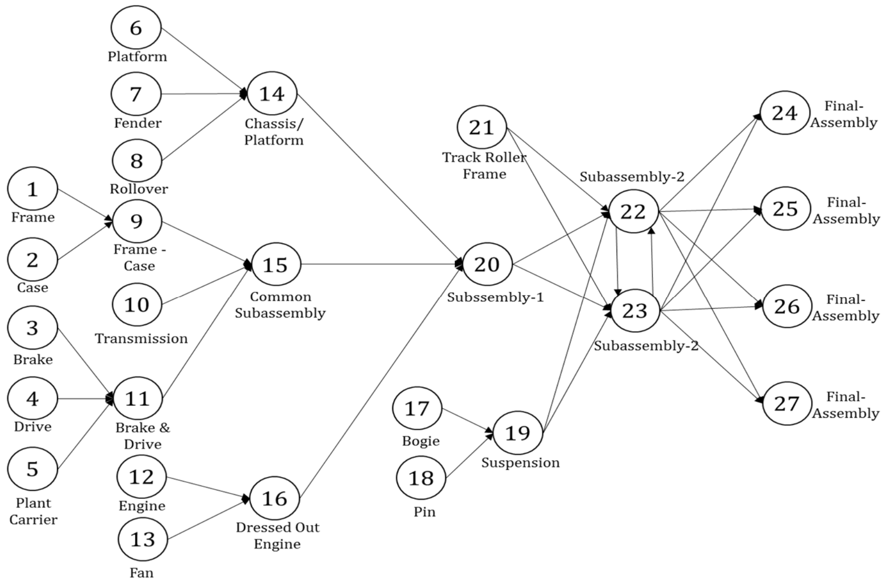


Figure 4.11 SC configuration for modular (MC1).

Table 4.4 Edge table of MC1W configuration.

		MC1W							
From		**To**	**Weight**	**To**	**Weight**	**To**	**Weight**	**To**	**Weight**
1	Frame	9	10						
2	Case	9	10						
3	Brake	11	10						
4	Drive	11	10						
5	Plant Carrier	11	10						
6	Platform	14	10						
7	Fender	14	10						
8	Rollover	14	10						
9	Frame-Case	15	5						
10	Transmission	15	5						
11	Brake & Drive	15	5						
12	Engine	16	10						
13	Fan	16	10						
14	Chassis/Platform	20	5						
15	Common Subassembly	20	5						
16	Dressed Out Engine	20	5						
17	Bogie	19	5						
18	Pin	19	5						
19	Suspension	22	2	23	2				
20	Subassembly-1	22	2	23	2				
21	Track Roller Frame	22	2	23	2				
22	Subassembly-2	24	1	25	1	26	1	27	1
23	Subassembly-2	24	1	25	1	26	1	27	1
24	Final-Assembly								
25	Final-Assembly								
26	Final-Assembly								
27	Final-Assembly								

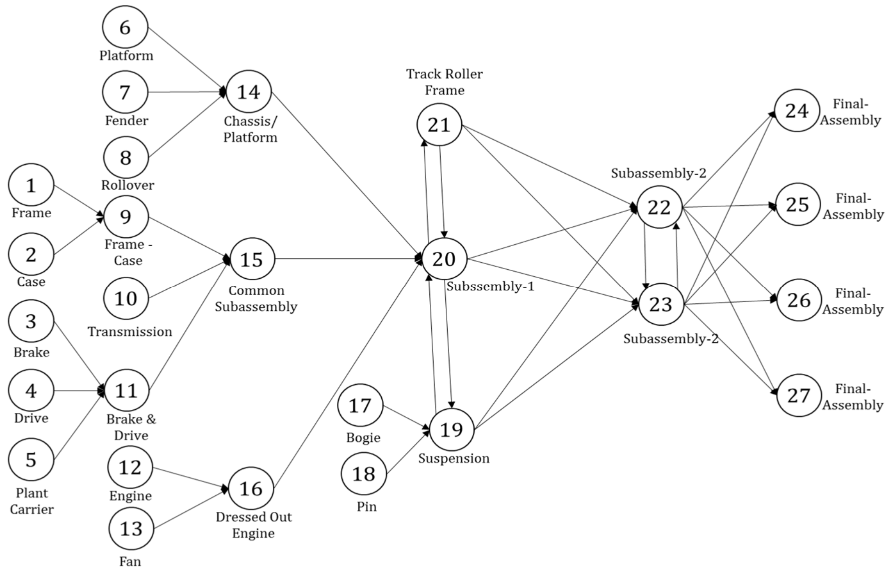


Figure 4.12 SC configuration for modular (MC2).

Table 4.5 Edge table of MC2W configuration.

		MC2W							
From		**To**	**Weight**	**To**	**Weight**	**To**	**Weight**	**To**	**Weight**
1	Frame	9	10						
2	Case	9	10						
3	Brake	11	10						
4	Drive	11	10						
5	Plant Carrier	11	10						
6	Platform	14	10						
7	Fender	14	10						
8	Rollover	14	10						
9	Frame-Case	15	5						
10	Transmission	15	5						
11	Brake & Drive	15	5						
12	Engine	16	10						
13	Fan	16	10						
14	Chassis/Platform	20	15	22	1				
15	Common Subassembly	20	15	22	1				
16	Dressed Out Engine	20	15	22	1				
17	Bogie	19	5						
18	Pin	19	5						
19	Suspension	20	1	22	1	23	15		
20	Subassembly-1	19	1	21	1	22	1	23	15
21	Track Roller Frame	20	1	22	1	23	15		
22	Subassembly-2	24	1	25	1	26	1	27	1
23	Subassembly-2	24	15	25	15	26	15	27	15
24	Final-Assembly								
25	Final-Assembly								
26	Final-Assembly								
27	Final-Assembly								

Table 4.6 Input and output nodes for each SC configuration.

Code	Inputs	Outputs
I1/I2	1,2,3,4,5,6,7,8,10,12,13,14,15,18	19
M1	1,2,3,4,5,6,7,8,10,12,13,17,18,21	22
M2	1,2,3,4,5,6,7,8,10,12,13,17,18,21	22,23,24
MC1	1,2,3,4,5,6,7,8,10,12,13,17,18,21	24,25,26,27
MC2	1,2,3,4,5,6,7,8,10,12,13,17,18,21	24,25,26,27

4.9 Results and Discussion

Six SC configurations were analyzed under three product architectures (integral, modular and modular customized). Unweighted and weighted versions for robustness were considered. As a result, twelve different scenarios were evaluated. The results are shown in Table 4.7. Structural SC complexity (SSCC) that results in 0 indicates the least complex SC structure, and as the number increases, the SC structure increases its complexity. Similarly, the structural SC robustness (SSCR) and the structural SC weighted robustness (SSCWR) that score 0 indicates that the SC structure is the least vulnerable or most robust, and as the score increases the SC is less robust.

4.9.1. *Structural Supply Chain Complexity (SSCC)*

To calculate the SSCC, five individual complexity indices were evaluated. For size index (SI), the structure with the least complexity is I1; this structure has the smallest number of nodes and links. In contrast, MC2 is the most complex because it has the largest number of nodes and edges. Although I1 is the least complex in size, it is the densest between all the analyzed structures. Similarly, MC2 is the least dense; the reason is the addition of SC entities. Regarding cycle index, configurations I2, M2, and MC2 are including cycles in their structures. Nevertheless, the three configurations have two cycles in total; the results are different. The results change due to the maximum theoretical number of cycles increases as the number of nodes increases. With respect to the path index, I2, M2, and MC2 are the most complex. These results are the effect of the inclusion of extra edges to form the cycles. In regard to decision points index, I1 is the least complex and M2 the most complex. These results are coherent with their structures. As the analysis of the individual complexity indices showed, the least complex structure in almost all the cases is the integral (I1), and the most complex is the modular customized (MC2). Although the results can change according to the SC structure, the product architectures analyzed in each configuration suggest that the least complex architecture is the integral and the most complex architecture is the modular customized.

Table 4.7 Comparison of complexity and robustness indices.

Least Complex					**Most Complex**
Most Robust					**Least Robust**

Indices		I1	I2	M1	M2	MC1	MC2
Size Index	SI	0.000	0.182	0.000	0.258	0.188	0.333
Density Index	DI	0.588	0.048	0.050	0.033	0.032	0.026
Cycle Index	CI	0.000	0.002	0.000	0.001	0.000	0.001
Path Index	PI	0.000	0.763	0.000	0.777	0.500	0.903
Decision Point Index	DPI	0.500	0.600	0.600	0.667	0.500	0.571
Structural SC Complexity(SSCC)		**0.059**	**1.564**	**0.060**	**1.897**	**0.952**	**2.113**
Rank of Complexity		**1**	**4**	**2**	**5**	**3**	**6**
Max In-Degree	MID	0.444	0.556	0.143	0.217	0.115	0.231
Maximum Out-Degree	MOD	0.056	0.167	0.048	0.130	0.154	0.154
Maximum Betweenness	MB	0.043	0.141	0.038	0.095	0.148	0.114
Maximum In-Closeness	MIC	0.522	0.669	0.368	0.390	0.298	0.414
Maximum Out-Closeness	MOC	0.083	0.167	0.076	0.130	0.154	0.205
Structural SC Robustness(SSCR)		**0.8351**	**2.0531**	**0.2875**	**0.685**	**0.538**	**0.9452**
Rank of Robustness		**4**	**6**	**1**	**3**	**2**	**5**
		I1W	**I2W**	**M1W**	**M2W**	**MC1W**	**MC2W**
Maximum In-Degree	MID	0.444	0.556	0.143	0.217	0.115	0.231
Maximum Out-Degree	MOD	0.056	0.167	0.048	0.130	0.154	0.154
Maximum Wt. Betweenness	MWB	0.043	0.141	0.038	0.130	0.148	0.179
Maximum Wt. In-Closeness	MWIC	0.105	0.112	0.077	0.084	0.069	0.099
Maximum Wt. Out-Closeness	MWOC	0.028	0.083	0.024	0.087	0.154	0.154
SSC Weighted Robustness(SSCWR)		**0.2421**	**0.7444**	**0.078**	**0.2886**	**0.322**	**0.5238**
Rank of Weighted Robustness		**2**	**6**	**1**	**3**	**4**	**5**

4.9.2. *Structural Supply Chain Robustness (SSCR)*

In order to compute the structural supply chain robustness (SSCR) and its weighted version (SSCWR), five individual indices of robustness are evaluated. For the maximum in-degree, MC1 is the most robust structure because its maximum direct connection is the smallest between all the structures. Contrary, I2 is the least robust structure. The reason is that this kind of structure aggregates several flows into one node. Regarding the maximum out-degree, M1 is the most robust, as just one flow goes out of each supplier and the network size is bigger than I1, so the direct disruption diffusion is lower. I2 has the maximum out-degree MOD between all the structures, although the maximum number of connections going out is three in most of the structures, the MOD is greater due to the network size. With respect to betweenness, M1 is the most robust. As a result, the maximum high-risk intermediary in this configuration is less risky than MC1. Fewer supply relationships are at risk in M1 because the intermediary does not control many relationships. Regarding the maximum in-closeness, I2 and I1 are the least robust structures, the cause of this result is the many inflows that the main assembly supplier has. Hence, a disruption happening in these structures will be propagated downstream quicker than in a structure like MC1 or M1. Similarly, in M1 the MOC is the best. Therefore, this structure is the most robust with the least affection for the disruption upstream. Regarding the overall robustness measure, M1 is the most robust and the integral with cycles (I2) is the least robust.

Regarding the weighted version of the SC robustness (SSCWR), MID and MOD remain the same due to we are not weighting these measures. MWB has changed in the weighted versions of M2 (M2W) and MC2 (MC2W). This metric is based on the shortest path between nodes; therefore, if a link is assigned a bigger weight, the measures will look to calculate the route with the smaller weight. For that, betweenness will change depending on the path taken and the high-risk intermediary could be a different one. In this case, M1W remains as the most robust structure. But, MC2W is now the least robust. Similarly, MWIC and MWOC have changed because the transit times have been weighted. Concerning MWIC, MC1W and I2W keep their position as the most robust and least robust respectively. But the values of MWIC have changed considerably due to the transit-time weights. Similarly, results for MWOC have changed. But the ranks of the most and least robust remain the same. Regarding the overall robustness, M1W remains the most robust and I2W the least robust. But, it is important to note that the I1W is the second most robust structure. It is worth mentioning that these results depend on the transit times assigned. Different transit times can change the metrics results and lead to choosing a different SC configuration.

4.9.3. *Cost analysis and trade-offs analysis*

The total costs shown in Table 4.8 are calculated according to Equation (11) for the basic structures (I1, M1, and MC1) in order to derive more general insights. The considered costs are as follows: f_{ji} = \$20, f_{ij} = \$20, f_n = \$100 and f_e = \$10. Additionally, for the sake of comparison, the percentage of increments in cost, complexity, and robustness are calculated, as shown in Table 4.8. It can be noted that changing from an integral to a modular architecture, cost increases almost by 16% and complexity increases by only 2%. Importantly, robustness increases are 65% (remember that SSCR that tends to 0 is better). Comparing an integral to a modular-customized architecture, there is an increment of almost 48% in cost. Notably, there is a 1,518% in the increase of complexity whilst the robustness is increased by 35% only. Albeit cost is important for designing the supply chain and product architecture, the reduction of decisions to cost could lead to a poor design decision. After analysing the three alternatives, the modular structure is best as an increase of 65 % of robustness is worth only 16% of cost increase. This increment in the cost is what is known as a cost of robustness (Ivanov 2018).

Table 4.8 Costs and trade-offs analysis.

	Integral (I)	Modular (M)	(MC)	%Δ I to M	%Δ I to MC
Cost	2326	2692	3434	16	48
SSCC	0.0588	0.06	0.9516	2	1518
SSCR	0.8351	0.2875	0.5380	-66	-36

4.9.4. *Ideal supply chain structure*

Certainly, a SC that offers less complexity is ideal. However, the robustness level of this ideal configuration can be low. Additionally, robustness can be increased with redundancies, but it will increase the complexity and cost. As a result, a balance between complexity, robustness and cost needs to be considered, as shown in the case study. A summary of the network topology characteristics that we consider key for an ideal SC configuration is shown in Figure 4.13. These basic characteristics (Figure 4.13) in some cases are contradictory, hence the complication of balancing them. As a result, we can state that complexity is needed to achieve and/or improve robustness.

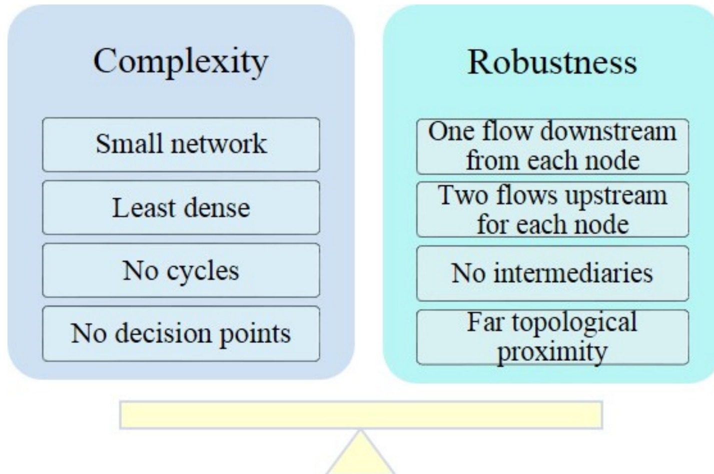


Figure 4.13 Ideal characteristics for less complexity and more robustness in SC.

4.10 Summary

Supply chain networks are complex because of a large number of interacting operations required in order to accomplish their objectives. Therefore, these complex networks are prone to suffer any kind of disruptions. In this research, a framework to analyze structural SC complexity and robustness is presented based on network characteristics. The framework considers the product architecture and its corresponding SC. The framework is intended to facilitate the comparison between different SC structures. The presented methodology can be used in the early stages of the product/supply chain design or redesign, as well as an evaluation method and risk analysis.

The application of the proposed framework is done with the purpose of identifying structural outliers or weak spots in the SC and not for a precise measurement. The structural metrics are intended to support systematic analysis of characteristics that could increase the complexity or robustness of the network. The overall indices allow grasping the current situation at one glance and can serve as a basis for decision-making. While different characteristics of the network structure would determine the supply chain performance, a parallel analysis that includes operational parameters is needed in order to make a decision. However, the conjoint analysis of complexity, robustness and product architecture can improve the decision process in the design of products and supply chains.

Moreover, it is shown that different product architectures for the same product could lead to different SC complexity and robustness. However, the increase in the structure cost will not determine the increase in complexity and robustness. The results of this work suggest that a modular architecture is preferable to achieve a more robust SC structure with a reasonable level of complexity. Additionally, structures that contain cycles increase complexity and decrease robustness considerably. Moreover, weighted structures lead to more descriptive results about the robustness of the SC structure.

There are several areas in which this research can be extended. First, the consideration of larger instances and different SCs types. Second, multi-domain matrices that use supply networks and contractual relationships as well as product variety level in each node. Finally, supplier selection is a future extension of this work.

CHAPTER 5. SUPPLY CHAIN DISRUPTION ANALYSIS: A SYSTEM DYNAMICS APPROACH

5.1 Overview

In this section, a decision support system (DSS) is developed using system dynamics methodology. The objective of the DSS is to offer guidance to supply chain managers to evaluate disruptions and possible mitigation strategies. The unique characteristic of the model is the inclusion of an assembly echelon, the usage of partial capacity degradation, and expediting of products after disruption restoration.

5.2 Introduction

Supply chains are networks that cooperate to fulfil the customer requirements. The study of supply chain disruptions has been catching interest in the last decade due to the magnitude of impacts that they could cause on the SC performance. Several studies have been dedicated to analyzing the effects of reactive or proactive mitigation strategies. Despite the increasing number of researchers working in this critical area, managers still need a tool to guide them to make the most beneficial decision.

Several risk mitigation strategies could be used to minimize the impacts of disruptions. Proactive strategies include backup-suppliers, inventory and capacity buffers, SC localization and segmentation, product and process flexibility, coordination and contracting and backup IT. Reactive strategies consider parametrical adaptation (e.g. expediting), process and product adaptation (flexibility reserves), SC structure adaptation (backup suppliers) and system adaptation (strategy and organization)(Ivanov, Dolgui, and Sokolov 2015). Depending on the disruption duration and severity, different strategies can be considered.

Due to the fact that the most dangerous disruptions are the black-swan events or high-impact low-probability situations, this research is focused on this kind of effects. Black-swan events are difficult to predict. As a result, it is easier to analyze the consequences rather than the causes. In this research, a methodology for decision making is developed to design disruption policies for supply chains that are prepared for the unexpected. We are trying to answer the following questions:

- How can decision-makers evaluate the impact of disruptions during SC design, planning stage?
- What is the performance of the SC in the presence of partial disruptions or full disruptions?
- What is the performance of the SC in the presence of order expediting after the disruption?
- What happens if the disruption occurs in the assembly echelon or the middle echelons?
- What if there is more than one disruption?

The approach used in this study to address the questions mentioned before is simulation. Simulation models can describe complex problems; they offer the opportunity to perform different experiments on systems. Although simulation is very useful to analyze different scenarios, managers are more concentrated in observing the trade-off of the possible scenarios. For that, the simulation model is not enough for managers. A pragmatic, implementable and yet cost-effective tool to provide organizational support is needed.

The first objective of this study is to develop a framework using system dynamics that reflect the behaviour of the supply chain and the possible disruptions and mitigation strategies that could be used. The second objective is to develop a quantitative approach to support decision making regarding the planning for disruptions. The primary focus of the framework is in assembly products. This kind of products needs all the components to be considered final products. Depending on the product and on the missing component, strategies, like building incomplete units and add missing components later, can be used to continue production. However, if there is a critical component that is missing, this strategy could not work.

System dynamics models are usually developed for the strategic or tactical level of decision, for that details are avoided. However, in the presence of disruption, most probably at least one material would not be supplied. In the developed model, a plant with an assembly process is simulated. For simplicity, two components are considered, one that is critical and a second one that is easy to get from alternative suppliers. For that reason, component segmentation can be carried out in advance to identify the critical components. The analysis is focused on the critical component. However, the structure for the other component is in place.

In this study, capacity disruption is considered. Full and partial disruptions are studied. In the full disruption, the affected supply chain echelon cannot produce, place orders or deliver during the disruption time. A similar approach is used by Sarkar and Kumar (2015). In the partial disruption, the supply chain will continue working but at a lower capacity level and with a higher production cost. Hence, the partial disruptions could represent mitigation strategies. Additionally, the model considers expediting products after the disruption.

Expediting is a common practice that is implemented in the SCs for securing timely delivery of goods and components. Depending on the echelon, orders are expedited with premium costs. Expediting is commonly achieved using production adjustments (overtime, additional shifts, etc.) and faster transportation options. Different triggers for expediting are used in the SCs (Schmitt et al. 2017). In this research, production expediting by reducing the production time is considered to mitigate the effects of the disruptions.

5.3 The Supply Chain System Dynamics Framework (SCSD)

The framework proposed by Mehrjoo and Pasek (2015) was modified and extended to present a model for assembly products. Similar modelling structures of order fulfilment, backlogged orders, pricing and production were used. Additionally, structure of raw material inventory, orders supply line, capacity disruption, expediting, cost and trade were designed and implemented. A four-echelon supply chain with an assembly echelon is represented. Shortages are allowed in the form of backorders. It has the capability of expediting at the middle echelons. Several key performance indicators such as profit, cost, service levels, inventories and backlogs are evaluated. The model enables simulation of disruptions in the tier-1 supplier and the assembly plant. However, the same structures for the end-echelons can be adapted to allow disruptions and expediting. Moreover, the model permits disruptions in both echelons in different periods.

Assumptions:

- Periodic-review, order-up-to level policy
- Capacitated echelons
- Production expediting is allowed after the disruption finishes
- Different expediting rates are used at different costs. Quicker expediting means more expensive
- Lead time is known and constant in normal operations
- Customer demand is distributed uniformly in each period U(350,370) units/day
- The disrupted facility cannot place orders, produce orders or make shipments during a full disruption
- During a partial disruption, the facility continues working but at specified rate and cost
- For simplicity, cost per truck, and capacity of each truck in all the echelons are the same
- Disruptions are represented as a time delay

- Each echelon only has access to the demand information from immediate lower echelons
- Disruptions can happen just in the two intermediate echelons (tier-1 supplier and plant)

In the model, a generic disruption event is simulated as a time delay. This time delay allows the representation of different disruptions (natural disaster, strikes, etc.). Additionally, partial disruptions enable the consideration of proactive strategies. That is, instead of simulating a full disruption, a partial disruption is considered. This partial disruption will let the system keep working, but with an increment rate cost to the regular production cost. Hence, the costs of generic proactive strategies are implicitly implemented in the model.

For simplicity, the model omits the suppliers of the second component of the product. However, the representation of the stock and flow diagram will be equal to the representation of the suppliers of the modelled component.

5.3.1. *The model*

The system dynamics model has flow variables, stock variables and auxiliary variables. Flow variables characterize the rate of quantities in a given period, and they are represented by arrows. Stock variables are levels, accumulations or state variables and they are represented by squares. Auxiliary variables are elements needed to calculate flow and stock variables. They can be represented by circles. To be able to write the differential equations, notations have been assigned to each variable. The summary of all the notations used and the definition of them is shown in Table 5.1.

Table 5.1 Definition of notations.

Notation	Definition
Indices	
j	Supply chain echelon $j = 1$(Supplier Tier 2), 2 (Supplier Tier 1), 3 (Plant), 4 (Distributor Centre)
t	Time (day)
Parameters	
Bcr_j	Backlogged penalty rate, $j = 1, \dots 4$ (dmnl)
Bt_j	Backlogged adjustment time, $j = 1, \dots 4$ (day)
CAT_{jt}	Total capacity $j = 1,2,3$ (unit/day)
DD_{jt}	Delivery delay $j = 1,2,3$ (unit/day)
DEt_j	Min time to delivery (day)
H_j	Holding rate (dmnl)
It_j	Inventory revision adjustment time (day)
L_j	Lead time for products (day)

LR_j	Lead time for raw materials (day)
LTN_{jt}	Normal production time (day)
MC_j	Manufacturing/purchase cost increment rate (dmnl)
ORt_j	Orders adjustment time of raw material (day)
Ot_j	Orders adjustment time of products (day)
PCb_j	Base product cost, j=1(dollar/unit)
PrI_j	Price increment rate (dmnl)
SS_j	Safety stock days of final product (day)
SSR_j	Safety stock days of raw product (day)
TO_j	Time to order for production (time)
TOR_j	Time to order for raw materials (time)
TRc_j	Cost per truck (dollar/truck)
$TRca$	Truck capacity (unit/truck)
$WIPt_j$	WIP adjustment time (day)
User Interface Parameters	
CAr_j	Disrupted capacity rate, $j = 2,3$ (dmnl)
CER_j	Currency exchange rate, $j = 1, \ldots 4$ (dmnl)
DIS_j	Disruption active or inactive (0 or 1)
ED_j	Number of expediting days, j=2,3 (day)
ER_{jt}	Expediting rate, j=2,3 (dmnl)
$Fday_j$	Disruption finish day j=2,3 (day)
$Sday_j$	Disruption start day j=2,3 (day)
Stock Variables	
BO_{jt}	Backlogged orders, $j = 1, \ldots 4$ (unit)
$CSCC_{jt}$	Cumulative supply chain cost (dollar)
$CSCP_{jt}$	Cumulative supply chain profit (dollar)
I_{jt}	Inventory of products (unit)
IR_{jt}	Inventory of raw materials (unit)
IRG_{jt}	Inventory of general raw materials $j = 3$ (unit)
On_{jt}	On order products to upstream echelon (unit)
WIP_{jt}	In process products/ Received Products (unit)
Flow Variables	
BD_{jt}	Backlogged orders delivered, $j = 1, \ldots 4$ (unit/day)
BIF_{jt}	Backlogged inflow, $j = 1, \ldots 4$ (unit/day)
DE_{jt}	Delivered products (unit/day)
F_{jt}	Feasible production rate, $j = 1,2,3$ (unit/day)
FL_{jt}	Flow of products $j = 4$ (unit/day)
$FLDO_{jt}$	Flow of delivered orders $j = 2,3,4$ (unit/day)
FLO_{jt}	Flow of orders $j = 2,3,4$ (unit/day)
FP_{jt}	Produced or ready to ship products (unit/day)
RR_{jt}	Received rate of raw materials (unit/day)
SCC_{jt}	Supply chain cost (dollar/day)
SCP_{jt}	Supply chain profit (dollar/day)
UR_{jt}	Usage rate of raw materials (unit/day)
URG_{jt}	Usage rate of general raw materials $j = 3$ (unit/day)
Auxiliary Variables	
BC_{jt}	Backlogged cost, $j = 1, \ldots 4$ (dollar/day)
CA_{jt}	Capacity $j = 1,2,3$ (unit/day)
$CArc_j$	Cost rate increment of disrupted capacity, $j = 2,3$ (dmnl)

$AdWIP_j$	Adjustment for WIP (unit/day)
D_{jt}	Demand for echelon (unit/day)
DPR_j	Desired production rate (unit/day)
ERc_{jt}	Increment cost rate of expediting, j=2,3 (dmnl)
FO_{jt}	Firm orders (unit/day)
IP_{jt}	Inventory position (unit)
LT_{jt}	Production time (day)
MI_j	Maximum inventory (unit)
MRI_j	Maximum raw material inventory (unit)
O_{jt}	Orders of final products (unit/day)
OR_{jt}	Orders of raw material (unit/day)
P_{jt}	Profit (dollar/day)
Pr_j	Price (dollar/unit)
R_{jt}	Revenue (dollar/day)
RIC_{jt}	Total raw material inventory cost (dollar/day)
RUC_j	Raw material unit cost (dollar/unit)
SL_{jt}	Service level in the echelon (dmnl)
TC_{jt}	Total cost (dollar/day)
TRn_{jt}	No. of trucks (truck/day)
$Trnc_{jt}$	Transportation cost (dollar/day)
TUC_j	Total unit cost (dollar/unit)
UC_j	Total base unit cost (dollar/unit)
UIC_j	Unit inventory cost (dollar/unit)
UPC_j	Base unit product cost (dollar/unit)
$WIPD_{jt}$	Desired in-process products (unit/day)

5.3.2. *Mathematical formulations*

The studied supply chain has four-echelons, one tier-2 supplier (ST2), one tier-1 supplier (ST1), one assembly plant (P) and one distribution centre (DC), as per Figure 5.1.

