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A Representation of Tactical and Strategic Precursors of Supply Network Resilience Using Simulation Based Experiments

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A REPRESENTATION OF TACTICAL AND STRATEGIC PRECURSORS OF SUPPLY NETWORK RESILIENCE USING SIMULATION BASED EXPERIMENTS

by

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ABSTRACT

A REPRESENTATION OF TACTICAL AND STRATEGIC PRECURSORS OF SUPPLY NETWORK RESILIENCE USING SIMULATION BASED EXPERIMENTS

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Modern supply chains are becoming increasingly complex and are exposed to higher levels of risk. Globalization, market uncertainty, mass customization, technological and innovation forces, among other factors, make supply networks more susceptible to disruptions (both those that are man-made and/or ones associated with natural events) that leave suppliers unavailable, shut-down facilities and entail lost capacity.

Whereas several models for disruption management exist, there is a need for operational representations of concepts such as resilience that expand the practitioners' understanding of the behavior of their supply chains. These representations must include not only specific characteristics of the firm's supply network but also its tactical and strategic decisions (such as sourcing and product design). Furthermore, the representations should capture the impact those characteristics have on the performance of the network facing disruptions, thus providing operations managers with insights on what tactical and strategic decisions are most suitable for their specific supply networks (and product types) in the event of a disruption.

This research uses Agent Based Modeling and Simulation (ABMS) and an experimental set-up to develop a representation of the relationships between tactical and strategic decisions and their impact on the performance of multi-echelon networks under supply uncertainty. Two main questions are answered: 1) How do different tactical and strategic decisions give rise to resilience in a multi-echelon system?, and 2) What is the nature of the interactions between those factors, the network's structure and its performance in the event of a disruption?

Product design was found to have the most significant impact on the reliability (Perfect Order Fulfillment) for products with high degrees of componentization when dual sourcing is the chosen strategy. However, when it comes to network responsiveness (Order Fulfillment Cycle Time), this effect was attenuated. Generally, it was found that the expected individual impact these factors have on the network performance are affected by the interactions between them.

This dissertation is dedicated to Leo, Sofia, Santiago, and Sarah. For always showing the way, whenever I veered away. For always finding me the light, whenever it was dark.

Together we are.

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1 INTRODUCTION

Natural and human-driven events continue to dramatically expose the vulnerability of supply networks to disruptions. For example, in May 2018, Ford shut down the two plants producing its best-selling vehicle, the F-150 truck, due to an explosion and fire at a key parts supplier [1]. As the company struggled to find another supplier that could make the part, ripple effects were felt throughout the automotive industry because the plant made parts for other automakers. Likewise, the high-technology sector and the automotive industry were severely affected by the Chennai floods of 2015 (which were estimated to have caused damages of a magnitude close to 1 billion dollars) and the Typhoon Halong of Southeast Asia in 2014 (estimated cost of more than 10 billion dollars) [2, 3]. Geopolitical unrest at the Turkish border after the downing of a Russian jet and labor disputes in some of the major African and Indian ports seriously impacted the fuel and agricultural sectors in 2014. Looking back further, hurricane Katrina in 2005 and a fire at a Philips semiconductor plant in 2001 are commonly used examples of how disruption management has become a strategic advantage for companies such as Nokia, WalMart, and Home-Depot and to demonstrate how its absence usually results in costly failures in both the private and public sectors [4, 5].

Disruption management is a critical component in supply chain risk management. Supply chain design involves decisions that generally are costly, have a long time horizon, and reduce the firm’s flexibility. Indeed, decisions such as the location of a warehouse or a major sourcing contract with a supplier are not easy to revise on short notice. When a disruption occurs, the firm has a limited ability to adjust to the unexpected condition, and its response to customers depends mainly on the inherent resilience of its supply chain design and the speed of its response. To further complicate matters, trends such as specialization, globalization, e-commerce, and mass-customization have rendered supply chains more complex and dynamic to the extent that the traditional view of a supply chain as a linear and static sequence of sourcing/production/distribution activities is no longer an adequate representation of the real environment in which a firm operates.

Novel analytical approaches that consider non-linearities, multiple scales, emergent behaviors, and adaptation are more relevant to real-world supply chains. Recently, the applicability of complexity theory and, more precisely, complex adaptive systems theory, in the supply chain management field has been explored by several authors [6-8].

Whereas several models for disruption management exist, the environment in which supply networks operate (global, highly complex) calls for representations of resilience that can be operationalized, and that provide practitioners with insights on the behavior of their supply chains. Those representations must consider characteristics of the supply network as well as tactical and strategic aspects (sourcing, product design), and should capture how those characteristics impact the performance of a network facing disruptions. A systematic analysis of supply chain risk management, and particularly of the concept of resilience, as a robust strategy for disruption management, is a need several authors have pointed out recently [5, 9-17]. Several quantitative models for disruption management have been developed [13, 17-22] and in the past 5 years, several authors have undertaken the task of developing quantitative models for the concept of resilience at the strategic level [19, 23-26] but only a few have undertaken the task of establishing operational metrics for the concept [13, 27-31].

Of particular interest is the work of Falasca et al. [23] who proposed a decision framework to assess the resilience of a supply chain by integrating two previous works: Craighead, Blackhurst, Rungtusanatham, & Handfield's [32] around the relationship between the severity of a disruption and the characteristics of the network topology, and Tierney & Bruneau's [33] that focuses on disaster loss reduction, where resilience is represented as a loss of functionality over time as well as subsequent recovery. Their framework facilitates the analysis of a supply network from a complex system perspective, since the topology of the network can be derived from the firm's product design and from the sourcing decisions made (amongst other tactical and strategic aspects). Additionally, the framework facilitates the incorporation of reference models (such as the Supply Chain Operations Reference Model –SCOR), to gauge the loss of functionality in a supply network facing a disruptive event. Snyder et al. [13] acknowledge that research on multi-echelon systems under the risk of disruptions is limited. Furthermore, they state a need for models that can increase the understanding of how disruptions propagate downstream in the supply network.

This dissertation develops a representation of the tactical and strategic decisions and their impact on the performance of multi-echelon networks under supply uncertainty, in order to address the gaps in the literature discussed above. In particular, this work analyzes how upstream disruptions propagate downstream in the supply network and the role that sourcing decisions and product design (captured in the bill of materials) play in mitigating the impact of a disruption. This research also explores interactions between operational decisions, the structure of the network and their performance under disruptive scenarios. The concept of network resilience has yet to be formalized by the research and industry communities, but several key performance indicators can be used as proxies to expand on its understanding. In this research, SCOR-Level-I metrics are used to capture the rate of response (recover plus readiness) of multi-echelon networks during disruptions. Figure 1.1 outlines the scope of this research based on the literature streams associated with Supply Chain Management, Supply Chain Performance Disruption Management, Complex Adaptive Systems, and simulation as a tool to analyze complex systems.

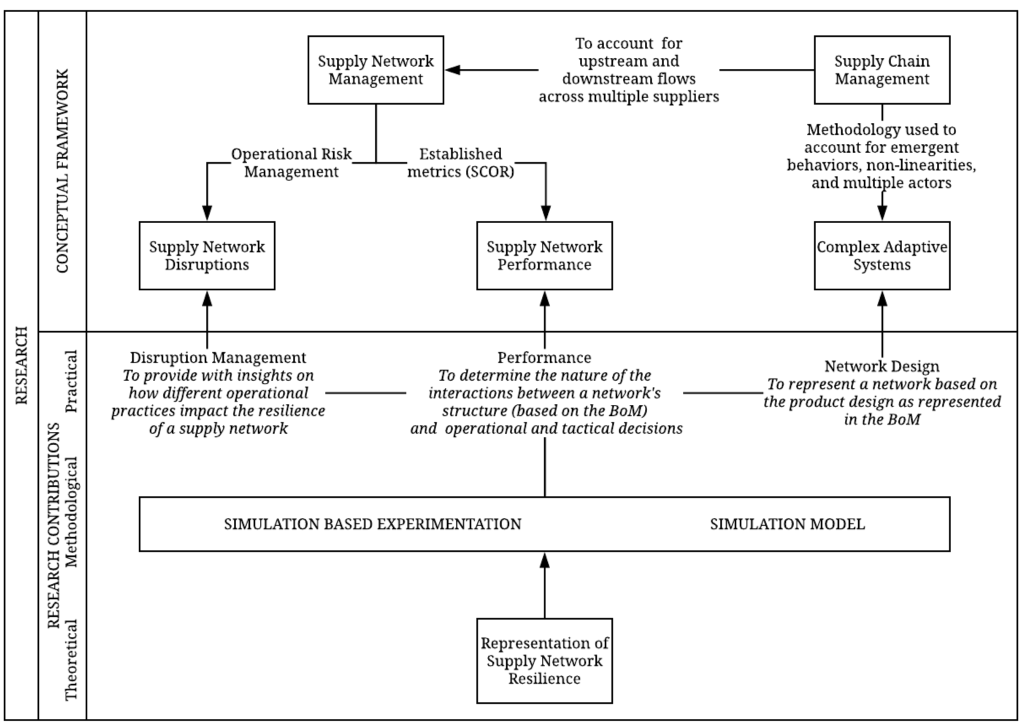


Figure 1.1 Research scope and delimitations.

1.1 Motivation and Purpose Statement

A robust disruption management strategy is critical to the profitability and survivability of a firm with constructs such as resilience being at the center of this strategy. However, quantification of resilience has proven to be a difficult yet fundamental task in supply chain risk management. In addition, when dealing with a disruption, there are embedded tradeoffs that need to be made between reactive and proactive disruption management strategies, consequently impacting the performance of the network in the presence of a disruptive scenario. Furthermore, the network's structural properties underlie strategic decisions such as the product design (as per the bill of materials). To provide insights on how those tactical and strategic decisions impact the ability of a network to respond and recover from a disruptive event, this research:

> *analyzes how upstream disruptions propagate downstream in the supply network and the role that sourcing decisions and product design (captured in the bill of materials)as well as network design play in mitigating the impact of a disruption. This research also explores interactions between tactical and strategic decisions, the structure of the network and its performance under disruptive scenarios.*

To achieve the purpose, this dissertation specifically addresses the following research questions:

- How do different tactical and strategic decisions give rise to different levels of resilience in a multi-echelon system?
- What is the nature of the interactions between those decisions, the network structure and its performance in the event of a disruption?

The first question addresses the need for a representation of the concept of resilience in terms of the supply network structure. These characteristics reflect some of the decisions managers face when designing their supply networks and some of the recovery actions that they need to implement to recover certain levels of performance.

The second research question describes the nature of the interactions between strategic aspects of the firm (such as the type of product) and strategic and operational aspects such us supplier selection (as reflected in the network topology) and sourcing decisions (single vs. dual). Furthermore, this research analyzes the impact these interactions have on the performance of the network performance (and changes in its resilience) in the event of macro or micro disruptive events.

As mentioned before, the ability of a supply network to cope and recover after a disruptive event is determined by several structural, tactical and strategic decisions made by the firm prior, during or in the aftermath of the event. The analysis and evaluation of the impact of these events have on the network using existing analytical tools is challenging [34-36]. Due to the nature of the network (complex interdependences between suppliers, manufacturers, distributors; imperfect and incomplete information; partial visibility of other firms' operations, etc.) and the environment in which it operates (globalize, uncertain, etc.), simulation, and specifically agent based simulation, is a natural tool to gain understanding and insights into which and how different configurations and decisions would increase the network's resilience.

This chapter briefly discusses the domains encompassed by the purpose of this research. More specifically, Section 1.2 presents an introduction to supply chain management while Section 1.3 specifically discusses the issues relevant to supply chain risk management and disruption management. Section 1.4 makes the case for using a complex adaptive system approach to analyze supply chains. Section 1.5 presents the significance and expected contributions of this research.

1.2 Supply Chain Management

Supply chain management crosses several disciplines making it a very rich yet only partially developed topic; most of the research work done in supply chain management is fragmented and focuses on one or just a few of the segments of the chain [37-39]. Research developments have been conducted along the lines of key conceptual bodies or areas such as strategic management, logistics and transportation, marketing, organizational behavior, sustainability, etc. and multiple definitions for supply chain management have emerged. This research approaches the supply chain from two perspectives: as complex adaptive systems and as networks instead of a chain. Consequently, this research adopts the definition of supply chain management given by Mentzer, DeWitt, Keebler, Min, Nix, & Smith's [40]:

> *The systemic, strategic coordination of the traditional business functions and the tactics across these business functions, within a particular company and across businesses within a supply chain, for the purposes of*

improving the long term performance of the individual companies and the supply chain as a whole (p. 18).

The reason for adopting Mentzer et al.'s definition is twofold. First, it accounts for upstream and downstream flows across multiple firms and within the firm (supporting the use of a network perspective). Second, it facilitates the use of a complex adaptive systems approach to gain insights about supply chain behaviors since it recognizes, among other factors, the interdependent character of a supply network. This suggests that, at the firm level, companies need to consider integration, coordination and cooperative behaviors upstream and downstream in the chain while guaranteeing that common goals are achieved along the chain [37].

Consequently, as the main objective of a robust supply chain risk management strategy, firms should focus on the identification and the effective and efficient management of those aspects of the supply chain that can compromise the achievement of collective and individual performance goals.

1.3 Supply Chain Risk Management

While supply chain risk management has been acknowledged as a core area of supply chain management, it has been a daunting task to define what constitutes risk management in supply chains and how risk is measured. Most of the concepts and constructs have been adopted from other areas such as finance, actuarial science, etc. Juttner et al. [10] explored the literature around supply chain risk management and concluded that four main constructs are used to probe the concept:

- Supply chain risk sources: environmental, organizational or other supply chain variables that cannot be predicted and that may impact the performance of the supply chain.
- Risk consequences: changes in the performance of the supply chain due to mismatches between demand and supply.
- Supply chain risk drivers: any trend or event that exacerbates the risk exposure as well as the impact of any disruptive event.
- Risk mitigating strategies (risk mitigation): actions to identify potential sources of risk and to avoid or contain supply chain vulnerabilities.

Furthermore, Ho et al. [41] provide a definition for supply chain risk management that spans across those four main constructs and the different methods to manage risk, but most importantly, their definition incorporates both endogenous and exogenous disruptive events. For the purpose of this research supply chain risk management is consider as:

> *"an inter-organizational collaborative endeavour utilizing quantitative and qualitative risk management methodologies to identify, evaluate, mitigate, and monitor unexpected macro and micro level events or conditions, which might adversely impact any part of a supply chain"* [41]

Although these constructs outline the key areas managers need to focus on when designing strategies for risk management, it is assumed that adequate risk management will acknowledge the vulnerabilities of the chain. As will be discussed in Chapter 2, risk is the execution of a threat in a vulnerable supply chain, and any comprehensive strategy of risk management requires a solid vulnerability analysis [42]. The distinction between these two concepts is crucial in understanding how operations managers establish the objectives of their risk management strategy. Accordingly, this research identifies product and network design, and sourcing strategies as potential intrinsic vulnerabilities of a supply network. This research extends the work of Talluri et al. [43] by utilizing the bill of materials as the driving factor in the configuration of the supply network and, analyzing the interactions between the resulting structure and the mitigation strategy associated with redundancy in suppliers (dual sourcing).

1.3.1 Risk and Vulnerability in the Supply Chain

Vulnerability and risk are two widely recognized concepts in supply chain management. The way these concepts are characterized and related is key to the development of a robust risk management strategy, and subsequently, to the design of more resilient supply chains. Vulnerabilities in today's complex supply networks have been recognized by researchers and practitioners but, as acknowledged by Svensson [44], the concept is presented from different perspectives and remains open to formalization. Nonetheless, different strategies/models for managing various types of vulnerabilities and risks have been developed, aiming to guarantee the profitability and continuity of a supply network through coordination and/or collaboration among the network entities [5, 22, 45-47]. In addition to the multiple perspectives around the concept of vulnerability, several authors point to the importance of understanding the nature of the relationship between vulnerability and risk [10, 46, 48-50]. Generally, it is assumed that risk is an underlying factor of supply chains. As will be discussed in Chapter 2, the approach taken to define risk and vulnerability and their relationships is crucial to expand understanding and representation of concepts related to robust risk management such as resilience.

1.3.2 Disruption Management

Supply networks are becoming larger and more complex with globally dispersed components (suppliers, distribution centers, retailers, customers, etc.). In this context, effective supply chain risk management is a challenging task, especially when the supply network faces unexpected disruptions. These disruptions have different forms and levels of impact, and their origins can range from transportation delays to port stoppages, from accidents and natural disasters to poor communication, from part shortages to quality issues, from operational issues to terrorism, etc. The increasing complexity of supply chain networks augments the types of disruptions they experience, and introduces new challenges when dealing with these emerging forms of disruption.

Similar to the literature in supply chain risk management, disruption management has been studied by several authors, mainly under two distinctive perspectives: proactive disruption management and reactive disruption management [51]. The former acknowledges the potential vulnerabilities and the associated risks in the design of the supply network [13, 52] while the latter considers actions that contribute to the recovery of the functionality of the network in the event of a disruption [53, 54]. This research bridges both approaches by analyzing both reactive and proactive approaches to deal with endogenous and exogenous disruptive events.

In summary, the representation of supply network resilience developed in this research accounts for the network structure as determined by the design of the product (based on the bill of materials); the network design (based on whether the suppliers are clustered in a specific region or dispersed across several regions) and the sourcing strategy (where redundant suppliers are made available and chosen based on both their performance and availability). A specific set of disruptive events, occurring at both the node and region level, and some of the mitigation strategies the literature provides for these events are also studied.

1.3.3 Disruptions Risks

Supply network risks can be classified into two main groups: operational risks and disruptions risks [55]. The first group impacts the operational and tactical plans and accounts for the inherent operational uncertainties: cost, demand and supply. The second group deals with rare events such as natural and man-made disasters, frequently interdependent, affecting strategic plans and having a greater impact on the overall network performance. This dissertation focuses on both, as previously discussed in Section 1.3.2.

Furthermore, this study specifically analyzes incidences with the following types of disruptions and proactive disruption management and mitigation strategies in supply and demand, as shown in Table 1.1.

Table 1.1 Proposed Hybrid Approach to Disruption Management

Disruption	Type	Proactive	Reactive
A supplier is no longer available	Endogenous: the firm's supplier was no longer able to meet the demand due to an in-situ disruptive event that is usually short in duration and relatively frequent.	• Dual Sourcing • Network structure (clustered)	
	Exogenous: the link between the firm and its supplier broke due to a disruptive event that is rare (infrequent) and that can potentially have an impact on other suppliers		• Dual sourcing • Network structure (disperse)

The supply disruptions deal with suppliers who no longer can meet the demand of their buyers because the node is not available or the link between the node and/or downstream node(s) is not available. A more formal definition of these types of disruptions will be given in Chapter 3 and revisited in Chapter 4.

1.4 Supply Chains as Complex Adaptive Networks

Holland [56] defines complex adaptive systems as systems composed of agents interacting with each other and with an external environment whose behaviors are a response to stimuli coming from the agents themselves or the environment. He further states that agents adapt by changing their rules as experience accumulates and can be aggregated into meta-agents whose behavior may be emergent, i.e. not determinable by analysis of lower level agents.

A supply network, as discussed in Section 1.2, involves upstream and downstream flows across multiple firms, agents, and within the network itself. Moreover, several authors have characterized supply networks as exhibiting emergent and multi-scale behaviors, different levels of granularity, multiple and dynamic time scales and several other characteristics [6, 8, 57] making the complex adaptive systems approach suitable to analyzing and gaining insights on how to design and effectively manage supply networks [58].

Examining Holland's definition of complex adaptive systems, it is feasible to understand supply networks as *artificial* complex adaptive systems: the network is "manufactured" to achieve a predefined set of objectives and will compromise a large number of interacting and interdependent entities with persistent movement and reconfiguration based on changes in context (specifically in this case, disruptive events) ordered through self-organization, with local governing rules for entities and increasing complexity as those rules become more sophisticated.

1.5 Research Significance

From a theoretical perspective, this research develops a representation of the resilience of a supply network. The resilience construct is analyzed using proxies from the Level I-Performance Metrics of the SCOR framework. Additionally, this research analyzes a hybrid disruption management approach (reactive and proactive) by relating the topological properties of a supply network with both performance and response to disruptions (in terms of adaptive reconfiguration and purposeful design).

The methodological contributions are twofold. The research highlights the advantages of using Agent Based Modeling and Simulation to analyze complex supply networks during disruptive events. It also provides a methodological approach to bridging two leading perspectives of disruption management and facilitates the concurrent analysis of both. Under a disruption, trade-offs between those two perspectives (reactive and proactive) may result in improved resilience.

Finally, this research provides practitioners with insights on which operational decisions are more suitable for their specific supply networks (and product types) in the event of a disruption.

1.6 Chapter Layout

This dissertation is organized in six chapters.

Chapter 1 introduces the context of this research in the supply chain field. This chapter also outlines the relevance of the concept of resilience in supply chain risk and disruption management; it asserts the need for a representation of the concept and discusses the use of network theory and a complex systems approach to supply chain disruption management. Finally, it states the research purpose and the questions addressed by it.

Chapter 2 critically reviews the literature and research dialogue around the domains of supply chain management, supply chain risk management, networks and complex systems sciences. The review provides the main constructs associated with each of these domains and situates the gap addressed by this research within the current state of knowledge in supply chain management.

Chapter 3 outlines the research methodology and the rationale for choosing an agent based simulation instead of other existing methodologies. This chapter also discusses the benefits of using complex systems methods in supply chain research.

Chapter 4 details the development of the simulation model and the associated analytical constructs used to represent a supply network. It uses UML to describe the agent based simulation model including the generic agent framework, their properties and behaviors, the decision making rules including reconfiguration strategies, and the feedback structure.

Chapter 5 presents the verification and validation process for the model developed in Chapter 4 as well as the experimental set-up and experimental variables used to answer the research questions.

Chapter 6 presents a series of experimental runs that were carried out to determine the validity of a relationship between the characteristics of the network structure (as define by tactical and strategic decisions of the firm) and its resilience. This chapter also provides an analysis of the results and a comparison of performance relating resilience with respect to variations of the disruption management decisions (reconfiguration or sourcing strategies). Finally, the chapter highlights the study contributions and limitations, and outlines further research and extensions of this work.

2 LITERATURE REVIEW

The concepts of risk, vulnerability and risk management have been extensively explored within the supply chain context and, for the most part, derived from other disciplines such as insurance and finance [16, 41, 46, 48, 59-72]. As companies reconfigure their supply networks to adapt to new economies, aspects such as the interdependences and clustering of suppliers, and complex product designs (usually produced in multi-tier, multi-level networks) have left both practitioners and researchers struggling to understand the behavior and performance of networks, especially in the event of disruption [36, 48, 65]. As a result, several constructs have emerged to represent the ability of a supply network to respond and adapt to man-made or nature-driven disruptive events [34, 73, 74]. Among those constructs, resilience has been widely discussed and analyzed in the literature. It was first introduced by Sheffi [5] and originally, it was defined as the ability of a supply network to "bounce back" from a disruption. As the concept evolved, several approaches to represent resilience in the literature emerged and the concept has been studied, mainly, on the strategic and tactical levels [23-27, 67, 69, 74-76]. While there is not a consensus among practitioners and academics on the definition of resilience, the concept is intrinsically associated with risk and disruption management of supply chains and remains relevant in the field of supply chain management [77].

This chapter provides a critical review of how risk, vulnerability, and disruption management have been addressed in the supply chain literature. The representation of resilience in several areas is discussed, focusing on the field of supply chain management. Subsequently, the reasons behind the lack of consensus on what this construct (that has been recognized as a key element in the design of robust risk management strategies) entails are discussed.

Furthermore, in this chapter, the use of a network perspective and the need for a complex adaptive systems (CAS) approach to represent modern supply chains is reviewed based on the current dialogue among academics and practitioners. The main arguments found in the literature supporting the use of complex systems methodologies such as Agent Based Modeling and Simulation in the supply chain management field are outlined.

Also, the dialogue around product modularity and its impact on supply chain design is critically analyzed. Since this work aims to produce a representation of the concept of resilience that is relevant to both practitioners and academics, the state of supply chain reference models, especially the Supply Chain Operations Reference model (SCOR) model, widely used in the field to understand supply chain processes is reviewed.