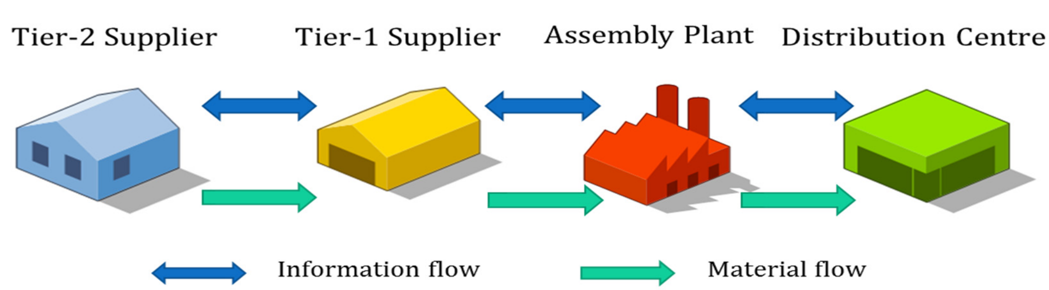


Figure 5.1 Top view of the SC model

Each echelon of the model can be represented by a policy structure diagram that shows the stocks, flows and decision structure of a model at a high level (Sterman 2000). The end-echelons (ST2 and DC) of our SC can be represented by the policy structure shown in Figure 5.2. Because tier-2 supplier has unlimited materials, it does not include the stocks and flows for raw material inventory and orders. The middle echelons (tier-1 supplier and assembler) are characterized by the policy structure presented in Figure 5.3. To develop the mathematical model and the differential equations, stock and flow diagrams are used.

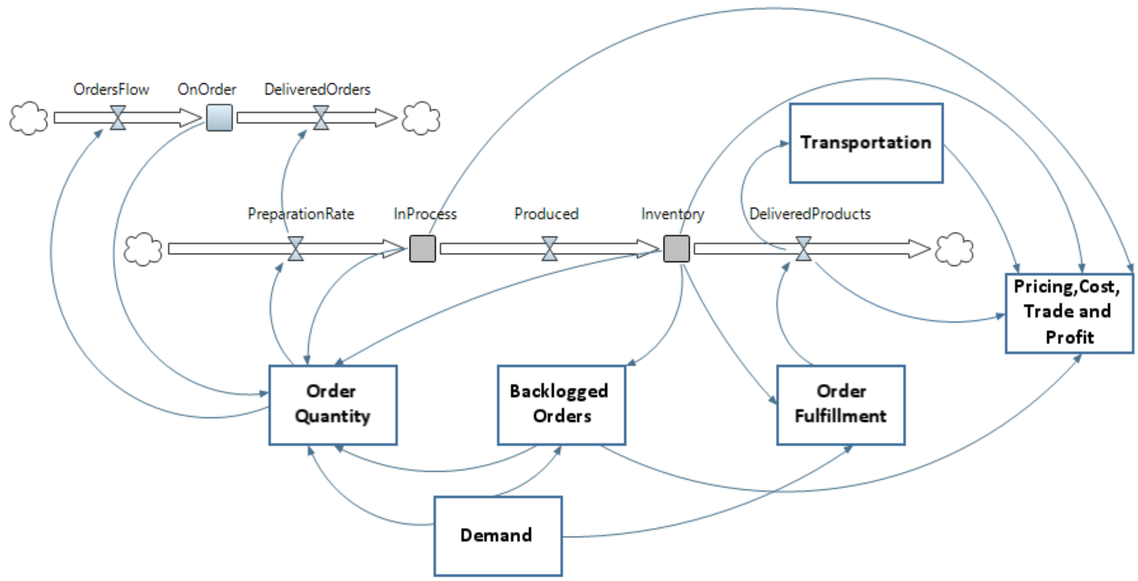


Figure 5.2 Policy structure of the end-echelons.

The expediting policy and the capacity-disruption policy presented in the middle-echelons can be easily replicated on the end-echelons to allow the analysis of them.

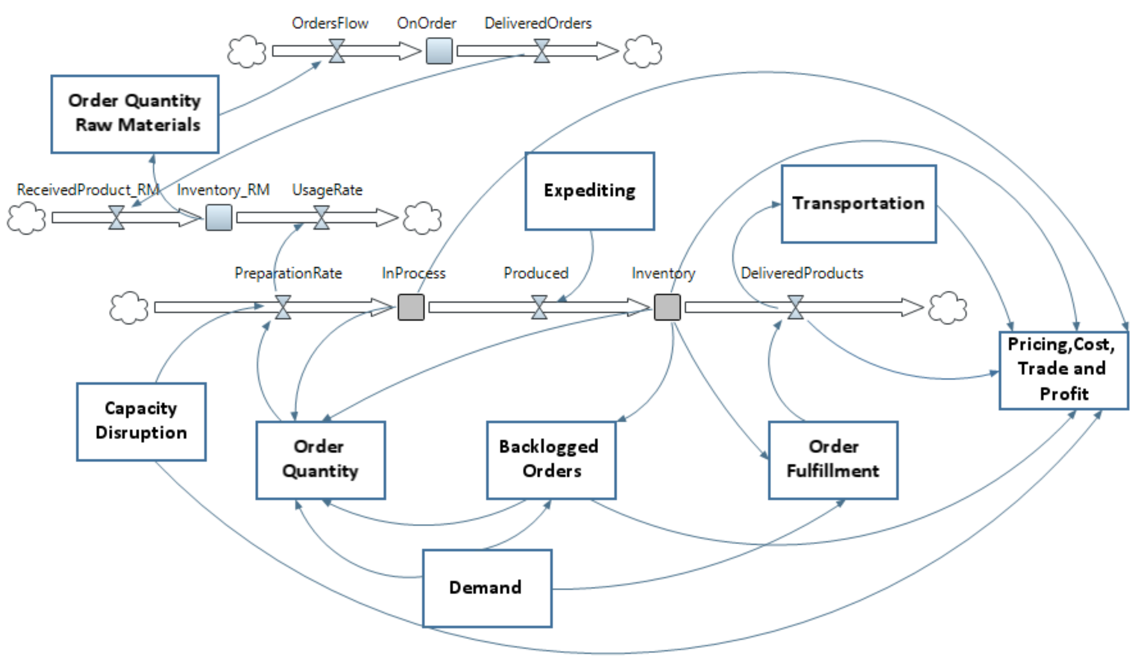


Figure 5.3 Policy structure of the middle-echelons.

5.3.2.1 Structure of demand and order fulfilment

In this model, just one general product is processed. At the distributor centre, the demand is modelled as Uniform (350,370) (units/day). For the assembler, the demand for products is ordered from the distributor centre. For the suppliers (tier 1 and tier 2), the demands are the orders of raw material from the downstream echelon, as presented in Equation (5.1). Product inventory is presented in Equation (5.2). The structure of demand and order fulfilment is shown in Figure 5.4.

$$D_j = \begin{cases} OR_{(j+1)t} & j = 1,2 \\ O_{(j+1)t} & j = 3 \\ Uniform(350,370) & j = 4 \end{cases} \tag{5.1}$$

$$\begin{cases} I_{jt} = I_{j0} + \int_0^t \left(FP_{jt} - DE_{jt}\right)dt \\ I_{j0} = I_{10} = 800 \quad I_{20} = 800 \quad I_{30} = 800 \quad I_{40} = 1200 \end{cases} \tag{5.2}$$

Delivery of products from the inventory to the downstream level depends on the firm orders and the inventory level, as represented by Equation (5.3) and Equation (5.4).

$$DE_{jt} = \begin{cases} 0, & DIS_j = 1 \ \& \ \text{Sday} \leq \text{t} \leq \text{Fday} \ \& \ CAr_j = 1 \\ 0, & I_{jt} < 0.001 \\ Min\left(FO_{jt}, \frac{I_{jt}}{DEt_j}\right), & O.W \end{cases} \quad j = 2,3 \tag{5.3}$$

$$DE_{jt} = Min\left(FO_{jt}, \frac{I_{jt}}{DEt_j}\right) \qquad j = 1,4 \tag{5.4}$$

The firm orders at any echelon are the sum of the demand plus the backlogged orders, as per Equation (5.5).

$$FO_{jt} = D_{jt} + \frac{BO_{jt}}{Bt_j} \tag{5.5}$$

The service level (fill rate) of each echelon is calculated as the rate between delivered products and firm orders as presented in Equation (5.6).

$$SL_{jt} = \frac{DE_{jt}}{FO_j} \tag{5.6}$$

5.3.2.2 Structure of backlogged orders

In all the considered levels of the SC, if there is not enough inventory to fulfil the demand, the orders are backlogged and added to the backlogged inflow (Equation (5.7)). The backlogged orders, as per Equation (5.8), in any echelon are fulfilled as soon as there is available inventory as shown in Equation (5.9). The structure of backlogged orders is shown in Figure 5.4.

$$BIF_{jt} = \begin{cases} D_{jt} - DE_{jt}, & DE_{jt} < D_{jt} \\ 0 & O.W. \end{cases} \tag{5.7}$$

$$BO_{jt} = BO_{j0} + \int_0^t \left(BIF_{jt} - BD_{jt}\right)dt \ ; \qquad BO_{j0} = 0 \tag{5.8}$$

$$BD_{jt} = \begin{cases} \dfrac{BO_{jt}}{Bt_j}, & DE_{jt} = FO_{jt} \\ DE_{jt} - D_{jt} & DE_{jt} > D_{jt} \\ 0 & O.W. \end{cases} \tag{5.9}$$

The work-in-process products are represented as Equation (5.10). The net inventory of products, named inventory position, in each echelon is a function of the inventory, work-in-process and backlogged orders as Equation (5.11). The inventory position in the non-production echelon (i.e. DC), considers the orders of products already placed to the upstream supplier, as shown in Equation (5.11).

$$WIP_{jt} = \begin{cases} WIP_{j0} + \int_0^t \left(F_{jt} - FP_{jt}\right)dt \ ; \ WIP_{j0} = 0, & j = 1,2,3 \\ WIP_{j0} + \int_0^t \left(FL_{jt} - FP_{jt}\right)dt \ ; \ WIP_{j0} = 0, & j = 4 \end{cases} \tag{5.10}$$

$$IP_{jt} = \begin{cases} I_{jt} - BO_{jt} + WIP_{jt}, & j = 1,2,3 \\ I_{jt} - BO_{jt} + WIP_{jt} + On_{jt}, & j = 4 \end{cases} \tag{5.11}$$

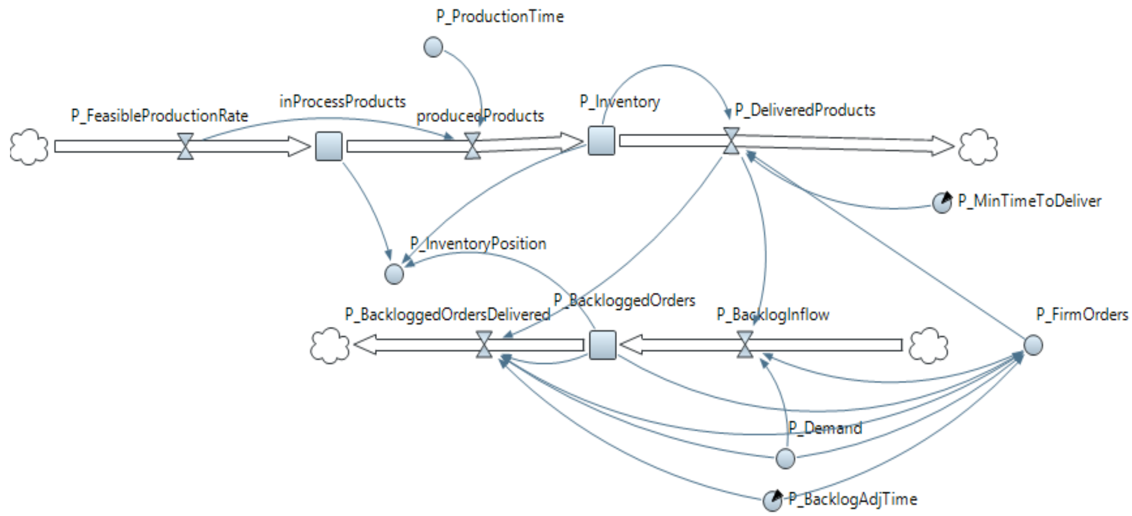


Figure 5.4 Structure of demand, order fulfilment and backlogged orders.

5.3.2.3 Structure of capacity disruption

Because capacity disruptions are just considered in the middle echelons (supplier tier 1 and plant), the production capacity of these echelons depends on the total capacity and the disrupted capacity rate, Equation (5.12). The disrupted capacity rate can range from 0 to 1. Where 1, represents a full disruption and in-between values represent a partial disruption. The structure of capacity disruption is shown in Figure 5.5.

$$CA_{jt} = \begin{cases} CAT_{jt} - (CAT_{jt} * CAr_j) & DIS_j = 1 \ \& \ Sday_j \leq \mathrm{t} \leq Fday_j \\ CAT_{jt} & O.W. \end{cases} \quad j = 2,3 \qquad (5.12)$$

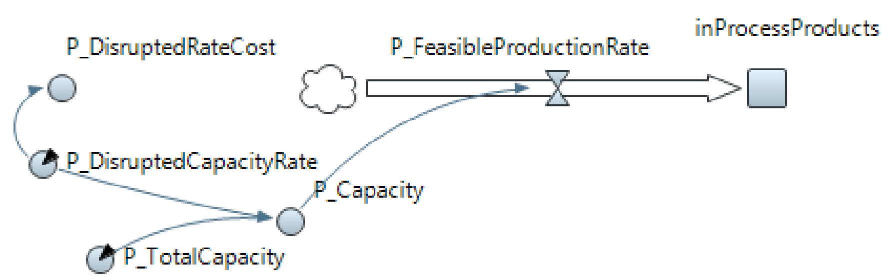


Figure 5.5 Structure of capacity disruption.

For the echelon 1 and 4 (supplier tier 2 and distribution centre), the capacity is equal to the total capacity, as per Equation (5.13).

$$CA_{jt} = CAT_{jt} \qquad j = 1,4 \qquad (5.13)$$

For the tier-2 supplier, the raw materials are unlimited. Hence, the feasible production rate is equal to the minimum between capacity and production orders, as per Equation (5.14).

$$F_{jt} = Min(CA_{jt}, O_{jt}) \quad j = 1 \tag{5.14}$$

For supplier tier-1, the feasible production in the middle echelons depends on the capacity and the raw materials available as shown in Equation (5.15).

$$F_{jt} = \begin{cases} 0, & CA_{jt} = 0 \\ Min(CA_{jt}, DPR_{jt}), & IR_j \geq Min(CA_{jt}, DPR_{jt}) \& \; CA_{jt} \neq 0 \\ IR_j, & IR_j < Min(CA_{jt}, DPR_{jt}) \& \; CA_{jt} \neq 0 \; \& \; IR_j > 0.001 \\ 0, & O.W. \end{cases} \quad j = 2 \tag{5.15}$$

For the assembly plant, two different materials are considered. A critical raw material that is denoted simply as raw material, and a second component that is considered a general raw material. The inventory for the general raw material is unlimited. Hence, this general component is represented by a stock (Equation (5.16)) that has enough material for the simulation run and a usage rate flow. The usage rate of this general raw material is equal to the feasible production rate as per Equation (5.17). Consequently, the feasible production rate in the plant depends on the availability of the two components as shown in (5.18).

$$IRG_{jt} = IRG_{j0} - \int_0^t (URG_{jt}) dt \, ; \; IRG_{j0} = 2000000, j = 3 \tag{5.16}$$

$$URG_{jt} = F_{jt}, \quad j = 3 \tag{5.17}$$

$$F_{3t} = \begin{cases} 0, & CA_{jt} = 0 \\ Min(CA_{jt}, DPR_{jt}), & Min(IR_j, IRG_j) \geq Min(CA_{jt}, DPR_{jt}) \& \; CA_{jt} \neq 0 \\ Min(IR_j, IRG_j), & Min(IR_j, IRG_j) < Min(CA_{jt}, DPR_{jt}) \& \; CA_{jt} \neq 0 \; \& \; IR_j > 0.001 \\ 0, & O.W. \end{cases} \tag{5.18}$$

For the distributor, the flow of products is equal to the products delivered from the next upstream echelon. This flow is delayed to represent transportation time, as per Equation (5.19).

$$FL_{jt} = Delay(DE_{(j-1)t}, \; DD_{(j-1)t}) \quad j = 4 \tag{5.19}$$

5.3.2.4 Structure of expediting

To convert in-process products to inventory in each of the end-echelons, the feasible production rate and the flow of products respectively (Equation (5.21)) incorporate a delay (processing time). In the middle-echelons, the processing time could change according to an expediting rate, as shown in Equation (5.20). Expediting is usually accomplished by reducing transportation time, production adjustments, overtime, outsourcing and others (Schmitt et al. 2017). In the simulation model, expediting is triggered as per managers' authorization just after the disruption ends, as specified on the user interface. Expediting in our model is represented as a reduction in production time, and it is just activated in the echelon with the disruption. The structure of expediting is presented in Figure 5.6.

$$LT_{jt} = \begin{cases} LTN_{jt} & j = 1{,}4 \\ LTN_{jt} - (LTN_{jt} * ER_{jt}) & j = 2{,}3 \end{cases} \quad (5.20)$$

$$FP_{jt} = \begin{cases} Delay(F_{jt}, LT_{jt}) & j = 1 \\ Delay(FL_{jt}, LT_{jt}) & j = 4 \end{cases} \quad (5.21)$$

Because disruptions are considered in the middle echelons, the conversion of in-process products to inventory depends on the available capacity of the echelons, as shown in Equation (5.22).

$$FP_{jt} = \begin{cases} 0, & DIS_j = 1 \,\&\, Sday_j \leq \mathrm{t} \leq Fday_j \,\&\, \mathrm{CAr}_j = 1 \\ Delay\left(F_{jt}, LT_{jt}\right), & O.W. \end{cases} \quad j = 2{,}3 \quad (5.22)$$

5.3.2.5 Structure of order quantity

In all the supply chain echelons, FIFO logic is followed. A replenishment order is launched if necessary using a dynamic order-up-to system. The order quantity in each period is equal to the maximum inventory position (Equation (5.23)) minus the inventory position, as long as there is no disruption in the echelon, as shown in Equation (5.24). The structure of order quantity is presented in Figure 5.6.

$$MI_j = D_j * (L_j + SS_j + TO_j) \quad (5.23)$$

$$O_{jt} = \begin{cases} 0, & DIS_j = 0 \,\&\, Sday_j \leq \mathrm{t} \leq Fday_j \,\&\, \mathrm{CAr}_j = 1 \\ \dfrac{Max\left(MI_j - IP_{jt}, 0\right)}{Ot_j} & O.W. \end{cases} \quad (5.24)$$

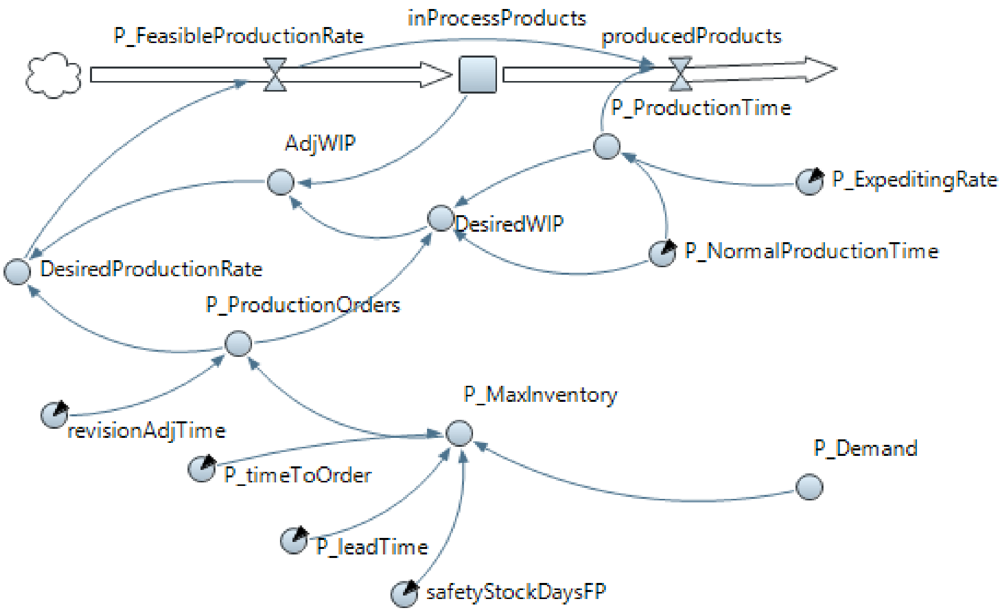


Figure 5.6 Structure of expediting and order quantity.

In order to avoid negative stocks of the in-process products for the middle echelons, the production orders are adjusted. As a result, the desired production rate represents the number of products that need to be injected in the feasible production rate, as shown in Equation (5.25). The adjustment for WIP represents the supply line of pending production (Equation (5.26)), which is the result of the desired WIP (Equation (5.27)) minus the WIP.

$$DPR_{jt} = O_{jt} + AdWIP_j \qquad j = 2,3 \tag{5.25}$$

$$AdWIP_j = Max\left(0, WIPD_{jt} - \left(\frac{WIP_{jt}}{WIPt_j}\right)\right) \qquad j = 2,3 \tag{5.26}$$

$$WIPD_{jt} = O_{jt} * \left(2 - \frac{LT_{jt}}{LTN_{jt}}\right) \qquad j = 2,3 \tag{5.27}$$

5.3.2.6 Structure of order quantity for the raw materials

Inventories of raw material are represented as per Equation (5.28). The received raw materials at the echelon j are equal to the delivered products at the upstream echelon ($j-1$). This flow is delayed because of transportation as shown in Equation (5.29). The structure of the order quantity for the raw materials is shown in Figure 5.7.

$$\begin{cases} IR_{jt} = IR_{j0} + \int_0^t (RR_{jt} - UR_{jt})dt \quad j = 2,3 \\ IR_{j0} = IR_{20} = 800 \quad IR_{30} = 800 \end{cases} \tag{5.28}$$

$$RR_{jt} = Delay(\, DE_{(j-1)t}, DD_{(j-1)t}\,) \qquad j = 2,3 \tag{5.29}$$

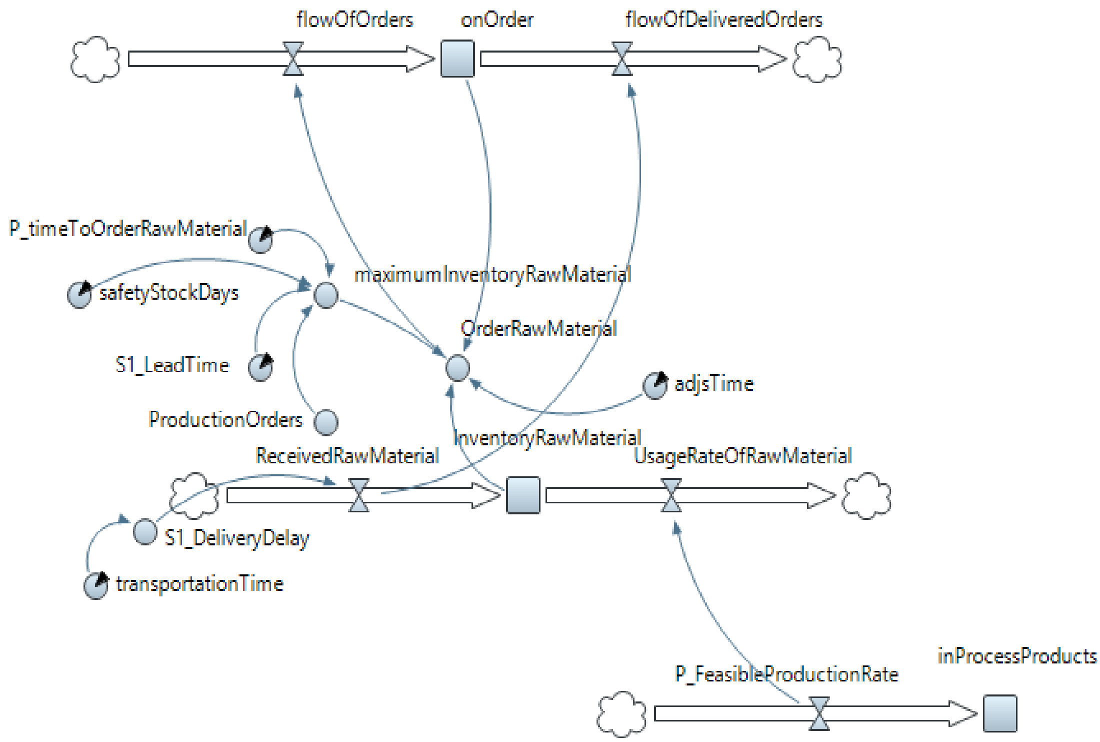


Figure 5.7 Structure of order quantity for the raw materials.