In summary, developing a representation of supply chain resilience, using a complex systems approach to supply chains, involves the domains of supply chain management, supply chain risk and disruption management, product modularity and design, network theory, and complex adaptive systems. This chapter systematically analyzes the current state of these domains and identifies the gap in the literature that gave this research its purpose and scope.

2.1 Supply Chain Management Frameworks

Mentzer et al. [40] found that supply chain management definitions usually can be classified into three main categories: as a management philosophy, as the implementation of that philosophy or as a set of management processes. However, when new emerging concepts such as resilience are proposed, it is difficult to classify them within those specific categories due to the lack of rigor and embryonic stage of the field [78]. Since the measurement of the efficiency and effectiveness associated with such concepts is fundamental in building a solid theory of supply chain management [79] and it is often contingent on the aforementioned classification (philosophical, implementation and operationalization), many of these constructs are often overlooked and a commonly accepted representation is elusive [77]. Furthermore, Croom, Romano, & Giannakis [39] state that the proper scientific development of the field requires more efforts on both: developing theoretical models that facilitate the understanding and consequently better managing of supply chain phenomena, and designing effective measurement instruments.

Chen & Paulraj [38, 80] proposed a set of unidimensional measurements that can be used to test theoretical representations with the aim of providing a systematic framework to foster the development of supply chain instruments. Their framework, depicted in Figure 2.1, gives emphasis to the findings of Anderson, Håkansson, & Johanson [81] who recognized the strategic impact of the buyer-supplier dyadic relationship on the performance of a supply chain.

For the purpose of this research, the framework of Chen & Paulraj's [38, 80] is adapted since it facilitates the development and refinement of a representation of resilience (with product design, network structure and sourcing decisions as its precursors) and its classification within one of the main categories defined by Mentzer et al. [40].

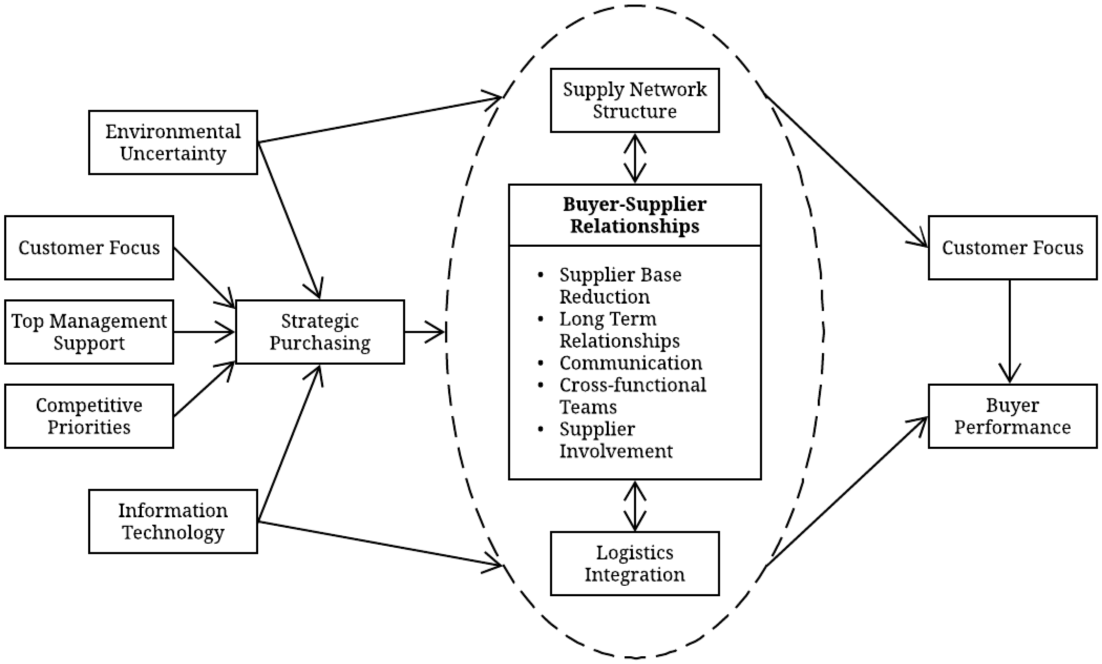


Figure 2.1 A Research Framework of Supply Chain Management

The framework supports building a representation of resilience as well as its analysis, using elements that, from the disruption management perspective, constitute proactive and reactive mitigation strategies to deal with disruptions, a need identified by Snyder [13]. Other proposed frameworks [37, 39, 82] lack the comprehensive approach taken by Chen & Paulraj [38, 80] since they are limited to: i) classifying the existing literature linked to supply chain management [39]; ii) discussing and providing a broader organizational perspective of supply chain management without establishing operational constructs/metrics to support such effort [82, 83] and, iii) outlining new research areas in the field [37].

Fundamental to the buyer-supplier dyadic relationship presented by Chen & Paulraj [38, 80] are the supply network structure, the concept of interdependence (geographical or otherwise) and the firm's strategic decisions associated with product design. The global economy in which firms operate has forced them to look for more efficient ways of coordinating the flow between buyers and suppliers, demanding more flexibility in supply chain relationships [40] and better responses to unexpected events altering that flow [5]. Giunipero et al. [37] point out that although researchers have acknowledged the interdependent nature of supply chains operating in current complex global markets, most of the research on supply chains has focused on the local firm or dyadic relationships. The following section discusses the network perspective of a supply chain, the way it has been addressed in the literature and the benefits of taking this approach when analyzing a supply network facing a disruptive event. It also provides with a detailed review of the constructs used in network theory and how those are related to modern supply networks. The limitations of using a network theory approach are also discussed.

2.2 The Network Perspective of Supply Chains

Although it is acknowledged by researchers and practitioners that supply chains are not linear, the term *chain* is still widely used. Supply chains are commonly described as systems of complex, interdependent networks [46] with flows of materials, goods and information between each of the involved firms and are linked by both physical and non-physical connections. Depending on the unit of analysis, authors have proposed several network-oriented definitions of supply chain: as a group of organizations synchronizing inter-related business process and practices to produce value in the form of products of families of products for the final costumer [84]; as a group of products or families of products with their own value stream [85]; as a cluster of coordinated and cooperative organizations [40] with connecting relationships [62, 86], etc. However, traditional approaches have focused on the design and maintenance of dyadic relationships and, the unit of analysis is the firm and its suppliers. Recently, this position has been challenged by several authors [11, 29, 34, 87, 88] and the research on theoretical models that assist in the understanding of how the network structure of the chain impacts its performance has increased in recent years [89-91].

Supply networks exhibit an intermediate form of control different from the traditional supply chains. In supply networks, there are low levels of vertical integration and interdependence between all agents of the chain is critical to the performance of the whole network [38]. This interdependence implies that although every firm attempts to operate at an optimal level, their overall network performance may be far from optimum. While there are constrains and objectives particular to each firm, its performance is also dependent on the performance of others and in the ability of all actors to properly coordinate and execute the associated processes [92]. The challenge is to deploy decision and coordination strategies guarantying that the network, as a whole, is flexible and can adapt to changing environments.

Firms currently operate in a globalized economy where highly dynamic markets are continuously rescaling themselves; suppliers are adapting their production lines to their customers' needs and, customers are demanding more in terms of quality and speed of response. In other words, it is implied that supply chains are far from a steady state [47]. Furthermore, it can be argued that due to the complex, nonlinear environment in which supply networks exist, they are by nature unstable networked systems [93].

Consequently, when studying modern supply networks, it is necessary to consider all the actors (distribution centers, customers, retailers, manufacturers, suppliers, etc.) as components linked through a network structure. This structure is determined by the strategic decisions companies make (e.g. type of product) and how they establish links with other agents (e.g. sourcing decisions) and this structure is as relevant as (or even more relevant than) the firms themselves when it comes to dealing with disruptive events [94].

When conceptualizing a supply chain as a supply network, the main focus drifts from sequential interdependencies (the traditional approach) to mutual or reciprocal interdependencies. This fact, coupled with the nature of the business environment, generates highly complex behaviors and structures stemming from the individual firm's goals and its relationships with the rest of the network and their suppliers/customers. The understanding of these complex behaviors and structures requires the adoption of a network-based perspective of the relationships between the different actors and several authors have pointed out that this approach will greatly benefit supply chain management [95, 96].

Some efforts towards adopting and implementing this network-based approach have been undertaken. For example, C.M. Harland et al. [94] provide a taxonomy derived from empirical studies. This taxonomy has two dimensions: the pattern of networking activities (dynamic vs. routinized supply networks) and the degree of the focal firms' influence over their supply networks. Pathak, Day, Nair, Sawaya, & Kristal [7] present a categorization scheme considering the topological characteristics of the supply networks and propose six structures: centralized, lineal, flat, hierarchical, federated and starburst. T.Y. Choi & Kim [87] introduce the concept of structural embeddedness to come up with two propositions related to the management of the supplier base. Recently, Blackhurst et al. [89] proposed a methodological approach to visualize supply networks and understand the dynamics between all the agents. In their work, they use a Petri net and triangulation clustering algorithm and consider structural elements of the network such as connectivity and dependencies.

In general, these efforts have been recognized as fruitful and have brought insights for practitioners and researchers on the advantages of using a network based approach to analyze supply chains. The next section presents the key concepts of network theory and maps those to the supply chain field. It also provides with and justifies the specific network representations that are analyzed in this research.

Network Definition

A network is a set of vertices or nodes that are connected with edges. As markets become more global, the study of supply networks have shifted its focus from the analysis of single sequential networks (as conceived in the traditional linear approach to distribution systems) and the properties of the individual vertices or edges (i.e., the individual firms or the transportation system) to consideration of large scale supply systems [97].

A logistics network or supply network can be defined as a man-made network, designed typically for distribution of goods. Surana et al., [8] provide with a more comprehensive definition of a supply network:

> *A supply chain is a complex network with an overwhelming number of interactions and inter-dependencies among different entities, processes and resources. The network is highly nonlinear, shows complex multi-scale behavior, has a structure spanning several scales, and evolves and self-organizes through a complex interplay of its structure and function (p. 1)*

The structure of a network is defined by its components and its properties. The components are the vertices or nodes (e.g. the distribution center, factory, etc.), the edges or arcs (e.g. transportation routes), and the set of paths (group of vertices that from each vertex there is an arc to another vertex and no vertex is repeated in the connecting sequence). The basic properties are: the directionality that indicates the way the flow goes from one node to the other (it is directed if it goes one-way or undirected if it goes in both directions); the degree or the number of edges connected to a vertex or node; the geodesic path or shortest path through the network from one vertex to another; the completeness or number of arcs between exiting nodes (the network or graph is complete if it has all possible edges), the diameter or the length (in number of edges) of the longest geodesic path between any two vertices [97]. Figure 2.2 shows a directed network with different vertex and edges weights.

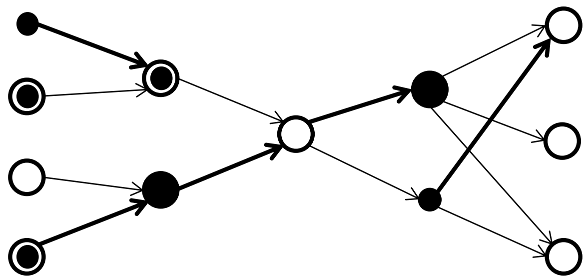
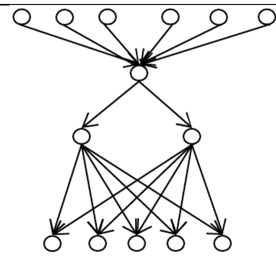
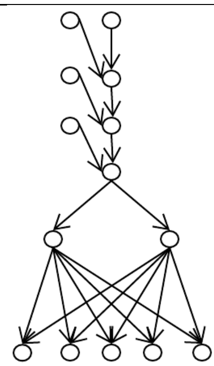
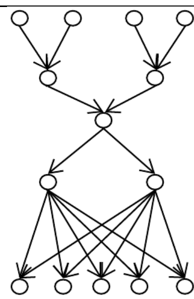


Figure 2.2 Directed graph or network

Pathak, Dilts, & Biswas [98] in their classification of supply networks based on the topological characteristics provide 6 types of supply networks: centralized, lineal, flat hierarchical, federated and starburst. In this research, the focus is on two of these structures: the centralized and the hierarchical structure. A centralized structure is a directed acyclical graph with a maximum depth of 1. This structure represents a single manufacturer with all of its suppliers delivering parts (or raw material) for it to assemble. Good examples or models of this type of supply network are eBay and aggregators such as Alta Energy or Ingram Micro. The other structure considered in this research is the hierarchical network, which is basically a directed acyclic graph. In a hierarchical topology, there is a manufacturer that through multiple tiers assemble one product. Figure 2.2 depicts a hierarchical supply network. Examples of these type of companies are found in the automobile industry and assembly companies. This research expands on Pathak, Dilts, & Biswas [98] by expanding the hierarchical structure to consider both the case of a manufacturer assembling components and subassemblies and the case of a manufacturer whose final product consists of subassemblies.

Since it is argued that product design (modularity) may have an impact on the resilience of a supply network, by including the latter case, the interdependencies between tiers (and their potential impact on the resilience of a network under disruptions) are considered. Table 2.1 presents the supply network categories considered in this research, their topologies (multi-echelon) and corresponding industries/companies.

Table 2.1 Categories of Supply Networks Analyzed

Category	Topology	Description/Industry
Centralized		• Upstream: One tier, 6 raw material/component suppliers, all going to one central node. • Downstream: Two distribution centers, 5 retailers • Forward aggregators/eBay/Ingra Micro
Hierarchical (Tall)		• Upstream: Three tiers, 2 sub-assembly suppliers, 4 raw material/component suppliers, all going to one central node. • Downstream: Two distribution centers, 5 retailers • Segments of the computer industry (modularization); specialized bicycle and motorcycle shops
Hierarchical (Complex)		• Upstream: Two tiers, 2 sub-assembly suppliers, 4 raw material/component suppliers, all going to one central node. • Downstream: Two distribution centers, 5 retailers • Automobile industry

In order to understand how these topologies and their emergent behaviors derived from reactive disruption management decisions influence the performance of a supply network, and more specifically, its resilience, the need for a more systemic approach: the complex adaptive systems approach is discussed in the next section.

2.3 Complex Adaptive Systems (CAS)

Recently, several authors have proposed a different perspective on how to handle complex, dynamic, non-linear supply networks[1] based on complexity theory [7, 8, 58, 99, 100].

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[1] From this point ahead, the research would focus on supply networks as the object of study. As pointed out Datta et at [62], supply networks can be seen as clusters of firms, clusters of vertical chains or furthermore, as

As the markets become more complex, globalized and highly dynamic and considering that the preferences of the customers are shifting widely and more frequently, firms face three main questions related to the supply network in which they operate:

- What are the topological characteristics of their current/desired network?
- How will those structural characteristics impact business performance?
- How is the network reacting to a changing environment and how can its response be improved?

Sheffi & Rice [101] point out that firms are continuously exposed to risks at the operational level and to unexpected disruptions and, only through a strategic response to the aforementioned questions, can competitiveness and high flexibility be achieved. However, such response is contingent on/upon: a) the systemic understanding of the complex, dynamic and emergent nature of the network and, b) an adequate system intervention. To cope with these two contingencies, a complexity oriented approach that acknowledges the adaptive, self-organizing nature of supply networks is required.

Supply Networks as Complex Adaptive Systems

Complex Adaptive Systems theory, originally proposed by Holland [102], deals with systems that are composed of agents interacting with each other and with an external environment, responding to stimuli and exhibiting collective emergent behavior. Agents adapt by changing their rules as experience accumulates, and can be aggregated into meta-agents whose behavior may also be emergent, i.e. not determinable by analysis of lower level agents [102]. CAS can be defined in terms of two main components: properties and mechanisms and they are usually immersed in a highly dynamic and complex environment [102]. The properties define the structural or topological characteristics of the system while the mechanisms determine the interactions or connecting relationships between the agents [103].

Based on the abovementioned definition of complex adaptive systems and their components, a supply network can be easily recognized as a complex adaptive system. Because a complex adaptive system is an open system, the system changes adapting complex responses in order to make itself more robust to uncertainty in the environment and to the actions of other

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clusters of networks with connecting relationships (both vertical and horizontal) at each granularity level. Lazzarini, Chaddad, & Cook [63] proposed the term netchain to describe the later.

members of the system [8]. Similarly, in order to stay competitive, supply networks need to react to changes in customer's demand/expectations, larger supplier's base, shorter product life cycles and especially, to unexpected disruptions altering parts or the whole network operation.

Table 2.2 and Table 2.3 relate Holland's basic concepts of CAS to a supply network, using the structure presented by Correa & Keating [103]. Choi et al. [58] presented a similar comparison on how a supply network can be framed as a CAS, but their comparison uses combinations of some of the properties and mechanisms initially proposed by Holland [56] to categorize those internal mechanisms, processes and conditions of a CAS that can be related to a supply network.

After mapping the core properties of a complex adaptive system to a supply network, it is possible to redefine a supply networks as

> *A complex adaptive system involving a large number of firms, continuously exchanging materials, knowledge and information; with persistent reconfiguration based on market dynamics and the actions of the involved firms. The network structure or topology is defined through self-organization, with local contractual relationships between firms and its complexity varies as those rules become more or less sophisticate and/or the topology of the network changes.*

Table 2.2 Parallel between the properties of Complex Adaptive Systems and Supply Networks

Property	CAS	Supply Network
Aggregation	Complex large-scale behaviors emerge from the integration of less complex agents.	Agencies are created among suppliers, manufacturers, wholesalers, distributors, retailers and customers. The network can be formed by individual firms or clusters of firms that have both vertical and horizontal connecting relationships.
Non-linearity	Any behavior of system cannot be deduced from averaging the behavior of the implicated agents.	Each firm reacts to the market dynamics and the actions of other firms by establishing degrees of connectivity. The emerging schema is not an aggregate of those relationships; it is usually complex, involving interrelated special and temporal effects.

Property	CAS	Supply Network
Flow	Flow is variable over time as well as the mechanisms for it.	The rules of exchange of materials and knowledge are continuously changing based on the firm's response to new market dynamics or other firms/chains actions. How the exchange is implemented, i.e. the contractual or connecting relationships, also changes continuously based on new performance objectives of individual firms or due to (un)expected constrains/disruptions [92].
Diversity	The greater the variety within the system the stronger it is. "Each kind of agent fills a niche that is defined by the interactions centering in that agent" [56]	If firms have more flexibility in their connecting relationships (e.g. having more variety of partners and contractual relationships), the supply network as a whole becomes more robust to disturbances since such variety facilitates rapid adaptation. However, there is a tradeoff between robustness and complexity since having many suppliers can protect a firm to the risk of a disruption but it may also increase the complexity of its contractual relationships.

Table 2.3 Parallel between the mechanisms of Complex Adaptive Systems and Supply Networks

Mechanism	CAS	Supply Network
Tagging	Pervasive mechanisms to facilitate interaction and hierarchical order.	Firms can independently decide on their connecting relationships but those are usually driven by some sort of affinity that facilitates specialization and collaboration between them. Along with the horizontal connectivity among firms, vertical relationships are also formed between firms or clusters of firms establishing hierarchies.
Internal Models	Each agent recreates internal models to anticipate and predict. As result the agent is able of both prescribe actions and explore alternatives.	Firms' response to environmental or agent-related stimuli is usually built upon the firm's model of the market. Thus, any action conducive to establish new connecting (contractual) relationships is based solely on the firm's perception of the supply network which usually involves imperfect asymmetric information.

Mechanism	CAS	Supply Network
Building blocks	Through learning, CAS use building blocks (elements that might be already reviewed) to generate the internal models.	Firms usually retain information or blocks of information related to the market structure and its dynamics as well as related to the other firms. Market models are built upon this information and reviewed as new stimuli is received.

But how can firms deal with the lack of control and prediction derived from operating within an unstable system? In addition, how can firms react to either expected or unexpected changes in their markets or in their suppliers' base? Due to the complex adaptive nature of a supply network, it is not possible to predict its performance using traditional forecasting techniques (which are mainly used in the dyadic buyer-supplier analysis).

Furthermore, to understand how the network (with a structure driven mainly by the bill of materials) may react to unexpected operational risks or disruptive events, the adaptive nature of the network needs to be studied. Accordingly, to develop successful interventions to manage the network in the event of a disruption (disruption management), it is required to a) identify the factors driving the structure of the supply network; b) identify the topological aspects (such clustered vs disperse suppliers) that can affect the ability to react to a particular event or set of events that compromise its performance, and c) characterize the disruptive events and the structural changes driven by those (type of disruptions, intensity, duration, etc.).

The current dialogue around risk management, and more specifically, around disruption management is at best vague [22]. The next sections critically analyze the current state of risk and disruption management and argue why the risk management framework chosen for the purpose of this research must consider strategic, tactical and operational measures (product design, network design, sourcing, etc.).

2.4 Supply Chain Risk

The concept of risk in supply chains, as well as in other disciplines, has been subject to several interpretations/definitions mainly due to its multidimensional nature. There are several definitions for risk in the supply chain field; mostly, the existing definitions discriminate risk by how its realization impacts the performance of the system under study [36, 62]. Nonetheless, there is not clarity nor universally accepted definitions of the concept in the field and, as Jemison

[104] and Baird & Thomas [105] state, it is crucial for managers to define the term appropriately [22].

Zsidisin and Heckmann et al. [22, 64] present comprehensive reviews of the proposed definitions of risk and the associated characteristics, and conclude that there are several ways of defining risk and, in the supply chain field as well as in other disciplines, the concept of risk is multidimensional since its scope includes both sources and outcomes. Mostly due to this fact, several authors [10, 44, 49, 55, 59, 60, 106] have proposed different typologies and taxonomies (Bailey [107] differentiates the former as merely conceptual and the later as empirically derived).

Tang [55] classifies supply network risks as either operational or disruptive. The former category deals with uncertainties in cost, demand and/or supply. The latter considers major events that have big impact across the entire supply network. In this paper, Tang [55] also classifies the mitigation strategies (or the network responses to disruptions) as belonging to four main areas: supply, demand, product and information and focusing either in tactics or strategy. This research will concentrate on risks associated with disruptions and the mitigation strategies dealing with supply management. In Figure 2.3, the focus of this research is positioned with respect to the approach to supply chain risk management proposed by Tang [55].

In order to have robust risk management strategies, Tang [108] argues that the strategies should be designed by taking into consideration two key properties: (i) efficiency that assures prompt, adequate risk management and, (ii) resilience that guarantees the firm (and in general, the supply network) will sustain operability and rapidly recover after a major disruption. In his paper, Tang [108] presents nine robust supply chain management strategies and their individual benefits pre and post disruptions. However, Tang’s mitigation strategies do not account for the possibility of adaptive behaviors of the network that, under certain topologies, after a disruption, may give rise to local and global performance levels higher than those experienced pre disruption.

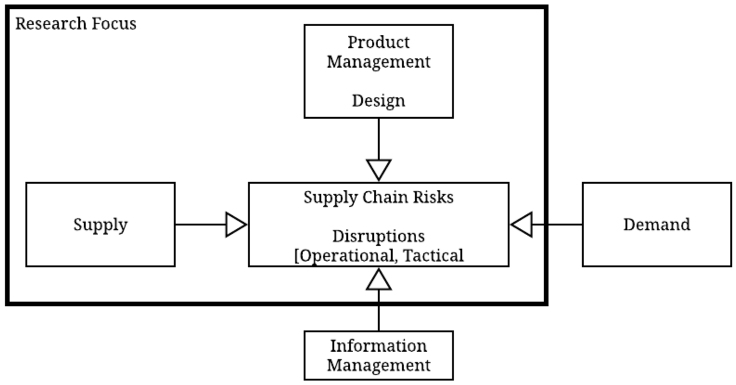


Figure 2.3 Four basic approaches for managing supply chain risks

Consequently, expanding on Tang's second property of a robust risk management strategy [55], the main objectives when (re)designing for more resilient supply chains are:

- To identify the structure of the supply network and the aspects of it that can affect the performance of the network and its ability to react to a particular event or set of events (threats) that compromise its performance.
- To characterize disruptive/operational events and their impact by: (a) associating them with structural changes in the supply network and (b) the associated loss/gain of performance due to the new structure post-disruption.
- To identify the trade-offs between recovery rate and the emerging structural responses post-event.

These objectives become the basis for analyzing the vulnerabilities, threats and associated risks in supply chains. However, they are more relevant when studying the behavior of supply chains exposed to disruptive events[46, 55].

2.5 Supply Chain Vulnerability

The characteristics of modern supply networks: lengthy, complex and immersed in highly dynamic markets, make these systems more *vulnerable* to events that can impact the performance of the chain and, disrupt the strategic coordination effort at both levels: the firm and the network itself. Adapting Haimes' definition of vulnerability [61] in the systems contexts to supply networks, it is possible to assert that

> *The vulnerabilities of a supply chain are related to the **structural**, **functional** and **contractual** characteristics of the chain that can compromise the performance of the constituent firms and/or the overall chain.*

Several authors [17, 48, 109] present supply chain vulnerability definitions that are aligned with Haines' general definition where vulnerability is defined as a supply network susceptibility to be weakened or have a limited ability to tolerate threats and survive external or internal accidental events. Ezell [42] applies a similar approach when defining and applying the relationship between risk and vulnerability to critical infrastructure: threat is the link between risk and vulnerability [42]. For example, consider a supply network that has some suppliers clustered in Asia and another cluster of suppliers close to Turkey. Those suppliers were chosen by design, based on, among others, the product design (represented by the bill of materials) and supplier selection. Asia is a region that is prone to typhoons and the potential and chances of occurrence have increased in the last decades. Turkey and its neighboring states have experienced political unrest in the past few years. This supply network is vulnerable by design and an efficient disruption management should provide reactive and proactive mitigation strategies. These strategies would facilitate adaptation and reconfiguration of the network, in the event that a threat materializes (disruption) and impacts the performance of the network. Table 2.4 illustrates the approach taken in this research to represent the relationships between threat, vulnerability and risk in a supply chain.

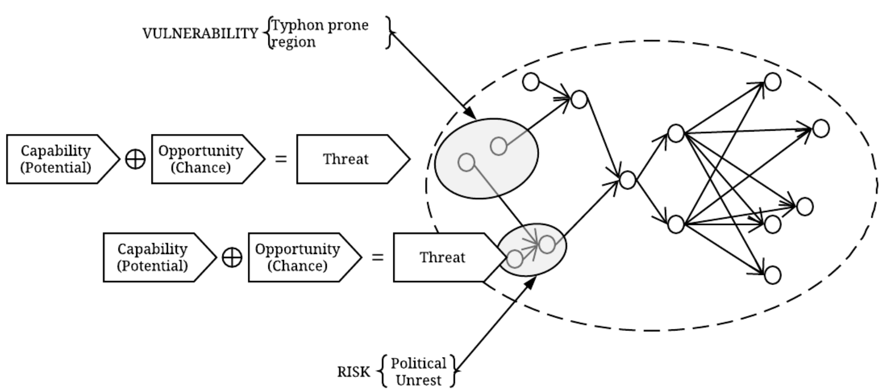


Table 2.4 Vulnerability, Threat and Risk in the Supply Chain

The importance of not considering risks as underlying factors to the vulnerability of the supply chain, allows managers to analyze the vulnerability of the supply chain through the elements of the network itself and not through the potential and/or unlike risks the network faces or will face. This approach lays the foundations for differentiating between risk analysis and vulnerability analysis in supply chains; Table 2.5 depicts this differentiation.

Table 2.5 Supply Chain Risk Analysis vs. Supply Chain Vulnerability Analysis

	Focus	Objective
SC Risk	Event	Determine what can go wrong in the supply chain
	Likelihood	Estimate the chances of an event occurring
	Consequences	Estimate the consequences associated with the event
SC Vulnerability Analysis	System states	Determine what constitutes a state where the performance of the supply chain can be compromised Determine how and what will compromise the performance of the chain
	Adaptive behaviors	Determine actions that will improve the supply chain performance
	Reconfiguration speed	Determine the time required for the supply chain reconfiguration

Svensson [44], based on an empirical, inductive-deductive two-phase study, proposes two dimensions to analyze and prevent disturbances: the sources and the categories of the disturbances. The former considers the nature of the vulnerabilities as direct, or those where only a portion of the supply chain is required to analyze its vulnerabilities, and undirected where an overall analysis of the chain is required to identify its vulnerabilities.

Disturbances can also be categorized as quantitative or deviations due to stock-outs, lack of availability of volume or components of the supply chain; and qualitative, or those deviations leading to lack of accuracy, reliability and precision of the components and material [44]. In addition to the aforementioned dimensions, the time constrains are also considered and include exposure to short-term and long-term vulnerabilities.

Despite works like Svensson's empirical studies [44, 110, 111], Bhattacharya, Geraghty, & Young [112], Juttner et al. [10], Peck [109] and other authors point to the conceptual immaturity of the concept of vulnerability in supply chains. Among others, authors have associated the concept of vulnerability with: increasing interdependence [88]; as an exposure to disturbances arising from risks internal and external to the supply chain [113]; potential reduction of the chances of a disruption, changes in resilience and impact level of consequences [101].

In summary, the body of knowledge of supply chain lacks a formulation and/or structured definition for supply chain vulnerability that is universally accepted and therefore, efforts to advance the conceptual framework are scattered and several constructs about vulnerability and its relationship with disruptive events have been proposed but have yet to be validated and/or tested. In this research, vulnerability is assessed based on the structural and functional elements of the supply network. This approach facilitates the representation of the concept of resilience in term of the relationships between the design and structure of the network (product design, network design, etc.) and the behaviors derived from reactive mitigation strategies (flexible supplier base, postponement, etc.).

2.6 Disruption Management

When designing a supply network, an optimal or near optimal plan is used to operate under normal conditions. These plans are based on decisions such as facility roles, locations, capacity, etc. In the event of disruption, such plans may not be near optimal or even feasible and the design decisions need to be revised. The speed at which this reconfiguration process takes place is as important as the level of functionality achieved post disruption: the resilience factor in the supply network design needs to account for both. Only then, the factor would enable supply chain managers to (re)design their supply chains and improve their decision making process.

Recently, quantitative models for disruption management have been developed at firm level [2, 18, 20] and a few authors have pointed to the concept of resilience as the core for a robust disruption management strategy [9, 19, 23, 75]. In this proposed research, a formulation for supply network resilience is proposed, within the framework proposed by Melnyk, Rodrigues, & Ragatz [114]. In their work, Melnyk et al. [114] identify four factors that influence the process that links the event(s) that take place inside or outside of the network with the loss of performance in one or more components of the network. These factors include the characteristics of the triggering event(s), the topology of the network, the current control structure and the performance measures used. In this proposed research, the focus is on disruptions originating in the supply side and disruptions originating in the demand side.

Figure 2.4 Main components of a disruption. Figure 2.4 shows the disruption profile, as described in Melnyk et al. [114].

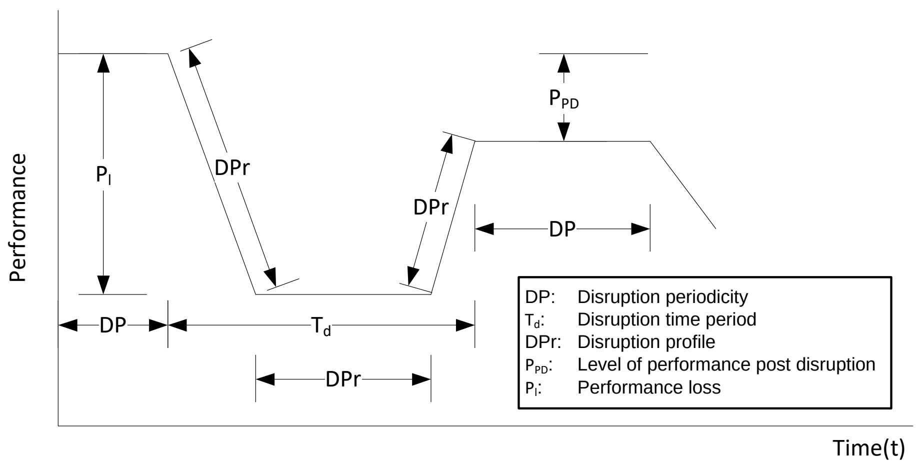


Figure 2.4 Main components of a disruption[2].

2.6.1 Supply Chain Disruptions

Among the various types of supply chain risks identified by Tang [108], the focus of this study is on supply chain disruptions. In line with Melnyk et al.'s disruption profile [114], Kleindorfer & Saad [115] point out that disruptions are substantially different from operational risks because they imply complete interruption of the normal production flow and tend to last longer that operational risks.

Lim [63] recognizes that a robust network design is critical to hedging a disruption mainly because contingency plans are limited due to the impact and duration of the disruption. In turn, for robust (re)designs where the impact of the disruption is minimized, it is necessary to

[2] Adapted from Melnyk et al. [114] S. A. Melnyk, A. Rodrigues, and G. L. Ragatz, "Using Simulation to Investigate Supply Chain Disruptions," in *Supply Chain Risk: A Handbook of Assessment, Management, and Performance* vol. 124, G. A. Zsidisin and B. Ritchie, Eds. (International Series in Operations Research & Management Science: Springer US, 2008.

understand the source, the nature and the potential mitigation strategies associated with the disruption.

Disruptions can be classified based on the type and level at which a mitigation strategy is implemented. Table 2.6 shows a classification of disruptions and mitigation strategies this research considering the abovementioned elements. The analysis if purposeful disruptions (targeted) is a planned extension of the scope of this research.

Table 2.6 A Classification of Supply Chain Disruptions.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Mitigation</th></tr>
<tr><th>Reactive</th><th>Proactive</th></tr>
<tr><th rowspan="2">Purposiveness</th><th>Random</th><td>• Tactical: Sourcing (Single vs. Dual)</td><td>• Tactical: Network design (clustering)
• Strategic: Product design (modularity)</td></tr>
<tr><th>Targeted</th><td></td><td></td></tr>
</table>

Implementation Level

The robust strategies can be implemented at two levels: tactical and strategic. The tactical level deals with operations and these strategies can be deployed at the component or network levels. Strategic aspects that impact the structure of the supply network are associated with the competitive strategy of the firm (including but not limited to product design and/or modularization, market segments, growth strategy, etc.)

Purposiveness

Disruptions can be caused by a random, unexpected event that does not target any specific component of the network or it can be caused by an event that was directed to specific components (in this case, those targets are chosen based on the exposed vulnerabilities of the networks.

Mitigation Function

The function is chosen based on the type of risk experienced. It can be reactive and/or proactive. In the case of disruptions, firms should hedge against the worst case scenario by minimizing the maximum possible damage [63]. Currently, there is a lack of research that analyzes the integration of proactive and reactive strategies [13]. This research integrates both types of strategies and studies the effect of this multi-pronged approach on the response and performance of a supply network subject to disruptive events.

Finally, authors have approach disruption management from a strategic/conceptual approach [60, 108, 115]; documenting best practices and doing empirical studies [9, 32, 48]; or proposing detailed tactical approaches. This work focuses on assessing the impact of those approaches using a simulation.

2.6.2 Strategies for Disruption Management

Tang [108] identifies a set of strategies that, if implemented, allow a supply network to continue effectively even when a major disruption occurs. The strategies are both cost effective, permitting to keep costs low even when mitigation and recovery efforts are being deploy, and time efficient, meaning that with the strategy the chain can significantly reduce the slope of the disruption profile and the disruption time period. Nonetheless, these strategies have an associated cost that needs to be compared with the cost of losing and/or not acquiring more customers. Table 2.7 shows the objectives of each strategy and describes its benefits after a major disruption.

In this research, two types of disruption events are studied: suppliers are not available due to a) operational disturbances impacting capacity (node it is no longer able of meeting demand) or b) regional disturbances impacting availability (node can produce but cannot meet demand due to distribution constrains or it cannot produce because the disturbance prevent it from producing). The first type of disruption requires that the firm can actively influence the demand by shifting it across time. The second type requires flexibility of firm in two aspects: product and supply flexibility. The chosen strategies to handle the aforementioned disruptions are briefly described as follows:

Flexible Supply Base

Once the topology of the network has been chosen (based on the product design as represented by the bill of materials), this strategy is implemented by handling two tactical decisions: by allowing the firm to decide whether or not the suppliers are clustered or disperse and by , it is necessary to determine how to allocate the order quantity among the chosen suppliers. For the purpose of this research, the focus is on the particular case when there is uncertainty in the supply capacity. In this case, multiple suppliers are treated as either "on" or "off", making the possible number of states of the system 2^n.

Postponement

The postponement models can be categorized based on the operating modes and the demand forecast. For the purpose of this research, the work of Gupta and Benjaafar [116] is core to the implementation of this strategy. The benefits of postponement post-disruption are examined when the capacity is limited under a Make-to-Stock system.

Table 2.7 Robust Supply Chain Strategies

Robust Strategy	Main Objective	Benefit(s) after a major disruption
Postponement	Increases product flexibility	Enables a firm to change the configurations of different products quickly
Strategic Stock	Increases product availability	Enables a firm to respond to market demand quickly during a major disruption
Flexible Supply Base	Increases supply flexibility	Enables a firm to shift production among suppliers promptly
Make-and-Buy	Increases supply flexibility	Enables a firm to shift production between in-house production facility and suppliers rapidly
Economic Supply Incentives	Increases product availability	Enables a firm to adjust order quantities quickly
Flexible Transportation	Increases flexibility in transportation	Enables a firm to change the mode of transportation rapidly
Revenue Management	Increases control of product demand	Enables a firm to influence the customer product selection dynamically
Dynamic Assortment Planning	Increases control of product demand	Enables a firm to influence the demands of different products quickly
Silent Product Rollover	Increases control of product exposure to customers	Enables a firm to manage the demands of different products swiftly

Note. Adapted from [55]

2.7 Product Design

Product design is recognized as a key element of the competitive advantage of a firm and it impacts sourcing decisions, production, distribution, transportation, retailing strategies, etc.[84]. Furthermore, several authors have recognized product design as a precursor of the efficient design of a supply network [117-119]. It has been argued that product design, and specifically product architecture[3] impacts the structure and behaviors of a supply network (up and downstream) [118]. However, according to Pashaei et al. [121], it is the current economic environment and how global operations are being conducted that impacts a company's decision regarding the product architecture. Several contradictory studies have analyzed the nature of the relationship between product design and supply network efficiency and responsiveness [122-124] but the divergent conclusions are mainly due to the different methodologies and approaches used to study the relationships.

Ro et al. [125], through an empirical analysis of the US automotive industry, found that product architecture (modularization) has restructured the sourcing landscape of the industry and suppliers are now more tightly integrated in the product design decisions[126]. These findings suggest product design impacts the sourcing decisions of companies. Furthermore, Gualandris & Kalchschmidt [117] state that by reducing the complexity of a supply network through product design, the impact of a disruptive event can be lessened. In another empirical study, Marsillac & Roh [127] discuss how, while theoretical approaches (3DCE) highlight the interdependence between decisions associated with product, process and supply chain design, the implementation of this approach has been very limited. Their case study analysis reveals that design decisions have an impact on the operations of a company and, the magnitude of the impact is dependent on the dimensions mentioned before (see Figure 2.5, adapted from Fixson [128]).

[3] For a detail analysis of product design theories and methodologies, the author suggests to review Tomiyama et al. [120] T. Tomiyama, P. Gu, Y. Jin, D. Lutters, C. Kind, and F. Kimura, "Design methodologies: Industrial and educational applications," *CIRP Annals-Manufacturing Technology,* vol. 58, no. 2, pp. 543-565, 2009.

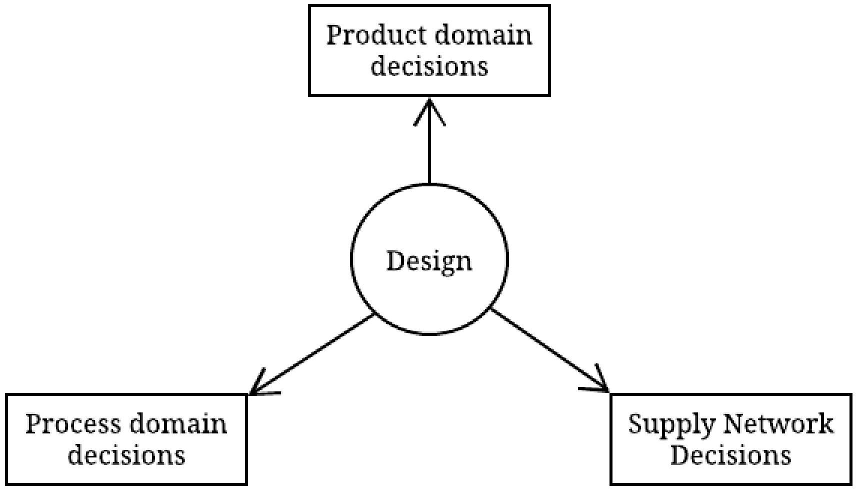


Figure 2.5 Interdependence between design decisions and other domains

In their work, Marsillac & Roh as well as other authors [123, 125, 126, 128] have highlighted the need for more research that simultaneously analyzes and represents the relationships between the product, the process domain and the supply chain decision domains. This research represents those relationships simultaneously and captures trade-offs and/or interactions between decisions made at each of the aforementioned domains and design decisions. Furthermore, this research captures the impact that the interdependencies between those decisions have in the performance and response of a supply network when facing a disruptive event.

2.8 The Construct of Resilience

Resilience in other disciplines or fields has been proven to be a powerful construct and it was originally associated with the capacity that systems have to absorb and persist after a disturbance [71, 72, 129]. While persistence is important, several authors in the ecological and social sciences have emphasized the need to extend this notion to more elaborate behaviors such as sustainability, self-organization and adaptation [68, 70, 76]. The inclusion of more complex behaviors and properties will guarantee that the equilibrium state achieved by the system post-disruption is not metastable[4] but stable.

[4] Metastable refers to the ability of the network to maintain its performance level for longer periods of time.

Although significant findings have positioned the concept of resilience in the social and ecological fields as core to the analysis of systems under disruptive events, its formulation and a universally accepted definition have been elusive to researchers and practitioners. According to Carpenter et al. [76], resilience measures are difficult to formulate because: a) they are *artificially* created by the observer and are applied to the whole system under consideration, not to its individual components[5] and, b) resilience has a dynamic character, *focusing on variables of the system that underlie the capacity to continuously react to changing conditions*, opposed to measure only the current state of the system.

A significant contribution to the formulation of resilience was done by Cimellaro, Reinhorn & Bruneau [66] and Bruneau & Reinhorn [130] in the field of earthquake engineering. Cimellaro et al. [66] implemented a procedure which defines resilience as a function of losses and recovery based on the fragility of the system. Bruneau & Reinhorn [130] proposed a similar formulation applied to acute care facilities that integrates event probabilities, the system fragility and the concept of resilience in one construct. The major contribution of their work is that the formulation integrates not only engineering but also social and political decisions, providing the practitioner with a more comprehensive measure.

2.9 Supply Network Resilience

The concept of resilience in supply chain has drawn a lot of attention from researchers and practitioners; however, there is not agreement on the definition, the scope and quantitative formulation of the term. Authors have reviewed the notion of resilience in other disciplines and have incorporated it to supply chain field as a key component of risk management [19, 23-26, 28, 49, 60, 73-75, 77, 131-133] but the research community still struggles to provide a detailed formulation of the construct that can be used to capture the response of a supply network, as a whole, to a disruptive event.

Most of the dialogue around resilience has been purely in the conceptual side. Authors have defined it as a characteristic or property of the supply network, as a method for supply network risk management or as a strategy core to risk management. Just a few authors have proposed approaches to quantify resilience in a supply network [23, 29-31, 33] but the literature

[5] This approach aligns with the perspective of resilience as a systemic property of complex systems, opposed to the traditional approach to evaluate system properties at the component level.

support the need for more research on representation of supply chain resilience and its precursors. Table 2.8 shows a sample survey of some of the threads for each of the aforementioned typologies and situates this research in current dialogue. For a comprehensive review of the different definitions of resilience for supply networks, the reader should look at Ribeiro & Barbosa-Povoa [77]

Table 2.8 A Sample of Typified Definitions of Resilience in the Supply Network Context

		Definition	Contributors
Resilience	Characteristic / Property	The ability to react to unexpected disruption and restore normal supply network operations.	[101, 134]
		The ability to bounce back from a disruption.	[101]
		The ability of a system to return to its original state or move to a new, more desirable state after being disturbed. Implicit in this definition are the notion of flexibility and adaptability.	[46, 49, 109]
		The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations.	[135]
		The ability to maintain control over performance variability in the face of disturbance, but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands.	[19]
		The ability to survive, adapt and grow in the face of turbulent change.	[67, 73]
		The ability of a supply chain system to reduce the probabilities of disruptions, to reduce the consequences of those disruptions, and to reduce the time to recover normal performance.	[23]
		The ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.	[69]
	Method / Strategy	Strategies aimed to protect networks from prone to excursion events that are characterized by Low Probability of occurrence and High Impact (LPHI).	[112]
		To proactively plan and design the Supply Chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post event robust state of operations, if possible, more favourable than the one prior to the event, thus gaining competitive advantage.	[136]
		Strategies result in the reduction of exposure to supply chain disruptions and/or the mitigation of disruption impacts.	[137]
	Operational Representation	The resilience of a supply network can be represented by identifying and quantifying the relationships of selected group of precursors of interest to the firm: product design (captured in the bill of materials), the structure of the supply network (captured by the bill of materials AND the network design derived from the suppliers selection), AND the firm's sourcing decisions.	**This research**

Towards an operational representation of Supply Chain Resilience

Lambert & Pohlen [138] state that in the supply chain literature, the performance measures focus on the organization and do not account for the performance of the supply network. This implies that there is not recognition of the supply chain processes, attributes and structures that drive the performance of the network as a whole. In addition, without global metrics, it is not possible to isolate the impact an action will have in the different levels of the network. Beamon [139] points to the orientation towards conceptual development vs. to the actual development of metrics as the main cause for the atomistic approach to supply chain performance measure. Similary, Gunasekaren, Macbeth, & Lamming [140] conclude that evaluation of supply chain performance needs further attention from researchers, especially from a modeling perspective.

The concept of resilience has been recognized and soundly examined as a property/characteristic of the supply network as whole. Its understanding would allow practitioners to reduce network vulnerabilities, to reduce consequences and the impact of disruptive events, and to reduce the time to recover normal performance (by integrating both reactive and proactive mitigation). Therefore, developing a representation using precursors that are of particular interest to the firm would allow practitioners and researchers to evaluate the performance of networks designs in a more systemic way and to use it to improve (re)designs after a disruption. Furthermore, if this representation is done by identifying and quantifying the relationships between those precursors and the response of the network to a disruption (as measured by commonly accepted industry standards such as the SCOR model), the gap between the theoretical development of this construct and its applicability to modern supply networks could be abridged.

3 METHODOLOGICAL FRAMEWORK AND RESEARCH METHOD

Modern supply chains are becoming increasingly complex and are exposed to higher levels of risk [41]. According to Basu et al. [59], today's supply networks face risks due to several factors including: i) Globalization, a phenomenon that is prompting more geographically disperse networks but, at the same time and mainly due to labor costs, promoting supplier clustering; ii) uncertainty, which is a common denominator in today's economies; iii) technology and innovation have shorten product life cycles and impose new challenging requirements on stock policies due to customers preferences; iv) unexpected events such as natural disasters and threats that exploit the structural and functional vulnerabilities of the networks, etc.

To gain a better understanding of how supply networks operate in these market conditions and to provide practitioners with insights on how to successfully address these challenges, it is necessary to acknowledge the dynamic, evolving and adapting nature of supply chains[8, 58]. Furthermore, any methodology used to approach modern supply networks must be able to capture the characteristics of the supply network from the ground-up, i.e., at the firm level. Thus, companies and industries can use the information available about themselves to gain understanding of the supply chain they operate and, possibly to use this knowledge to their advantage [141].

The next section provides a review of the existing methods and techniques used in supply chain analysis and a justification of the ones used in this study. Subsequently, it outlines the research methodology used to address the research questions identified in the introductory section.

3.1 Quantitative Modeling of Supply Chains

Bertrand & Fransoo [142] and Snyder et al. [13] provide comprehensive classification of quantitative (model-based) research in operations management The later specifically focus on operations research and modeling and simulation models used in disruption management whereas Bertrand & Fransoo discuss the role of quantitative modeling in the evolution of operations management in general. Following Meredith et al.'s [143], Bertrand & Fransoo [142] build their classification on the premise that it is possible to derive objective models that can explain (part of) the operations of a company and that capture (part of) the challenges operations managers face.