The usage of raw material inventory in supplier tier 1 and plant to produce products is equal to the feasible production rate as represented in Equation (5.30).

$$UR_{jt} = F_{jt} \qquad j = 2,3 \tag{5.30}$$

In the middle echelons, orders are sent to the echelon upstream to get supplies of raw material. Every period, a raw-material order is sent following a dynamic order-up-to system. The order quantity, Equation (5.31), depends on the maximum level allowed of raw material (5.32), the on-hand inventory and the on-order inventory (5.33).

$$OR_{jt} = \frac{Max(0, MRI_j - On_{jt} - IR_{jt})}{ORt_j} \tag{5.31}$$

$$MRI_j = O_{jt} * (LR_j + SSR_j + TOR_j) \tag{5.32}$$

The on-order inventory depends on the flow of orders as per Equation (5.34), and the flow of orders delivered as per Equation (5.35).

$$On_{jt} = On_{j0} + \int_0^t (FLO_{jt} - FLDO_{jt})dt\,;\ On_{j0} = 0\ j = 2,3,4 \tag{5.33}$$

$$FLO_{jt=}\begin{cases} OR_{jt} & j = 2,3 \\ O_{jt} & j = 4 \end{cases} \tag{5.34}$$

$$FLDO_{jt} = RR_{jt} \tag{5.35}$$

5.3.2.7 Structure of transportation

Trucks of equal capacity are considered in all the echelons. The cost of a truck in all the echelons is assumed to be the same. The number of trucks used depends on the truck capacity and the delivered products. Because the product that is transported is critical, we assume that a truck can be dispatched with more than 20% of the truck capacity. The calculation of the number of trucks is represented by Equation (5.36). The structure of transportation is presented in Figure 5.8.

$$TRn_{jt} = \begin{cases} 0, & \frac{DE_{jt}}{TRca} = 0 \\ 1, & 0 < \frac{DE_{jt}}{TRca} < 1 \\ ceil\left(\frac{DE_{jt}}{TRca}\right), & \frac{DE_{jt}}{TRca} - floor\left(\frac{DE_{jt}}{TRca}\right) > 0.2 \\ floor\left(\frac{DE_{jt}}{TRca}\right), & O.W. \end{cases} \tag{5.36}$$

The associated transportation cost of each echelon depends on the number of trucks used, as per Equation (5.37).

$$TrnC_{jt} = TRn_{jt} * TRc_j \tag{5.37}$$

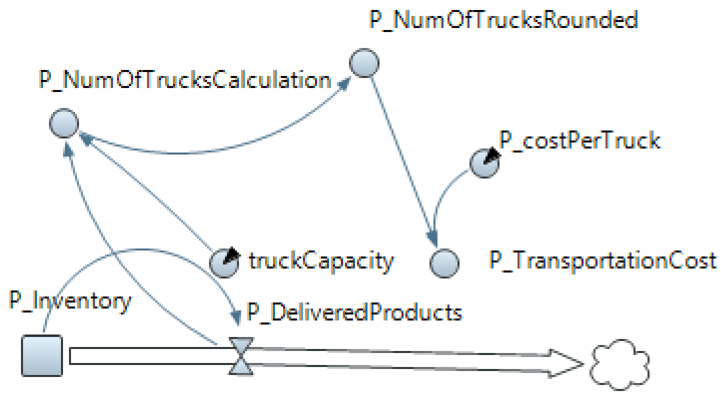


Figure 5.8 Structure of transportation.

5.3.2.8 Structure of cost, trade, pricing and profit

Usually, supply chain performance is evaluated with cost or profit. For that reason, the model includes the calculation of costs, currency exchange rates and profits as presented in Figure 5.9. For the all the echelons, the raw material cost is equal to the base cost or the price of the previous echelon plus the currency exchange rate as shown in Equation (5.38). For all the echelons, the base unit product cost is equal to the raw material cost plus an increment rate for manufacturing or purchasing as per Equation (5.39). The cost of holding a unit of inventory cost is represented by Equation (5.40).

$$RUC_j = \begin{cases} PCb_j + (PCb_j * CER_j), & j = 1,2,3 \\ Pr_{(j-1)} + (PCb_j * CER_j), & j = 4 \end{cases} \tag{5.38}$$

$$UPC_j = RUC_j + (RUC_j * MC_j) \tag{5.39}$$

$$UIC_j = H_j * UPC_j \tag{5.40}$$

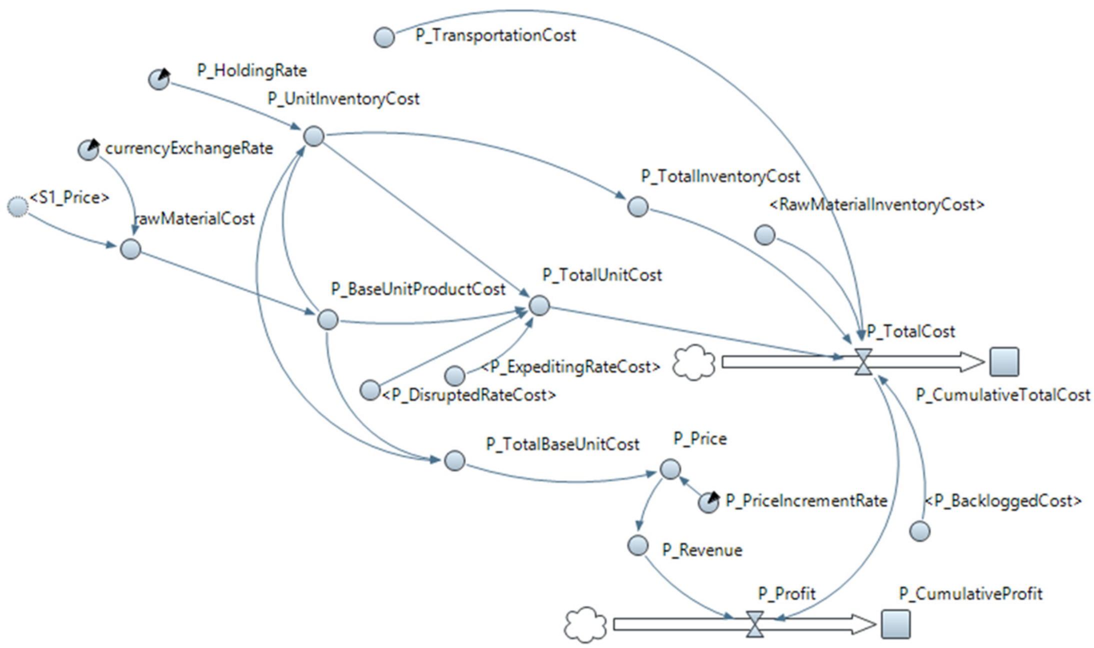


Figure 5.9 Structure of cost, pricing and profit.

For the middle-echelons, depending on the capacity that is working during disruption (Equation (5.41)) and the expediting rate (Equation (5.42)) after disruption, the total unit product cost will vary. A percentage increment to the base unit product price is considered as shown in Equation (5.43). For the end-echelons, the total unit cost is simply the inventory cost plus the base unit cost as per Equation (5.44). Additionally, the total base unit cost is calculated as Equation (5.45).

$$CArc_j = \begin{cases} 0, & CAr_j = 0 \\ 0.1, & CAr_j = 0.5 \\ 0.5, & CAr_j = 1 \\ 1, & CAr_j = 2 \end{cases} \qquad j = 2,3 \tag{5.41}$$

$$ERc_j = \begin{cases} 0.2, & ER_{jt} = 0.5 \\ 0.4, & ER_{jt} = 1 \\ 0.6, & ER_{jt} = 1.5 \\ 0.8, & ER_{jt} = 2 \\ 1, & ER_{jt} = 4 \end{cases} \qquad j = 2,3 \tag{5.42}$$

$$TUC_j = \begin{cases} UPC_j + (UPC_j * CArc_j) + UIC_j, & DIS_j = 1 \ \& \ Sday_j \leq \mathrm{t} \leq Fday_j \\ UPC_j + (UPC_j * ERc_j) + UIC_j, & DIS_j = 1 \ \& \ Fday_j \leq \mathrm{t} \leq (Fday_j + ED_j) \\ UPC_j + UIC_j, & O.W. \end{cases} \tag{5.43}$$

$$j = 2,3$$

$$TUC_j = UPC_j + UIC_j, \qquad j = 1{,}4 \tag{5.44}$$

$$UC_j = UIC_j + UPC_j \tag{5.45}$$

The cost of the backlogged orders is calculated as the backlogged inflow times the rate of the cost of the total base unit cost of the product in the following echelon, as per Equation (5.46).

$$BC_{jt} = Bcr_{jt} * UC_{(j+1)} * BIF_{jt} \tag{5.46}$$

The cost of holding raw materials is calculated as shown in Equation (5.47).

$$RIC_{jt} = \frac{RUC_j * H_j * IR_{jt}}{It_j} \tag{5.47}$$

The total cost of each supply chain echelon includes product cost, transportation cost, backlog cost, and inventory holding cost for the products and the raw material, as per Equation (5.48).

$$TC_{jt} = \left[TUC_j * DE_{jt}\right] + Trnc_{jt} + BC_{jt} + \left[UIC_j * \left(I_{jt} + WIP_{jt}\right)\right] + RIC_{jt} \tag{5.48}$$

The price in each echelon is calculated as the total base unit cost times a percentage increment, as Equation (5.49). The considered price is used to calculate the revenue as per Equation (5.50).

$$Pr_{jt} = UC_j * PrI_j \tag{5.49}$$

$$R_{jt} = Pr_j * DE_{jt} \tag{5.50}$$

The profit of each echelon is calculated as the revenue minus cost, Equation (5.51).

$$P_{jt} = R_{jt} - TC_{jt} \tag{5.51}$$

The model was created in AnyLogic 7.3.4. In AnyLogic, complex models can be defined in a hierarchical manner where logically separate parts of the stock-and-flow diagram are encapsulated into different agent types and exposed to their interface variables (output/input variables). In this model, each SC echelon is represented by an agent. The interface variables represent the information of the requested orders, received orders, costs and prices. For presentation purposes, the input and output variables in each echelon are displayed in a rectangle located in the top right of the stock and flow diagram. The complete stock-and-flow diagram for each SC echelon is presented in Figure 5.10 through Figure 5.13.

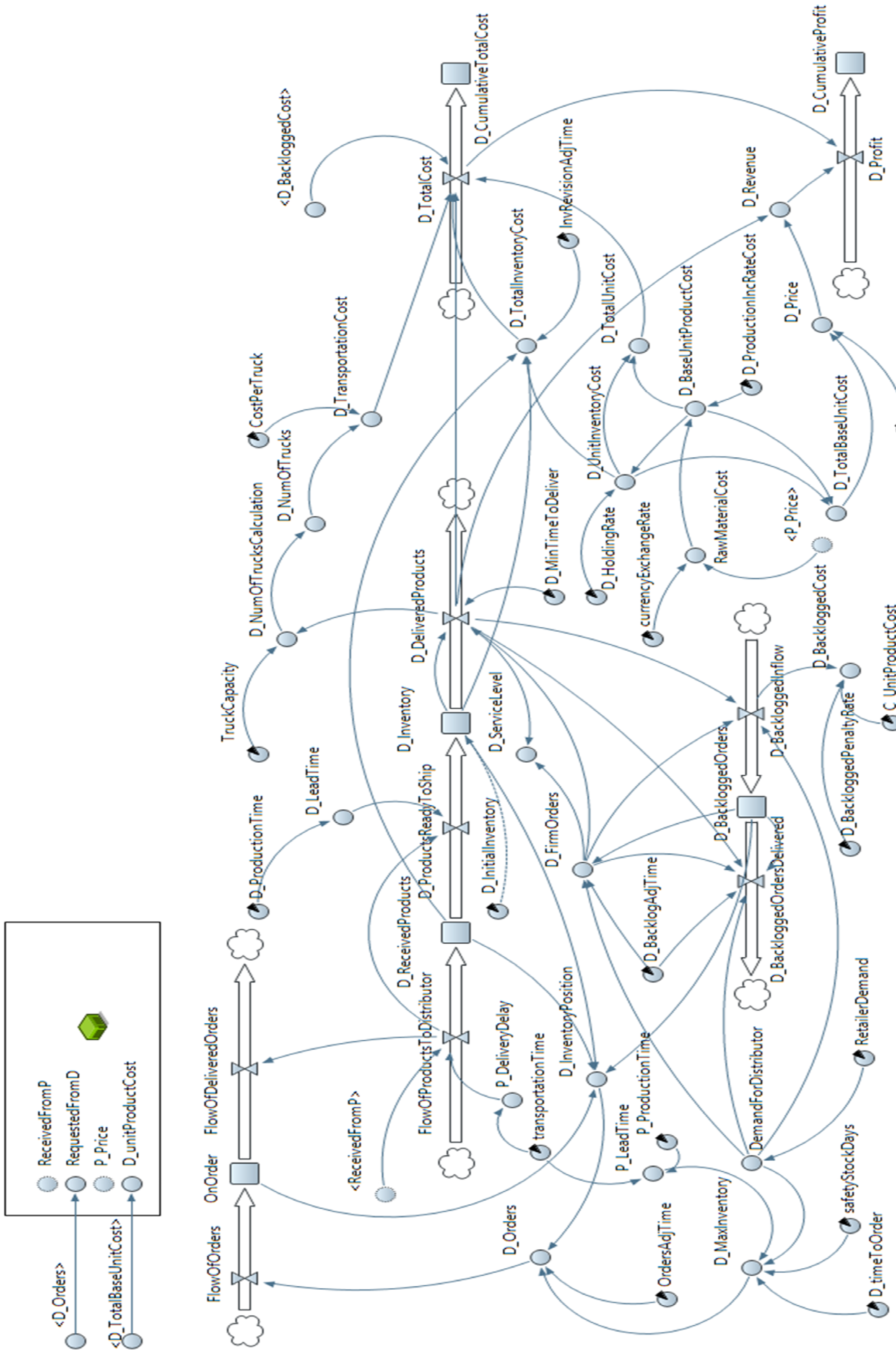


Figure 5.10 The stock and flow diagram of the distribution centre.

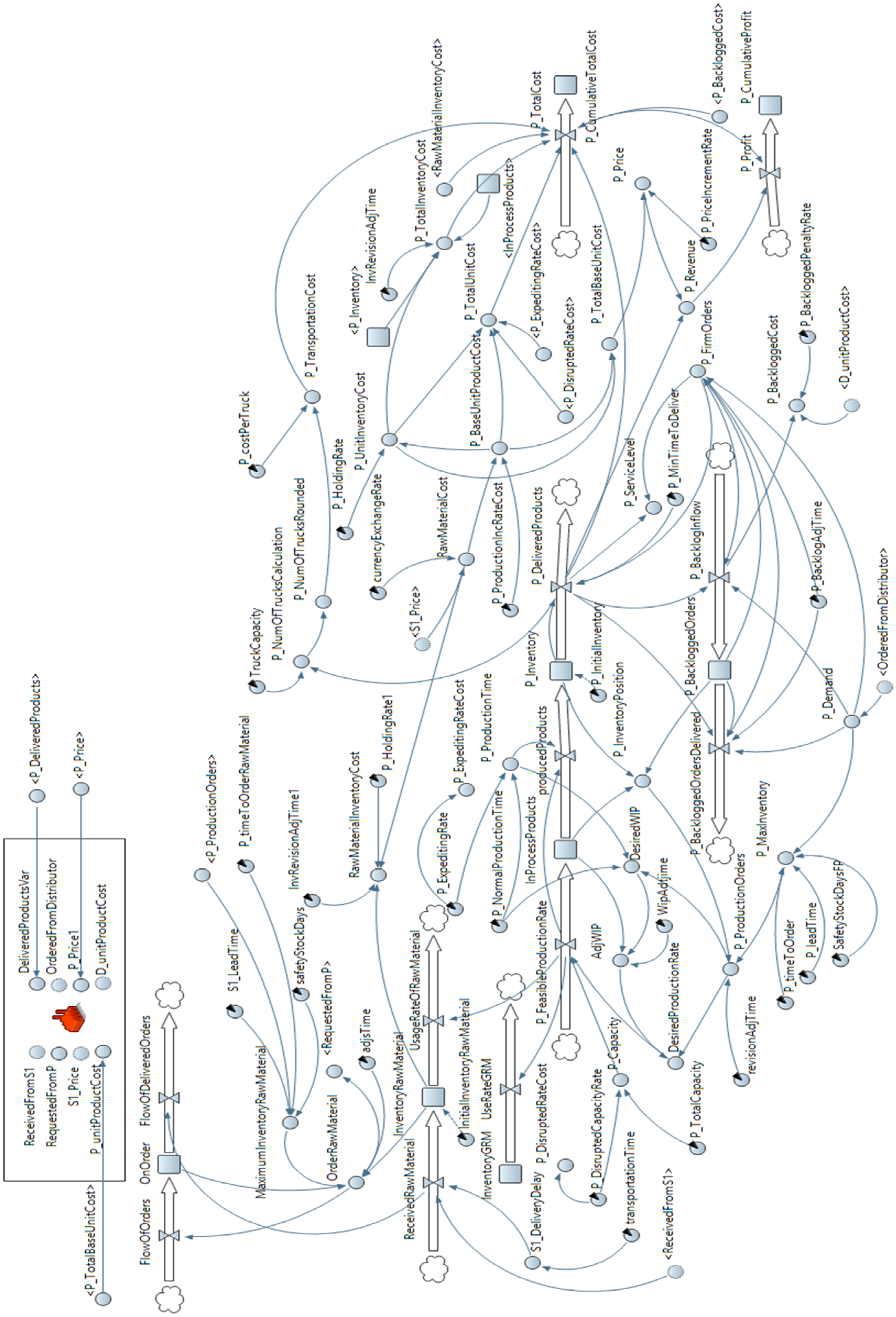


Figure 5.11 The stock and flow diagram of the assembly plant.

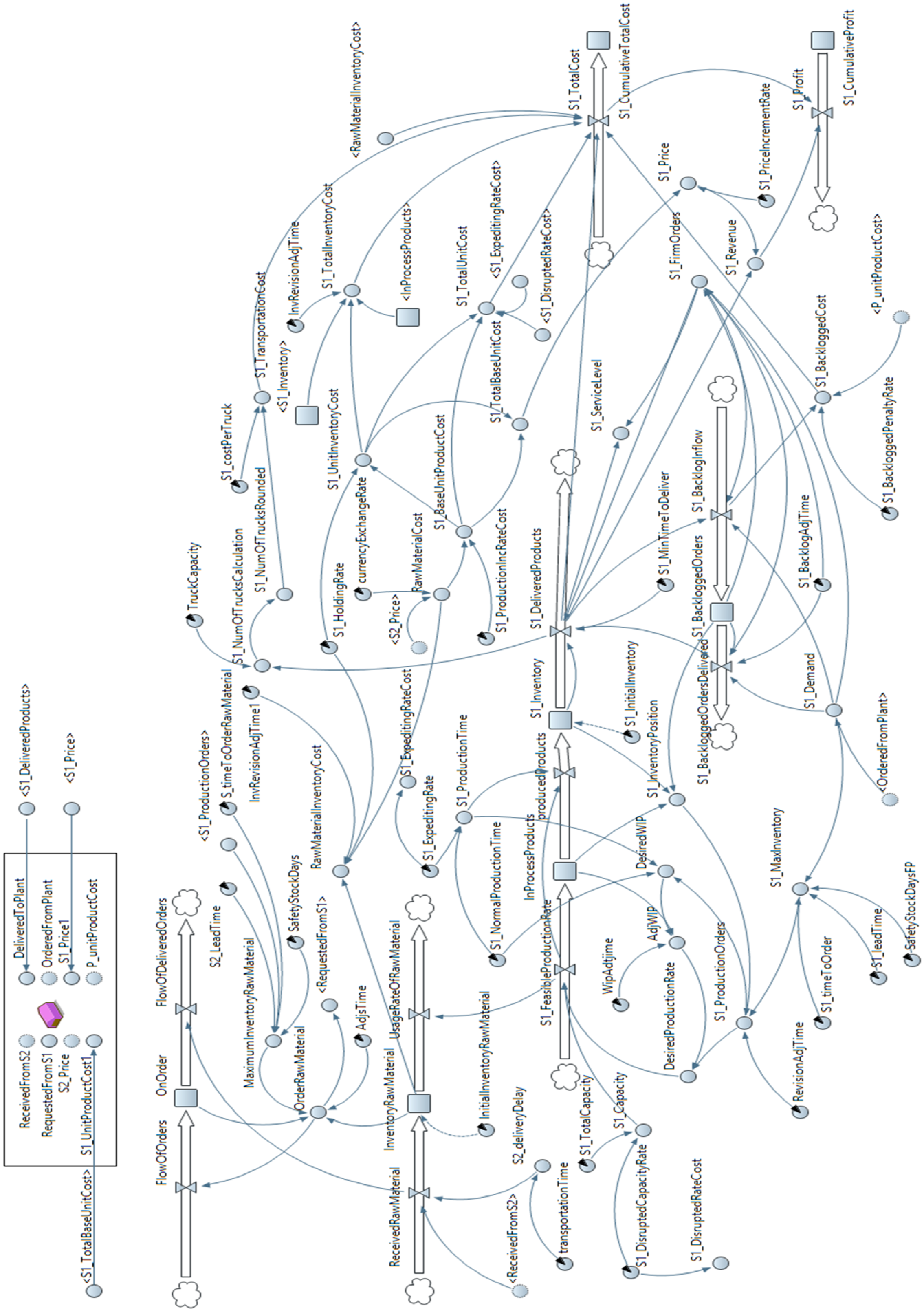


Figure 5.12 The stock and flow diagram of the supplier tier-1.

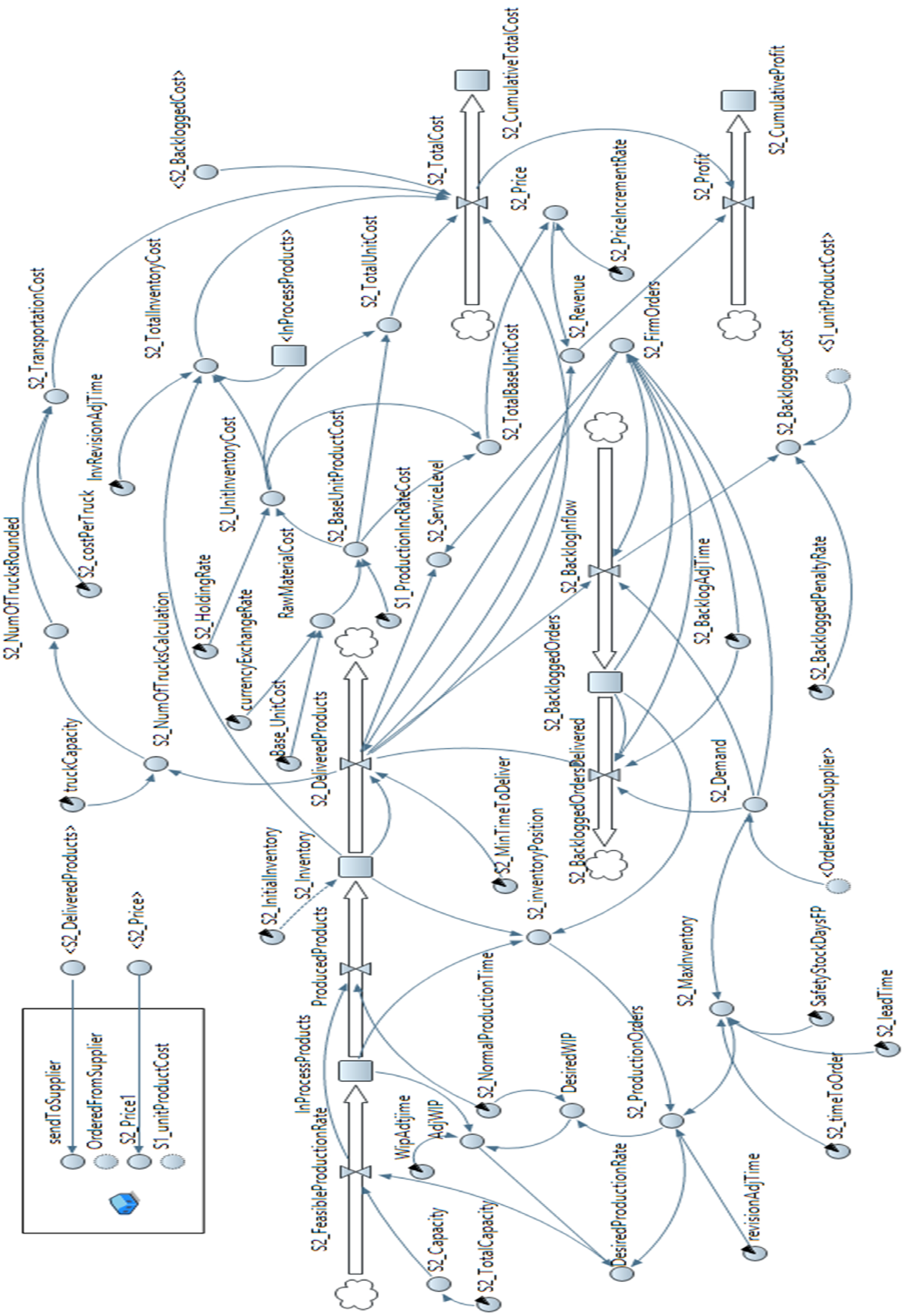


Figure 5.13 The stock and flow diagram of the supplier tier-2.

5.4 Model Validation

Confidence in a system dynamics model is gradually built as the model passes model structure and behaviour tests. The model validation is needed to build confidence that the equations are appropriate for the purpose. For structure assessment, structure-verification tests, extreme-conditions tests and dimensional-consistency tests can be used. For model behaviour assessment, several tests such as extreme policy, behaviour sensitivity and behaviour anomaly can be performed to assess the model structure adequacy. These tests, analyze the behaviour generated by the structure (Forrester and Senge 1980).

Tests of model structure are performed in this study as follows: policy structures, stock and flows maps, and equations are analyzed using direct inspection and comparing with the knowledge about the structure of a generic assembly SC. For dimensional consistency, the AnyLogic build-in tool is used to check the model units.

Tests for model behaviour are implemented in this study as follows: behaviour anomaly test has been used during the development and validation of the model. In the presence of abnormal behaviour, the model structure was examined to identify the errors and correct them. The extreme policy test was used mainly in the validation stage; several policies were modified to represent extreme conditions in order to determine dynamic consequences. The behaviour sensitivity was used to validate and enhance the confidence in the model. The results of behaviour sensitivity (oscillation in demand, Scenario 1), extreme conditions (Scenario 2- Capacity zero in the assembler and Scenario 3-Capacity zero in the supplier tier 1) and extreme policy (Scenario 4-Extreme high demand and Scenario 5-Extreme low demand) are presented in Table 5.2.

For verification, testing with deterministic data, simulation run monitoring and analysis of the outputs have been used. For testing, replications with a duration of 2000 days with a warming period of 500 days are carried out. Hence, the time window considered is 1500 days for all the scenarios. Additionally, the behaviour of the SC echelon in the different scenarios is presented in Table 5.2.

The base case, Figure 5.14, represents the normal inventory behaviour with the parameter settings as presented in Table B.1 in Appendix B. The normal behaviour shows the bullwhip effect that is caused by the demand variability. The demand fluctuation increases as it moves to the upstream SC echelons, as shown in Figure 5.14.

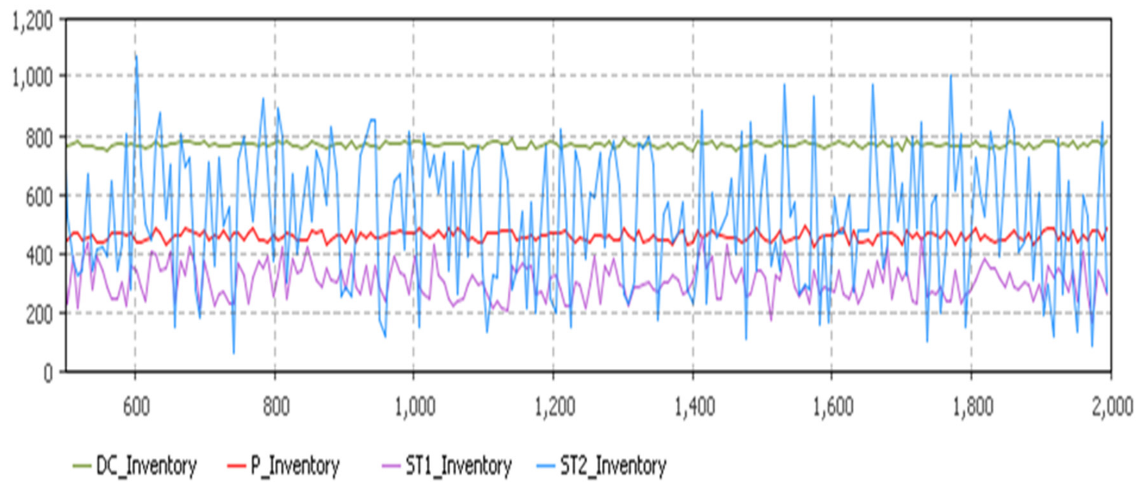


Figure 5.14 Base case, daily inventories for all SC echelons.

For Scenario 1, oscillation in demand is simulated. As a result, cycles that represent the increase and decrease of demand are observed on the behaviour of each echelon of the SC as shown in Figure 5.15.

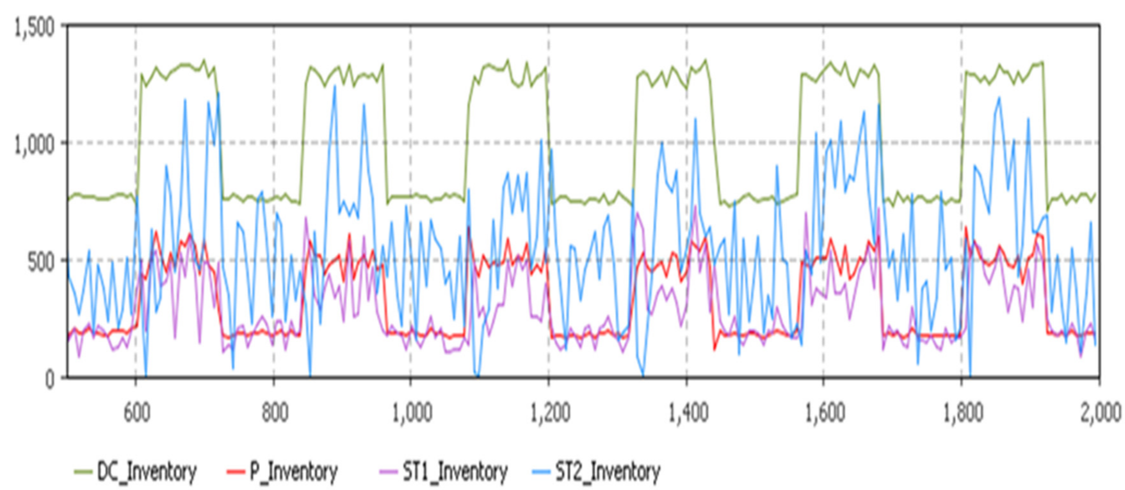


Figure 5.15 Scenario 1, daily inventories for each SC echelon.

For Scenario 2, zero capacity in the plant is defined. Hence, the inventory of final products at the distribution center and assembler is zero, as per Figure 5.16. The behaviour of inventory in the upstream echelons (supplier tier 1 and supplier tier 2) is different from the downstream echelons. In the plant or assembler, there is no capacity. However, this echelon continues requesting raw material to the upstream supplier (S1). Supplier tier-1 continues working normally. As a result, the tier-2 supplier also continues working. For that, an excessive accumulation of raw material is observed in the plant, as per Table 5.2.

Table 5.2 Scenarios for model validation.

Variable	Echelon \ Scenario	Base Case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Average demand	DC	360	443	360	360	560	60
	Plant	358	442	358	358	561	58
	Tier-1 S.	356	440	1,071	1,070	571	55
	Tier-2 S.	333	391	1,067	3,207	645	43
Average delivered	DC	360	443	1	3	560	60
	Plant	358	442	1	1	561	59
	Tier-1 S.	356	444	1,071	0	561	56
	Tier-2 S.	333	419	1,068	1,594	551	50
Average backlogs	DC	0	0	355,557	354,015	0	0
	Plant	0	8	356,623	355,083	0	3
	Tier-1 S.	0	68	0	1,066,773	0	39
	Tier-2 S.	6	196	4	1,620,320	7	16
Average inventory	DC	770	1,009	4	7	1,173	132
	DC (received)	153	155	2	0	244	25
	Plant	458	363	3	3	673	64
	Plant WIP	151	350	0	29	263	40
	Tier-1 S.	309	304	1,349	3	579	71
	Tier-1 S. WIP	266	441	458	0	330	117
	Tier-2 S.	543	566	1,191	800	707	269
	Tier-2 S. WIP	507	523	678	981	592	364
Average RM inventory	Plant	359	551	1,071,033	3	558	91
	Tier-1 S.	491	903	1,097	1,584,041	674	270
Average cost	DC	565,632	700,894	8,231	9,781	877,089	94,357
	Plant	162,461	201,579	23,229,568	106,821	253,146	27,885
	Tier-1 S.	37,822	49,632	112,099	8,665,942	59,515	8,265
	Tier-2 S.	13,186	16,183	38,143	67,714	21,410	3,303
Average profit	DC	280,515	341,414	-5,243	-3,893	439,576	45,878
	Plant	143,095	175,066	-23,228,920	-105,861	224,685	22,125
	Tier-1 S.	26,314	30,216	80,651	-8,665,942	41,427	1,850
	Tier-2 S.	4,906	6,585	19,891	18,925	8,538	-598

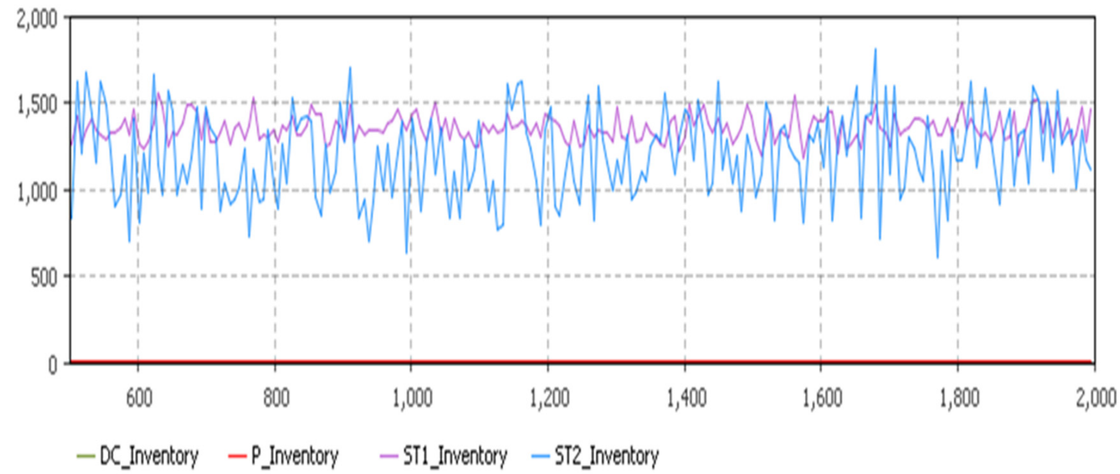


Figure 5.16 Scenario 2, daily inventories for each SC echelon.

For Scenario 3, capacity zero in supplier tier-1 is set. As a result, inventories of the distribution centre, plant and supplier tier-1 are zero. However, this supplier continues receiving the demand from the downstream echelon, for that it continues requesting material to the upstream echelon. Consequently, supplier tier-2 keeps working normally. Because supplier tier-2 does not have raw material constraints, it continues working at maximum capacity. As a result, the inventory is almost constant for this supplier, as per Figure 5.17. Hence, the raw material inventory in supplier tier-1 is excessively increased, as per Table 5.2.

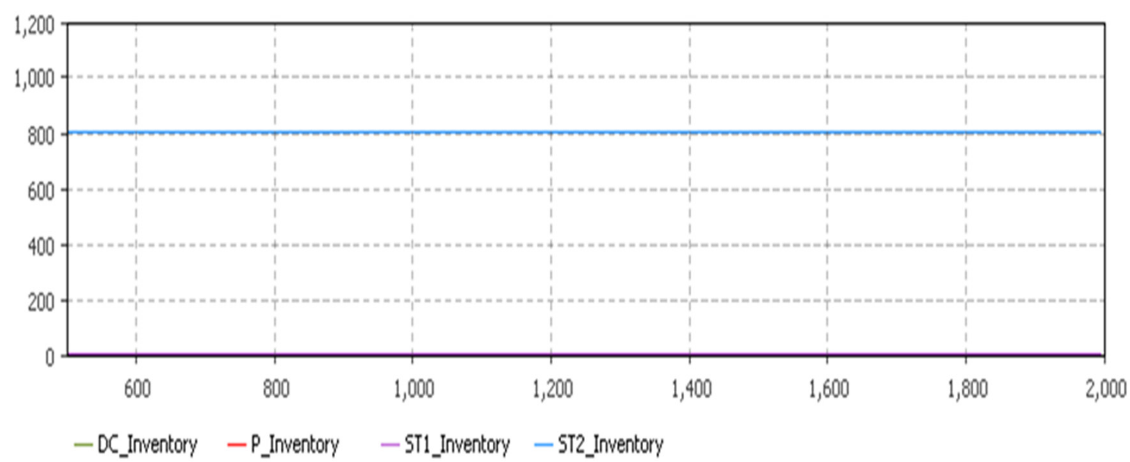


Figure 5.17 Scenario 3, daily inventories for each SC echelon.

Scenario 4 represents extreme high demand. As a result, inventories, Figure 5.18, and other SC performance indicators as shown in Table 5.2 are at the highest levels. The contrary effect happens when the extremely-low demand is simulated as shown in Figure 5.19, the inventories and the rest of the SC performance indicators are at the lowest levels, as per Table 5.2. Based on the results of the different scenarios, the model passes the structural and behavioural tests. Hence, the model is validated.

Figure 5.18 Scenario 4, daily inventories for each SC echelon.

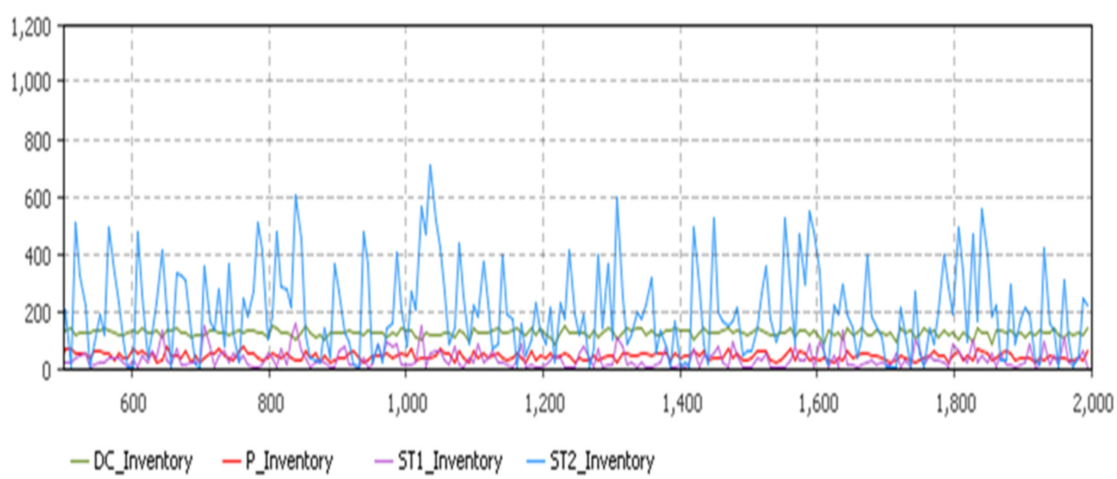


Figure 5.19 Scenario 5, daily inventories for each SC echelon.

5.5 The Decision Support Package

The system dynamics model is packaged in a decision support tool that can be modified according to the parameters of a specific supply chain, as per Figure 5.20. The setup of the SC is read from an excel file. Additionally, customizable settings that represent the possible mitigation strategies can be set up in an initial screen before the simulation starts to run.

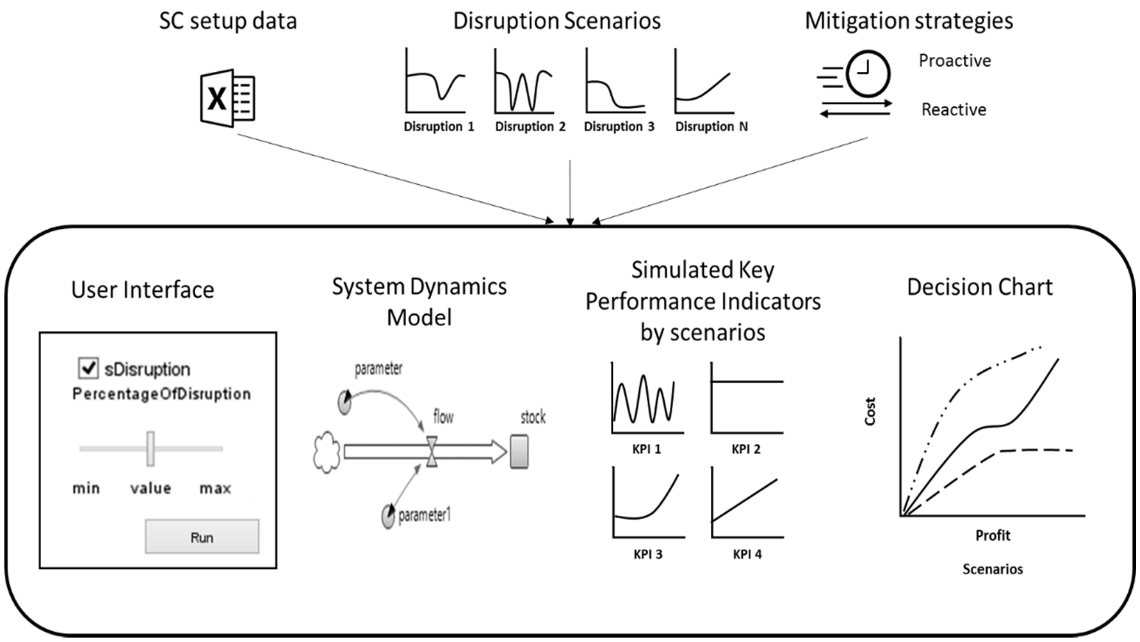


Figure 5.20 A System-Dynamics-based DSS.

The user interface enables to specify in which echelon the disruption(s) take place, the start-day and end-day of the disruption. Additionally, partial capacity degradation is allowed on the specified days. Moreover, different expediting rates can be defined for a period after the disruption.

Generation of different scenarios will help to make the movie of what could happen in the SC. Hence, it will be prepared to expect different situations. Additionally, a key performance dashboard is used to observe the behaviour of the key performance indicators. Different experiments can be performed to analyze different strategies. At the end of these experiments, a decision graph that shows the SC profit and cost will be displayed to support the decision. Managers will have the possibility to change the SC policies, and they will be able to choose the best strategy. The presented decision support system is very general, and adaptations should be performed to address different SCs. However, the main concept of a pragmatic tool should be used.

5.6 Scenarios

Several scenarios are designed with the objective of analyzing the SC behaviour when facing full and partial disruptions in the supplier tier-1 and the plant. Additionally, scenarios where expediting is activated after the disruption are considered. SC performance indicators as the inventory of products, inventory of raw materials, backlogs, cost and profit are analyzed in each echelon of the SC under the proposed scenarios.

The experimental part comprises the consideration of the following disruptions as shown in Table 5.3. The designed scenarios are selected to make results and their analyses more depictive. A base scenario and ten disrupted scenarios are run. On the first row of Table 5.3, the parameters that were used to simulate the disruptions and to expedite are shown. For instance, scenario 3 considers one partial disruption that decreases capacity by 80% at supplier tier-1, the disruption starts on day 800 and finishes on day 840. Moreover, scenario 3 considers expediting of 50% during 20 days after the disruption.

Table 5.3 Scenarios to analyze the impact of disruptions and expediting.

Scenario	Capacity Disruption in ST1 CAr_2	Disruption Days in ST1 $Sday_2$-$Fday_2$	Expediting Rate ER_{jt}	Expediting Days ED_j	Capacity Disruption in P CAr_3	Disruption days in P $Sday_3$-$Fday_3$	Expediting Rate ER_{jt}	Expediting Days ED_j
1	80%	800-840						
2					80%	800-840		
3	80%	800-840	50%	20				
4					80%	800-840	50%	20
5	100%	800-840						
6					100%	800-840		
7	100%	800-840	50%	40				
8					100%	800-840	50%	40
9	100%	800-840			100%	800-840		
10	100%	800-840			100%	1200-1240		

5.7 Results

Different scenarios as presented in the section before were implemented in the system dynamics model. For all the scenarios, SC performance indicators were collected as shown in Figure 5.21 through Figure 5.25. All the data used to graph the charts of Figure 5.21 through Figure 5.25 is presented in the Table B.4 through Table B.7 in Appendix B.

To perform the analysis, all the scenarios are compared with the base scenario. The base scenario does not include any disruption or expediting.

5.7.1. *Effect of individual partial disruptions*

In this section, scenarios 1 and 2 as specified in section 5.6 are analyzed. For scenario 1, a partial disruption in the supplier tier-1 is simulated. As a result of this disruption, there is an increment in the inventory of ST2 of 30% with respect to the base scenario and a decrease in inventory of ST1 of 31 %. The reason for the decrease in ST1 is due to the lack of material during the disruption days. Regarding the raw material inventory, there is an increase of 201% on ST1. The reason for this increment is because, after the disruption, ST1 starts requesting raw material to fulfil the accumulated backlog which also increases by 20,618%, as it can be observed in Figure 5.21. Consequently, the profit in ST1 is decremented by 29% and the SC profit is decreased by 1%.

For scenario 2, a partial disruption in the plant is implemented. From Figure 5.21, it can be observed that the inventory in the DC, plant and ST1 decreased by 3%, 7% and 31% respectively with regard to the base scenario. These decrements are the consequence of the disruption which caused backlog increments in all the SC echelons ranging from 17,469% to 95,610%. After the system is re-established, the raw material is notably increased in the plant (89%) and tier 1 supplier (1,263%). As a result, there is a notable decrease in the profit of ST1 of 134%. Hence, the total SC profit is decreased by 9%.

From the results of these two scenarios, it is observed that partial disruptions happening in downstream echelons provoke more damage to the SC performance than disruptions happening in upstream echelons.

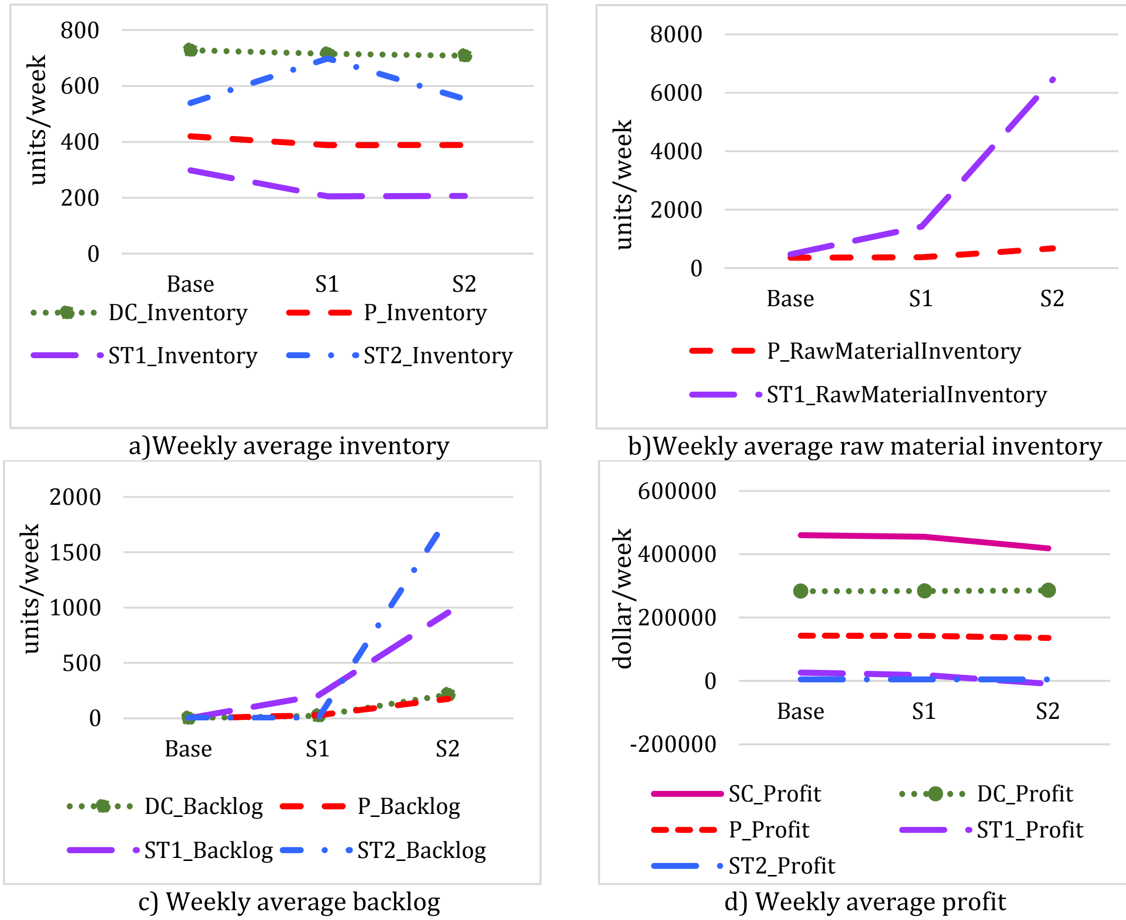
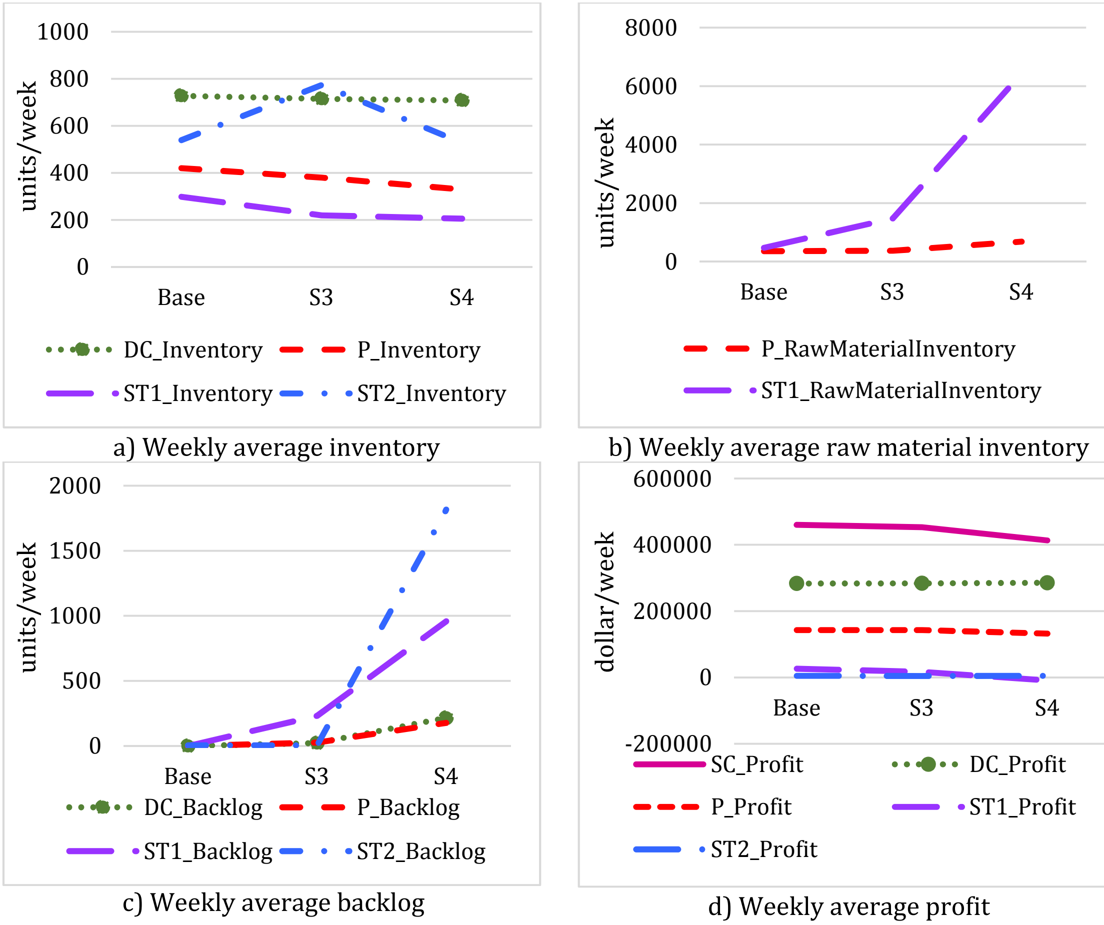


Figure 5.21 Effect of individual partial disruptions on SC performance.