They argue that most of the development in quantitative modeling has focused on model-based analysis that lacks the validation of the models component. Furthermore, they classify research efforts in operations management either as axiomatic or as empirical [142]. In axiomatic research, researchers must guarantee that the set of solutions, derived from their model, provide insights about the behavior of the system, within the domain in which the model was developed. Empirical research aims to find a match between the real behavior of the system and the representation of that reality that was constructed by the researcher.

Subsequently, Bertrand & Fransoo [142] differentiate between descriptive and prescriptive approaches. Prescriptive research has three potential avenues: to develop policies and strategies, to find optimal solutions, and to compare various strategies to address specific problems. Descriptive research develops a model and proceeds to analyze it with the aim of gaining understanding about the model itself.

Of particular interest for this research is the category of axiomatic research. As supply networks become increasingly complex, and uncertainty is a given in the environmental dynamics surrounding them, formal mathematical analysis falls short to represent these characteristics. The aim of this research is to represent the behavior of a supply network, based on the characteristics of the product (as per the bill of materials) and the firm's decisions regarding sourcing and network design. The objective is to make explicit (represent) the relationships between those variables and to provide practitioners with insights on how the network resilience varies as a result of these variables and the interactions among them. To describe those variable, this research uses existing conceptualizations but, by analyzing the interactions between them (e.g. product design vs. sourcing strategies), this model-based research attempts to represent resilience of a supply network in a more realistic, applicable way.

According to Mitroff et al. [144], in modeling, researchers aimed to formulate "significant relationships within some formal system of abstract thought." This research, in addition to building (upon existing theories) a model of a modern supply network, aims to derive insights about those relationships and how they impact the behavior of the network as a whole, bringing this work to a closer to real-life operational processes.

Reiner [145] recognizes that among the main challenges of research methodology in the supply chain field is that of empirical theory building. Quantitative empirical research has provided some methodological elements that have contributed to the field but has received strong criticism due to difficulty of isolating the impact of practices from other phenomena intrinsic to the supply network. This has made the process of judging and validating this research approach difficult [142].

Thus, to answer the research questions stated in Chapter 1, this research will adopt the methodological framework adapted from Bertrand & Fransoo [142], with the intension of providing an avenue to bridge axiomatic research (theoretical quantitative research) and empirical quantitative research. The way the proposed model was design and implemented would allow for it to be parametrize with a real life processes (most likely from a small manufacturing business), and its behavior could be compared to a real-life case study. In such a way, feedback could be obtained regarding the quality of the model used for and the quality of the solutions obtained from the analysis. For the purpose of this research, an axiomatic approach is taken but further extensions could involve case-based analysis of the proposed modeled. The research framework is show in Figure 3.1.

Framework Components

- Identification of the assumptions behind the representation. The basic assumptions around the characteristics of supply network are stated. This step includes, among others, the type of production system to be analyzed (pull), the type of demand, the planning horizon, etc.
- Identification of the model domain. The type of operational processes and the type of decision problems associated with a supply network (re) design strategy are identified. Here, the type of strategic and operational domain under which the model will operate are identified (e.g., the decision of whether or not to choose suppliers that geographically clustered, whether or not to purposefully have a sole supplier for an specific component, etc.)
- Characterization of the operational definitions. Precise and objective criteria to differentiate network structures are established (here, elements such as the concept of geographically distance, forecasting methods used by the firm, etc. are formalized).
- Development of the representation. The concept of resilience is represented as relationships existing between the set of strategic and operational decisions a firms makes and the performance of the supply network in the presence of diverse disruptive events.

- Hypotheses. Hypotheses regarding the performance of a supply network, operating under different structures (associated with the strategic and operational decisions mentioned above) are formulated.
- Measurement development. Metrics for supply network performance are identified and documented.
- Definition of simulation specifications. The requirements for the simulation model are defined in agreement with the set of assumptions and operational definitions.
- Simulation Implementation. A model, using the chosen approach (agent based modeling) is implemented in the Netlogo platform.
- V&V. Verification and (construct) Validation of the simulation model.
- Data generation (experimental design), collection and analysis. The methods and techniques to generate, collect and analyze data are documented and implemented. tests
- Interpretation of results. Results are used to validate the assumptions and operational definitions and, subsequently, the formulation. Also, the hypotheses are either accepted or rejected and insights are derived.

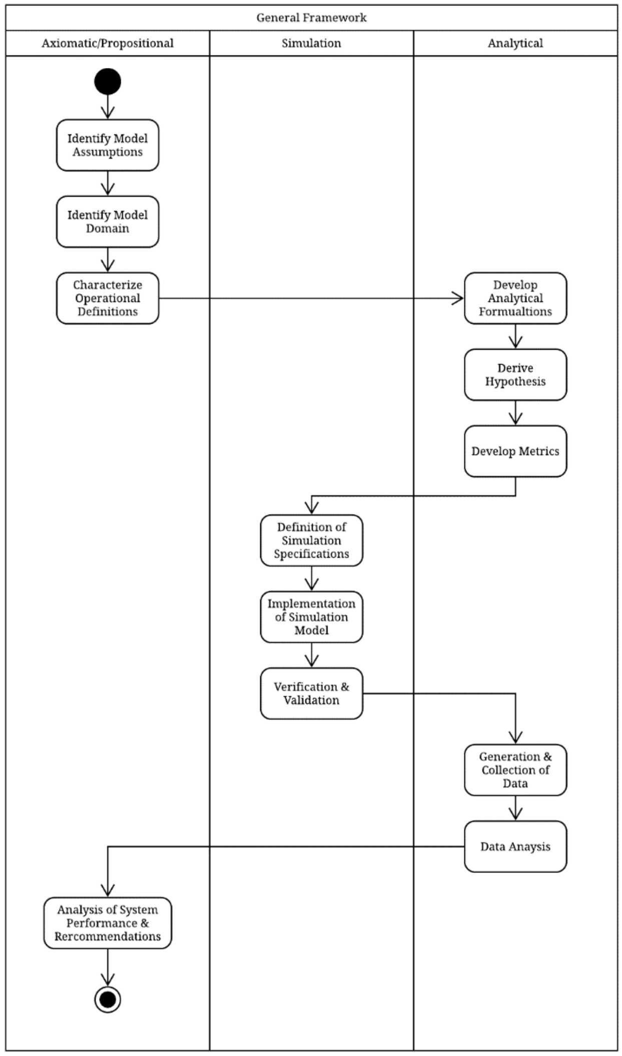


Figure 3.1 Methodological Framework for the Proposed Research Method

3.1.1 Supply Chain Modeling Methods

According to Law & Kelton [146], when analyzing a system, a researcher can either experiment with the actual system or with a model of the system. Rarely is the former possible. For supply networks, it is virtually impossible to run controlled experiments with the network due to the complexities and interdependencies between the components. As a result, researchers use various types of (mathematical) models for analyzing different aspects of the supply network.

There are two main axiomatic quantitative methods used in supply chain modeling and analysis: operations research (analytical and numerical) and simulation [142]. These methods can be categorized based on the unit of analysis, the parameterization of time, the static/dynamic character and the level of analysis. Table 3.1 details these typologies.

Table 3.1 Typologies of Supply Chain Modeling Methods

	Operations Research	**Simulation**		
		Discrete Event	**Systems Dynamics**	**Agent Based**
Unit of Analysis	Component	Component / Network	Component / Network	Component / Network
Static/Dynamic	Static / Dynamic	Dynamic	Dynamic	Dynamic
Time	Discrete / Continuous	Discrete	Continuous	-
Level of analysis	Operative / Tactical	Operative / Tactical	Tactical / Strategic	Operative / Tactical / Strategic

The relevance of any modeling method depends on how well it can represent the supply network properties that are of interest to the researcher/practitioner as well as all the processes, interdependencies and complexity associated with the operation of the network [92, 147, 148]. In addition, the selection of the modeling method and the adequate model formulation are key to represent any exogenous variables that can affect the network performance. In other words, quantitative method chosen to model a supply network, must facilitate the understanding of the dynamic behaviors and complexities intrinsic to modern supply networks [149].

Table 3.2 shows each challenge and the requirements of a modeling method that will facilitate the modeling of supply networks as complex adaptive systems.

Table 3.2 Modeling Requirements to Represent Modern Supply Networks.

Challenge	Modeling Method Requirements
Representation of Emergence	Must facilitate the representation of the behavior of the whole network as the result of the interactions and interdependences between the components (suppliers, distributions, routes, geographies, political environment, etc.) and the environment in which the network operates. Contrasting with traditional approaches, the behavior of the network cannot be inferred from the behavior of the components.
Representation of Behavioral Dynamics[6]	Must provide the tools and techniques to represent the dynamics of the environment, including but not limited to unexpected events such as a disruption or sudden change in the demand of a product. Must accommodate inter-component dynamics.
Representation of Hierarchical Object Complexity	Components have different roles (manufacturer, supplier, distributor, etc.), properties (e.g. capacity) and behaviors (sourcing decisions, supplier flexibility, etc.) and, there is a hierarchical structure based on the flow of material and information. The chosen method needs to be able to address this type of complexity.
Representation of Hierarchical Process Complexity	Method must be able to represent the different stages each component goes through (forecasting, production planning, etc.).
Representation of Conflicting Local vs. Global Objectives	Performance objectives for each component as well as for the network as a whole. The chosen method must be able of representing those as well as the tradeoff made between the components and the network as a whole (local performance metrics such as cycle time vs. network performance).
Representation of Self-organizing Behaviors	As the network interacts with the environment, there are adaptive responses to handle environmental changes. The method must be able to recreate these responses.

On existing modeling approaches and their shortcomings

According to Suh [150], supply networks become complex as the result of conflicting or interacting functional requirements and design parameters. The way existing methodologies have approached the representation of the interdependences between suppliers, manufacturers,

[6] Behavioral dynamics makes reference to a supply network's ability to transform and adapt its structure and responses to a wide range of endogenous and exogenous stimuli. The behavioral dynamics is then the result of the complex interactions between the network agents (supplier, distribution centers, manufacturers, etc.) and their environment.

distributors, and retailers and their business decisions is by reducing complexity either through a simplification of the functional requirements or through limiting the domain in which the problem lies.

The following table presents three of the most prominent methodological approaches used in supply chain modeling (all encompassed by the meta-framework of operations research) [13], and discusses how each approach tackles complexity when modeling industrial operations in general.

Table 3.3 Prominent approaches to model supply networks[7]

Operations research: This methodology offers a broad set of tools, techniques and methods aimed to "study & analysis of problems involving complex systems." [151]	
Approach	**Description**
Optimization	This approach analyzes the supply network with the objective of finding best solutions to problems that can be straightforwardly represented using a mathematical notation.
Statistical Analysis	This approach analyzes the supply network with the objective of understanding the relationship between the outputs the inputs of individual or groups processes or entities without considering their internal structure.
Data Analytics	This approach collets, disseminates, analyzes and uses data (as it is available) from the supply network to provide insights regarding strategic, tactical and operational occurrences that facilitate the decision making process [152, 153].
Simulation	
System dynamics	This approach analyzes the supply network from a strategic perspective. The objective is to understand how global processes behave over time. It models the chain with low granularity, i.e., disregarding individual entities and aggregating behaviors, structures, etc.
Discrete event	This approach analyzes the supply network from a process oriented perspective. The objective is to understand how the productive process work, hence requiring high levels of granularity in the representation of the entities involved in the productive process and the representation of time as an event driver (i.e. triggering actions from the modeled components.
Experimental economics	This approach uses a non-computerized simulation setting, where controlled human experiments are run "to identify and better understand the behavioral factors that affect efforts to coordinate supply chains." [154]

[7] Adapted from [141] M. J. North and C. M. Macal, *Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation*. Oxford University Press, Inc., 2007.

Reducing complexity in modeling operations in general, and the supply network specifically, has its drawbacks. While every methodology is appropriate within the right domain, there is an increasing need for a methodological framework that helps in understanding tradeoffs and interdependences between the agents in a supply network and the environment on which that network operates [92]. This way, managers can approach supply network management with a more systemic perspective and gain insights on how all the different components (structural, strategic, operational, etc.) and their interactions impact the performance of a network.

3.1.2 Agent Based Modeling and Simulation

Agent based modeling and simulation has emerged as a powerful method to represent complex systems and, specifically complex adaptive systems since it facilitates the modeling of large, complex systems, using simple, autonomous components [155]. Agent modeling contributes to the existing modeling approaches by adding the ability to show emergent interdependences and links between micro-level behaviors and macro-level results, providing practitioners and researchers with a test bed to examine otherwise hidden interactions and to test a wide range of interventions [19].

Supply networks, when analyzed as complex adaptive systems, present several challenges to the traditional modeling approaches. Through aggregation, supply networks create hierarchical structures or agencies that cluster suppliers, manufacturers, wholesalers and distributors and produce aggregate behaviors (e.g. bullwhip effect) that makes it impossible to infer from the individual behaviors of each entity. Linked to this property is the mechanism of tagging that creates interdependencies and relationships based on some sort of affinity that facilitates specialization and collaboration between them [19, 58]. Along with the horizontal connectivity among firms, vertical relationships are also formed between firms or clusters of firms establishing hierarchies [141, 156].

The property of diversity is challenging because it requires that the chosen methodology be able to represent flexibility in the development of relationships between, for example, manufacturers and supplier and manufacturers and distribution centers, as response(s) to stimuli from the environment, i.e., the network adapts its response according to the stimuli it receives from the environment such us abrupt changes in the demand, disturbances that impact the state of suppliers, distribution networks, etc. [6, 7, 92, 141, 156, 157].

Agent based methods have been widely recognized as a new paradigm in research methods [158-160] where its applicability domain, as outlined by N.R. Jennings & Wooldridge [160], falls in the complex systems category of the specified types of systems:

- Open systems, where the system under consideration is capable of changing and adapting itself. The components of the systems are not necessarily known in advance and may be highly heterogeneous (diverse).
- Complex systems, with problem domains that involve a large variety of process and objects that interact and give rise to behaviors that cannot be inferred or represented based on the properties of those components or processes.
- Ubiquitous systems, that implies domains where the components act and react autonomously (self-organizing) and are proactive in nature, i.e. the components have building blocks that they use to structure the responses to the stimuli.

An agent is defined as "a computer system situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives." [160]. Gilbert [159] describes agent based modeling as "a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment" (p. 2).

Considering the requirements described in Table 3.2, agent based modeling and simulation seems to be the most suitable method for addressing the research questions identified in Chapter 1. Table 3.4 describes how agent based modeling and simulation can address each of the challenges the modeling of modern supply networks entails, and specifically, the representation of the resilience construct.

Table 3.4 Challenges of Modeling Supply Networks as Complex Adaptive Systems

Challenge	Agent Based Modeling Contribution
Representation of Emergence	ABM facilitates the representation of individual agents of the network (manufacturers, distributors, etc.) and their interactions and interdependences which gives rise to global behaviors. This ability provides a better approximation of the real life supply networks.

Challenge	Agent Based Modeling Contribution
Representation of Behavioral Dynamics	The construct of resilience is intrinsically associated with the dynamic and evolving character of the supply network. ABM facilitates the representation of the individual behaviors of each component of the network (suppliers, manufacturer, distributors, etc.) without sacrificing the representation of the dynamics of the overall network.
Representation of Conflicting Local vs. Global Objectives	A supply network is a cluster of diverse production systems that have individual goals that are constrained by their resources and the actions of other subsystems and that respond individually to expected and unexpected stimuli. Due to the agent-centric approach of ABM, it is possible to build better approximations to real supply networks.
Representation Hierarchical Process Complexity	The complexity of the interdependences is driven by processes of interchange of information and materials. ABM uses agents' behaviors and properties to build up interdependences and allows for the representation of both flow of information and material.
Representation of Self-Organizing Behaviors	In response to stimuli from the environments, agents have the ability of adjust/adapt their behaviors and expectations accordingly. Supply networks experience the same when the components have to adjust the production plans as new information becomes available.

Agent based modeling and simulation provides an adequate method for modeling and representing modern supply networks, and several authors have recognized its benefits [19, 65, 92, 133, 141, 161, 162]. Furthermore, several authors have combined ABMS with traditional methodologies to represent the micro and the macro level of the supply networks. Among others, Gjerdrum, Shah, & Papageorgiou [162] use a multi-agent simulation to represent a supply network driven by its demand and optimize the scheduling problem of each production site using mixed integer programming. Akkermans [163] and Schieritz & Größler [164] use system dynamics and agent based modeling and simulation. The former analyzes structure emergence based on attachment preferences of the agents and concludes that the "network stability emerges spontaneously as relative preferences become fixed over time" [163]. The latter runs simulation experiments with order fulfillment and supplier evaluations as experimental factors.

The works discussed above expand the analytical capabilities of agent based modeling and simulation by incorporating traditional approaches, and they demonstrate that ABMS can be used as an overarching methodology that describes the supply network based on its components , or it can be used as an underlying methodology where the entities of a supply chain are embedded in larger systems (e.g. multi-industry supply networks) [141].

To better represent modern supply networks and, furthermore, to understand their dynamics (as a result of the interactions between the network properties) in the presence of uncertain events such disruptions, ABMS is a robust methodology. Modern supply networks consist of a diverse group of companies that interact with each other and with the environment. These interactions are driven by each firm's strategic and operational behaviors, properties and goals. Moreover, ABMS expands understanding and provides insights for representing theoretical constructs such as resilience as a derivation of the network properties and multi-pronged approaches used by practitioners to deal with the uncertainty of disruptive events.

4 MODEL FORMULATION

As supply chains have become increasingly complex and geographically unbounded, firms are more interested in protecting their networks from the disastrous impacts even small disruptions can have in terms of cost and customer satisfaction. Whether caused by natural events and/or operational conditions, disruptions strain supply chains across the globe, in a new economy where companies are mostly operating under a lean approach. Furthermore, in the push for adding value through cost reduction, companies are expanding the boundaries of the supply chain and suppliers are usually balancing sourcing cost versus transportation cost. All these aspects imply that the structure of modern supply networks is susceptible to different types of disruptions, endogenous vs exogenous [13], with different probabilities of occurrence and durations.

As discussed in Chapter 3, to understand the impact of a disruption (or concurrent disruptions) and how the effect propagates through the network, simulation comes as the more suitable approach. Simulation, and specifically, agent based simulation, allows the design and deployment of a model that: a) can capture both individual (node level) and collective behaviors (chain); and b) the structural properties of the supply network as a whole and of its components. The flexibility of using simulation to analyze disruptions also allows for the incorporation of other factors such as the Bill of Materials of the product(s) produced by the network under consideration. This is a critical aspect when it comes to disruption management, since the propagation of a disruption through the chain is closely associated with sourcing decisions which, in turn, are heavily influenced by the type of product being produced.

Thus, this research provides both practitioners and academics, with a robust simulation model that incorporates, in the same platform, the characteristics of the product with the structure of the sourcing network. Among others, the model allows i) the analysis of different operational practices and their impact on disruption management; ii) understanding of the propagation patterns of different disruption types (at different levels of resolution: network, node and network-node); iii) understanding of the behavior of multi-echelon systems subject to disruptions; iv) understanding of the impact different product configurations have on the supply network response to disruptions; and v) understanding of the effect concurrently implementing operational strategies to manage disruptions.

Accordingly, the agent-based simulation model developed for this research uses the Bill of Materials of a single product as the core structural element that defines the configuration of the supply chain network (see Figure 4.1). The network consists of a manufacturer, with upstream suppliers that specialized on either components or assemblies. Assembly nodes have raw materials suppliers and/or subassemblies suppliers. The technological order vector arbitrarily orders the raw materials suppliers and, the components appear as their parts and assembly units are listed.

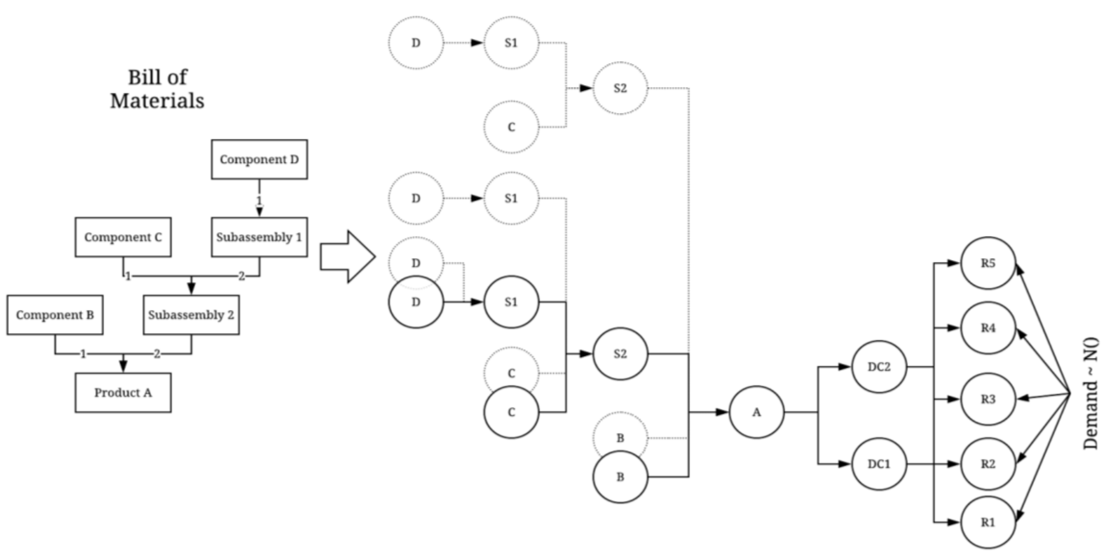


Figure 4.1. The generic supply network characterized in the agent based model
This network is the result of a BoM for a single product assembled by one manufacturer that requires two subassemblies, has three raw material suppliers, and sources two distribution centers that fulfill the demand of 5 retailers. The manufacturer's dual sourcing options are represented by the dotted lines.

The manufacturer can consider both single and dual sourcing. Downstream, the network considers variable number of distribution centers that serve a potentially variable number of retailers. While retailers sourcing directly from the manufacturer are not within the scope of this research, the model can encompass this scenario as well. The distribution centers order based on their master production plan and store all finished product. Retailers have stochastic demand patterns and source their demand from the distribution centers. Each node of the network (downstream and upstream) forecasts their demand based on historical demand patterns. Each node of the network is located in a given region and the sourcing decisions involving supplier selection take into consideration proximity of the suppliers as well as service metrics. The simulation model can be further extended to include other sourcing strategies, different demand patterns, and more complex supplier selection mechanisms.

4.1 System Identification and Decomposition

As mentioned in Chapter 1, this research aims to characterize the concept of resilience, from an operational perspective, considering the network's sourcing structure (topology) derived from a product's technological assembly order (as represented by its BoM). For this purpose, the architecture of the proposed model adapts the formal representation of the Bill of Materials proposed by Bunke et al. [165]. The supply network is represented using an adaptation of the supply-chain operations reference (SCOR) Model[8], a process reference model developed and endorsed by the Supply Chain Council as the cross-industry, standard diagnostic tool for supply chain management [166]. The performance metrics used to characterize the system's response to different disruptive scenarios are also derived from the SCOR model. In the following sections, the model's architectural elements are discussed in detail.

4.1.1 The Bill of Materials representation

In their work, Bunke et al. [165], represent the production vector $\vec{z}$ as satisfying both the internal demand $\vec{a}$ (components and subassemblies) and the external demand (customer orders, including final product and/or customer demand for additional components) represented by a vector $\vec{x}$. Clearly, a linear relationship exists between the internal demand and the given production:

$$\vec{a} = P \cdot \vec{z} \qquad \text{Equation 4-1}$$

where P is the amount matrix of dimension i, with $i = total\ number\ of\ components + 1$, as per the BoM. All the main diagonal entries of P are zero (since to produce one part, the part itself is not required) as well as all the entries below the main diagonal due to the technological order also given by the BoM.

Using the linearity property of matrices, it is possible to express $\vec{a}$ as

[8] For a detailed description of the SCOR model, see [166] S. C. C. SCC, "Supply Chain Operations Reference Model," Supply Chain Council, USAOctober, 2012 2012.

$$\vec{a} = P \cdot \vec{z} = P \cdot (z_1\vec{e}_1 + z_2\vec{e}_2 + \cdots + z_i\vec{e}_i) \qquad \text{Equation 4-2}$$

$$\vec{a} = P \cdot \vec{z} = x_1 P \cdot \vec{e}_1 + x_2 P \cdot \vec{e}_2 + \cdots + x_i P \cdot \vec{e}_i \qquad \text{Equation 4-3}$$

where x_i is the demanded quantity of the component (subassembly/final product) i and $P \cdot \vec{e}_1$ is the production vector for exactly one part of sort i (component/subassembly/final product). Thus, $P \cdot \vec{e}_1$ represents the column i^{th} of the amount matrix P. After an order $\vec{x}$[9] is received, the production volume, $\vec{z}$, is given by

$$\vec{z} = (E - P)^{-1}\vec{x} \qquad \text{Equation 4-4}$$

[10]

where E is the unit matrix.

Since P is nilpotent, $(E - P)$ is invertible and its inverse is given by

$$(E - P)^{-1} = E + P + P^2 + \cdots + P^{n_0 - 1} \qquad \text{Equation 4-5}$$

[11]

Thus, the production volume, $\vec{z}$, is given by

$$\vec{z} = (E + P + P^2 + \cdots + P^{n_0 - 1})\vec{x} \qquad \text{Equation 4-6}$$

The proposed model uses this representation to determine the production volume of each node of the supply network. For example, using the network shown in Figure 4.1, and assuming an external demand of 12 units of product A, the production volume is calculated as follows:

$$\vec{x} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 12 \end{bmatrix}$$

$$(E - P) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -2 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -2 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

---

[9] This research considers only the case where customers demand is restricted to the final product, hence all the entries of the vector $\vec{x}$ are 0 except for the last one that represents the quantity demanded.

[11] For a more detailed derivation of these results see [165] F. Bunke, H. W. Hamacher, A. Maurer, and S. Muller, "Bills of Material and Linear Algebra," in "Management Mathematics for European Schools -MaMaEuSch," University of Kaiserslautern, Kaiserslautern, GermanyOctober, 2004 2004.

$$(E-P)^{-1} = \begin{bmatrix} 1 & 1 & 0 & 2 & 0 & 4 \\ 0 & 1 & 0 & 2 & 0 & 4 \\ 0 & 0 & 1 & 1 & 0 & 2 \\ 0 & 0 & 0 & 1 & 0 & 2 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\vec{z} = (E-P)^{-1}\vec{x} = \begin{bmatrix} 1 & 1 & 0 & 2 & 0 & 4 \\ 0 & 1 & 0 & 2 & 0 & 4 \\ 0 & 0 & 1 & 1 & 0 & 2 \\ 0 & 0 & 0 & 1 & 0 & 2 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 12 \end{bmatrix} = \begin{bmatrix} 48 \\ 48 \\ 24 \\ 24 \\ 12 \\ 12 \end{bmatrix}$$

The proposed model uses $\vec{z}$ to balance inventories and account for incoming order inventories and, finally, make decisions regarding the quantity to manufacture. The matrix P is also used in the proposed model to configure the upstream echelon through the links given by the technological order.

4.1.2 Supply Chain Operations Reference Model (SCOR)

The SCOR model (see Figure **4.2**) was developed in 2004 with the intent of providing a systematic approach to model, characterize, and evaluate the performance of the operational processes of supply chains. The model proposes six fundamental processes types that are required to describe any supply chain: Plan, Source, Make, Deliver, Return, Enable.

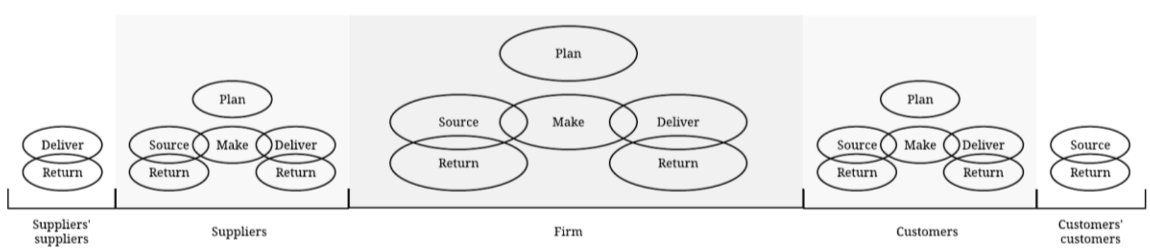
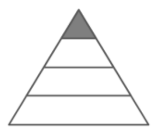
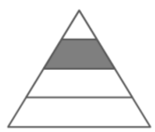


Figure 4.2. SCOR Model

Due to the globalization of operations, a standardization of the productive processes is required to guarantee smooth communication and integration of the different agents of the supply network [167] and, ultimately, to satisfy a customer's demand [166]. Thus, due the wide acceptance of the SCOR Model among practitioners and, since it allows to capture the complexities of the modern supply chains described in the introduction of this chapter, this research uses five out of the six elementary processes proposed by the Supply Chain Council. Table 4.1 briefly describes the model’s processes types, its different levels, and provides examples of those.

Table 4.1. Elements of the SCOR Model[12]

	Level #	Elements	Examples	Description
SCOR scope	1 	Process Types (Scope)	**Plan, Source, Make, Deliver**, Return, **Enable**	Defines the scope and content of the supply chain. The performance targets are set.
	2 	Process Categories (Configuration)	**MTS**, MTO, ETO, Defectives Products, MRO Products, Excess Products	Operations strategy and process capabilities are set.
	3 	Process Elements (Steps)	**Schedule Deliver, Receive Produc**t, Verify Product, Transfer Product, Authorize Payment	The firm sets the ability to execute
Beyond SCOR scope	4 	Activities (Implementation)	Firm, Industry, Location, and/or Technology Specific steps	Specific processes and practices aimed to achieve performance

As mentioned before, the SCOR model identifies six main components, associated with six basic supply management processes: Plan, Source, Make, Deliver, Return, and Enable. Plan includes processes that balance resources to determine the production plans that best meet the requirements of a supply chain and its sourcing, production, delivery, and return processes.

[12] Adapted from [166] S. C. C. SCC, "Supply Chain Operations Reference Model," Supply Chain Council, USAOctober, 2012 2012.. The elements incorporated in the model proposed in this dissertation are bolded.

Source includes processes that manage the procurement, delivery, receipt, and transfer of raw material items, subassemblies, products, and services. Make includes processes that transform products to a finished state. Deliver includes processes that provide finished goods and services. Return includes post-delivery customer support and processes that are associated with returning or receiving returned products. Enable describes the associated processes with the management of the supply chain. The model proposed by this research, embeds the Enable elements into other of the Level 1 elements[13]. At Level 2, the relationship and interactions among supply chain agents are specified and, it can be extended to capture the process workflow through Level 3. It is a Level 3 that the firm determines and acquires the information required for planning and sets up supply chain performance metrics.

All nodes in the supply network (upstream and downstream) are modeled as independent agents (identified as prodnodes for the upstream network and distnodes for downstream network) that make decisions autonomously. These decisions are associated with four of the Level 1 processes: Plan, Source, Make, and Deliver. Return processes are not performed by the network nodes within the scope of this research. However, the model could be extended to include this process as part of the decision-making process.

The proposed model was developed using Netlogo 6.0.2, a multi-agent programmable modeling environment; the code can be found in Appendix A. The agents' architecture as well as the properties of the environment where the supply chain will operate are discussed in the next section.

4.1.3 Model Decomposition: the agents

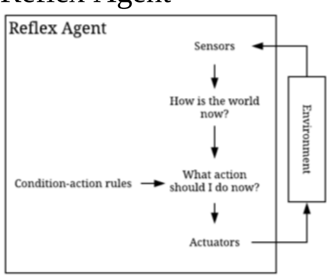
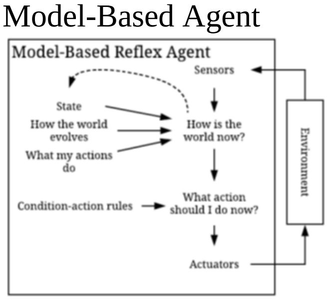
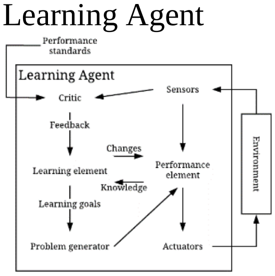
To represent a supply network as complex adaptive system, it is necessary to recreate the different levels of complexity by taking into consideration: a) the different types of tasks and actions (processes) performed by the different components (network nodes, orders) and b) the environmental conditions in which the network operates (disruptive scenarios at the node level and at the region level). According to Russell et al. [168], an agent program implements the functions an agent carries out. For the purpose of this study, three types of agent architectures are combined to represent a hierarchical supply network: simple reflex agents, model-based agents, and learning

[13] Previous versions of SCOR follow a similar approach: it wasn't until Revision 11.0 that the Enable process was elevated to a Level 1 process.

agents. A brief description of these agents as well as the corresponding model constructs are provided in Table 4.2:

As it has been previously argued, production systems are characterized as highly complex systems and, the design, development and implementation of model constructs in a simulation platform requires a well-define and standardized approach. This research uses Unified Modeling Language (UML) [168-171] to describe the abstractions and decompositions of the high-level structures (such as a manufacturing company, a distribution center, etc.) and their behaviors that were required to answer the research questions under consideration. The UML diagrams for both the structure and the behaviors of the model constructs discussed in this section will be described in section 4.2.

Table 4.2. Agents' architectures and corresponding model constructs

<table>
<tr><th>Agent Type</th><th>Description</th><th>Model Construct</th></tr>
<tr><td>Reflex Agent

</td><td>The agent finds a rule whose condition matches the current situation, as defined by the percept and the stored internal state and then performs the action associated with that rule.</td><td>Links
Orders</td></tr>
<tr><td>Model-Based Agent

</td><td>The agent does not have complete visibility of the system and the environment. The agent creates an internal state (model) using the history of stimuli perceptions and this state, combined with the current stimuli perception and the agent's actions impact on the environment, generates an updated description of the current state.</td><td rowspan="2">Network nodes (upstream and downstream)</td></tr>
<tr><td>Learning Agent

</td><td>This type of agent modifies its own components (behaviors and condition-action rules) to improve its overall performance. The critic provides feedback on agent's performance based on a fixed performance standard. The performance element allows the agent to select actions based on percept. Then, the problem generator suggests actions that will lead to new, informative experiences.</td></tr>
</table>

4.1.4 Model decomposition: the environment

Critical to the analysis of the supply network, it is the understanding of the properties of the environment in which it operates. All the agents in a supply network have a connection to the environment: they perform processes (plan, source, make, deliver) that have an impact on the environment (end customers) and the environment (customers) then responds to the agents' actions with insights that will, eventually determine the future response of the agent (adjust supplier's base in case of disruptions).

For the purpose of this research, the properties of the environment in the supply chain are described as follows: (Russell et al., 2003)

- *Partially accessible*: Not all the agents in the supply network have access to the demand patterns, critical to their choice of actions in each of the processes: plan, source, make, deliver.
- *Nondeterministic:* The demand is modeled as a stochastic variable that follows a normal distribution. The disruptions at the node and region level are modeled as stochastic events as well, following exponential distributions.
- *Sequential*: The network nodes actions are impacted by whatever decisions (actions) were taken in previous periods.
- *Dynamic*: Since the demand is stochastic, the environment changes every period.
- *Discrete*: The set of decisions and actions the network nodes take are discrete as well as the different states of the environment (demand).

4.2 Model representation: behavior diagrams

The primary focus of UML is on modeling a system [172], and it provides with two main categories of diagrams to do so: structural and behavioral. These diagrams facilitate the representation, over time, of the agents and their interdependencies in a supply network. UML then provides a solid foundation towards implementing an algorithmic model (simulation) to analyze the behavior of those entities operating as a whole. First, the behaviors of the agents, as a whole (the network) and individually (the production/distribution node), are discussed and the activity (state) diagrams are derived. Subsequently, a structural representation of the supply network is provided and the class diagrams are developed.

4.2.1 The network behavior

Figure 4.3 shows the sequence diagram for the network analyzed in this research. This diagram shows how the network nodes interact in a time sequence. There are two differentiable sequences in this diagram: the operational phase and the managerial phase. A product's BoM determines the basic structure of the sourcing network. The nodes capture information from the environment (demand and disruptive states) and evaluate how well they have met this demand in the past (assessing performance of their upstream suppliers, and determining safety stock levels, dispatching and replenishment plans, etc.). Subsequently, the nodes generate a forecast (based on an internal model of the demand) and determine its actions (production volume, current state). Based on the desired performance level (target KPIs), the nodes adjust their production plan and execute it considering constrains imposed by their current state (inventory levels, safety stock, other agents' disruptive states, etc.). Their performance is then stored and processed at the beginning of the next time period.

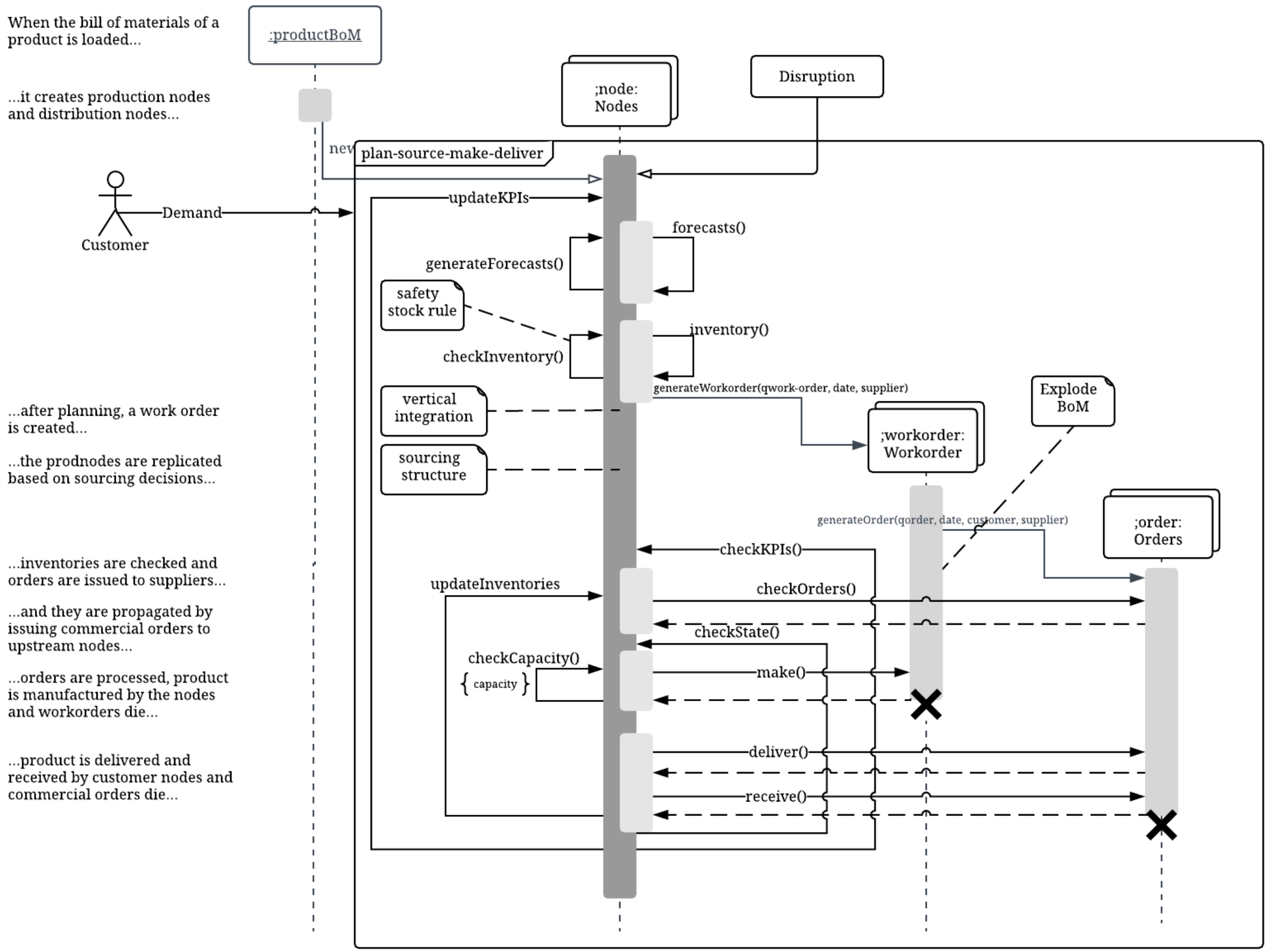


Figure 4.3. Sequence diagram of the supply network

4.2.2 The nodes behavior

In the design of this simulation model, there are two types of supply network nodes that are considered: production nodes and distribution nodes. All nodes run the processes of plan, source, make, and deliver every time unit. While most of the activities in each of these processes are performed similarly by all nodes, there are some differences based on where in the network the node is located (upstream/downstream) as well as whether the node is or is not an assembly node. The activity diagrams and pseudo algorithms for the nodes' behavior are discussed in the following section.

4.2.2.1 The Plan Process

This process is performed only by the upstream nodes (prodnodes). For each period over the planning horizon, the node uses its demand history to forecast its demand using a moving average with an n of length equal to ph or an autoregressive model with a lag of 1. The node determines its master plan schedule comparing its forecast to the committed demand, DC_{ph}, for the planning period. The node checks the proyected level of inventory of finished goods, $Projected\ I_{FG_{ph}}$, accounting for outstanding work-orders, QP_{ph}, and determines whether it can meet the committed demand. If demand can be met, the node schedules work-orders for production, QS_{ph}, and updates its projected inventory of finished goods for the next planning period. If not, the node then proceeds to check the inventory of components, $Projected\ I_{c_{ph}}$, accounting for any outstanding work-orders, scheduled in previous planning periods, QS_{t-ph}, and any incoming orders from its suppliers (*i*), $QO_{i_{ph}}$, and calculate the minimum quantity available to manufacture, atm_{ph}. If atm_{ph} is sufficient to satisfy the demand for the planning period, the node schedules work-orders, accounting for the lead time. If the node determines that is has a stock out of components, it issues work-orders tagged as upstream, QSU_{ph}, meaning, it will be required to explode the bill of materials in order to source those orders, accounting for its lead time. At the end of the planning period, the node updates both inventory of finished goods and inventory of components.

For prodnode j,

For each ph,

Forecast Demand -AR

$$F_{ph} = \beta_0 + \beta_1 D_{t-1}$$

Forecast Demand -MA(n)

$$F_{ph} = \sum_{i=1}^{ph} \frac{D_{ph-i}}{ph}$$

Calculate Committed Demand

$$DC_{ph} = \sum_{date=0}^{ph} qorder_{ph}$$

Update Proyected Inventory of Finished Goods

$$set\ Proyected\ I_{FG_{ph}} = I_{FG_{ph}} + QP_{ph}$$

Master Plan Schedule

$$QMPS_{ph} = max[F_{ph}, DC_{ph}]$$

$$If\ Proyected\ I_{FG_t} \geq\ QMPS_{t_{ph}}$$

$$set\ QS_{ph} = QMPS_{t_{ph}}$$

$$set\ Proyected\ I_{FG_t} = Proyected\ I_{FG_t} - QMPS_{t_{ph}}$$

$$Else$$

$$Let\ \hat{I}_{c_{ph}} = \begin{bmatrix} c_{ij} \\ \vdots \\ 0 \end{bmatrix}$$

$$set\ Proyected\ \hat{I}_{c_{ph}} = \hat{I}_{c_{ph}}$$

$$set\ Proyected\ c_{i_{ph}} = Proyected\ c_{i_{ph}} + QO_{i_{ph}} - QS_{i_{ph}}$$

$$Let\ \widehat{p^j} =\ column\ j\ of\ P = \begin{bmatrix} p_{1j} \\ \vdots \\ 0 \end{bmatrix}$$

$$Let\ \widehat{m^j} = \begin{bmatrix} {p_{1j}}^{-1} \\ \vdots \\ 0 \end{bmatrix}$$

$$atm_{\ ph} = min\left(I_{c_{ph}} \cdot \widehat{m^j}\right)$$

$$set\ Stockout_{ph} = QMPS_{ph} - I_{FG_{ph}} -\ atm_{\ ph}$$

$$set\ QS_{ph} = atm_{ph}$$

$$set\ QSU_{ph} = Stockout_{ph}$$

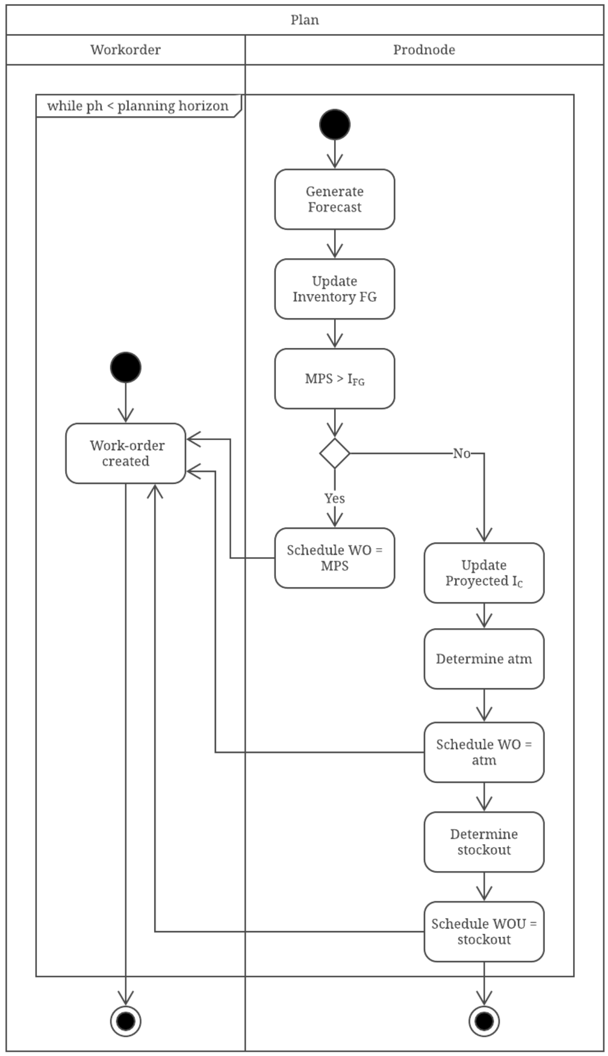


Figure 4.4. Activity diagram for SCOR processes Level 1: Plan

4.2.2.2 The Source Process

This process is performed only by the upstream nodes (prodnodes) that are assembly nodes. Once every node completes its planning, the quantity of the order(s), $qorder$, to be issued to its suppliers is calculated. Then, the node chooses the sourcing structure based on its review of the KPIs, assigning the order to the best supplier. Subsequently, the node updates its production plan. The mathematical representation of each of these functions for *prodnode j*, and the corresponding activity diagram of the process *make* are shown below. The model assumes one day as one time pulse and nodes plan for ph periods of time.

For prodnode j,

For each ph,

Aggregation of work-orders

$$load_t = \sum_{date=0}^{t} qwork - order_t$$

Determine components requirements

$$Let\ \widehat{p^j} = column\ j\ of\ P = \begin{bmatrix} p_{1j} \\ \vdots \\ 0 \end{bmatrix}$$

$$Let\ work\widehat{order}vct = load_t \cdot \begin{bmatrix} p_{1j} \\ \vdots \\ 0 \end{bmatrix}$$

$$qorder_i = \left(load_t \times p_{ij}\right)$$

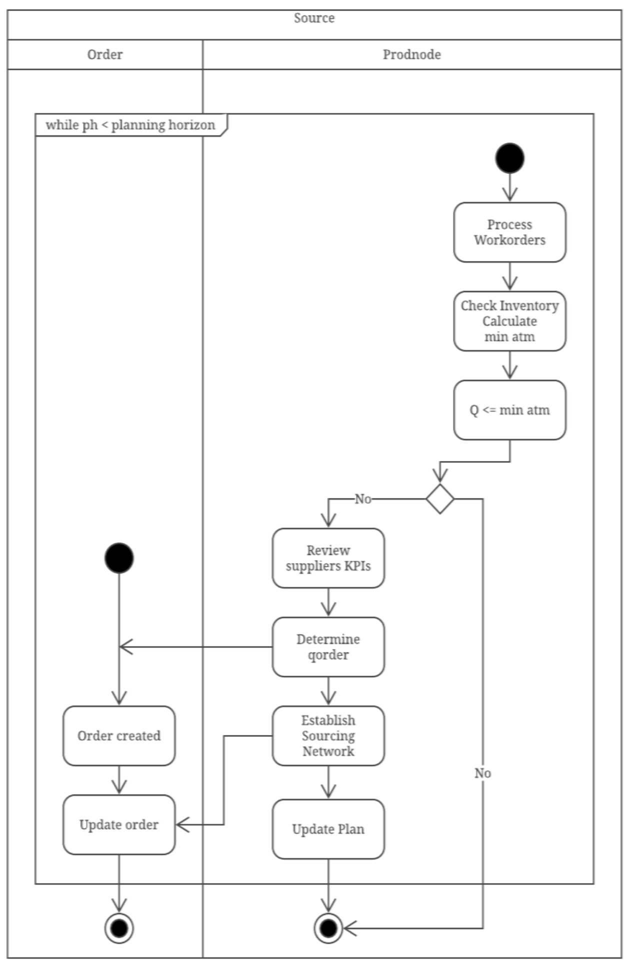


Figure 4.5. Activity diagram for SCOR processes Level 1: Source

4.2.2.3 The Make Process

This process is performed only by the upstream nodes (prodnodes). At the beginning of each time period, the node reviews work-orders scheduled for that period and any outstanding work-orders and it aggregates the quantity to manufacture, QWO_t. Then, it proceeds to check inventory of components $\hat{I}$, (if it is an assembly node; raw material nodes have unlimited raw material but limited capacity *cap* and a lead time). If not, there is insufficient inventory, the node schedules production for the difference between the available inventory of components and the aggregation of work-orders and updates back-work-orders for the difference. If there is sufficient inventory, the node schedules the aggregation of work-orders to be produced, $atm_{\,t}$. After accounting for the lead time, the inventory of finished goods is updated. The mathematical representation of each of these functions for *prodnode j*, and the corresponding activity diagram of the process *make* are shown below. The model assumes one day as one time pulse.