5.7.2. *Effect of individual partial disruptions with expediting*

For this section, scenario 3 and scenario 4 are analyzed. From Figure 5.22, the behaviour of different SC indicators is presented for scenarios 3 and 4.

For scenario 3, the disruption in ST1 is simulated and expediting after disruption is activated. Consequently, ST1 has a decrease in inventory of 26% and an increase in inventory of 44% in ST2. After the system recovers from the disruption and starts expediting, the system starts to accumulate raw material inventory. Increments of 212% on the raw material inventory is observed in ST1. Backlogs are increased during disruptions and expediting phases. The increases range from 2,175% for DC to 23,053% for ST1. ST2 reduces its backlog due to it having unlimited raw material inventory, and it has more capacity than ST1. Profit in ST1 is reduced by 35% due to the disruption and expediting. Hence the SC profit is reduced by 2%.



a) Weekly average inventory b) Weekly average raw material inventory

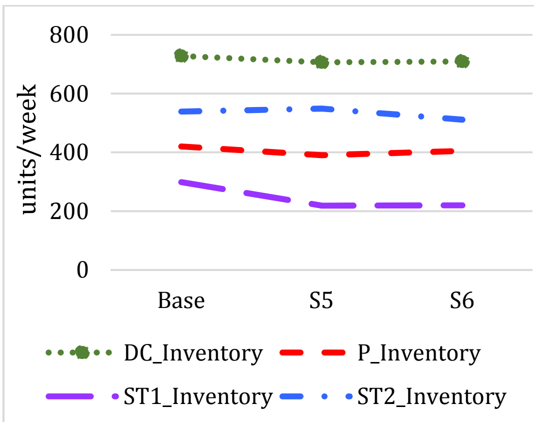
c) Weekly average backlog d) Weekly average profit

Figure 5.22 Effect of individual partial disruptions with expediting on SC performance.

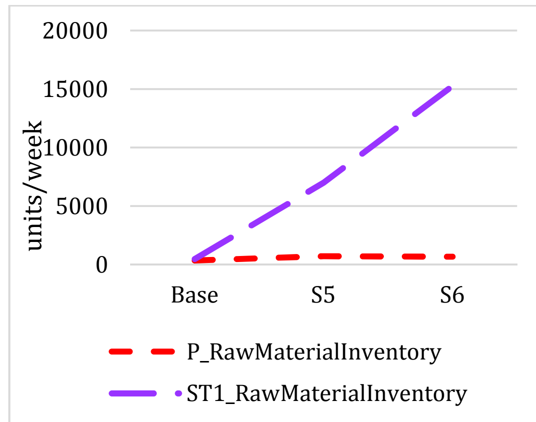
For scenario 4, the disruption in the plant is simulated and expediting after disruption is permitted. This scenario has more impacts than scenario 3 as we can observe from Figure 5.22. Scenario 4 has a decrease of inventory of 22% and 33% in inventory in plant and ST1 respectively. In order to keep up the inventory, more production orders are released. These production orders cause that more orders to request raw materials are placed. As a result, an increase of 91% and 1,259% of raw material inventories in the plant and ST1 can be observed. The disruption and the expediting cause increments in backlogs in all the SC echelons ranging from 17,673% to 95,790%. Due to these situations, profits are decreased in the plant (7%), ST1 (133%) and the SC (10%). The results suggest that partial disruptions with expediting causes more damage in the SC if the disruption is in the downstream echelons.

5.7.3. *Effect of individual full disruptions*

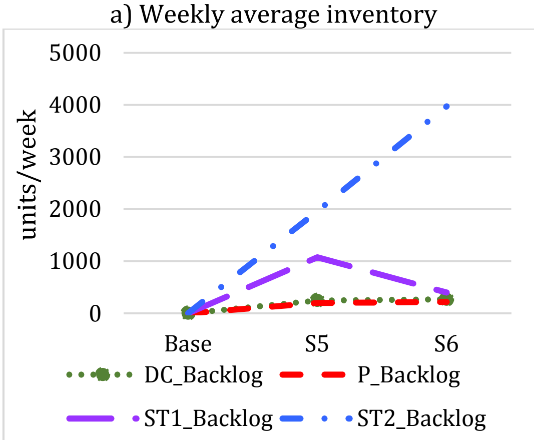
Scenarios 5 and 6 are used to study the impact of full disruptions. The behaviour of different SC performance indicators is shown in Figure 5.23. Similar behaviours from the partial disruption scenarios are observed when simulating a full disruption. However, the impacts are greater.



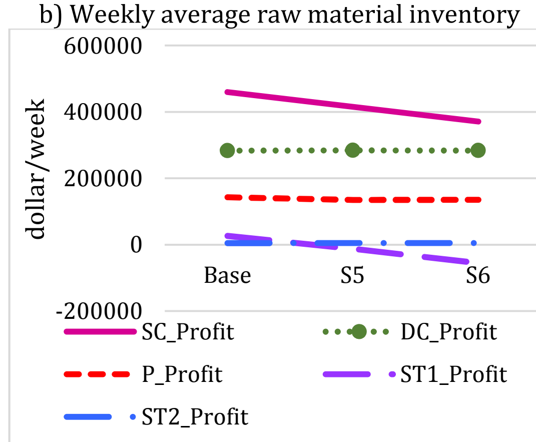
a) Weekly average inventory



b) Weekly average raw material inventory



c) Weekly average backlog



d) Weekly average profit

Figure 5.23 Effect of individual full disruptions on SC performance.

For scenario 5, the full disruption was simulated in the ST1. As a consequence of the disruption, the inventory levels in all the SC echelons decreased in a range of 3% (DC) to 27% (ST1). After the disruption, the system starts to require raw material to the upstream levels. These orders are already affected by the lack of material downstream. As a result, an increment of raw material inventory is observed (101% in the plant and 1,378% in the ST1). The disruption causes backlogs in all the SC echelons. Notably, there is a backlog increment of 107,495% in ST1. Consequently, the profit in ST1 decreases by 146% and the profit of the SC decreases by 10%.

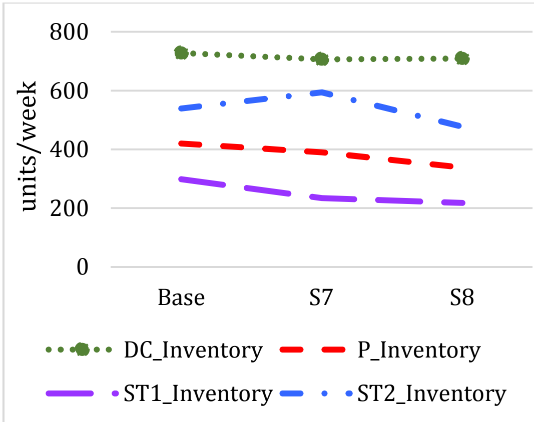
Scenario 6 has a full disruption in the plant. Hence the inventories in all the SC echelons decreased as shown in Figure 5.23. The decrements range from 3% for the DC to 26% for ST1. After the disruption is over, the system starts placing orders of raw material to the upstream echelons. As a result, an increment of 89% of the raw material in the plant and 3,123% in the ST1 is observed. As the orders placed after the disruptions request material to fulfill the demand during the disruption plus the demand generated on that day, the backlogs increase. The backlogs range from 26,831% in the DC to 66,146% in the ST2. Hence, losses are observed in the ST1 (with a decrease in profit of 308%). As a result, the SC has a reduction of 19% in the profit.

5.7.4. *Effect of individual full disruptions with expediting*

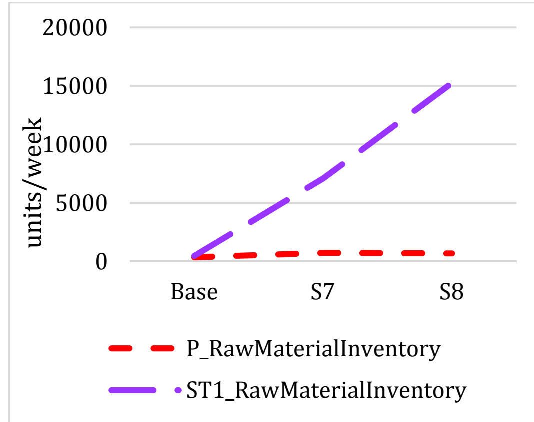
Scenarios 7 and 8 are implemented to study the effect of full disruptions and the effect of expediting after disruptions when comparing with the base scenario. The behaviour of different SC performance indicators is shown in Figure 5.24.

Scenario 7 has a full disruption in ST1 and expediting after the disruption. The inventory is diminished in downstream levels in ranges from 3% to 22%. These reductions in inventory are the effect of the disruption. As expediting is allowed, more raw material is needed. Hence an increment of raw material inventory is detected in the plant (105%) and the ST1 (1,399%). The disruption and the expediting causes backlogs in all the SC echelons from 24,624% increment in the DC to 107,572% increment in ST1. Hence, the profit in ST1 decreases by 159%, causing losses for this echelon and a reduction of 11% of the SC profit.

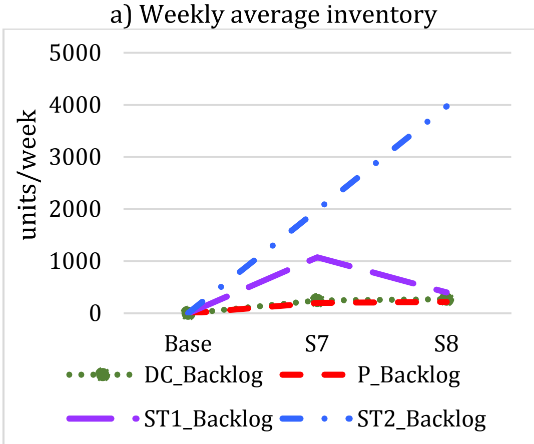
In scenario 8, a disruption in the plant is simulated and expediting after disruption is activated. The inventories are decreased in all the SC echelon in a range of 3% in the DC to 27% in the ST1. These decrements are the effect of the disruption and expediting. The expediting also affects the raw material inventory, in the plant an increase of 92% is observed. Notably, an increase of raw material inventory of 3,118% is detected in the ST1. Backlogged orders are increased in all the SC echelons increasing in a range of 21,967% in the plant to 66,161% in the ST2. The effect of the increased raw material inventory and backlogged orders cause a decrement in the profit of the plant of 9%, of the ST1 of 30% (causing losses) and a 21% decrement in the SC profit.



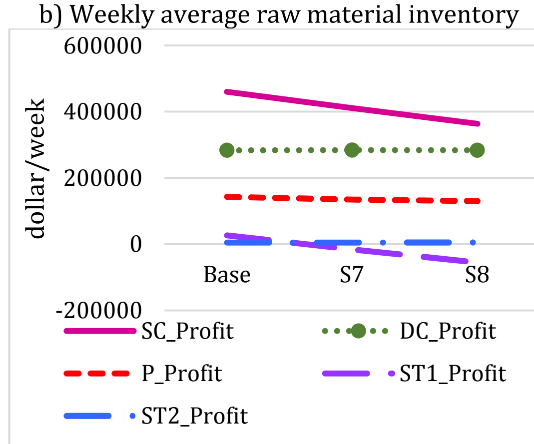
a) Weekly average inventory



b) Weekly average raw material inventory



c) Weekly average backlog



d) Weekly average profit

Figure 5.24 Effect of individual full disruptions with expediting on SC performance.

5.7.5. *Effect of simultaneous full disruptions*

Two full disruptions are simulated for scenario 9; the disruptions occur in ST1 and the plant in the same period. As expected, both echelons stopped producing and restarted at the same time. Hence the behaviour produced in the SC is the same as scenario 6, where a disruption in the plant is activated. This scenario is not further discussed in this section as the analysis will lead to an equal result than scenario 6. In Figure B.1 in Appendix B, the graphs for the behaviour of this scenario are presented.

5.7.6. *Effect of non-simultaneous full disruptions*

Non-simultaneous full disruptions are implemented in scenario 10. In total, the SC is disrupted 80 days in periods of 40 days in each echelon. Each disruption happens in ST1 and the plant. The behaviour of the SC performance indicators is presented in Figure 5.25.

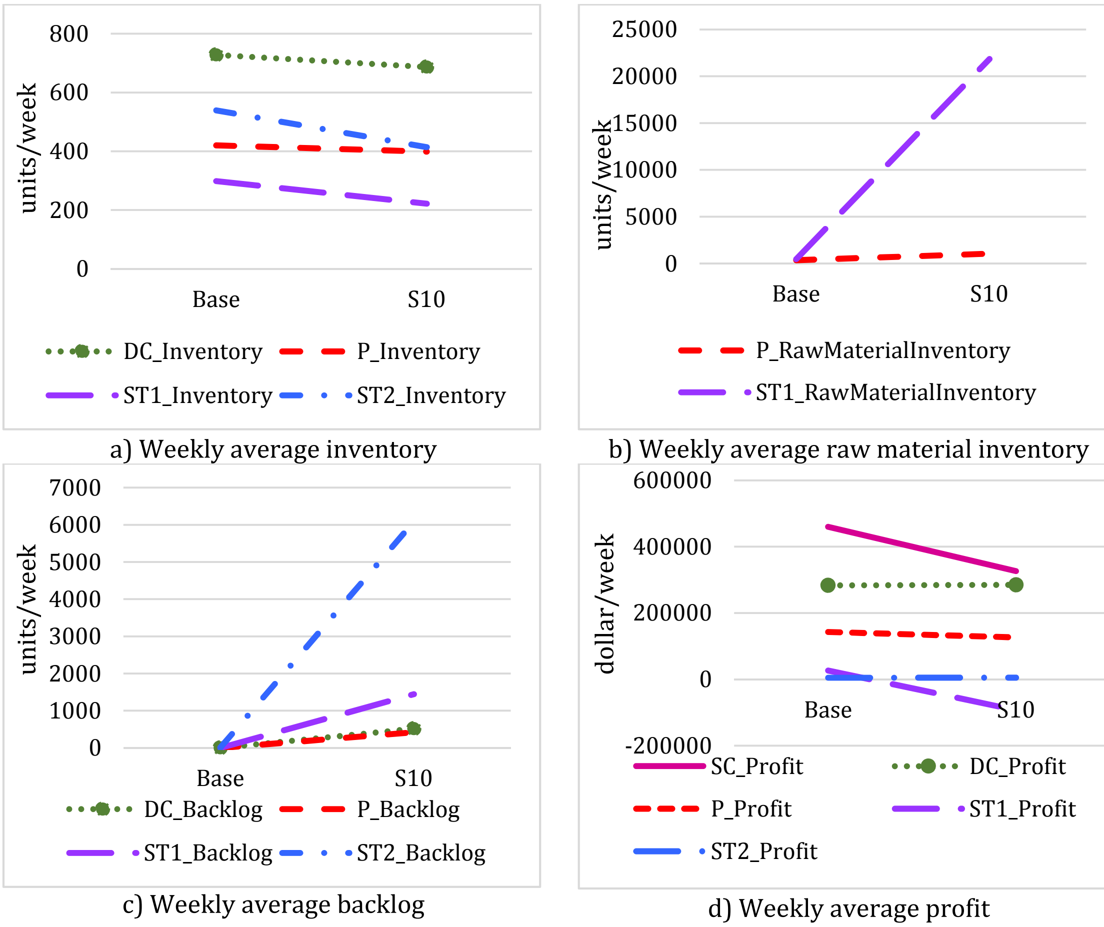


Figure 5.25 Effect of non-simultaneous full disruptions on SC performance.

The disruptions caused a fall in the inventory levels in all the SC echelons ranging from 5% decrement for the plant to 26% decrement for the ST1. The disruption causes these decrements in the inventories. As the disrupted SC echelon is recovered, the system starts placing orders of raw material to fulfil the backlogged demand. Hence, increments of 194% in the plant and 4,510% in ST1 are observed. Similarly, there is a considerable increase in backlogged orders. The backlogs increased in a range of 41,883% for the plant to 144,353% in the ST1. As a result, there is a decrement in the profit for the plant of 11%, for the ST1 of 450% (generating losses in ST1), and a decrease in the SC profit of 29%. The behaviour of the SC performance in scenario 10 shows that this kind of scenario has the more intense damage.

5.7.7. *Trade-off analysis between cost and service level*

A critical trade-off that managers face when designing policies is between cost and level of responsiveness. For that reason, an analysis between the total SC cost and service level (fulfillment rate) at the final SC echelon (in this case the distribution centre) is performed as shown in Table 5.4 and Table 5.5.

From Table 5.4, it is observed that expediting after a partial disruption happening in ST1 leads to an increment of SC cost of 1.01% (higher than the 0.75% without expediting). Moreover, the service levels in a partial disruption (scenario - S1) and in a partial disruption with expediting (S3) lead to almost the same result (1.12% and 1.14 % decrement). A similar situation happens when comparing a partial disruption in the plant (S2) and a partial disruption in the plant with expediting (S4). There is an increment in cost (5.40% and 6.06% respectively), and service levels for both scenarios are almost the same (98%). Likewise, the same effect can be observed when a full disruption happens, as per Table 5.5. These results, raise concerns about the value of expediting as a mitigation strategy.

Table 5.4 Cost and service level analysis in partial disruptions.

		Partial Disruption in ST1		Partial Disruption in ST1+ Expediting		Partial Disruption in P		Partial Disruption in P+ Expediting	
	Base	**S1**	**%Δ B-S1**	**S3**	**%Δ B-S3**	**S2**	**%Δ B-S2**	**S4**	**%Δ B-S4**
SC Cost	777,704	783,523	0.75	785,578	1.01	819,723	5.40	824,818	6.06
DC_SL	1.00	0.99	-1.12	0.99	-1.14	0.98	-2.40	0.98	-2.42

Table 5.5 Cost and service level analysis in full disruptions.

		Full Disruption in ST1		Full Disruption in ST1+ Expediting		Full Disruption in P		Full Disruption in P + Expediting	
	Base	**S5**	**%Δ B-S5**	**S7**	**%Δ B-S7**	**S6**	**%Δ B-S6**	**S8**	**%Δ B-S8**
SC Cost	777,704	823,079	5.83	827,210	6.37	866,640	11.44	874,271	12.42
DC_SL	1.00	0.97	-2.58	0.97	-2.59	0.97	-2.70	0.97	-2.71

Comparing Table 5.4 and Table 5.5 for partial and full disruptions in ST1 and plant, it is observed that partial disruptions have fewer impacts on cost and service level than full disruptions. Additionally, it is found that the effects in the plant are higher than in ST1. For that reason, proactive strategies (in this case the partial disruption is treated as a proactive strategy) should be put in place primarily in the downstream echelons in order to diminish the disruption impacts. Furthermore, it can be noted that the increment in cost does not reflect the increase in service level.

5.8 Summary

Manufacturing supply chain networks are dynamic organizations that interact to fulfil customer demands and to generate profits along the production process. Therefore, the SC analysis should be performed on the dynamic level in order to study the behaviour when facing unexpected events. In this chapter, a system dynamics framework was presented to investigate the dynamics of the SC behaviour in different scenarios.

From the scenario analysis, it is observed that disruptions affect the performance of the SC. Moreover, it is detected that the disruption effects are propagated to upstream and downstream levels. Importantly, it is observed that the SC is affected more when the disruptions take place near to the end-echelon or consumption stages.

In this research, partial disruptions are considered as a proactive mitigation strategy where the SC continues working at a specified level at an increased cost. From the results, it is observed that partial disruptions have less impact on the SC performance. Hence, operating at a partial capacity is better for the SC. However, depending on the cost of the strategy used to maintain the partial degradation, decision makers need to evaluate the trade-off between cost and service level.

Also, it is noted that scenarios, where two non-simultaneous disruptions take place, have the potential of damaging the SC performance in a high magnitude. Hence, the scenario analysis should be performed in a wide range of possible events and considering several potential disruptions in a single scenario.

Furthermore, it is found that expediting after disruptions affect more the already damaged SC performance. This effect can be detected in the increased raw material inventory that the disrupted SC echelon accumulates. Expediting increases the variability in the orders, hence a combined impact of ripple effect and bullwhip effect is observed when disruptions and expediting happen. Additionally, it is found that expediting increases SC cost but the service levels at the DC remain almost the same.

The analysis of the scenarios will permit supply chain practitioners to design disruption policies in advance. Higher priority and more preparations of disruption policies and mitigation strategies need to be performed in advance to diminish the disruption impacts happening in the downstream levels.

CHAPTER 6. RESILIENCE MEASUREMENT

6.1 Overview

In this chapter, a measure to evaluate supply chain resilience is developed considering the system impact cost and the recovery effort from the results of the company performance.

6.2 Introduction

Supply chain (SC) disruptions are unexpected events that may interrupt in high magnitude the SC operations and cascade through several levels of the SC. The effects of such events can range from halting operations for some days to those where operations are suspended indefinitely. These situations underline the necessity to consider disruption effects at the strategic decisions level. Hence, an assessment of how resilient the SC is can be carried out. Based on this result, top management has to make cost-benefit decisions.

Ponomarov and Holcomb (2009) defined supply chain resilience as the “adaptive capability of the SC to be prepared for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at desired level of connectedness and control over structure and function.”

Several representations of the disruption impacts have been drawn in the literature. Sheffi and Rice Jr (2005) mentioned that any severe disruption might affect the performance over time. They considered that the performance during disruption has eight phases, as shown in Figure 6.1.

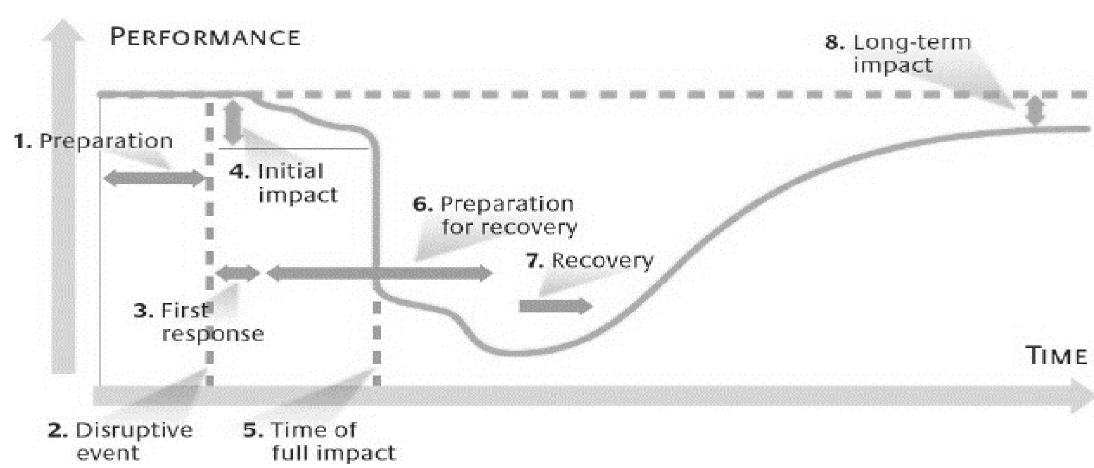


Figure 6.1 The disruption profile (Sheffi and Rice Jr 2005).

Similarly, Tierney and Bruneau (2007) presented the resilience triangle that represents the loss of functionality from damage and disruption and the restoration and recovery pattern over time. The resilience triangle assumes that the quality of the infrastructure is 100% before the disruption and it returns to the same level after the disruption is over, as highlighted in Figure 6.2.

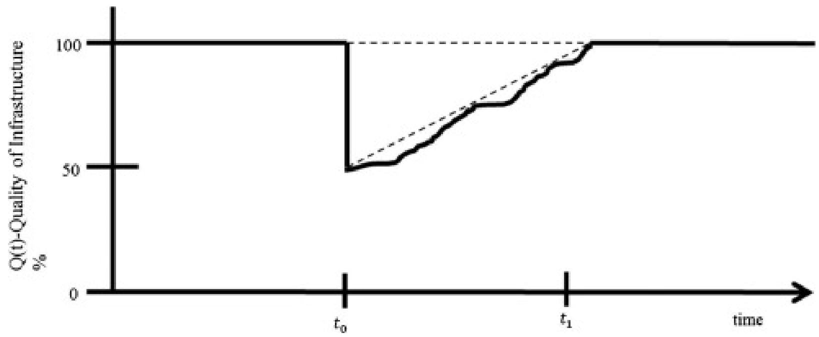


Figure 6.2 Resilience triangle (Tierney and Bruneau 2007).

The dotted triangle in Figure 6.2, represents the loss of resilience (R) that can be calculated as per Equation (6.1). Where $Q(t)$ is the quality over time, and t_0 and t_1 the evaluation period of the disruption.

$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt \tag{6.1}$$

Vugrin et al. (2010) pointed out that there could be the case where two systems experienced identical disruptions and the same output decrement. Also, both systems returned to the normal level at the same time. However, system 1 required more recovery effort than system 2. As a result, in the approaches where just the impact is considered, both systems seem to be equally resilient. However, System 2 should be considered more resilient because it requires less recovery effort than System 1, as per Figure 6.3. They proposed the recovery-dependant resilience (RDR) cost. RDR cost refers to the system resilience cost to a disruption under a particular recovery strategy (RE) as shown in Equation (6.2). In other words, RDR of each recovery strategy is the proportion of the impact cost and the recovery cost, compared with the target cost.

$$RDR(RE) = \frac{\int_{t_0}^{t_f} [TSP(t) - SP(t)]dt + \alpha \int_{t_0}^{t_f} [RE(t)]dt}{\int_{t_0}^{t_f} |TSP(t)|dt} \tag{6.2}$$

Where t_0 and t_f are the lower and upper limit of time where the resilience cost is evaluated. They represent the time where the disruption begins and when the system is recovered respectively. The subtraction in the numerator represents the system impact (SI), where TSP is the target system performance, and SP is the system performance during the evaluation interval. RE is the area under the recovery effort curve. And, α is a weighting factor to give more or less importance to the RE. RDR(RE) gives a relative dimensionless result.

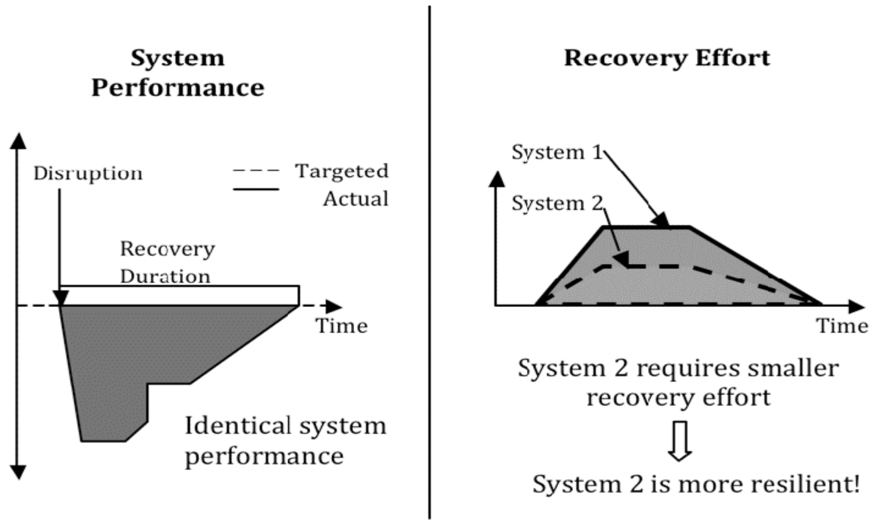


Figure 6.3 Comparison of the resilience of two systems (Vugrin et al. 2010).

6.3 Supply Chain Resilience Index (SCRI)

Most of the time the design of a SC is determined by a driving force that usually is an economic factor. For that, to evaluate the SC performance, the proposed supply chain resilience index is based on the recovery-dependent resilience cost (RDR) presented by Vugrin et al. (2010). Looking for a measure that can have an absolute meaning, this resilience cost metric was transformed to get the Company Resilience Index (CRI). For simplicity, summations instead of integrals are used which is also convenient as the discrete event simulation software deals with day to day results. Additionally, in this research TSP is defined as the assigned cost to produce 100% of the planned demand. Furthermore, we propose to add SI and RE to TSP in the denominator. As a result, the denominator represents the total cost spent during the evaluation period. The numerator characterizes the system impact and recovery costs. The CRI as given in Equation (6.3) has a scale from 0 to 1, having 0 for a company with null resilience and 1 for the most resilient.

$$\mathrm{CRI} = 1 - \frac{\sum_{\mathrm{t}=t_0}^{t_f}[\mathrm{TSP(t)} - \mathrm{SP(t)}] + \alpha \sum_{\mathrm{t}=t_0}^{t_f}[\mathrm{RE(t)}]}{\sum_{\mathrm{t}=t_0}^{t_f}|\mathrm{TSP(t)}| + \sum_{\mathrm{t}=t_0}^{t_f}[\mathrm{SI(t)}] + \alpha \sum_{\mathrm{t}=t_0}^{t_f}[\mathrm{RE(t)}]} \qquad (6.3)$$

To measure the SI, RE and TSP, the costs of the associated company fulfilling rate (FR) are used. The FR represents the ratio between the units fulfilled and the total demand in each period as presented by Barroso, Machado, Carvalho, and Machado (2015). Where $Q_{delivered,j}$ is the quantity delivered and $Q_{ordered,j}$ the quantity ordered from order j. And $J_{i,t}$ corresponds to the number of orders placed to supplier i during time period t. Costs for fulfilling rate are accounted as shown in Equation (6.4). Consequently, the system performance (SP) corresponds to the cost spent in each period. The target system performance is the cost considered to fulfil the orders during a period of time. When there is not a disruption, the SP and TSP should be equal.

$$FRCost_{i,t} = Cost_{i,j} \times \left[\frac{1}{J_{i,t}} \sum_{j=1}^{J_{i,t}} \frac{Q_{delivered,j}}{Q_{ordered,j}} \right] \tag{6.4}$$

FRCosts are decomposed to evaluate the CRI. The SI is the cost for the area where the fulfilling rate falls below the TSP (lower area Figure 6.4), and RE is the cost invested in getting the area that exceeds the TSP (upper area) as shown in Figure 6.4. To give less importance to the costs or to allow more budget, α can be used to weigh the SI and RE (Vugrin et al. 2010). However, when α is 1, we can compare CRIs of each company in different scenarios as we are dealing with monetary units. That is when CRI=1 the cost is the least expensive strategy, and when CRI is 0, the cost is the most expensive. For that reason, we keep α=1.

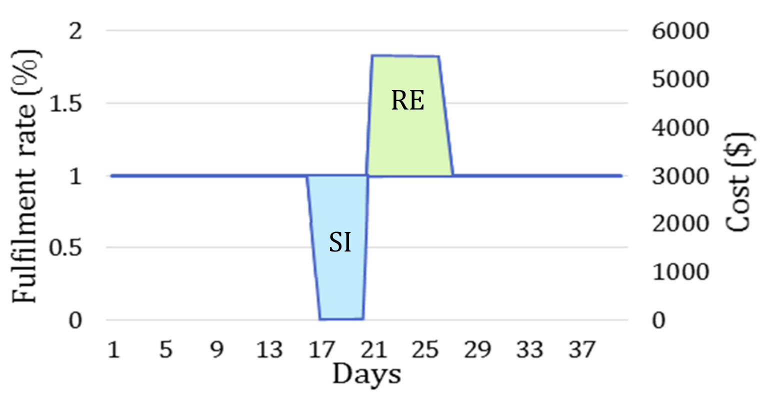


Figure 6.4 System impact (SI) and recovery effort (RE) areas.

CRI is used to evaluate the performance of each company within the SC. Then, three approaches (average method, multiplicative method and worst case scenario) as presented in (Barroso, Machado, Carvalho, and Machado 2015) are used to obtain the supply chain resilience index (SCRI).

In order to obtain the fulfilling rate and consequently the fulfilment rate cost, the examined system should be simulated. As a result, the system behaviour disruption or disruption profile and cost over time can be analyzed.

6.4 Case Study

The considered SC network is based on the case study presented in (Carvalho et al. 2012). A four-echelon SC is used as shown in Figure 6.5. The automaker releases orders every 2 hours, 7 days a week, in a shift of 8 hours to the first- tier suppliers (supplier 1_3 and supplier 1_1). The orders must be delivered 2 hours after the order is placed. The simulation was developed in AnyLogic 7.3.4. A possible disruption between days 11 to 18 in the zone where supplier 2_1 is located was considered as in (Barroso, Machado, Carvalho, and Machado 2015).

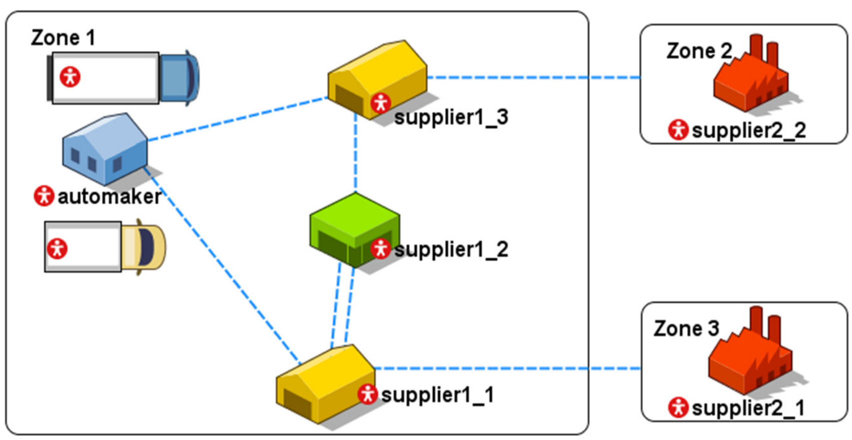


Figure 6.5 Supply chain case study (adapted from (Carvalho et al. 2012)).

Three scenarios were used; scenario I has a disruption in the zone where supplier 2_1 is located. So there is no an alternative other than wait until the zone is cleared. For that, supplier 2_1 cannot produce or deliver material 6 to supplier 1_1. From scenario I, two scenarios were used with different mitigation strategies (buffer stock strategy and backup supplier strategy). In scenario II, the disruption takes place on the same days, but there is a buffer stock in supplier 1_2. It has stock to satisfy 7 days of material requirements (Carvalho et al. 2012). In scenario III, disruption also happens. However, this scenario considers supplier redundancy, where another supplier is located in other location zone and can supply the demand. Supplier 2_3 was added as a backup of supplier 2_1. So, supplier 2_3 will work only when the disruption takes place, starting the next day.

In this case study, costs for handling the extra stock and costs to produce in the alternative supplier were added. For warehousing, the extra stock units cost of 1.25 dollar/unit/day was assumed during the simulation of 55 days. For the backup supplier, the same total costs were charged as for the original supplier. In order to measure the recovery effort, an increment of 30% of the total cost was added to achieve the extra production during the recovery days. It is important to mention that this case study should be taken as a guide on how to use the framework, not as the actual state of the current SC.

6.5 Results

Disruption profiles for each scenario are as follow:

Scenario I: Supplier 2_1 had FR=0 during the disruption days due to the disruption being in its zone. The effect was also observed in supplier1_1 and supplier1_2. Both had material shortages that provoked FR=0 for 2 and 4 days respectively. They had to work more than usual to recover their stocks. For that, FR was more than 100% during 6 days for supplier1_2 and 4 days for supplier1_1.

Scenario II: Supplier 2_1 had FR=0 during the disruption days. Supplier 1_2 had material shortages on day 17, and then it had FR higher than 100% during 2 days due to it working to recover its normal performance. Other suppliers were not affected.

Scenario III: Due to there being an alternative supplier, disruption effects are observed just in supplier 2_1. However, the backup supplier had FR=0 during the days where it did not produce. The fulfilment rate equal to zero is a penalty that is reflected in the cost of missed production.

Once the fulfilling rate per each day, supplier, and scenario are calculated, the cost associated with the FR are decomposed into recovery effort costs and system impact costs. Table 6.1 shows the costs in monetary units for each supplier in each scenario. Then, CRIs for each scenario/supplier were calculated as shown in Figure 6.6.

Table 6.1 **TSP, RE and SI Costs.**

	Scenario I			Scenario II			Scenario II		
	TSP	**RE**	**SI**	**TSP**	**RE**	**SI**	**TSP**	**RE**	**SI**
Sup1_1	148,500	6,756	5,400	148,500	0	0	148,500	0	0
Sup1_2	30,250	1,859	2,200	30,250	16,605	550	30,250	0	0
Sup1_3	24,750	0	0	24,750	0	0	24,750	0	0
Sup2_1	13,750	0	1,750	13,750	0	1,750	13,750	0	1,750
Sup2_2	11,000	0	0	11,000	0	0	11,000	0	0
Sup2_3	-	-	-	-	-	-	11,000	0	9,600

Scenario	**Supplier1_1**	**Supplier1_2**	**Supplier1_3**	**Supplier2_1**	**Supplier2_2**	**Supplier2_3**
I	0.92	0.88	1.00	0.89	1.00	
II	1.00	0.64	1.00	0.89	1.00	
III	1.00	1.00	1.00	0.89	1.00	0.53

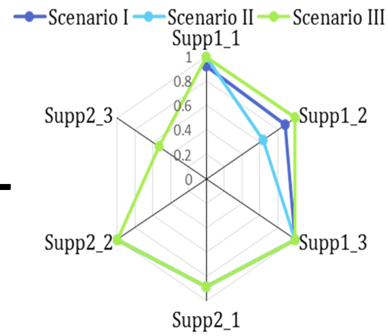


Figure 6.6 Results of company resilience indices for each scenario.

In order to get the supply chain resilience index (SCRI), the CRIs were used under the additive, multiplicative and network approach. The results are presented in Figure 6.7, together with the strategies costs in thousands of monetary units. After comparing the three approaches, the network approach represents the worst case scenario as it has more extreme values than the other two approaches. The best and worst scenario are always consistent no matter what approach is used.

Scenario	**Strategy Cost**	**Average**	**Multiplicative**	**Minimum**
I	246	0.94	0.72	0.88
II	247	0.91	0.57	0.64
III	250	0.90	0.47	0.53

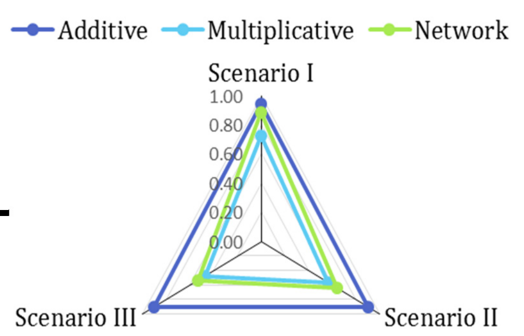


Figure 6.7 SCRI results for each scenario/approach.

6.6 Summary

Decision under uncertainties is difficult to make primarily because many economic factors and lack of information can limit the strategies to deal with this situation. Moreover, SCs looking for strategies that maximize the overall value generated are prone to adopt strategies like outsourcing and offshoring. Therefore, this chapter proposed a supply chain resilience index to evaluate and compare the design of the SC and possible mitigation strategies. The proposed supply chain resilience index considers the associated cost to operate at specific delivery performance, the system impact cost and the cost to recover from a disruption. Finally, a case study was presented to demonstrate the applicability of the proposed index.

While the supply chain resilience index presented in this chapter enables the comparison between strategies, the estimation of the recovery effort is not always available. Hence, methods to evaluate the possible recovery effort are needed.

CHAPTER 7. CONCLUSION

7.1 Overview

In this chapter, a summary of the research and a synopsis of the novelties and contributions achieved are described. The limitations of the proposed methodologies are presented as well as the conclusions.

7.2 Summary

This research is motivated by the increased number of disruptions that supply chain networks face on a daily basis. Hence, in this research, SC network design and analysis are presented. Moreover, dynamic analysis of the SC network at the tactical level of decision is provided.

In order to design the globally distributed manufacturing supply chain, the phases proposed by Chopra and Meindl (2007) are adapted and enhanced with the inclusion of the product architecture design. The methodologies presented in this research are integrated into the standard framework as shown in Figure 7.1.

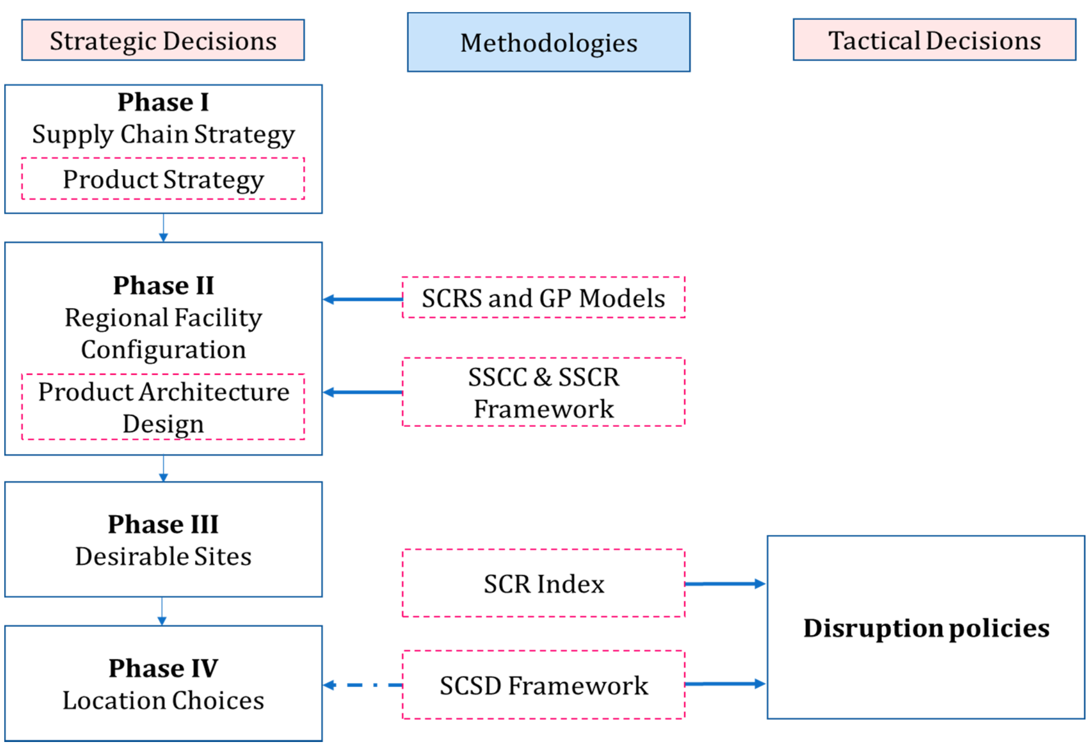


Figure 7.1 Supply chain design and analysis methodologies.

In phase I, the supply chain strategy and product strategy are defined. This phase is not carried out in this research, but it is essential for the SC design. This definition will delimit and influence both designs. In this phase, identification of the customers' needs is made. In parallel, the supply chain strategy is drawn in order to get a strategic fit. As a result, a schematic product and the corresponding potential supply chain are drawn.

In phase II, regional facility configuration and product architecture are defined. Identification of regions where facilities will be located is made taking into consideration zones that have less exposure and vulnerability towards natural disasters. Additionally, a definition of product architecture and modules is done considering the location zone of the possible suppliers. A mathematical model (section 3.4.1) is used to determine the suitable countries for the deployment of the supply chain and the modules for the product. Moreover, the model presented in section 3.7 allows the inclusion of cost and risk-attitudes. As a result, the mathematical models presented are intended to be a starting point of rational decision making regarding the setup of the supply chain and the product architecture.

Moreover, in this phase, analysis of structural complexity and robustness of the resulting SC configuration and product architecture can be performed as presented in section 4.3. This analysis facilitates the comparison between different product architectures and their corresponding SC configurations. As a result, SC designers will be able to identify structural outliers or weak spots in the SC.

Phase III selects a set of the possible locations for the SC. Hence, a narrowed set of product architectures is delimited. A methodology to help in this phase is still needed and represents an open opportunity for future research.

In phase IV, selection of locations is performed. This phase is not included in this dissertation. However, the system dynamics framework presented in section 5.3 can be used in this phase in the following manner: different scenarios are tried in the SCSD framework to imitate the behaviour of the possible supply chain structure, after the analysis of trade-offs, the supply chain manager will be able to decide a SC configuration or design.

For the tactical decisions, the SCSD framework is intended to be used to analyze possible disruptions and to design SC disruption policies that help to cope with the effect of them. Moreover, the supply chain resilience index is envisioned to be used in the evaluation of possible mitigation strategies.

7.3 Limitations

The assumptions considered represent limitations for the models. The SCRS model, in chapter 3, is provided for the concurrent design of the supply chain and product architecture considering the exposure and vulnerability towards natural disasters. Due to the granularity of the World Risk Indices used to weight the geographical location of the SC entities, this model only allows the configuration at a country level. Another limitation of this model is that the configurations only receive a score that is used to decide the product and SC configurations. However, the score has no real value. The model has limitations on the computational level. Several examples have been solved using Xpress-IVE optimization tool on processor AMD at a 2.20 GHz and 8 GB of RAM. The elapsed CPU time for the base case, scenario 1 and scenario 2 is approximately 1 second. On the same computer configuration, the elapsed CPU time increases to 47 seconds for a problem size of 20 suppliers, 20 plants, 20 distribution centres, 20 customers, 20 products, 20 configurations per product and 20 modules. The ILP could not provide an optimal solution after running the model for 23,816 seconds for a problem size of 40 suppliers, 40 plants, 40 distribution centres, 40 customers, 40 products, 40 configurations per product and 40 modules.

Building on the SCRS model, the GP model is proposed. This model enables the inclusion of cost and risk-attitude considerations. However, this model does not consider relevant issues as tariffs and tax incentives or political and demand risks. For that, the model needs to be adapted for the inclusion of those critical issues. Moreover, these models do not consider the evolution effort of changing from one product architecture to another and the effect on the supply chain. Hence, a different model is required when deciding on both architectures.

Furthermore, the GP has computational limitations. The GP model can be solved for small problems sizes such as the scenarios BC-A, BC-B, BC-C, S1-A, S1-B, S1-C, S2-A, S2-B, and S2-C. The computational time for these scenarios is approximately 1 second in a PC with an AMD at a 2.20 GHz processor and 8 GB of RAM. On the same computer configuration, the computational time increases to 70 seconds when solving for a problem size of 10 suppliers, 10 plants, 10 distribution centres, 10 customers, 10 products, 10 configurations per product and 10 modules. The GP model could not provide an optimal solution after running 5,383 seconds for a problem size of 20 suppliers, 20 plants, 20 distribution centres, 20 customers, 20 products, 20 configurations per product and 20 modules.

The framework in chapter 4 analyzes the robustness, complexity and structural cost of the supply chain. This framework is intended to examine the structure of the SC network and the effect of different product architectures on them. However, dynamic analysis and a trade-off analysis between the efficiency and effectiveness of the resulting configurations are needed in parallel in order to make a decision.

The system dynamics model allows the simulation of a generic capacity disruption where the facility will not work (e.g. natural disasters, strikes, fire) or will work partially (capacity risk). However, operational risks (e.g., forecast risk, inventory risk, lead-time risk, delivery delay risk) are not considered in the model. Structures for currency-exchange rate risk are available in the model. However, the analysis of the impact of this kind of risk is not performed. Moreover, the expediting is allowed just in the echelon where the disruption is simulated. No expediting is activated in other situations. For that, more detailed analysis of expediting is needed.

A general limitation of this research is the inability of finding real case studies that include all the parameters needed to carry out this research. Another general limitation is that the primary focus is on assembly products. However, in this broad classification of products, there can be products that need to be analyzed as perishable products.

7.4 Novelties and Contributions

- A novel integer programming model is proposed to simultaneously design product architectures and their corresponding supply chain. The model has as unique characteristic the inclusion of the disaster risk to determine the optimal SC configuration. The model has been used in an example to show applicability. The model can be used to identify the potential natural disaster risks in the SC, and the impact of the SC decisions on the product architecture.
- A novel goal programming model is derived from the integer programming model. It considers the natural disaster risk and cost, where risk attitudes of the decision-makers are implicitly assumed as the costs.
- A novel framework to evaluate structural supply chain complexity and robustness is designed considering the product architecture and its corresponding SC. The framework allows comparison between different supply chains/product

architectures. The results of a case study suggest that the modular architecture offers a balanced level of complexity and robustness.

- A framework that uses system dynamics is introduced to evaluate disruption policies in the SC. The framework allows simulation of full and partial disruptions and the expedition of materials after disruptions. The model demonstrated that disruptions happening downstream affect in higher magnitude than disruptions in the upstream echelons. The model can be used to design disruption policies before unexpected events happen.
- A supply chain resilience index is presented to allow comparison between different supply chain systems. The index uses the cost of the fulfilment rate to calculate the supply chain resilience cost.

7.5 Significance

The presented research is intended to facilitate the process of designing and planning supply chains that are prepared for unexpected events. The methods used and developed in this research can be used individually or together to design and perform analysis, as presented in section 7.2. While the proposed methodologies presented in this research represent a partial solution of the big problem, the development of this research serves to identify the potential of unexpected events, to prepare the strategic/tactical level of decision and to look for ways to decrease the potential impacts of these situations.

7.6 Future Work

Several extensions can be included as a part of future work. Perspectives for the goal programming model include analysis of real case studies, the inclusion of more supply chain echelons, consideration of product variants, integration of service levels, and consideration of other types of risks. For the inclusion of product variants, a generic bill of materials can be considered as the input of the model. Additionally, service levels can be viewed in the model as another goal that needs to be optimized. Moreover, the comparison between the results from our model and the models that do not consider risk needs to be performed. Another future research avenue includes the examination of the Pareto frontier to observe how the goals play against each other. Moreover, future research that presents heuristics or metaheuristics for global optimization should provide means for obtaining efficient and better solutions for the problem.

For the structural analysis of complexity and robustness, future extensions are the analysis of contractual relationships, the inclusion of product variants and selection of suppliers. Moreover, an analysis of the trade-offs of changing from one product architecture to another need to be carried out. Additionally, it is required a trade-off analysis between efficiency and effectiveness of the resulting SC configurations.

For the system dynamics framework, future work considers inclusion of more SC echelons, analysis of other types of risks, other ordering policies and the effect of information sharing on the SC dynamic behaviour. Moreover, future work includes the analysis of the severity of impacts and the recommendation of possible proactive and reactive strategies, e.g. redundancies like inventories and backup suppliers. Furthermore, an important issue that needs to be addressed is the definition of the scenarios to be analyzed for the design of the disruption policies.

The SD decision support system can be used as a basis to implement the industry 4.0 concepts. The model should be synchronized with information from inside and outside the factories. For example, information related to raw material, finished goods and transportation of materials can be updated in real time. Moreover, external factors that could alter the performance of the supply chain, e.g. weather, border news, etc. should be considered.

Industry 4.0 can be a great help to mitigate disruptions, as soon as a disruption happens calculations of the inventory in real time can be performed. So the factory will be able to know what the time to survive is and start making preparations.

It is important to mention that integration between the different levels of the supply chain should be achieved to implement the industry 4.0 concept. A change in corporate culture and organization is needed for a successful implementation. Additionally, interconnections between systems should be allowed to get real-time information. In this manner, radio-frequency identification (RFID) and sensors can be installed at strategic points to collect and update the data to the system.

7.7 Conclusion

This research was motivated by the fact that SCs face unexpected events that affect their performance. Hence, companies need to design SCs that can identify, assess and mitigate potential disruptions. Different approaches have been presented in the literature to tackle this complex problem. The studies that consider a holistic view that integrates the dynamic and structural aspects are limited. Additionally, the studies that incorporate the product architecture which the SCs produce are scarce. Moreover, organizations are not keeping up with the task of preparing for unexpected events.

In this research, various tools and measures have been developed to analyze the structure and dynamic performance of the SC networks. Additionally, each methodology has been applied to case studies in order to demonstrate applicability.

A contribution to a growing field of concurrent supply and product architecture design has been achieved by considering natural risk exposure, cost and decision-makers risk attitudes. This model looks for the optimal product architecture and SC configuration that has less exposure and vulnerability towards natural disasters according to the World Risk Index. The presented model facilitates the comparison of different supply chains/product architectures during the design or redesign of supply chains and products. The inclusion of cost and risk-attitudes help decision makers to reach balanced decisions.

To evaluate the complexity and robustness of the proposed designs (SC and product architecture), a framework that includes a morphological analysis and evaluates quantitative indicators of complexity and robustness based on network characteristics has been proposed. Additionally, overall metrics are presented. As a result, a decision matrix is drawn to allow the comparison between different product architectures and their corresponding SC network. Moreover, a cost analysis is performed to analyze the trade-offs between complexity vs cost and robustness vs cost. The results suggest that complexity is required to achieve robustness and an increase in cost is needed to attain a balanced level of complexity and robustness. Moreover, the results demonstrate that the modular architecture is preferable as it has a balance between complexity and robustness.