For prodnode j,

Aggregation of work-orders

$$QWO_t = \sum_{date=0}^{t} qwork - order_t$$

Load considering available inventory of components

$$Let\ \widehat{p^j} = \ column\ j\ of\ P = \begin{bmatrix} p_{1j} \\ \vdots \\ 0 \end{bmatrix}$$

$$Let\ \widehat{m^j} = \begin{bmatrix} {p_{1j}}^{-1} \\ \vdots \\ 0 \end{bmatrix}$$

$$Let\ \hat{I}_{c_t} = \begin{bmatrix} c_{ij} \\ \vdots \\ 0 \end{bmatrix}$$

$$atm_{\,t} = min\left(\hat{I}_{c_t} \cdot \widehat{m^j}\right)$$

Lot to manufacture considering inventory and capacity

$If\ QWO_t \leq\ atm_{\,t}$

$\qquad set\ L_t = QWO_t$

$Else$

$\qquad set\ L_t = \ atm_{\,t}$

$If\ L_t \geq$ cap

$\qquad set\ L_t = cap$

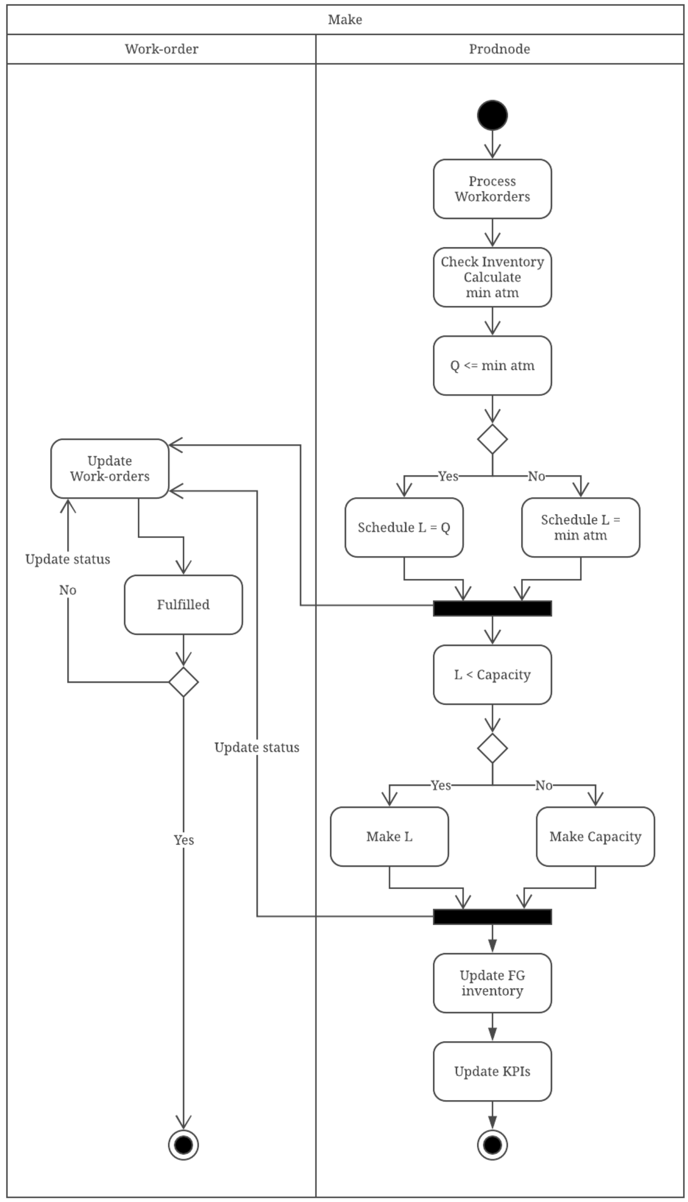


Figure 4.6. Activity diagram for SCOR processes Level 1: Make

4.2.2.4 The Deliver Process

This process is divided in two sub-processes *distribute* and *receive* and it is performed by all the nodes in the network (upstream and downstream). However, there are differences in how production nodes and distribution nodes handle these sub-processes. The mathematical representation of each of these functions for *prodnode/distnode j*, and the corresponding activity diagram of the processes *distribute and receive* are shown below.

- *Distribute upstream in the network.* Nodes determine what work-orders are to be completed on time t and update their finished goods inventories by that amount. Then, the nodes start dispatching individual commercial orders using one of two rules: Smallest Order Quantity (SOQ) or Earliest Due Date (EDD). Once the inventory has been depleted (to a point when not more orders can be dispatch), the remaining orders are identified as backordered. Nodes proceed to update their KPIs.

For prodnode j,

Production volume at time t

$$QP_{\boldsymbol{t}} = \sum_{date=0}^{t} qwork - order_t$$

Update inventory of finish goods

$$Let\ I_{FG_t} = I_{FG_{t-1}} + QP_t$$

Calculate Demand

$$D_t = \sum_{date=0}^{t} qorder_t$$

Dispatching rule (SOQ)

$$Sort\ orders < qorder$$

Dispatching rule (EDD)

$$Sort\ orders < date$$

Dispatch order

$$if\ I_{\boldsymbol{FG_t}} \leq qorder$$

$$set\ I_{FG_t} = I_{FG_t} - qorder$$

$$Else$$

$$update\ KPIs$$

- *Distribute downstream in the network.* Distribution nodes check their inventory and start dispatching individual commercial orders using one of two rules: Smallest Order Quantity (SOQ) or Earliest Due Date (EDD). Once the inventory has been depleted (to a point when not more orders can be dispatch), the remaining orders are identified as backordered. Nodes proceed to update their KPIs.

For distnode j,

Update inventory of finish goods

$$Let\ I_{FG_t} = I_{FG_{t-1}}$$

Calculate Demand

$$D_t = \sum_{date=0}^{t} qorder_t$$

Dispatching rule (SOQ)

$Sort\ orders < qorder$

Dispatching rule (EDD)

$Sort\ orders < date$

$if\ I_{\boldsymbol{FG_t}} \leq qorder$

$set\ I_{FG_t} = I_{FG_t} - qorder$

$Else$

$update\ KPIs$

- *Receive upstream in the network.* This process is performed only by assembly nodes. The nodes determine the quantity that is ready to be delivered by each of their suppliers and, upon receipt, update their inventory of components.

For prodnode j,

Delivery schedule for time t, from supplier i

$$Q_{t_i} = \sum_{date=t} order_{t_i},$$

Update inventory of components

$$Let\ \hat{I}_{c_{t-1}} = \begin{bmatrix} c_{ij} \\ \vdots \\ 0 \end{bmatrix}$$

$$Set\ c_{ij_t} = c_{ij_{t-1}} + QP_t$$

- *Receive downstream in the network.* This process is performed only by distribution nodes. The nodes determine the quantity that is ready to be delivered by the chosen distribution center and, upon receipt, update their inventory of finished goods.

For distnode j,

Delivery schedule for time t, from distribution center i

$$Q_{t_i} = \sum_{date=t} order_{t_i}$$

Update inventory of finished goods

$$set\ I_{FG_t} = I_{FG_{t-1}} + Q_{t_i}$$

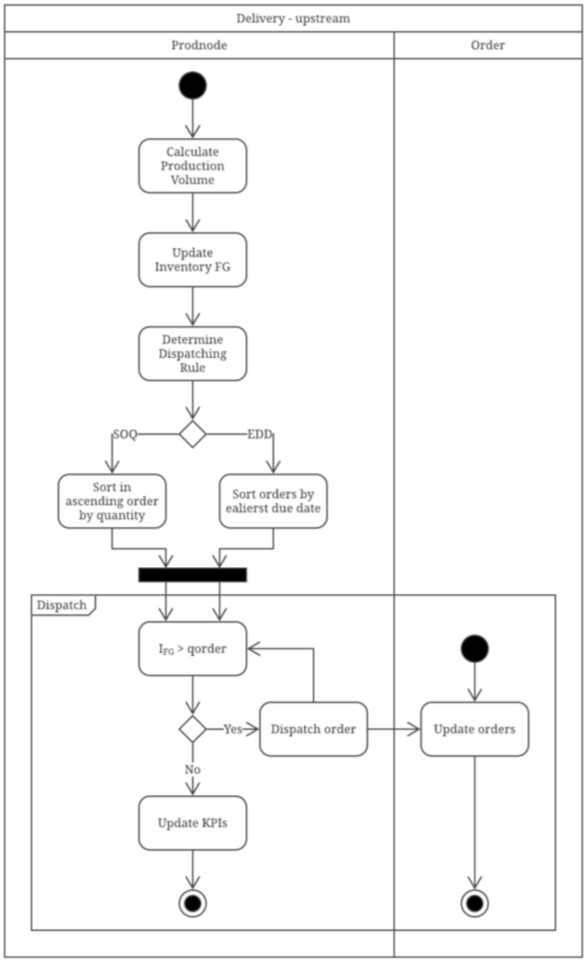


Figure 4.7 Activity diagram for SCOR process Level 1: Distribute (upstream)

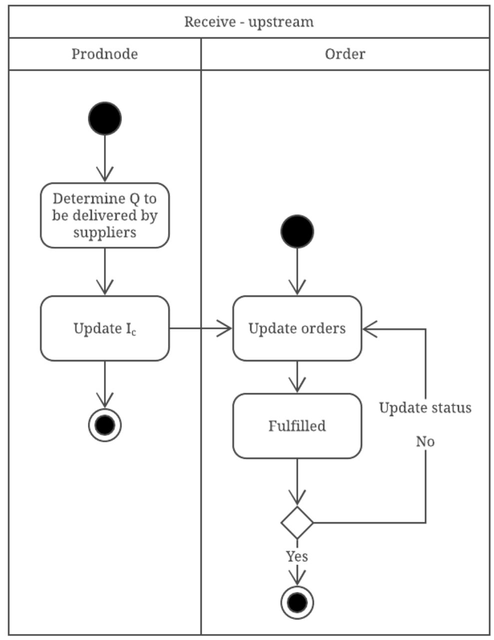


Figure 4.8 Activity diagram for SCOR process Level 1: Receive (upstream)

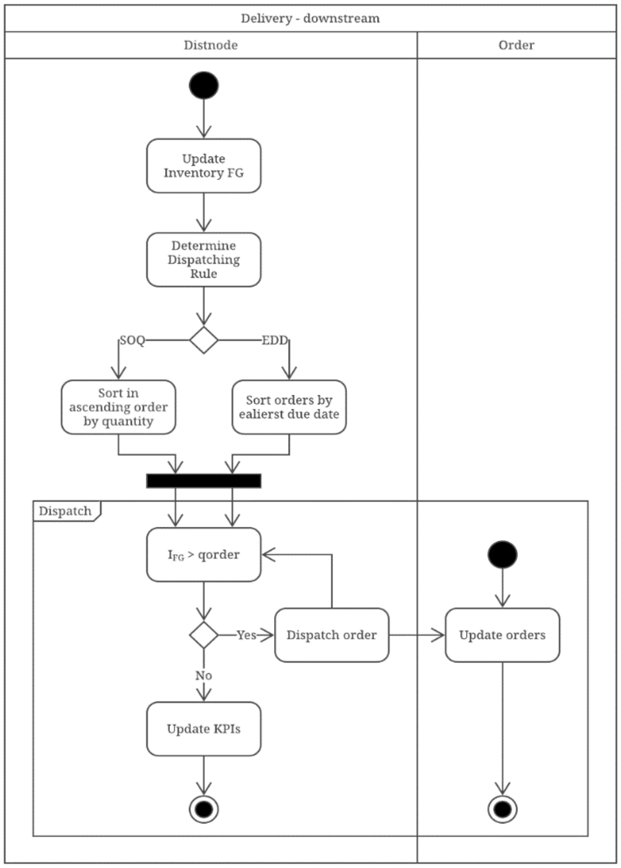


Figure 4.9 Activity diagram for SCOR process Level 1: Distribute (downstream)

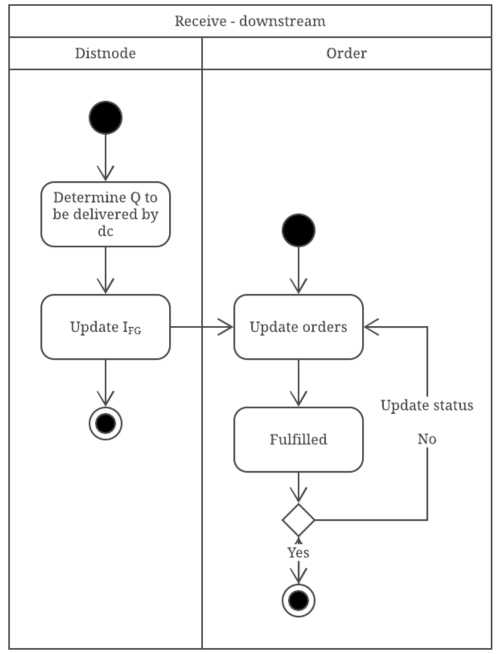


Figure 4.10 Activity diagram for SCOR process Level 1: Receive (downstream)

4.2.3 The network structure

As mentioned before, the supply network structure is originated from the Bill of Materials of a single product and the sourcing and distribution decisions of the firm manufacturing that product. There is an upstream network, where production nodes (both assembly and raw material suppliers) are connected through technological requirements and sourcing decisions; the manufacturer of the single product has the choice of dual source both assemblies and raw materials. The downstream network is created by distribution decisions that involve distribution centers as well as retailers. It is assumed that final customers cannot directly satisfy their demands from the distribution centers and must order from the retailers. Figure 4.11 shows the class diagram for the supply network.

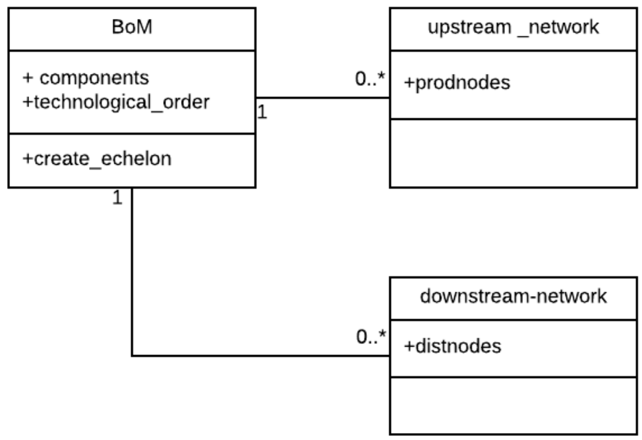


Figure 4.11. Class diagram for the Supply Network Nodes

4.2.4 The nodes structure

The supply network has two types of nodes: production nodes and distribution nodes. The former creates the sourcing structure for the firm manufacturing one single product. The later determine the distribution network for the product. These agents are model-based and learning agents, considering the internal mechanisms used to interact within the network and with the environment.

Production nodes can be either assembly nodes or raw materials suppliers. Each production node, including the manufacturer, can keep inventory and has a limited capacity. Raw materials producers have unlimited materials but have limited production capacity. Nodes plan their operations for a given planning horizon that is the same for the whole chain and nodes have lead times that, for the purpose of this research, are deterministic in nature[14]. Each node forecasts its demand using historical data and all nodes use the same forecasting. The work-orders are reflex agents that can be created by production nodes and orders are reflex agents that

[14] This assumption can be easily relax to explore other scenarios and network behaviors associated with stochastic lead times.

can be created by both production nodes (through sourcing) and distribution nodes (through planning). These agents (work-orders and orders) update their status based on the interaction with the network nodes.

Nodes are randomly assigned a region (sourcing region or distribution region) and proximity between regions is calculated as an index. Nodes use this index as part of the decision making process when it comes to sourcing. The model does not consider transportation cost but the proximity index is a proxy to determine what nodes are closer and, the nodes consider proximity (among other performance indicators) when choosing their suppliers. Each node determines its safety inventory as a function of the desire service level of the chain as a whole. The forecast model and the service level are the only centralized variables that are considered by the nodes. Finally, each node has a probability of being disrupted (to replicate the behavior of endogenous disruptions such as machine breakdowns, strikes, etc.) and a disruption duration that are distributed exponentially. Sourcing regions are given a disruption probability (to replicate disruptions associated with natural disasters and/or geopolitically induced disruptions) and a disruption duration distributed exponentially. Figure 4.11 depicts the class diagram for the different agents used to model the multi-echelon supply network studied in this research. Figure 4.12 shows the use case diagram the relationships between the different agents (nodes, work-orders and orders) and the requirements to replicate the supply network behavior.

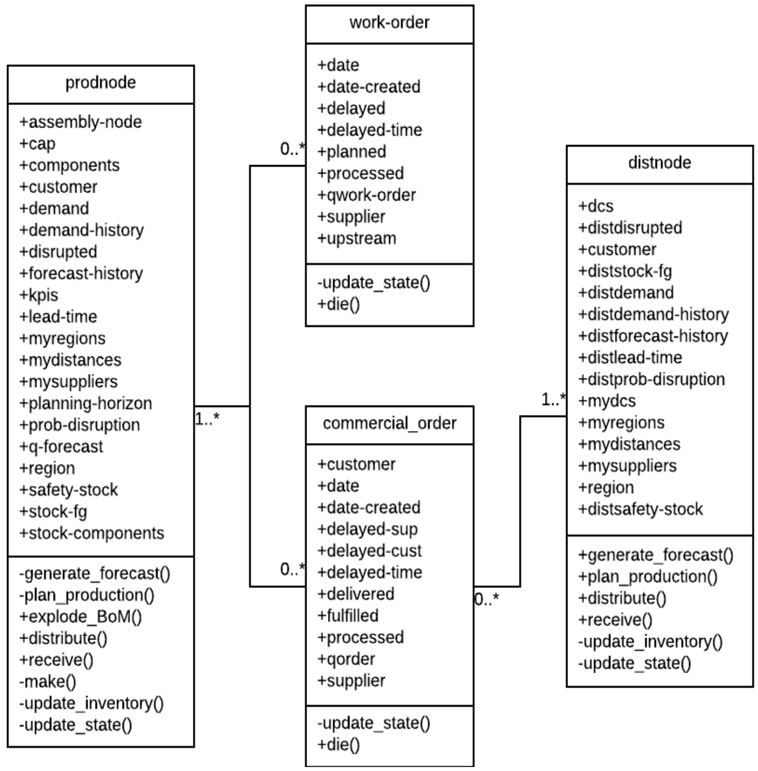


Figure 4.12. Class diagram for the Supply Network Nodes

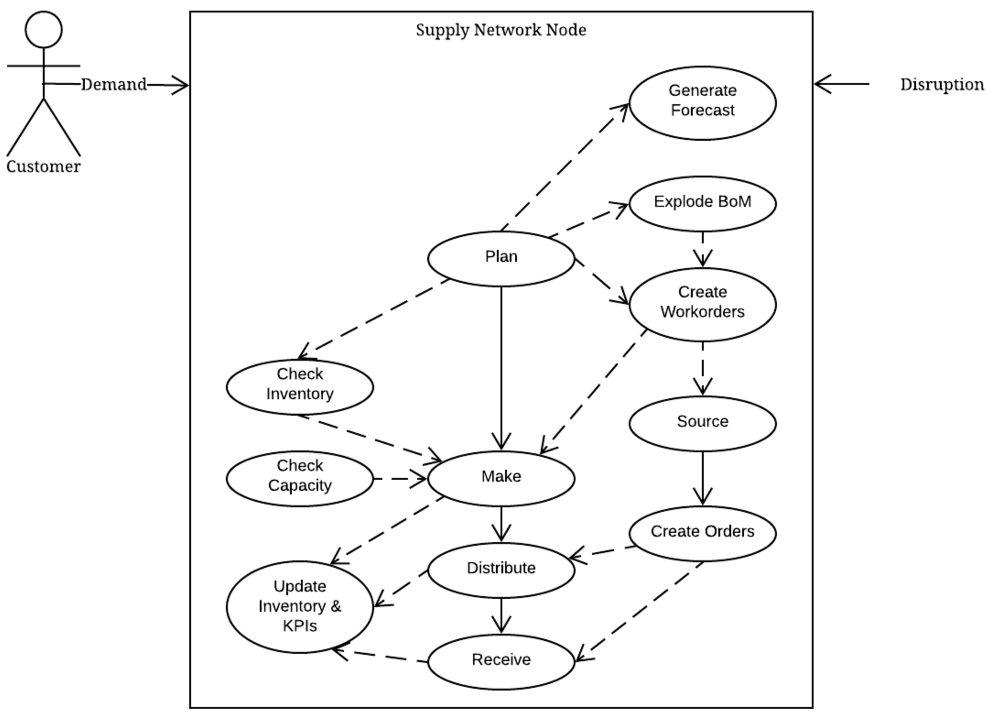


Figure 4.13. Use case diagram for the Supply Network

4.2.5 The model interface

The model was implemented in Netlogo 6.0.3. Table 4.3 and Figure 4.14 to Figure 4.19 present a summary of the model components and how they are reflected in the interface used for the experimentation.