To assess the dynamics of the SCs, a system dynamics framework has been proposed to evaluate the impact of disruptions. The results of the scenario analysis demonstrated that the disruptions close to the consumption stages have the potential to damage in a higher magnitude the SC performance. Hence, proactive strategies should be laid down in advance to avoid the effect of disruptions in the downstream echelons. Moreover, it is observed that expediting increases cost but the service level at the distribution centre remains almost the same. The usage of the framework and the findings can serve to define disruption policies, and assist in the decisions relating to the SC design.

To estimate and compare possible mitigation strategies, the SC resilience index is proposed. It considers the system impact cost and the recovery effort from the results of the company performance.

Important conclusions derived from this dissertation are summarized as:

- SC design and the product architecture design influence each other directly. For that reason, their design should be performed simultaneously;
- consideration of risk attitudes of the decision makers is required when designing SCs and product architectures. Different risk-attitudes could lead to different SC designs;
- structural metrics can be used to support systematic analysis of characteristics that could increase structural complexity and robustness of the SC;
- increments in structural SC cost will not determine the increase in structural SC complexity and robustness;
- modular architectures are preferable because they have a balanced level of complexity and robustness;
- structures that contain cycles increase complexity and decrease robustness considerably;
- disruptions have the potential of propagating the effects to upstream and downstream levels;
- partial disruptions have a lesser impact on the SC performance; hence, proactive strategies are required in advance to contain a full disruption and reduce it to a partial disruption;
- disruptions happening in the downstream levels have higher impacts on the SC performance than disruptions in the upstream levels. For that reason, proactive strategies for downstream levels should be a high priority for SC practitioners;
- expediting as a mitigation strategy causes more damages to the already disrupted SC performance; this effect can be detected in the increased raw material inventory which the disrupted SC echelon accumulates;
- expediting increases SC cost but the service levels at the distribution centre remain almost the same.

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APPENDIX A: COMPLEXITY AND ROBUSTNESS MEASURES

A.1 Algorithms to find paths and cycles

In the adjacency matrix $\boldsymbol{A}_{i\times j}$, the entries that have a value different than zero represent that there is a path of length 1 between the nodes i and j. An adjacency matrix has the property that if it is multiplied by itself ($\boldsymbol{A}_{i\times j}\boldsymbol{A}_{i\times j}$), the resulting matrix will show the number of paths of length 2 between the entries of the intersection of nodes i and j. Hence, an adjacency matrix powered a certain number l (i.e. $\boldsymbol{A}^{\boldsymbol{l}}$) returns the number of paths of length l between the nodes described by the adjacency matrix (Newman 2010).

The mentioned property of the adjacency matrix allows calculating the actual number of paths EP in the SC and the minimum theoretical number of paths p as presented in the following pseudocode. The algorithm counts the number of paths of a length equal to or less to a specified maximum path length (kk).

Pseudocode for finding paths

Input: $\boldsymbol{A}_{i\times j}$, $\boldsymbol{vi}$, $\boldsymbol{vo}$, kk =(maximum path length)
Output: p, EP, sp, lp
Let $EP = 0,\ p = 0, sp = 0, lp = 0$
Set $\boldsymbol{An}_{i\times j} = \boldsymbol{A}_{i\times j}$
$set\ a\ counter = 0$
$For\ i = \boldsymbol{vi}$
    $For\ j = \boldsymbol{vo}$
      $If\ \boldsymbol{An}_{i\times j} \sim= 0$
        $Increase\ the\ counter\ by$ 1
        $EP = EP + (\boldsymbol{An}_{i\times j})$
        $p = p + 1$
        $If\ counter = 1$
          $sp = 2$
        End
      End
    End
End
$For\ ii = 2{:}\,kk$
Set $\boldsymbol{An}_{i\times j} = \boldsymbol{An}_{i\times j}\boldsymbol{A}_{i\times j}$
    $For\ i = \boldsymbol{vi}$
      $For\ j = \boldsymbol{vo}$
        $If\ \boldsymbol{An}_{i\times j} \sim= 0$
          $Increase\ the\ counter\ by$ 1
          $EP = EP + (\boldsymbol{An}_{i\times j})$
          $p = p + 1$

```
            If counter = 1
                sp = ii + 1
            End
            If counter > 1
                lp = ii + 1
            End
        End
      End
    End
  End
End
If lp = 0
  lp = sp
End
```

In order to calculate the cycles c and the theoretical number of cycles MC, the following pseudocode is used. To find the cycles, the depth-first search algorithm is used as stated in the pseudocode.

Pseudocode for calculating cycles

Input: $\boldsymbol{A}_{i\times j}$, $\boldsymbol{vi}$, $\boldsymbol{vo}$, kk =(maximum path length)
Output: c, MC
Let $c = 0$, $MC = 0$
Set $size$= $number\ of\ rows$ of $\boldsymbol{A}_{i\times j}$
Set v = vector of nodes in order or their discovery
Set $\boldsymbol{AA} = digraph\ of\ \boldsymbol{A}_{i\times j}$

```
For i = 1: size
  v = Depth − first graph search(i, edgetodiscovered)
  vsize = number of rows of v
  For ii = 1: vsize
    For j = 2
      If v(ii, j) == i and i < v(ii, 1)
          c = c + 1
      End
    End
  End
End
For jj = 2: 3
  MC = MC + (the number of combinations of (size) items taken (jj) at a time)
End
```

A.2 Complexity and robustness measures comparison

It is needed to establish the validity of our proposed measures of complexity and robustness. Hence, previous validated analyses are performed to measure the complexity and robustness of the SC structures presented. The results of these analyses are then compared with the results of the proposed metrics. In that way, the presented metrics are validated.

One of the most common measures of complexity is the one proposed by Shannon (2001). From Shannon's entropy, the index of vertex degree has been derived and used in several studies to assess structural supply chain complexity, e.g. (Modrak and Marton 2014; Cheng, Chen, and Chen 2014). For that reason, we calculated entropy (H_{graph}) for our three basic supply chain structures (Integral, modular and modular customized) as in Equation (A.1). Where $\deg(v_i)$ is the sum of all the incoming and outgoing arcs of node or vertex v_i. e is the number of edges in the SC and n is the number of nodes or vertex in the SC.

$$H_{graph} = \sum_{i=1}^{n} \frac{\deg(v_i)}{e} * log_2\left(\frac{\deg(v_i)}{e}\right) \tag{A.1}$$

The entropy results and their ranks of complexity for the basic structures are shown in Table A.1. As we can observe, the ranks for the entropy measure are the same ranks that are obtained from our proposed SSCC. It is important to mention that we are not comparing the numerical results between our SSCC and entropy because the metrics are designed from different characteristics. Though, both metrics lead to the same result.

Table A.1 Entropy results and comparison of ranks.

	Entropy	Rank	SSCC- Rank
Integral	3.76	1	1
Modular	4.18	2	2
Modular customized	4.40	3	3

A similar analysis was performed to validate the proposed structural supply chain robustness (SSCR). For that reason, the method to evaluate structural robustness proposed by Han and Shin (2016) was carried out. They calculated robustness (ROB) with a function that employs average path length (APL), in-degree (ID'), out-degree (OD') and two weighting factors (α and β) as shown in equation (A.2). Where APL, ID' and OD' can be calculated as Equation (A.3), Equation (A.4) and Equation (A.5), respectively, according to Han and Shin (2016) approach. Specific notations for these formulas are presented in Table A.2.

Table A.2 Notations for the evaluation model of (Han and Shin (2016)) (Eq. A.2 to A.5).

Notation	Definition
ROB	Robustness measure according to (Han and Shin (2016))
N	Set of nodes in the SC
L	Set of layers in the SC (All nodes in the same layer are suppliers for nodes in upper layers)
l_{jn}	1 if node j in layer n is a leaf node, 0 otherwise, $j \in N, n \in L$
p_{jn}	1 if node j in layer n has at least one outgoing arc, 0 otherwise, $j \in N, n \in L$
q_{jn}	1 if node j in layer n has at least one incoming arc, 0 otherwise, $j \in N, n \in L$
a_{ijn}	1 if node i in layer $n - \sigma$ where $(\sigma < n)$ is connected to node j in layer n, 0 otherwise, $i, j \in N, n \in L, a \in A$
$t(l_{jn})$	Depth from Leaf node l_{jn} to root node
α	Linear combination ratio between the value of APL and ID/OD
β	Linear combination ratio between the value of ID and OD

$$ROB = \alpha \cdot -log(APL) + (1-\alpha) \cdot \{\beta \cdot -log(OD) + (1-\beta) \cdot -log(ID)\} \qquad (A.\ 2)$$

$$APL = \frac{\sum_n \sum_j t(l_{jn})}{\sum_n \sum_j l_{jn}}, \qquad j \in N, n \in L \qquad (A.3)$$

$$OD' = \frac{\sum_n \sum_j \sum_i a_{ijn}}{\sum_n \sum_j p_{jn}}, \qquad i, j \in N, n \in L \qquad (A.4)$$

$$ID' = \frac{\sum_n \sum_j \sum_i a_{ijn}}{\sum_n \sum_j q_{jn}}, \qquad i, j \in N, n \in L \qquad (A.5)$$

In order to use their method to analyze the robustness of our structures, 3 different combinations of α and β were used, one with the low values, one with the highest values and one with an average of the range values. The ROB results under this approach are shown in Table A.3.

Table A.3 Robustness results with different combinations of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$.

	Scenario 1	Scenario 2	Scenario 3
α	0.1	0.25	0.4
β	0.4	0.55	0.7
SC structure	ROB	ROB	ROB
Integral	-0.336	-0.277	-0.243
Modular	-0.275	-0.263	-0.270
Modular customized	-0.324	-0.343	-0.374

The ranks for the SC structures in the different scenarios that can be compared with our SSCR and SSCWR are presented in Table A.4. As we can observe from the table, the rankings for the ROB change according to the chosen α and β. We can observe that our ranks from the SSCR match with scenario 1, and the ranks for scenario 2 match with our SSCWR. Both metrics can be influenced by the parameters or weights chosen. However, we can observe that most of the time, the modular architecture is the most robust.

Table A.4 Ranking comparison.

	ROB-Rank Scenario 1	ROB-Rank Scenario 2	SSCR-Rank	SSCWR-Rank
Integral	3	2	3	2
Modular	1	1	1	1
Modular customized	2	3	2	3

APPENDIX B: SYSTEM DYNAMIC FRAMEWORK SETUP

Table B.1 Parameter settings for base case scenario.

		Supply Chain Echelon				
Parameters	**Description**	$j = 1$	$j = 2$	$j = 3$	$j = 4$	**Unit**
Bcr_j	Backlogged penalty rate	0.1	0.15	0.25	0.2	(dmnl)
Bt_j	Backlogged adjustment time	1	1	1	1	(day)
CAT_{jt}	Total capacity	1600	1400	1200	-	(unit/day)
DD_{jt}	Delivery delay	-	0.5	0.5	0.5	(unit/day)
DEt_j	Min time to delivery	0.5	0.5	0.5	0.5	(day)
H_j	Holding rate	0.1	0.1	0.12	0.15	(dmnl)
It_j	Inventory revision adjustment time	1	1	1	1	(day)
L_j	Lead time for products	1	1	1	0.5	(day)
LR_j	Lead time for raw materials	1	1	-	-	(day)
LTN_{jt}	Normal production time	0.5	0.5	0.5	0.5	(day)
MC_j	Manufacturing/purchase cost increment rat	0.3	0.4	0.8	0.2	(dmnl)
ORt_j	Orders adjustment time of raw material	-	1	1	-	(day)
Ot_j	Orders adjustment time of products	1	1	1	1	(day)
PCb_j	Base product cost, j=1	20	-	-	-	(dollar/unit)
PrI_j	Price increment rate	1.9	2.15	2.35	2	(dmnl)
SS_j	Safety stock days of final product	1	0.5	0.5	2	(day)
SSR_j	Safety stock days of raw product	-	1	1	-	(day)
TO_j	Time to order for production	1	1	1	1	(time)
TOR_j	Time to order for raw materials	-	1	1	-	(time)
TRc_j	Cost per truck	200	200	200	200	(dollar/truck)
$TRca$	Truck capacity	80	80	80	80	(unit/truck)
$WIPt_j$	WIP adjustment time	1	1	1	1	(day)

Table B.2 Model notations in AnyLogic.

Notation	Name in AnyLogic	Notation	Name in AnyLogic
Parameters		**Flow Variables**	
t	time	BD_{jt}	P_BackloggedOrdersDelivered
Bcr_j	D_BackloggedPenaltyRate	BIF_{jt}	P_BackloggedInflow
Bt_j	D_BacklogAdjTime	DE_{jt}	P_DeliveredProducts
CAT_{jt}	P_TotalCapacity	F_{jt}	P_FeasibleProductionRate
DD_{jt}	S1_DeliveryDelay	FL_{jt}	FlowOfProductsToDistributor
DEt_j	P_MinTimeToDeliver	$FLDO_{jt}$	FlowOfDeliveredOrders
H_j	P_HoldingRate	FLO_{jt}	FlowOfOrders
It_j	InvRevisionAdjTime	FP_{jt}	ProducedProducts / D_ProductsReadyToShip
L_j	P_leadTime	RR_{jt}	ReceivedRawMaterial
LR_j	S1_LeadTime	SCC_{jt}	SupplyChainCost
LTN_{jt}	P_NormalProductionTime	SCP_{jt}	SuppyChainProfit
MC_j	P_ProductionIncRateCost	UR_{jt}	UsageRateOfRawMaterial
ORt_j	AdjsTime	URG_{jt}	UseRateGRM
Ot_j	RevisionAdjTime	**Auxiliary Variables**	
PCb_j	Base_UnitCost	BC_{jt}	P_BackloggedCost
PrI_j	S2_PriceIncrementRate	CA_{jt}	P_Capacity
SS_j	SafetyStockDaysFP	$CArc_j$	P_DisruptedRateCost
SSR_j	SafetyStockDays	$AdWIP_j$	AdjWIP
TO_j	P_timeToOrder	D_{jt}	P_Demand
TOR_j	P_timeToOrderRawMaterial	DPR_j	DesiredProductionRate
TRc_j	P_costPerTruck	ERc_{jt}	P_ExpeditingRateCost
$TRca$	TruckCapacity	FO_{jt}	P_FirmOrders
$WIPt_j$	WipAdtjime	IP_{jt}	P_InventoryPosition
User Interface Parameters		LT_{jt}	P_ProductionTime
CAr_j	P_DisruptedCapacityRate	MI_j	P_MaxInventory
CER_j	CurrencyExchangeRate	MRI_j	MaximumInventoryRawMaterial
DIS_j	pDisruption	O_{jt}	D_Orders
ED_j	pED	OR_{jt}	OrderRawMaterial
ER_{jt}	P_ExpeditingRate	P_{jt}	P_Profit
$Fday_j$	pdispFinish	Pr_j	P_Price
$Sday_j$	pdispStart	R_{jt}	P_Revenue

Table B.3 Model notations in AnyLogic continued.

Stock Variables		Auxiliary Variables	
BO_{jt}	P_BackloggedOrders	RIC_{jt}	RawMaterialInventoryCost
$CSCC_{jt}$	CumulativeTotalCost	RUC_{j}	RawMaterialCost
$CSCP_{jt}$	CumulativeSupplyChainProfit	SL_{jt}	P_ServiceLevel
I_{jt}	P_Inventory	TC_{jt}	P_TotalCost
IR_{jt}	InventoryRawMaterial	TRn_{jt}	P_NumOfTrucksCalculation
IRG_{jt}	InventoryGRM	$Trnc_{jt}$	P_TransportationCost
On_{jt}	OnOrder	TUC_{j}	P_TotalUnitCost
WIP_{jt}	InProcessProducts/ D_ReceivedProducts	UC_{j}	P_TotalBaseUnitCost
		UIC_{j}	P_UnitInventoryCost
		UPC_{j}	P_BaseUnitProductCost
		$WIPD_{jt}$	DesiredWIP

Table B.4 Effect of disruptions on SC performance (scenario 1 – scenario 4).

	Base (B)	S1	%Δ B-S1	S2	%Δ B-S2	S3	%Δ B-S3	S4	%Δ B-S4	S5	%Δ B-S5
DC_Inventory	728	715	-2	708	-3	715	-2	708	-3	707	-3
P_Inventory	420	389	-7	389	-7	380	-9	330	-22	391	-7
ST1_Inventory	299	206	-31	207	-31	220	-26	206	-31	219	-27
ST2_Inventory	539	698	30	553	3	774	44	528	-2	549	2
P_RawMaterialInventory	358	373	4	677	89	376	5	686	91	721	101
ST1_RawMaterialInentory	474	1,426	201	6,462	1,263	1,481	212	6,441	1,259	7,006	1,378
SC_Cost	777,704	783,523	1	819,723	5	785,578	1	824,818	6	823,079	6
DC_Cost	562,898	559,411	-1	559,407	-1	559,473	-1	559,441	-1	557,397	-1
P_Cost	161,879	161,152	0	168,250	4	160,979	-1	171,753	6	168,517	4
ST1_Cost	37,776	44,938	19	73,130	94	46,543	23	72,886	93	76,149	102
ST2_Cost	13,235	13,918		13,395	1	13,841	5	13,356	1	13,503	2
SC_Profit	459,933	454,835	-1	418,533	-9	452,730	-2	413,284	-10	415,084	-10
DC_Profit	283,454	283,897	0	285,758	1	283,962	0	285,794	1	284,272	0
P_Profit	143,041	142,673	0	135,885	-5	142,885	0	132,407	-7	134,938	-6
ST1_Profit	26,539	18,712	-29	-9,008	-134	17,150	-35	-8,871	-133	-12,082	-146
ST2_Profit	4,911	4,907	0	4,975	1	4,596	-6	5,036	3	5,083	4
DC_Backlog	1	23	2,169	214	21,323	23	2,175	217	21,595	246	24,475
P_Backlog	1	27	2,577	176	17,469	27	2,581	178	17,673	201	19,974
ST1_Backlog	1	207	20,618	957	95,610	232	23,053	959	95,790	1,076	107,495
ST2_Backlog	6	4	-38	1,817	30,183	5	-19	1,817	30,191	1,962	32,602

Table B.5 Effect of disruptions on SC performance (scenario 1 – scenario 4) continued.

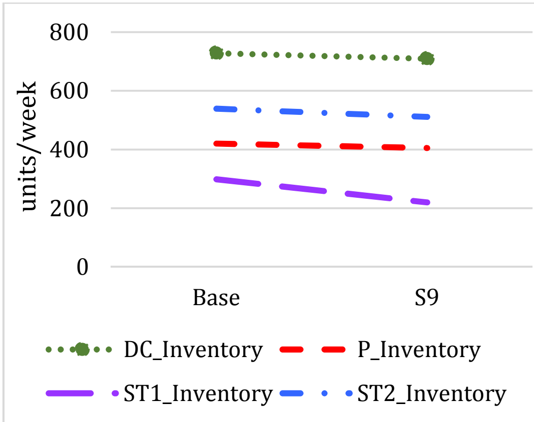
	Base (B)	S1	%Δ B-S1	S2	%Δ B-S2	S3	%Δ B-S3	S4	%Δ B-S4	S5	%Δ B-S5
DC_ReceivedInventory	176	176	0	176	0	176	0	176	0	176	0
P_WIP	180	180	0	179	-1	180	0	236	31	180	0
ST1_WIP	270	416	54	420	55	420	56	420	55	411	52
ST2_WIP	515	516	0	525	2	519	1	525	2	525	2
DC_SL	1.00	0.99	-1.12	0.98	-2.40	0.99	-1.14	0.98	-2.42	0.97	-2.58
P_SL	1.00	0.99	-1.47	0.97	-2.58	0.99	-1.48	0.97	-2.59	0.97	-2.69
STI_SL	1.00	0.84	-15.56	0.82	-18.39	0.83	-16.72	0.81	-18.55	0.82	-17.57
ST2_SL	0.99	1.00	0.34	0.86	-13.48	1.00	0.47	0.86	-13.56	0.85	-14.11

Table B.6 Effect of disruptions on SC performance (scenario 6 – scenario 10).

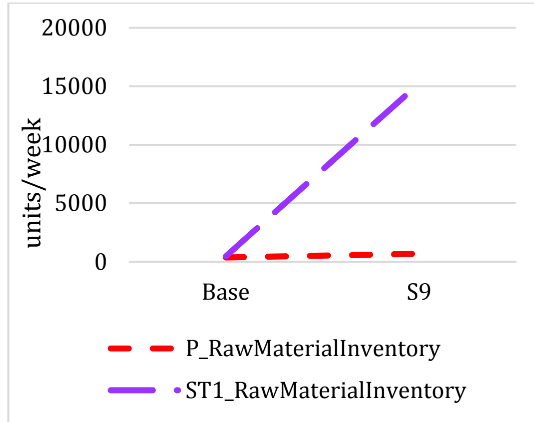
	S6	%Δ B-S6	S7	%Δ B-S7	S8	%Δ B-S8	S9	%Δ B-S9	S10	%Δ B-S10
DC_Inventory	709	-3	706.6	-3	709.4	-3	709.4	-3	687	-6
P_Inventory	405	-4	390.4	-7	338.3	-19	405.3	-4	399	-5
ST1_Inventory	220	-26	234.5	-22	218.0	-27	220.0	-26	222	-26
ST2_Inventory	511	-5	594.4	10	477.5	-11	511.4	-5	414	-23
P_RawMaterialInventory	676	89	733.1	105	685.9	92	675.9	89	1,054	194
ST1_RawMaterialInentory	15,279	3,123	7,107.0	1,399	15,258.7	3,118	15,279.4	3,123	21,857	4,510
SC_Cost	866,640	11	827,210.2	6	874,271.2	12	866,639.8	11	911,515	17
DC_Cost	557,605	-1	557,423.7	-1	557,658.3	-1	557,604.9	-1	552,528	-2
P_Cost	168,109	4	168,707.7	4	173,201.8	7	168,108.8	4	175,878	9
ST1_Cost	119,617	217	79,442.5	110	119,298.3	216	119,616.8	217	156,573	314
ST2_Cost	13,458	2	13,523.7	2	13,506.3	2	13,457.9	2	13,036	-2
SC_Profit	371,061	-19	410,953.4	-11	363,529.6	-21	371,061.1	-19	326,236	-29
DC_Profit	283,624	0	284,300.0	0	283,680.2	0	283,624.4	0	285,180	1

Table B.7 Effect of disruptions on SC performance (scenario 6 – scenario 10) continued.

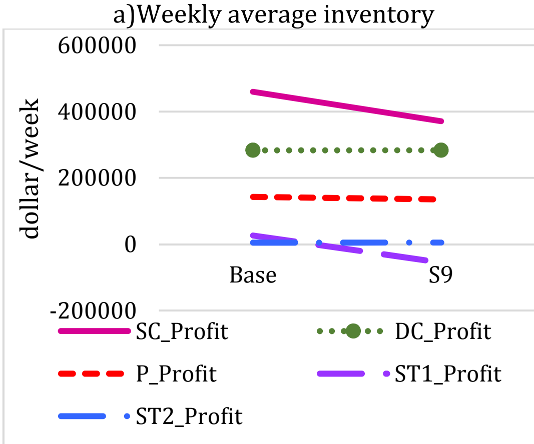
	S6	%Δ B-S6	S7	%Δ B-S7	S8	%Δ B-S8	S9	%Δ B-S9	S10	%Δ B-S10
P_Profit	135,330	-5	134,764.0	-6	130,271.1	-9	135,329.9	-5	126,651	-11
ST1_Profit	-55,197	-308	-15,771.0	-159	-55,112.9	-308	-55,197.3	-308	-92,906	-450
ST2_Profit	5,197	6	4,963.1	1	5,344.2	9	5,196.7	6	5,197	6
DC_Backlog	269	26,831	247.2	24,624	272.0	27,104	269.3	26,831	516	51,478
P_Backlog	219	21,761	201.9	20,087	220.7	21,967	218.6	21,761	420	41,883
ST1_Backlog	399	39,833	1,076.7	107,572	401.6	40,059	399.3	39,833	1,445	144,353
ST2_Backlog	3,974	66,146	1,984.8	32,984	3,975.1	66,161	3,974.2	66,146	6,091	101,438
DC_ReceivedInventory	176	0	175.9	0	175.9	0	175.9	0	176	0
P_WIP	177	-2	180.2	0	241.7	34	176.8	-2	178	-1
ST1_WIP	411	52	386.4	43	411.3	52	411.3	52	409	52
ST2_WIP	525	2	525.0	2	525.1	2	524.9	2	533	3
DC_SL	0.97	-3	0.97	-3	0.97	-3	0.97	-3	0.95	-5
P_SL	0.97	-3	0.97	-3	0.97	-3	0.97	-3	0.94	-6
STI_SL	0.85	-15	0.84	-16	0.85	-15	0.83	-17	0.80	-20
ST2_SL	0.78	-21	0.85	-14	0.78	-21	0.78	-21	0.64	-35



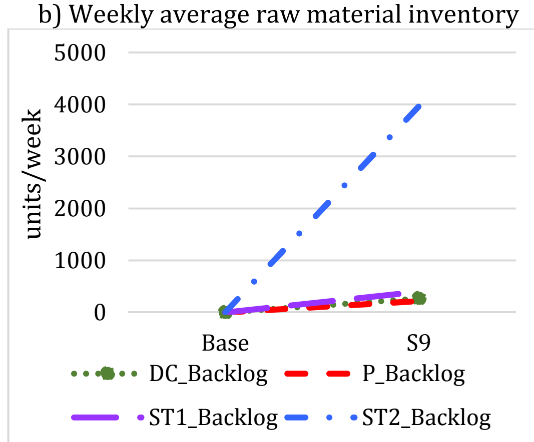
a)Weekly average inventory



b) Weekly average raw material inventory



c)Weekly average profit



d) Weekly average backlog

Figure B.1 Effect of simultaneous full disruptions on SC performance.