Table 4.3 Model's Implementation Summary

<table>
<tr><td colspan="2">Driving questions:
• How different tactical and strategic decisions give rise to different levels of resilience in a multi-echelon system?
• What is the nature of the interactions between those decisions, the network structure and its performance in the event of a disruption?</td></tr>
<tr><td>Agent Types: Reflex</td><td>Links, work orders, commercial orders</td></tr>
<tr><td>Agent Types: Model Based and Intelligent</td><td>Production nodes (upstream), distributions nodes (downstream)</td></tr>
<tr><td>Agent Properties</td><td>• assembly node
• capacity
• production vector
• customer
• demand
• disrupted
• Lead time
• Minimum quantity available to be manufactured
• Region
• Proximity
• Suppliers
• Probability disruption
• Stock finished goods
• Stock components</td></tr>
<tr><td>Agent Behaviors</td><td>• Forecast
• Plan Production
• Explode Bill of Materials
• Make
• Distribute
• Die</td></tr>
<tr><td>Parameters</td><td>• No. of regions
• No. of manufacturing regions
• Planning horizon
• Forecasting method
• Safety stock
• Duration disruption
• Frequency disruption</td></tr>
</table>

Driving questions: • How different tactical and strategic decisions give rise to different levels of resilience in a multi-echelon system? • What is the nature of the interactions between those decisions, the network structure and its performance in the event of a disruption?	
Metrics	• Commercial orders filled on-time • Commercial orders fill rate • Work orders fill rate • Work orders filled on-time • Utilization • Order's average time in the system • Inventory of finished goods • Inventory of components (assembly node only)

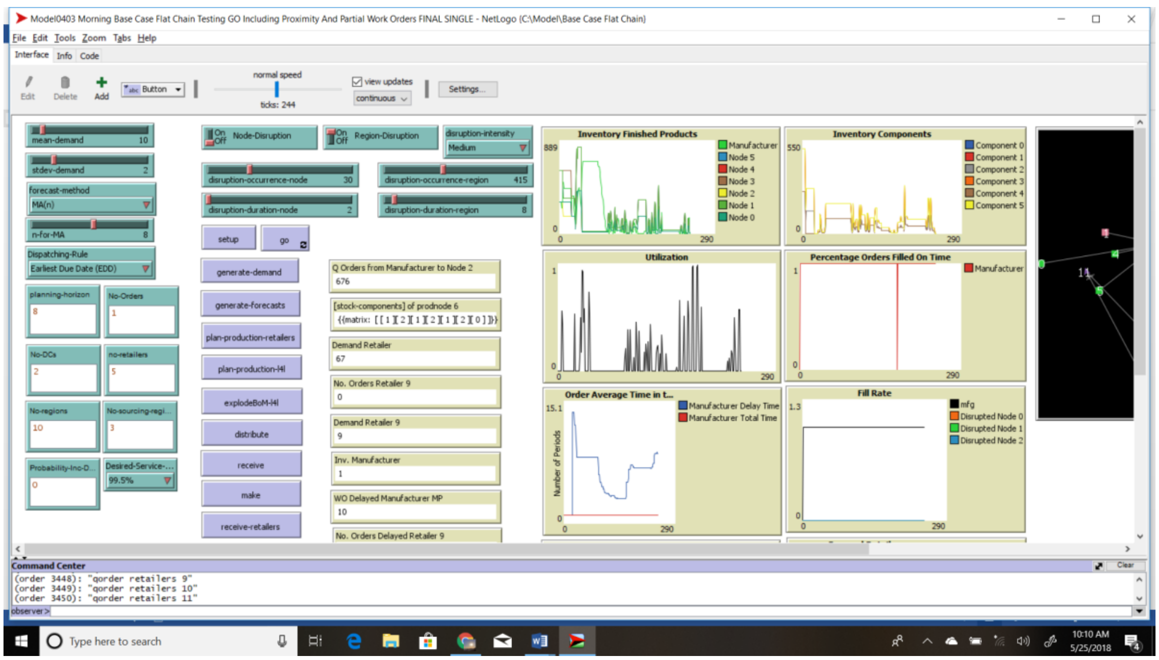


Figure 4.14 Model Interface

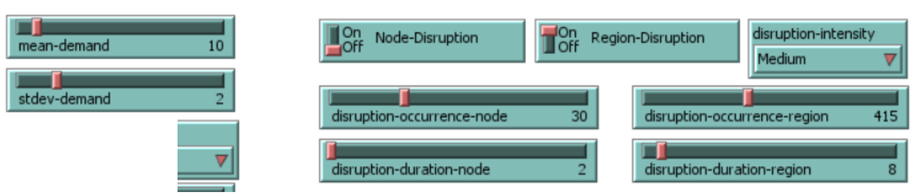


Figure 4.15 Environmental Stimuli

Figure 4.16 A sample of model parameters

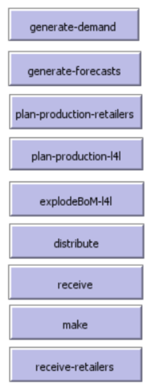


Figure 4.17 Controls for Model Verification

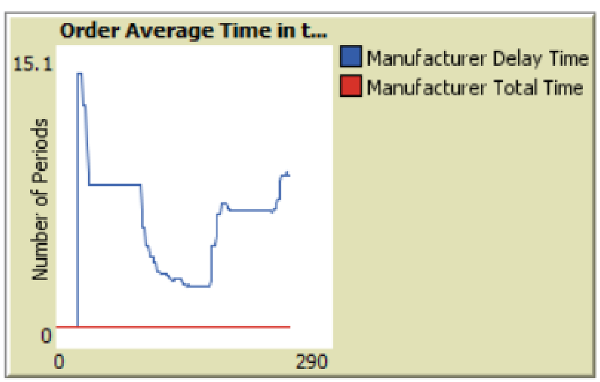


Figure 4.18 Model metrics

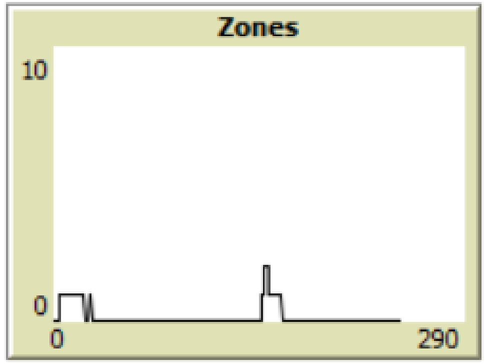


Figure 4.19 Environmental stimuli monitoring

The next section will address the model verification. The model behavior will be checked against the conceptual and construct design. These checks are performed at three levels: i) at the variable level to describe key performance indicators and how they are measured in the model; ii) at the agent level, in which the behavior of the production and distribution nodes as well as the behavior of work-orders and orders is verified; and iii) at the model level, where multi-agent interactions are verified, including the analysis of emergent behavior of the agents.

5 VERIFICATION, VALIDATION AND EXPERIMENTAL DESIGN

5.1 System Verification and Validation

Simulation-based research uses computational models to test and develop theories around the behavior and response of real-world systems. This research approach requires the conceptualization and development of a set of abstractions to represent the system in which the problem the researcher is interested in is embed. Those abstractions are interconnected through relationships that, once implemented in a platform, become the simulation model to be used in the experimentation [173]. However, before experimentation can take place, it is necessary to evaluate the computational model in terms of its clarity, parsimony, generality and testability [174]. Sargent [175] presented a simplified version of the modeling process that outlines the process to evaluate the testability of the computational model (See Figure 5.1).

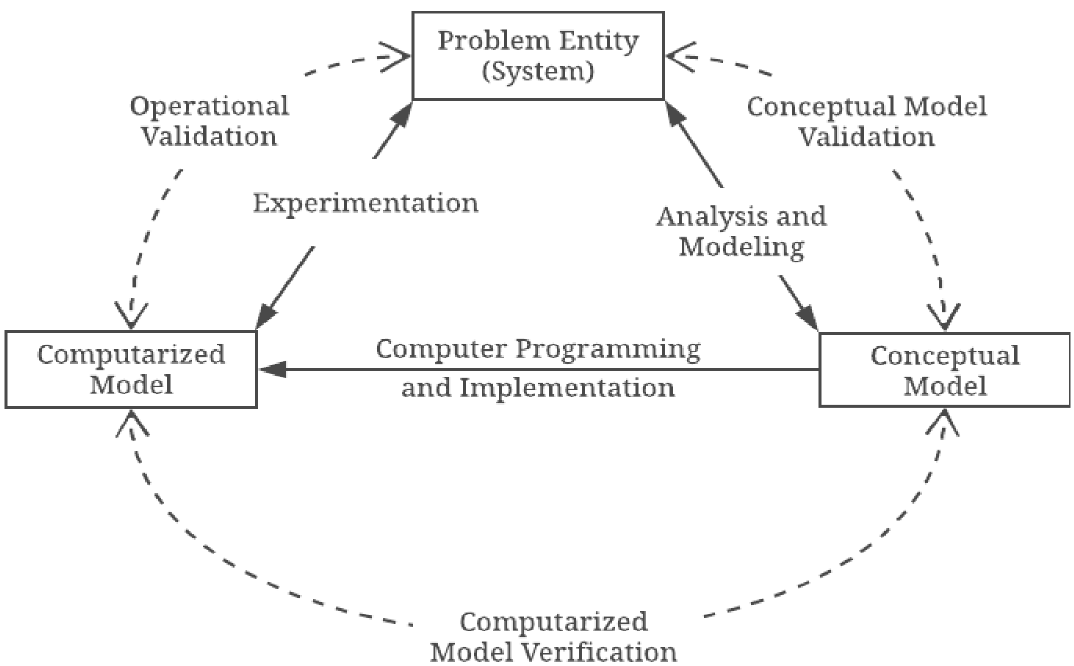


Figure 5.1 Simplified version of the modeling process. Adapted from Sargent

For the purpose of this research, Sargent's model was followed and included in the research's methodological framework as shown in Chapter 3. Sargent [175] places validation taking place at both the operational and the conceptual level. Verification of the computerized model is also required to guarantee that the implementation in the chosen platform is correct.

Table 5.1 outlines the objectives for each of the main sub processes of the modeling process as outlined by Sargent and maps it to Mayhew's model evaluation.

Table 5.1. Main sub processes and objectives of the modeling process

<table>
<tr><th>Sub-process</th><th colspan="4">Objective</th></tr>
<tr><td>Computerized Model Verification</td><td>To assure that the coding and implementation of the conceptualization is correct.</td><td></td><td rowspan="3">Parsimony</td><td rowspan="2"></td></tr>
<tr><td>Conceptual Validation</td><td>To assure that the theories and assumptions underlying the conceptual model are appropriate to represent the problem of interest. The model needs to address as many conceptualizations as needed to answer the stated research questions.</td><td rowspan="2">Testability
Generality</td></tr>
<tr><td>Operational Validation</td><td>To ensure that the model is producing results that are an accurate representation of the model's domain, purpose and applicability.</td><td>Clarity</td></tr>
</table>

5.1.1 Agents behavior and model verification

In this type of verification, the focus was on guaranteeing that single agents reflect consistent behaviors. Theoretical prediction of behaviors and "sanity checks" as well as extreme values tests are considered to be the main types of assessment tools used for verification purposes of this model. In the former, the output of the agents is analyzed under a set of well-defined inputs. Any deviation from the expected theoretical behaviors was analyzed as a potential implementation error. The latter involves border conditions that can impact the behavior of the agent by making it produce unintended behaviors. Once an extreme behavior was identified as a potential limitation of the coding effort or as an implementation error. Table 5.2 present examples of the verification tests performed and their results for the theoretical predictions. Table 5.3 presents examples of the results for the extreme value analysis.

Table 5.2 Single Agent Verification: A Sample of Theoretical Predictions and Sanity Checks

Behavior	Input	Results
Issue work orders if inventory of finished goods is less than expected demand	Forecast Aggregated expected demand over planning horizon	Confirmed

Behavior	Input	Results
Issue commercial orders if inventory of components is less than materials requirements for planned production	Stock components Production plan Components requirements	Confirmed
Produce not more than available capacity	Lot to manufacture Node capacity	Confirmed
Select supplier that is currently available	Supplier status	Confirmed
Mark orders as delivered upon delivery	Order quantity Customer Supplier Date created Date delivered	Confirmed
Mark orders as in-production	Order quantity Inventory of components Component requirements Date created	Confirmed

Table 5.3 Single agent Verification: A Sample of Extreme Value Checks

Behavior	Input	Results
Retailers select closest, available, distribution center	Inventory of Finished Goods (Manufacturer and Distribution Center) set to a large value Proximity	Confirmed
Production nodes issue work orders and commercial orders to their suppliers to meet demand	Inventory of Finished Goods and Inventory of Components for all upstream nodes set to zero	Confirmed
Downstream nodes issue commercial orders to its chosen Distribution Center (or to the manufacturer) to meet demand	Inventory of Finished Goods set to zero for all downstream nodes	Confirmed
Production nodes manufacturing either final product or subassemblies issue work-orders based on their demands and available inventory of components	Inventory of Finished Goods set to zero and large Inventory of Components for all nodes manufacturing either final product or subassemblies	Confirmed
Upstream nodes issue backorders based on unmet demand	Node capacity set to zero and Inventory of Components set to a large value	Confirmed

5.1.2 Multi-agent behavior: minimal environment verification

Interaction testing takes place in a minimal environment. The behavior of a minimal set of agents is verified. This model uses four types of agents: prodnodes (upstream network), distnodes (downstream network), work orders and commercial orders. The same type of tests used in 5.1.1 were used for this verification.

Table 5.4 Minimal environment verification: A Sample of Theoretical Prediction and Sanity Checks

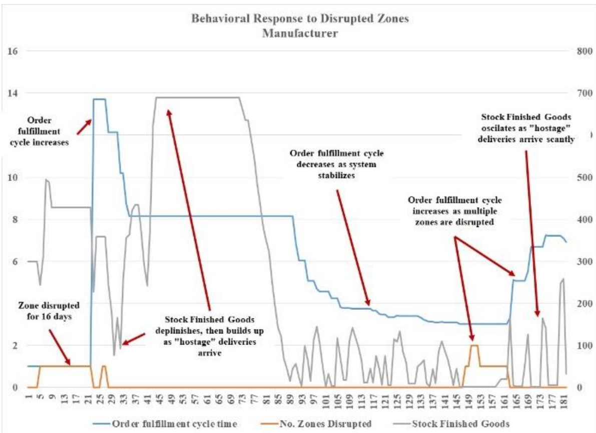
Behavior	Input	Results
The node needs to explode the bill of materials and issue commercial orders to its upstream based on its production plan	Components requirements Production Plan Bill of materials Supplier ID Customer ID Date created	Confirmed
The node reviews the KPIs and proximity with its linked neighbors and determines its preferred supplier	KPIs Customer ID Supplier ID Proximity	Confirmed
The retailers calculate their proximity with all the nodes connected to it and selects the closest distribution center	Region [node] Region [out-link neighbors]	Confirmed

Table 5.5 Minimal environment verification: A Sample of Extreme Values Verification

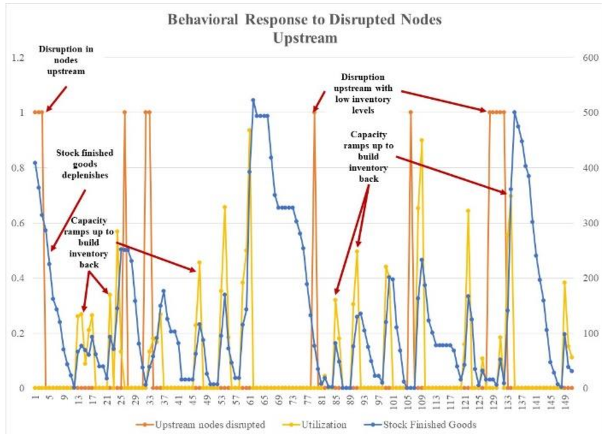
Behavior	Input	Results
Node determines the status of its linked neighbors and tags then as available or not	Disrupted Customer ID Supplier ID	Confirmed
Node tags an order as backlogged and updates its date	Order quantity Customer Supplier Date created	Confirmed
Orders are tagged as fulfilled and are eliminated of the system	Order quantity Customer Supplier Date created Date delivered	Confirmed

5.2 Model validation

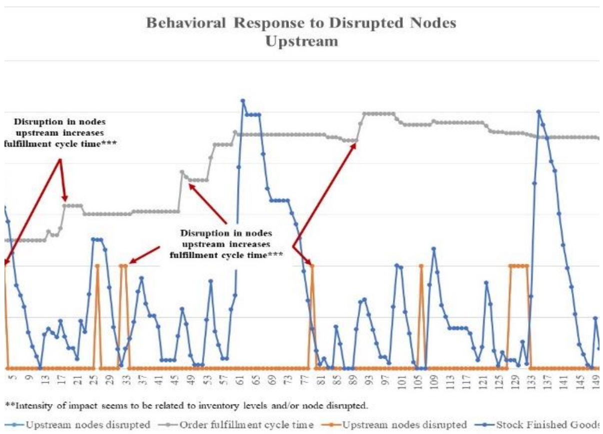
Microvalidation [176] was performed concurrently with the verification process. The behaviors of the agents and the encoded mechanisms were based on the standard theory of production systems. Emergent behavioral patterns such as fill rates, order fulfillment lead times, etc. were compared with the predicted patterns were used to perform the macrovalidation [176]. A sample of these validation exercises is presented as follows.



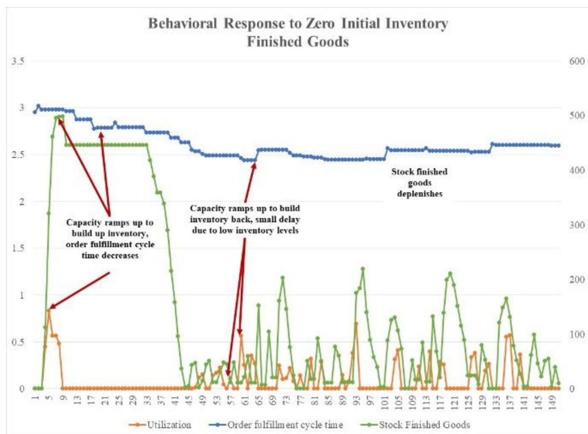
(a)



(b)



(c)



(d)

Figure 5.2 Behavioral validation

(a) Behavioral response to zone disruptions. (b) Behavioral response to node disruptions upstream in the network -capacity. (c) Behavioral response to node disruptions upstream in the network –order fulfillment cycle time. (d) Behavioral response to extreme initial conditions –zero inventory of finished goods. Several of these type of analysis were performed and the model was found to be consistent with the response real supply networks and their node would have.

5.3 Experimental Set up

In order to expand the understanding around the concept of resilience and how different firm decisions and capabilities impact the response of its supply network in the presence of disruptive event, a set of experiments that include different strategic and operational strategies is conducted. Furthermore, the experiment set up considers different types of disruptive events in order to understand the interactions between the company's decisions and both, exogenous and endogenous disturbances. The configurations are listed below and described in Table 5.6. The aim of this chapter is to evaluate the performance of a supply network using the model presented in Chapter 4 so a representation of supply network resilience can be developed.

5.3.1 Experimental Factors and Design

Bill of Materials (Product Design). The need to align the product design with the supply network has been found not only to be critical for a company to be competitive but also, authors argue that this alignment is critical to more resilient, responsive supply networks [177]. Furthermore, Marsillac & Roh [127] state that it is key for operations managers to understand what supply network design better suits their particular product design and recognize the adaptive nature of supply networks as a function, among others, of the product design. In this research, product design is introduced as an experimental factor and formalized through a matrix representation of the bill of materials.

Table 5.6 Experimental Formulation

Structure	**Flat**			**Tall**			**Complex**		
Sourcing	**Single**	**Dual**	**Dual**	**Single**	**Dual**	**Dual**	**Single**	**Dual**	**Dual**
Network Design	**Clustered**	**Clustered**	**Disperse**	**Clustered**	**Clustered**	**Disperse**	**Clustered**	**Clustered**	**Disperse**
Base Case	ND	ND	ND	ND	ND	ND	ND	ND	ND
Scenario 1 A	OD [Node]	OD [Node]	OD [Node]	OD [Node]	OD [Node]	OD [Node]	OD [Node]	OD [Node]	OD [Node]
Scenario 2 B1	OD [Region]	OD [Region]	OD [Region]	OD [Region]	OD [Region]	OD [Region]	OD [Region]	OD [Region]	OD [Region]
Scenario 3 B2	TD [Region]	TD [Region]	TD [Region]	TD [Region]	TD [Region]	TD [Region]	TD [Region]	TD [Region]	TD [Region]
Scenario 4 C	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]	OD [Node, Region]
Scenario 5 D	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]	OD [Node] TD [Region]

Note:
ND: No Disruption
OD: Operational Disruption
TD: Tactical Disruption

The bill of materials, represented by the product matrix, is a mathematical formulation that captures the interactions, and interdependencies between components of a complex system in a compact and clear representation. Based on the technological order, product components can interact in a parallel (flat), serial (tall) or coupled (complex) manner (this representation is similar to the one proposed by Farid & McFarlene [165]).

- *Flat:* This product requires components with productive processes are not interrelated. For experimentation purposes, we consider a single product that requires six components that are source from 6 different suppliers. The product is manufactured in a MTS system, and the manufacturer uses moving average with a length n = planning period to forecast demand. Orders are placed on a daily basis. The lead time for the manufacturer is 1 unit. The manufacturer is also aware of the lead time of its tier one suppliers. The manufacturer keeps record of KPIs for its suppliers and, when dual sourcing, it chooses suppliers based on their performance. Orders can be delay but cannot be canceled (this is a future extension of this research) without additional penalties. The manufacturer has two distribution centers downstream that send orders also on a daily basis and that fulfill the demand of five retailers (retailers choose a distribution center based on a simple rule: proximity). Figure 5.3 shows the supply network based on this type of product architecture.

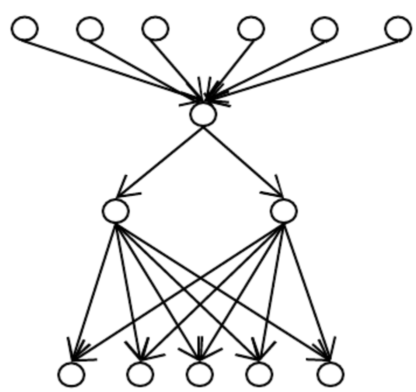


Figure 5.3 Supply Network derived from a flat (parallel) Bill of Materials

- *Tall*: This product requires a vertically integrated manufacturing structure. For experimentation purposes, we consider a single product that requires a sequence of two subassemblies before the assembly of the final product. Each of these subassemblies has a component added at each tier; thus, three tiers and six suppliers are required. The product is manufactured in a MTS system, and the manufacturer uses moving average with a length n = planning period to forecast demand. Orders are placed on a daily basis. The lead time for the manufacturer is 1 unit. The manufacturer is also aware of the lead time of its tier one suppliers. The manufacturer keeps record of KPIs for its suppliers and, when dual sourcing, it chooses suppliers based on their performance. Orders can be delay but cannot be canceled (this is a future extension of this research) without additional penalties. The manufacturer has two distribution centers downstream that send orders also on a daily basis and that fulfill the demand of five retailers (retailers choose a distribution center based on a simple rule: proximity). Figure 5.4 shows the supply network based on this type of product architecture.

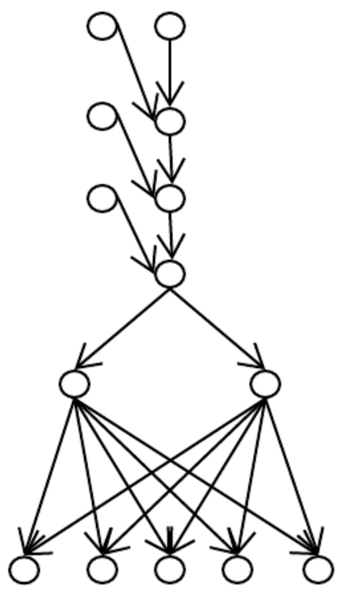


Figure 5.4 Supply Network derived from a tall (sequential) Bill of Materials

- *Complex*: This product requires a complex manufacturing structure. Here, the driver for complexity is associated with the product complexity (see Vogel and Lasch [157] for a comprehensive discussion internal correlated complexity) For experimentation purposes, we consider a single product that requires two subassemblies before the assembly of the final product. Each of this subassemblies has two components added; thus, two tiers and six suppliers are required. The product is manufactured in a MTS system, and the manufacturer uses moving average with a length n = planning period to forecast demand. Orders are placed on a daily basis. The lead time for the manufacturer is 1 unit. The manufacturer is also aware of the lead time of its tier one suppliers. The manufacturer keeps record of KPIs for its suppliers and, when dual sourcing, it chooses suppliers based on their performance. Orders can be delay but cannot be canceled (this is a future extension of this research) without additional penalties. The manufacturer has two distribution centers downstream that send orders also on a daily basis and that fulfill the demand of five retailers (retailers choose a distribution center based on a simple rule: proximity). Figure 5.5 shows the supply network based on this type of product architecture.

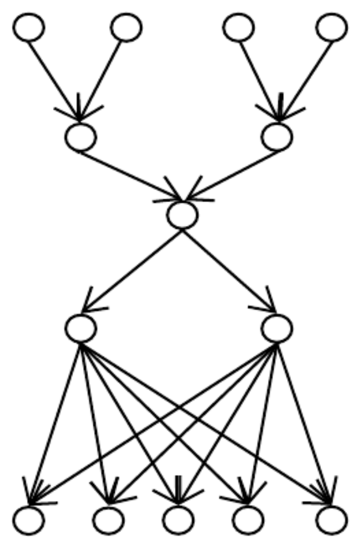


Figure 5.5 Supply Network derived from a complex (coupled) Bill of Materials

Sourcing Strategy. Early authors discuss the implications of sourcing when it comes to risk management. Treleven & Schweikhart [178] state that while organizations that rely on one single supplier can develop stronger sourcing relationships, they exhibit higher levels of vulnerability and are exposed to a greater probability of disruption. Along those same lines, Berger and Zeng [179] conclude that some forms of risk cannot be mitigated by diversification. In the work, Treleven and Schweikhart [178] recognize that other firm's risk management decisions can reduce both the probability of a disruption (risk) and the impact the disruptive event can have on the firm thus lessening the value of having a dual source strategy. As a future extension of this work, the analysis of dual vs. single sourcing will be performed downstream in the network.