ANYLOGIC EQUATIONS

Distribution Centre

DemandForDistributor= UNIFORM (350, 370)

D_BackloggedCost= D_BackloggedPenaltyRate * D_BackloggedInflow * C_UnitProductCost

D_BackloggedInflow= Function (D_FirmOrders, D_DeliveredProducts, DemandForDistributor)

```
Function (D_FirmOrders, D_DeliveredProducts, DemandForDistributor)
    If (D_DeliveredProducts < DemandForDistributor)
            Return DemandForDistributor - D_DeliveredProducts;
    Return 0;
```

D_BackloggedOrders= Classic

D_BackloggedOrdersDelivered= Function1 (D_FirmOrders, DemandForDistributor, D_BackloggedOrders, D_DeliveredProducts, D_BacklogAdjTime)

```
Function1 (D_FirmOrders, DemandForDistributor, D_BackloggedOrders, D_DeliveredProducts,
    D_BacklogAdjTime)
    If (D_DeliveredProducts==D_FirmOrders)
            Return D_BackloggedOrders / D_BacklogAdjTime;
    If (D_DeliveredProducts > DemandForDistributor)
            Return D_DeliveredProducts - DemandForDistributor;
    Return 0;
```

D_BaseUnitProductCost= (D_ProductionIncRateCost * RawMaterialCost) + RawMaterialCost

D_CumulativeProfit= Classic

D_CumulativeTotalCost= Classic

D_DeliveredProducts= MIN (D_FirmOrders, (D_Inventory/ D_MinTimeToDeliver))

D_FirmOrders= (D_BackloggedOrders / D_BacklogAdjTime) + DemandForDistributor

D_Inventory= Classic

D_InventoryPosition= (D_Inventory + D_ReceivedProducts + OnOrder -D_BackloggedOrders)

D_LeadTime= D_ProductionTime

D_MaxInventory=DemandForDistributor * (D_timeToOrder + P_LeadTime + SafetyStockDays)

D_NumOfTrucks= Function2 (D_NumOfTrucksCalculation)

```
Function2 (D_NumOfTrucksCalculation)
    If      (D_NumOfTrucksCalculation >=1)
            If (D_NumOfTrucksCalculation - FLOOR (D_NumOfTrucksCalculation) > 0.2)
```

```
            Return CEIL (D_DeliveredProducts / TruckCapacity);
        Return FLOOR (D_NumOfTrucksCalculation);
    Else
        If (D_NumOfTrucksCalculation < 0.001)
            Return 0;
    Return 1;
```

D_NumOfTrucksCalculation= D_DeliveredProducts / TruckCapacity

D_Orders= MAX ((D_MaxInventory-D_InventoryPosition, 0))/OrdersAdjTime;

D_Price= D_PriceIncrementRate*D_TotalBaseUnitCost

D_ProductsReadyToShip= Delay (FlowOfProductsToDistributor, D_LeadTime)

D_Profit= D_Revenue - D_TotalCost

D_ReceivedProducts=Classic

D_Revenue= D_DeliveredProducts*D_Price

D_ServiceLevel= XIDZ (D_DeliveredProducts, D_FirmOrders, 1)

D_TotalBaseUnitCost= D_BaseUnitProductCost+ D_UnitInventoryCost

D_TotalCost= D_TransportationCost + (D_TotalUnitCost * D_DeliveredProducts) + D_BackloggedCost + D_TotalInventoryCost

D_TotalInventoryCost= (D_UnitInventoryCost * (D_ReceivedProducts+ D_Inventory)) /InvRevisionAdjTime

D_TotalUnitCost= D_UnitInventoryCost + D_BaseUnitProductCost

D_TransportationCost= CostPerTruck * D_NumOfTrucks

D_UnitInventoryCost= D_HoldingRate * D_BaseUnitProductCost

D_unitProductCost= D_TotalBaseUnitCost

FlowOfDeliveredOrders= FlowOfProductsToDistributor

FlowOfOrders= D_Orders

FlowOfProductsToDistributor= Delay (ReceivedFromP, P_DeliveryDelay)

OnOrder =Classic

P_DeliveryDelay= transportationTime

P_LeadTime= P_ProductionTime + transportationTime

P_Price= (Input from another SC echelon)

RawMaterialCost= P_Price+ (P_Price * currencyExchangeRate)

ReceivedFromP= (Input from another SC echelon)

RequestedFromD= D_Orders (Output variable to another echelon)

Plant

AdjWIP= MAX (0, DesiredWIP - InProcessProducts / WipAdtjime)

DeliveredProductsVar= P_DeliveredProducts (Output variable to another echelon)

DesiredProductionRate= P_ProductionOrders + AdjWIP

DesiredWIP= P_ProductionOrders * (2-(P_ProductionTime / P_NormalProductionTime))

D_unitProductCost= (Input from another SC echelon)

FlowOfDeliveredOrders= ReceivedRawMaterial

FlowOfOrders= OrderRawMaterial

InProcessProducts =Classic

InventoryGRM= Classic

InventoryRawMaterial= Classic

MaximumInventoryRawMaterial= P_ProductionOrders* (S1_LeadTime + P_timeToOrderRawMaterial + SafetyStockDays)

OnOrder= Classic

OrderedFromDistributor= (input from another SC echelon)

OrderRawMaterial= Function10 (MaximumInventoryRawMaterial, OnOrder, InventoryRawMaterial, AdjsTime)

```
Function10 (MaximumInventoryRawMaterial, OnOrder, InventoryRawMaterial, adjsTime)
    If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish
    && P_DisruptedCapacityRate==1)
        Return 0;
    Return (MAX ((MaximumInventoryRawMaterial-OnOrder-InventoryRawMaterial), 0)/
        AdjsTime);
```

P_BacklogInflow= Function (P_FirmOrders, P_DeliveredProducts, P_Demand)

```
Function (P_FirmOrders, P_DeliveredProducts, P_Demand)
        If (P_DeliveredProducts<P_Demand)
                Return P_Demand - P_DeliveredProducts;
        Return 0;
```

P_BackloggedCost= P_BackloggedPenaltyRate * P_BacklogInflow * D_unitProductCost

P_BackloggedOrders= Classic

P_BackloggedOrdersDelivered= Function3 (P_DeliveredProducts, P_Demand, P_FirmOrders, P_BackloggedOrders, P_BacklogAdjTime)

```
Function3 (P_DeliveredProducts, P_Demand, P_FirmOrders, P_BackloggedOrders,
                P_BacklogAdjTime)
        If (P_DeliveredProducts == P_FirmOrders)
                Return P_BackloggedOrders / P_BacklogAdjTime;
        If (P_DeliveredProducts > P_Demand)
                Return P_DeliveredProducts - P_Demand;
        Return 0;
```

P_BaseUnitProductCost= RawMaterialCost + (P_ProductionIncRateCost * RawMaterialCost)

P_Capacity= Function8 (P_TotalCapacity, P_DisruptedCapacityRate)

```
Function8 (P_TotalCapacity, P_DisruptedCapacityRate)
        Double dayCapacity=P_TotalCapacity-(P_TotalCapacity*P_DisruptedCapacityRate);
        If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish)
                If (P_DisruptedCapacityRate>0)
                        Return dayCapacity;
        Return P_TotalCapacity;
```

P_CumulativeTotalCost= Classic

P_CumulativeProfit= Classic

P_DeliveredProducts= Function1 (P_Inventory, P_FirmOrders, P_MinTimeToDeliver)

```
Function1 (P_Inventory, P_FirmOrders, P_MinTimeToDeliver)
        If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish
                && P_DisruptedCapacityRate==1)
                Return 0;
        Else
                If (P_Inventory>0.001)
                        Return MIN (P_FirmOrders, (P_Inventory/P_MinTimeToDeliver));
                Return 0;
```

P_Demand= OrderedFromDistributor

P_DisruptedRateCost= DisruptedRateCostFunction (P_DisruptedCapacityRate)

Table Function: DisruptedRateCostFunction

Argument	Value
0.0	0.0
0.1	0.5
0.5	1.5
1.0	2.0

P_ExpeditingRateCost= ExpeditingRateCostFunction (P_ExpeditingRate)

Table Function: ExpeditingRateCostFunction

Argument	Value
0.2	0.5
0.4	1.0
0.6	1.5
0.8	2.0
1.0	4.0

P_FeasibleProductionRate= Function2 (P_Capacity, DesiredProductionRate)

```
Function2 (P_Capacity, DesiredProductionRate)
    Double a= MIN (P_Capacity, DesiredProductionRate);
    Double b= MIN (InventoryRawMaterial, InventoryGRM);
    If (P_Capacity==0)
        Return 0;
    Else
        If (a<InventoryRawMaterial && a<InventoryGRM)
            Return a;
        Else if (b>0.01)
            Return b;
    Return 0;
```

P_FirmOrders= P_Demand + (P_BackloggedOrders / P_BacklogAdjTime)

P_Inventory= Classic

P_InventoryPosition= P_Inventory + InProcessProducts - P_BackloggedOrders

P_MaxInventory= P_Demand * (P_timeToOrder + P_leadTime + safetyStockDaysFP)

P_NumOfTrucksCalculation= P_DeliveredProducts / truckCapacity

P_NumOfTrucksRounded= Function5 (P_NumOfTrucksCalculation)

```
Function5 (P_NumOfTrucksCalculation)
    If (P_NumOfTrucksCalculation >= 1)
        If (P_NumOfTrucksCalculation - FLOOR (P_NumOfTrucksCalculation) > 0.2)
            Return CEIL (P_DeliveredProducts / truckCapacity);
        Return FLOOR (P_NumOfTrucksCalculation);
```

```
        Else
            If (P_NumOfTrucksCalculation < 0.001)
                Return 0;
        Return 1;
```

P_Price= P_PriceIncrementRate*P_TotalBaseUnitCost

P_Price1= P_Price (Output variable)

P_ProductionOrders= Function9 (P_MaxInventory, P_InventoryPosition, RevisionAdjTime)

```
    Function9 (P_MaxInventory, P_InventoryPosition, revisionAdjTime)
        If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish
        &&    P_DisruptedCapacityRate==1)
            Return 0;
         Return MAX ((P_MaxInventory)-P_InventoryPosition, 0)/RevisionAdjTime;
```

P_ProductionTime= Function4 (P_NormalProductionTime, P_ExpeditingRate)

```
    Function4 (P_NormalProductionTime, P_ExpeditingRate)
        If (main.pExp== TRUE && main.pDisruption== TRUE && time ()>=main.pdispFinish &&
            time ()   <= (main.pdispFinish + main.pED))
            Return (P_NormalProductionTime- (P_NormalProductionTime * P_ExpeditingRate));
        Return P_NormalProductionTime;
```

P_Profit= P_Revenue - P_TotalCost

P_Revenue= P_DeliveredProducts * P_Price

P_ServiceLevel= XIDZ (P_DeliveredProducts, P_FirmOrders, 1)

P_TotalBaseUnitCost= P_BaseUnitProductCost+ P_UnitInventoryCost

P_TotalCost= P_TransportationCost + (P_TotalUnitCost*P_DeliveredProducts) + P_BackloggedCost +P_TotalInventoryCost + RawMaterialInventoryCost

P_TotalInventoryCost= ((InProcessProducts + P_Inventory) * P_UnitInventoryCost)/ InvRevisionAdjTime)

P_TotalUnitCost= Function7 (P_BaseUnitProductCost, P_UnitInventoryCost, P_ExpeditingRateCost, P_DisruptedRateCost)

```
    Function7 (P_BaseUnitProductCost, P_UnitInventoryCost, P_ExpeditingRateCost,
        P_DisruptedRateCost)
        If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish)
            Return (P_BaseUnitProductCost + (P_BaseUnitProductCost * P_DisruptedRateCost))
             + P_UnitInventoryCost;
        If (main.pExp== TRUE && main.pDisruption== TRUE && time ()>=main.pdispFinish &&
            time () <= (main.pdispFinish+main.pED))
            Return (P_BaseUnitProductCost+ (P_BaseUnitProductCost * P_ExpeditingRateCost))
                + P_UnitInventoryCost;
```

Return P_BaseUnitProductCost + P_UnitInventoryCost;

P_TransportationCost= P_NumOfTrucksRounded * P_costPerTruck

P_UnitInventoryCost= P_HoldingRate * P_BaseUnitProductCost

P_unitProductCost= P_TotalBaseUnitCost

ProducedProducts= DELAY (Function16 (P_FeasibleProductionRate), P_ProductionTime)

```
Function16 (P_FeasibleProductionRate)
    If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish
    && P_DisruptedCapacityRate==1)
        Return 0;
    Return P_FeasibleProductionRate;
```

RawMaterialCost= S1_Price + (S1_Price * CurrencyExchangeRate)

RawMaterialInventoryCost= (RawMaterialCost * P_HoldingRate1 * InventoryRawMaterial) / InvRevisionAdjTime1

ReceivedFromS1= (Input from other SC echelon)

ReceivedRawMaterial= DELAY (ReceivedFromS1, S1_DeliveryDelay)

RequestedFromP= OrderRawMaterial

S1_DeliveryDelay= transportationTime

S1_Price= (Input from other SC echelon)

UsageRateOfRawMaterial= P_FeasibleProductionRate

UseRateGRM= P_FeasibleProductionRate

Supplier Tier-1

AdjWIP= MAX (0, DesiredWIP – inProcessProducts / WipAdtjime)

DeliveredToPlant= S1_DeliveredProducts

DesiredProductionRate= S1_ProductionOrders+AdjWIP

DesiredWIP= S1_ProductionOrders* (2-(S1_ProductionTime/S1_NormalProductionTime))

FlowOfDeliveredOrders= ReceivedRawMaterial

FlowOfOrders= OrderRawMaterial

InProcessProducts= Classic

InventoryRawMaterial= Classic

MaximumInventoryRawMaterial= S1_ProductionOrders*(S2_LeadTime +S_timeToOrderRawMaterial + SafetyStockDays)

OnOrder =Classic

OrderRawMaterial= Function12 (MaximumInventoryRawMaterial, OnOrder, InventoryRawMaterial, AdjsTime)

```
Function12 (MaximumInventoryRawMaterial, OnOrder, InventoryRawMaterial, AdjsTime)
    If (main.pDisruption== TRUE && time ()>=main.pdispStart && time () <=main.pdispFinish
    && S1_DisruptedCapacityRate==1)
        Return 0;
    Return (MAX ((MaximumInventoryRawMaterial -OnOrder- InventoryRawMaterial), 0)/
    AdjsTime);
```

ProducedProducts= DELAY (Function16 (S1_FeasibleProductionRate), S1_ProductionTime)

```
Function16 (S1_FeasibleProductionRate)
    If (main.sDisruption== TRUE && time ()>=main.sdispStart && time () <=main.sdispFinish
    && S1_DisruptedCapacityRate==1)
        Return 0;
    Return S1_FeasibleProductionRate;
```

RawMaterialInventoryCost= (RawMaterialCost * S1_HoldingRate * InventoryRawMaterial) / InvRevisionAdjTime1

ReceivedFromS2= (Dependent variable)

ReceivedRawMaterial= DELAY (ReceivedFromS2, deliveryDelay)

RequestedFromS1= OrderRawMaterial

S1_BackloggedCost= S1_BackloggedPenaltyRate * S1_BacklogInflow * P_unitProductCost

S1_BacklogInflow= Function (S1_FirmOrders, S1_DeliveredProducts, S1_Demand)

```
Function (S1_FirmOrders, S1_DeliveredProducts, S1_Demand)
    If (S1_DeliveredProducts<S1_Demand)
        Return S1_Demand-S1_DeliveredProducts;
    Return 0;
```

S1_BackloggedOrders= Classic

S1_BackloggedOrdersDelivered= Function3 (S1_DeliveredProducts, S1_Demand, S1_FirmOrders, S1_BackloggedOrders, S1_BacklogAdjTime)

```
Function3 (S1_DeliveredProducts, S1_Demand, S1_FirmOrders, S1_BackloggedOrders,
        S1_BacklogAdjTime)
        If (S1_DeliveredProducts == S1_FirmOrders)
                Return S1_BackloggedOrders / S1_BacklogAdjTime;
        If (S1_DeliveredProducts > S1_Demand)
                Return S1_DeliveredProducts - S1_Demand;
        Return 0;
```

S1_BaseUnitProductCost= RawMaterialCost + (S1_ProductionIncRateCost * RawMaterialCost)

S1_Capacity= Function11 (S1_TotalCapacity, S1_DisruptedCapacityRate)

```
Function11 (S1_TotalCapacity, S1_DisruptedCapacityRate)
        Double DayCapacity=S1_TotalCapacity - (S1_TotalCapacity * S1_DisruptedCapacityRate);
        If (main.sDisruption== TRUE && time ()>=main.sdispStart && time () <=main.sdispFinish)
                If (S1_DisruptedCapacityRate>0)
            Return DayCapacity;
        Return S1_TotalCapacity;
```

S1_CumulativeProfit= Classic

S1_CumulativeTotalCost= Classic

S1_DeliveredProducts= Function1 (S1_Inventory, S1_FirmOrders, S1_MinTimeToDeliver)

```
Function1 (S1_Inventory, S1_FirmOrders, S1_MinTimeToDeliver)
        If (main.sDisruption == TRUE && time ()>=main.sdispStart && time () <=main.sdispFinish
        && S1_DisruptedCapacityRate==1)
                Return 0;
        Else
                If (S1_Inventory > 0.001)
                        Return MIN (S1_FirmOrders, (S1_Inventory/S1_MinTimeToDeliver));
                Return 0;
```

S1_Demand= OrderedFromPlant

S1_DisruptedRateCost= DisruptedRateCostFunction (S1_DisruptedCapacityRate)

Table Function: DisruptedRateCostFunction

Argument	Value
0.0	0.0
0.1	0.5
0.5	1.5
1.0	2.0

S1_ExpeditingRateCost= ExpeditingRateCostFunction (S1_ExpeditingRate)

Table Function: ExpeditingRateCostFunction

Argument	Value
0.2	0.5
0.4	1.0
0.6	1.5
0.8	2.0
1.0	4.0

```
S1_FeasibleProductionRate= Function2 (S1_Capacity, DesiredProductionRate)

        Function2 (S1_Capacity, DesiredProductionRate)
                Double a= MIN (S1_Capacity, DesiredProductionRate);
                If (S1_Capacity==0)
                        Return 0;
                Else
                        If (a < InventoryRawMaterial)
                                Return a;
                        Else if (InventoryRawMaterial > 0.01)
                                Return InventoryRawMaterial;
                        Return 0;
S1_FirmOrders= S1_Demand + (S1_BackloggedOrders/ S1_BacklogAdjTime)

S1_Inventory= Classic

S1_InventoryPosition= (S1_Inventory + InProcessProducts-S1_BackloggedOrders)

S1_MaxInventory= S1_Demand * (S1_timeToOrder + S1_leadTime + SafetyStockDaysFP)

S1_NumOfTrucksCalculation= S1_DeliveredProducts / TruckCapacity

S1_NumOfTrucksRounded= Function5 (S1_NumOfTrucksCalculation)

        Function5 (S1_NumOfTrucksCalculation)
                If (S1_NumOfTrucksCalculation >= 1)
                        If (S1_NumOfTrucksCalculation - FLOOR (S1_NumOfTrucksCalculation)>0.2)
                                Return CEIL (S1_DeliveredProducts / TruckCapacity);
                        Return FLOOR (S1_NumOfTrucksCalculation);
                Else
                        If (S1_NumOfTrucksCalculation<0.001)
                                Return 0;
                Return 1;
S1_Price= S1_PriceIncrementRate*S1_TotalBaseUnitCost

S1_Price1= S1_Price

S1_ProductionOrders= Function14 (S1_InventoryPosition, RevisionAdjTime, S1_MaxInventory)

        Function14 (S1_InventoryPosition, RevisionAdjTime, S1_MaxInventory)
                If (main.sDisruption== TRUE && time ()>=main.sdispStart && time () <=main.sdispFinish
                && S1_DisruptedCapacityRate==1)
                        Return 0;
                 Return MAX ((S1_MaxInventory) - S1_InventoryPosition, 0)/RevisionAdjTime;
S1_ProductionTime= Function4 (S1_NormalProductionTime, S1_ExpeditingRate)

        Function4 (S1_NormalProductionTime, S1_ExpeditingRate)
                If (main.sExp== TRUE && main.sDisruption== TRUE && time ()>=main.sdispFinish &&
                time () <= (main.sdispFinish + main.sED))
                        Return (S1_NormalProductionTime-(S1_NormalProductionTime*
                        S1_ExpeditingRate));
```

Return S1_NormalProductionTime;

S1_Profit= S1_Revenue - S1_TotalCost

S1_Revenue= S1_DeliveredProducts * S1_Price

S1_ServiceLevel= XIDZ (S1_DeliveredProducts, S1_FirmOrders, 1)

S1_TotalBaseUnitCost= S1_UnitInventoryCost + S1_BaseUnitProductCost

S1_TotalCost= S1_TransportationCost + (S1_TotalUnitCost * S1_DeliveredProducts) + S1_BackloggedCost + S1_TotalInventoryCost + RawMaterialInventoryCost

S1_TotalInventoryCost= ((inProcessProducts + S1_Inventory) * S1_UnitInventoryCost) / InvRevisionAdjTime

S1_TotalUnitCost= Function10 (S1_ExpeditingRateCost, S1_DisruptedRateCost, S1_BaseUnitProductCost, S1_UnitInventoryCost)

```
Function10 (S1_ExpeditingRateCost, S1_DisruptedRateCost, S1_BaseUnitProductCost,
    S1_UnitInventoryCost)
    If (main.sDisruption== TRUE && time ()>=main.sdispStart && time () <=main.sdispFinish)
        Return (S1_BaseUnitProductCost+ (S1_BaseUnitProductCost * S1_DisruptedRateCost) +
        S1_UnitInventoryCost);
    If (main.sExp== TRUE && main.sDisruption== TRUE && time ()>=main.sdispFinish &&
    time () <= (main.sdispFinish+main.sED))
        Return (S1_BaseUnitProductCost+ (S1_BaseUnitProductCost * S1_ExpeditingRateCost)
        + S1_UnitInventoryCost);
    Return S1_BaseUnitProductCost+S1_UnitInventoryCost;
```

S1_TransportationCost= S1_NumOfTrucksRounded * S1_costPerTruck

S1_UnitInventoryCost= S1_HoldingRate * S1_BaseUnitProductCost

S1_UnitProductCost1= S1_TotalBaseUnitCost

S2_DeliveryDelay= transportationTime

S2_Price= (Dependent variable)

UsageRateOfRawMaterial= S1_FeasibleProductionRate

Supplier Tier-2

AdjWIP= MAX (0, DesiredWIP - InProcessProducts / WipAdtjime)

DesiredProductionRate= S2_ProductionOrders+AdjWIP

DesiredWIP= S2_ProductionOrders * S2_NormalProductionTime

InProcessProducts =Classic

OrderedFromSupplier= (Dependent variable)

ProducedProducts= DELAY (S2_FeasibleProductionRate, S2_NormalProductionTime)

RawMaterialCost= Base_UnitCost + (Base_UnitCost*currencyExchangeRate)

SendToSupplier= S2_DeliveredProducts (Output variable)

S1_unitProductCost= (Dependent variable)

S2_BacklogInflow= Function (S2_FirmOrders, S2_DeliveredProducts, S2_Demand)

```
Function (S2_FirmOrders, S2_DeliveredProducts, S2_Demand)
    If (S2_DeliveredProducts<S2_Demand)
        Return S2_Demand-S2_DeliveredProducts;
    Return 0;
```

S2_BackloggedCost= S2_BackloggedPenaltyRate * S2_BacklogInflow * S1_unitProductCost

S2_BackloggedOrders= Classic

S2_BackloggedOrdersDelivered= Function3 (S2_DeliveredProducts, S2_Demand, S2_FirmOrders, S2_BackloggedOrders, S2_BacklogAdjTime)

```
Function3 (S2_DeliveredProducts, S2_Demand, S2_FirmOrders, S2_BackloggedOrders,
        S2_BacklogAdjTime)
    If (S2_DeliveredProducts==S2_FirmOrders)
        Return S2_BackloggedOrders/S2_BacklogAdjTime;
    If (S2_DeliveredProducts>S2_Demand)
        Return S2_DeliveredProducts-S2_Demand;
    Return 0;
```

S2_BaseUnitProductCost= RawMaterialCost + (RawMaterialCost * S1_ProductionIncRateCost)

S2_Capacity= S2_TotalCapacity

S2_CumulativeTotalCost= Classic

S2_CumulativeProfit= Classic

S2_DeliveredProducts= Function1 (S2_MinTimeToDeliver, S2_FirmOrders, S2_Inventory)

```
Function1 (S2_MinTimeToDeliver, S2_FirmOrders, S2_Inventory)
        If (S2_Inventory > 0.001)
                Return MIN (S2_FirmOrders, (S2_Inventory/S2_MinTimeToDeliver));
        Return 0;
```

S2_Demand= OrderedFromSupplier

S2_FeasibleProductionRate= MIN ((S2_Capacity), (DesiredProductionRate))

S2_FirmOrders= S2_Demand+ (S2_BackloggedOrders / S2_BacklogAdjTime)

S2_Inventory= Classic

S2_inventoryPosition= S2_Inventory - S2_BackloggedOrders + InProcessProducts

S2_MaxInventory= S2_Demand * (S2_timeToOrder + S2_leadTime + SafetyStockDaysFP)

S2_NumOfTrucksCalculation= S2_DeliveredProducts / TruckCapacity

S2_NumOfTrucksRounded= Function5 (S2_NumOfTrucksCalculation)

```
Function5 (S2_NumOfTrucksCalculation)
If (S2_NumOfTrucksCalculation>=1)
    If (S2_NumOfTrucksCalculation – FLOOR (S2_NumOfTrucksCalculation)>0.2)
        Return CEIL (S2_DeliveredProducts/TruckCapacity);
    Return FLOOR (S2_NumOfTrucksCalculation);
Else
    If (S2_NumOfTrucksCalculation<0.001)
        Return 0;
Return 1;
```

S2_Price= S2_PriceIncrementRate * S2_TotalBaseUnitCost

S2_Price1= S2_Price (Output variable)

S2_ProductionOrders= MAX ((S2_MaxInventory)-S2_inventoryPosition, 0) / RevisionAdjTime

S2_Profit= S2_Revenue - S2_TotalCost

S2_Revenue= S2_DeliveredProducts * S2_Price

S2_ServiceLevel= XIDZ (S2_DeliveredProducts, S2_FirmOrders, 1)

S2_TotalBaseUnitCost= S2_UnitInventoryCost + S2_BaseUnitProductCost

S2_TotalCost= S2_TransportationCost + (S2_TotalUnitCost * S2_DeliveredProducts) + S2_BackloggedCost + S2_TotalInventoryCost)

S2_TotalInventoryCost= ((InProcessProducts + S2_Inventory) * S2_UnitInventoryCost) / InvRevisionAdjTime)

S2_TotalUnitCost= S2_BaseUnitProductCost + S2_UnitInventoryCost

S2_TransportationCost= S2_NumOfTrucksRounded * S2_costPerTruck

S2_UnitInventoryCost= S2_HoldingRate * S2_BaseUnitProductCost

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1. Olivares Aguila, J., and W. ElMaraghy. 2018. "Structural complexity and robustness of supply chain networks based on product architecture." International Journal of Production Research:1-18. doi: 10.1080/00207543.2018.1489158.

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