- *Single*: For the purpose of this research, sourcing is an intentional decision of the firm (node) [178]. The firm chooses to have one source based on the operational, tactical, and strategic objectives. The sourcing decision is based solely in the architecture of the product or product design as per represented in the bill of materials. Suppliers can be unavailable due to disruptive events. If a supplier cannot fulfill an order, it gets backlog and delivery takes places at a later date and its performance is recorded.
- *Dual*: The firm chooses, intentionally, to have two vendors for the required part of sub-assembly. A supplier is chosen based on its proximity and on its past performance. If one of the suppliers is not available, by the default, the firm orders from the other. If a supplier cannot fulfill an order, it gets backlog and delivery takes places at a later date and its performance is recorded.

Network Structure (Network Design). When it comes to designing a supply network, several factors, at different organizational levels, need to be considered (See **Error! Reference source not found.**, adapted from Farahani et al. [180]). Among those, the strategic decisions associated with the number of facilities and the location of those facilities are key to the firm's risk management strategy. Furthermore, Childerhouse et al. [181] identify supply chain strategic decisions as critical to the performance of the supply network, and Blackhurst et al. [182] argue that the structure of a supply network determines the magnitude of the impact that those variables can have on the performance of the network. Thus, as companies compete in a more globalized, descentralized environment, factors such as the number of direct suppliers and the geographical distances between the firm and its suppliers are precursors to a firm's ability to deal with disruptive events.

To capture the element of geographical distance (and subsequently a really important structural aspect of the network: clustering), an artifact was recreated in the model. Ten zones were generated and label from 1 to 10. Then, a subset of three (or eight) randomly selected regions (from the larger set of ten) were chosen to be "upstream regions" meaning, nodes upstream of the supply network would get assigned only to that subset. Since the regions were labeled in ascending order, proximity between two nodes was defined as the absolute value of the difference between the regions the nodes got assigned. Thus, two nodes with low proximity were, geographically, closer than two nodes with a higher proximity value. When a disruptive event occurs at the region level (such as a natural disaster), all the nodes in that region are disrupted. The number of regions available for "upstream" nodes determine the degree of clustering or dispersion of the network since the more regions available, the less likely the "upstream" nodes will be in the same regions.

- *Clustered*: There are only three regions available to host upstream network nodes.
- *Disperse*: There are eight regions available to host upstream network nodes.

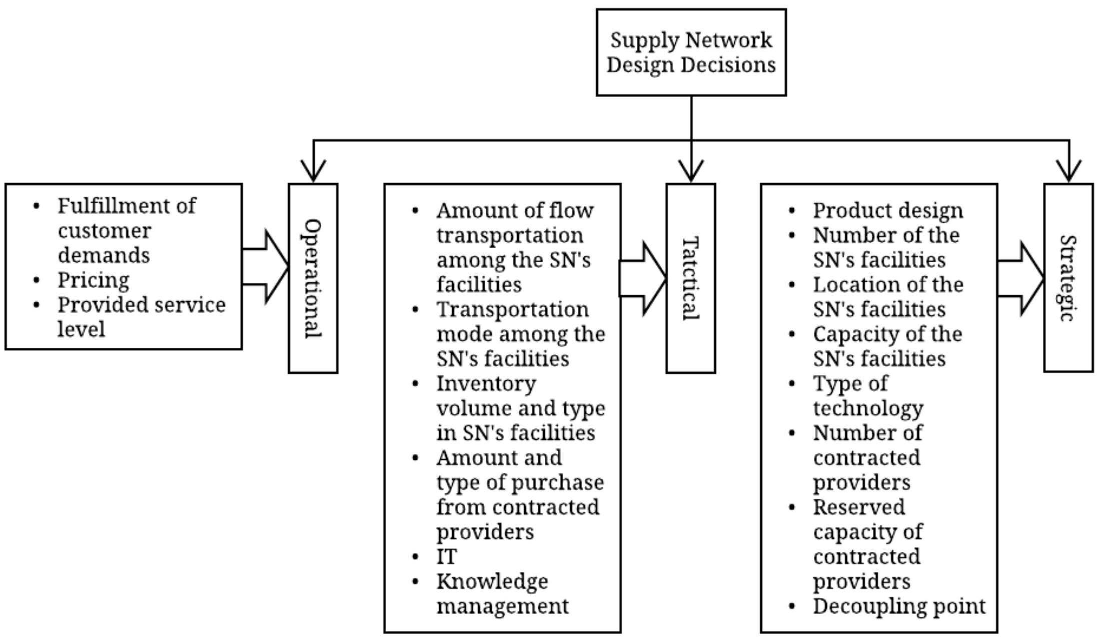


Figure 5.6 Decisions regarding Supply Network Design

While it is clear that disruptions at the region level vary across geographical areas, this work makes the assumption that all regions have the same statistical distribution for the frequency of a disruption. Further research will explore different distributions for different regions since the vulnerability and risk of disruption of a globalized supply network increases due to a larger number of geographical areas the components or product go.

Scenarios

The parameters of the scenarios considered in this analysis are presented in Table 5.7 For this experimental set up, a distinction between the types of disruption is made based on its duration and frequency. Natural disasters are rare events, i.e. with low occurrence and relatively long durations that impact a region. Endogenous disruptions are events that can have a relative high frequency (unexpected breakdowns, strikes, transportation shutdowns, etc.), short duration and can impact both the node and a region.

- Base case: No disruptions
- Scenario A: Operational disruption at the node level
- Scenario B1: Operational disruption at the region level
- Scenario B2: Strategic disruption at the region level
- Scenario C: Operational disruption at both the node and region levels
- Scenario D: Operational disruption at the node level and strategic disruption at the region level

5.3.2 Calculation the number of replications and warm-up period

If the percentage of order filled on time by the manufacturer is the measure of performance used, then the number of replications can be calculated either by using:

$$n = z_{\alpha/2}^{2} \frac{\sigma^2}{H^2} \qquad \text{Equation 5-1}$$

where σ is the standard deviation, *H* is the desired margin of error on the selected measure of performance, and *z* is the standard value corresponding to a (1 – α)100% confidence level. If we assume a 95% confidence level then *z* = 1.96, *s* can be used as an unbiased estimator for σ, and defining *H* as 0.02% or two hundredth percentage as the margin of error, hence:

$$n = 1.96^2 \frac{0.0006^2}{0.0002^2} \cong 38$$

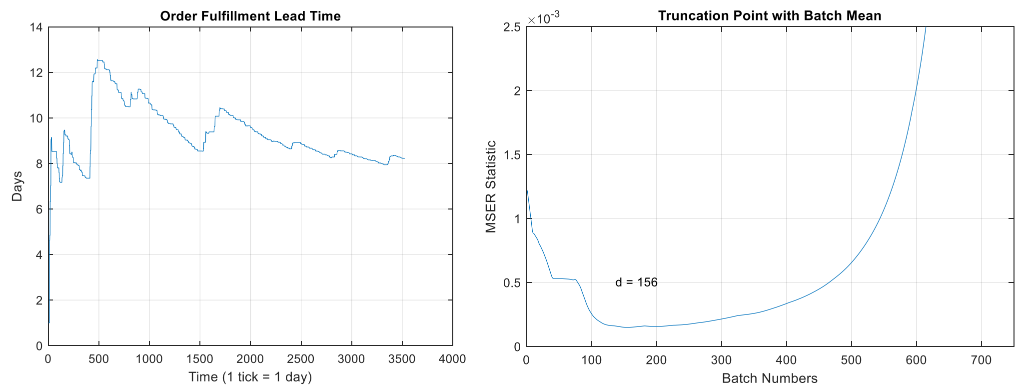
On the other hand, if the average delayed days a commercial order placed to the manufacturer is the measure of performance used, then the number of replications can be calculated by using the equation above. Again, assuming a 95% confidence level, using *s* as an unbiased estimator for σ, and defining *H* as 0.035 days (~50 minutes) as the margin of error, hence:

$$n = 1.96^2 \frac{0.1103^2}{0.035^2} \cong 38$$

Warm-up period. The Marginal Standard Error Rule 5 (MSER-5) was used to determine the warm-up period and the initial 780 ticks of the simulation were removed for the purpose of data analysis. The truncation point is given by Equation 5-2, applied to a series of $b = \left\lfloor \frac{n}{m} \right\rfloor$ batch averages.

$$\boldsymbol{d(j)^* = \arg min_{n>d(j)\geq 0}\left[\frac{1}{(n(j)-d(j))^2}\sum_{i=d+1}^{n}\left(Y_i(j)-\bar{Y}_{n,d}(j)\right)^2\right]} \quad \text{Equation 5-2}$$

MSER-5 was chosen because it is recommended with models that have a long run length [183]. Additionally, MSER-5 has been found to be effective and robust, especially in the presence of big bias, and it is computationally efficient [184, 185]. Appendix B presents the code adapted from Hwang [186] and used in this research to determine the warm-up period of the simulation.



(a) (b)

Figure 5.7 MSEr-5 results

(a) Raw Data Series (b) MSER Statistic

Table 5.7 Scenarios Parameters

Scenario / Parameter	Base Case	1A			1B1		
Demand	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)
Forecasting method	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8
Dispatching rule	EDD	EDD	EDD	EDD	EDD	EDD	EDD
Planning horizon	8	8	8	8	8	8	8
No. of regions	10	10	10	10	10	10	10
No. of sourcing regions	3	3	3	8	3	3	8
Sourcing	Single	Single	Dual	Dual	Single	Dual	Dual
Node disruption	OFF	ON	ON	ON	OFF	OFF	OFF
Node disruption occurrence	--	exp ~ (30)	exp ~ (30)	exp ~ (30)	--	--	--
Node disruption duration	--	exp ~ (2)	exp ~ (2)	exp ~ (2)	--	--	--
Region disruption	OFF	OFF	OFF	OFF	ON	ON	ON
Region disruption occurrence	--	--	--	--	exp ~ (30)	exp ~ (30)	exp ~ (30)
Node disruption duration	--	--	--	--	exp ~ (2)	exp ~ (2)	exp ~ (2)
Disruption intensity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity
KPIs collected	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization

Cont.

Scenario / Parameter	1B2			1C			1D		
Demand	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)	N ~ (10,2)
Forecasting method	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8	MA, n = 8
Dispatching rule	EDD	EDD	EDD	EDD	EDD	EDD	EDD	EDD	EDD
Planning horizon	8	8	8	8	8	8	8	8	8
No. of regions	10	10	10	10	10	10	10	10	10
No. of sourcing regions	3	3	8	3	3	8	3	3	8
Sourcing	Single	Dual	Dual	Single	Dual	Dual	Single	Dual	Dual
Node disruption	OFF	OFF	OFF	ON	ON	ON	ON	ON	ON
Node disruption occurrence	--	--	--	exp ~ (30)	exp ~ (30)	exp ~ (30)	exp ~ (30)	exp ~ (30)	exp ~ (30)
Node disruption duration	--	--	--	exp ~ (2)	exp ~ (2)	exp ~ (2)	exp ~ (2)	exp ~ (2)	exp ~ (2)
Region disruption	ON	ON	ON	ON	ON	ON	ON	ON	ON
Region disruption occurrence	exp ~ (180)	exp ~ (180)	exp ~ (180)	exp ~ (30)	exp ~ (30)	exp ~ (30)	exp ~ (180)	exp ~ (180)	exp ~ (180)
Node disruption duration	exp ~ (8)	exp ~ (8)	exp ~ (8)	exp ~ (2)	exp ~ (2)	exp ~ (2)	exp ~ (8)	exp ~ (8)	exp ~ (8)
Disruption intensity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity	Medium 50% capacity
KPIs collected	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization	Fill rate Average time in the system Utilization

In summary with this experimental design, the intention is to develop a representation of the concept of resilience as a function of a specific set of supply chain management decisions at all levels (operational, tactical and strategic) and to gain insights regarding the interactions among those factors. Finally, for a given product design, this design intents to leads to a better operational performance. The next chapter presents the results of the experiments, discusses the derived implications, and outlines future research avenues based on the findings of this research.

6 ANALYSIS OF RESULTS AND CONCLUSIONS

Practitioners and researchers acknowledge the challenges of evaluating disruptions using analytical tools [2, 17, 34, 51]. The characteristics of modern supply networks make them suitable to be analyzed using simulation, and specifically, agents based simulation [114, 141]. This chapter presents the analysis of the results obtained from the simulation of multi-echelon supply chain subject to two main types of disruptions: endogenous (i.e. disruptions that occurred at the node or region level, with a relative high frequency and lasting for a short period of time) and exogenous (disruptions occurring at a regional level, infrequent in time but with long durations). The objective of this research was to develop a representation of the concept of resilience, which has been difficult to formalize but, as acknowledged by both researchers and practitioners, plays a critical role in evaluating the performance of supply networks in the event of disruption.

This chapter is divided in four sections: Section 6.1 discusses the results from the angle of the proposed precursors of resilience: a firm's product design, and its decisions regarding sourcing and network design. Two main SCOR Level I metrics are analyzed: i) Perfect Order Fulfillment -POF, as a measure of the reliability (RL) of the supply network, and ii) Order Fulfillment Cycle Time -OFCT, as measure of the network responsiveness (RS) in the event of disruption. Section 0 presents a representation of supply network resilience based on the interactions among those precursors; it discusses potential confounding effects among those precursors (from an exploratory perspective); and, it outlines the implications of these interactions for the performance of the network. Section **Error! Reference source not found.** outlines the research avenues derived from this research findings and identifies the limitations of the study. Section 6.4 lists the publications that will be derived of this research.

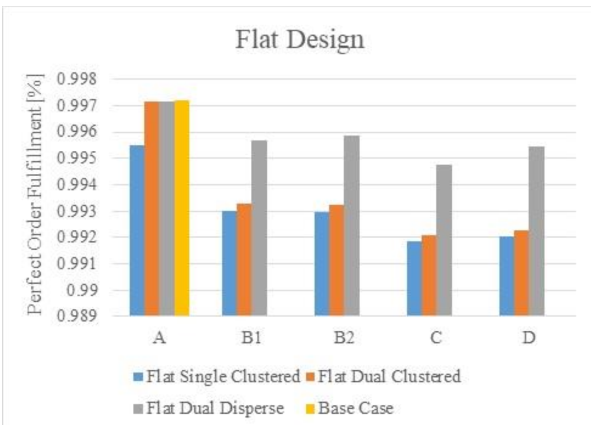
6.1 Representation of the construct of supply network resilience

As mentioned in previous chapters, practitioners and researchers do not agree about what constitutes resilience or on a formal representation of the concept. Based on the results obtained in the experimental set up described in Chapter 5, this research formulates a series of propositions to represent the concept in terms of the relationships between the structure of the network (as established by the bill of materials), the sourcing, and design decisions made by the firm. Each proposition is followed by the analysis of the results that support it.

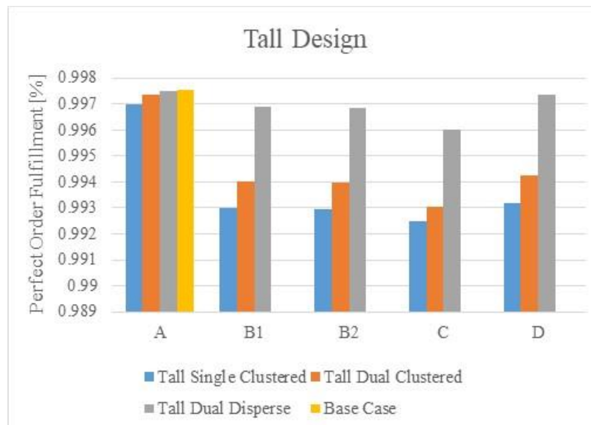
6.1.1 Regarding product design and resilience

Proposition 1a. *The lower the structural complexity of the product, the higher the benefits of disperse dual sourcing strategies for the network's reliability.*

Proposition 1b. *The higher the structural complexity of the product, the more moderate the benefits of dual sourcing strategies on the network's responsiveness.*



(a)



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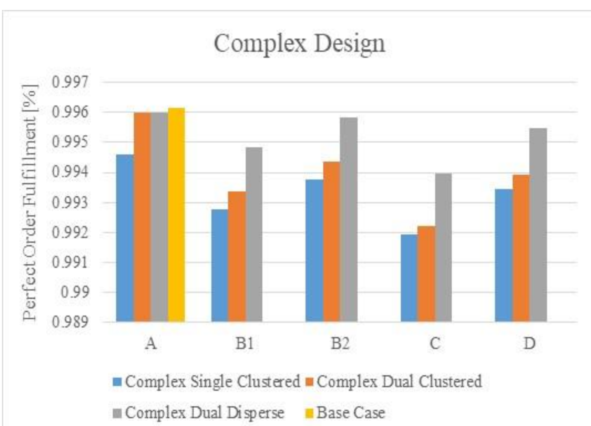
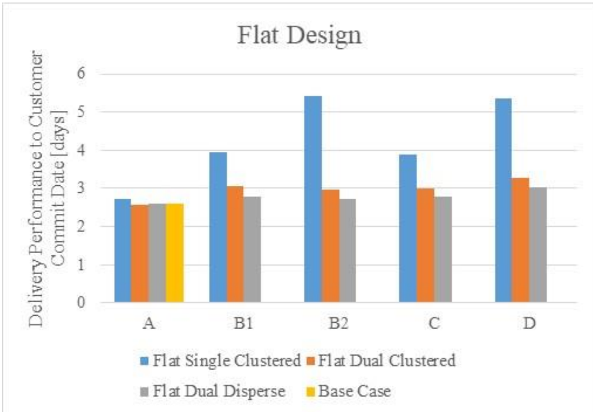


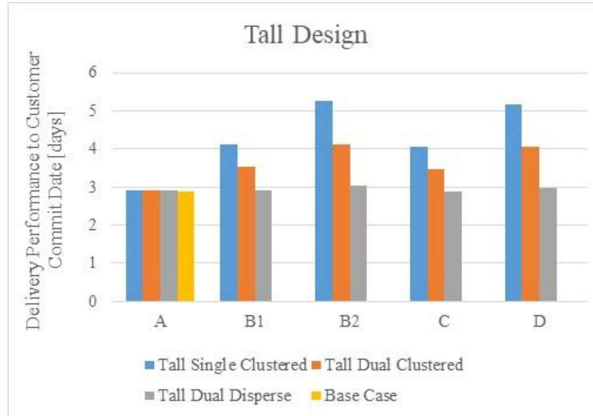
(c)

Base case: No disruptions
Scenario A: Operational disruption at the node level
Scenario B1: Operational disruption at the region level
Scenario B2: Strategic disruption at the region level
Scenario C: Operational disruption at both the node and region levels
Scenario D: Operational disruption at the node level and strategic disruption at the region level

Figure 6.1 Product complexity and network reliability



(a)



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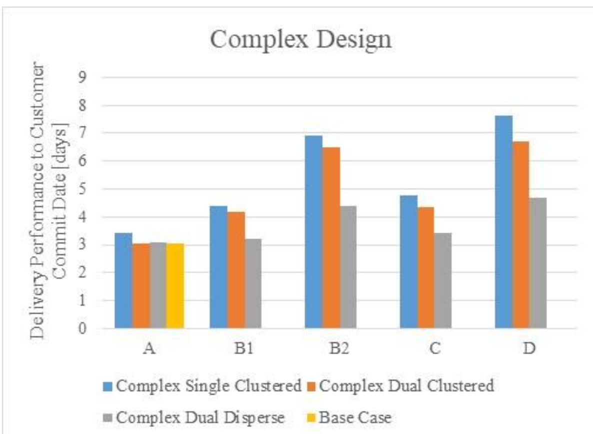


(c)

Base case: No disruptions
Scenario A: Operational disruption at the node level
Scenario B1: Operational disruption at the region level
Scenario B2: Strategic disruption at the region level
Scenario C: Operational disruption at both the node and region levels
Scenario D: Operational disruption at the node level and strategic disruption at the region level

Figure 6.2 Product complexity and network responsiveness

Analysis. While the number of components has been regarded as a complexity driver in supply chains [187], elements of structural complexity such as the level a component is in the bill of materials seem to play a more significant role on the reliability of a supply network in the event of disruption. Thus, there is more flexibility in sourcing decisions for components that are produced lower in the bill of materials. The gap in POF for (a) and (b) in Figure 6.1 is wider in the structures that have more components lower in the technological order of the product assembly.

Using Orfi et al.'s part-level index [188] [15] with the analyzed structures, the indexes for the structures were 6 for the flat structure, 12 for the tall structure, and 8 for the complex structure. Companies with products that have a low level of structural complexity should opt for dual sourcing the components that are lower in the bill of materials through multiple suppliers that are geographically disperse, especially if the main suppliers for these components are located in regions prone to disruptions.

When it comes to network responsiveness, dual sourcing, especially disperse, is critical to the responsiveness of the low complexity designs as seen in (a) of Figure 6.2. However, the impact of the network design is less significant as the product's complexity increases. The effect of network design is also dependent on the type of disruption.

Table 6.1 shows the results of the mean comparisons of the POF and for OFCT for the three structures, for scenarios B2 and D. It can be observed that for tall structures, there is a significant difference among the sourcing strategies in both scenarios. This finding suggests that tall structures benefit more from the flexibility in sourcing decisions (especially, disperse sourcing) due to having lower subassemblies in the bill of materials. The responsiveness of the network is the highest in a disperse design, as shown by lower OFCTs.

Table 6.1 Tukey Pairwise Comparisons by structure by scenarios B2 and D

		Flat			**Tall**				**Complex**		
	Factor	**Mean**	**Grouping**		**Mean**	**Grouping**			**Mean**	**Grouping**	
Reliability	Single-B2	5.418	A		5.276	A			6.898	**A**	
	Dual Clustered-B2	2.976		**B**	4.110		B		6.495	**A**	
	Dual Disperse-B2	2.726		**B**	3.031			C	4.405		B
Responsiveness	Single-D	5.356	A		5.180	A			7.620	**A**	
	Dual Clustered-D	3.270		**B**	4.045		B		6.721	**A**	
	Dual Disperse-D	3.017		**B**	2.978			C	4.667		B

Means that do not share a letter are significantly different.

[15] Lowest level in the BoM is assumed as 1 and, as levels go higher, the part level increases by 1. The part-level index is calculated as:

$$part - level\ index = \sum_{i}^{n} e_i BoM_i$$

where e_t is the number of elements in a component t and BoM_t is the BoM level of component i.

Reducing the complexity of a product by outsourcing earlier subassemblies and, hence, relocating the complexity to upstream suppliers, has been theoretically discussed by Orfi et al. [188]. Furthermore, in a qualitative study, Yongyi et al. found that firms producing products with lower complexity are less likely to promote internal integration, hence, outsourcing low level components (and/or sub-assemblies) [189].

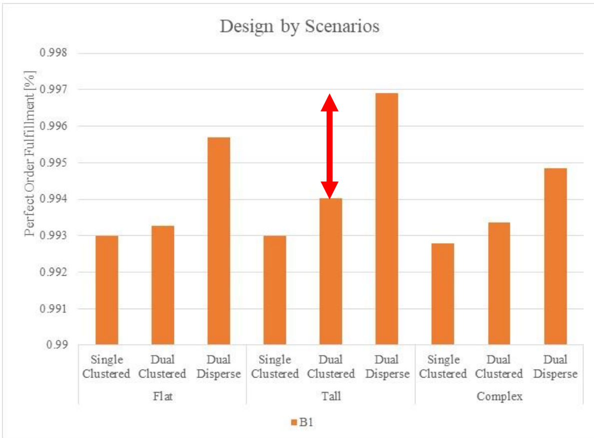
At the network level, there is not reduction but transference of complexity to lower levels of the network. Two aspects are key to the success of this strategy for companies that decide to adopt it: i) external integration must be implemented to guarantee visibility upstream in the network; ii) companies need to establish relationships with suppliers that produce components for diverse customers, thus hedging the disruption risk. Future extension of this research would include: a) a cooperative behavior for the upstream nodes that require a certain level of information sharing; b) a set of rules that will include the customer diversity of the suppliers in the performance metrics evaluated by the node when selecting its supplier.

6.1.2 Regarding network design and resilience

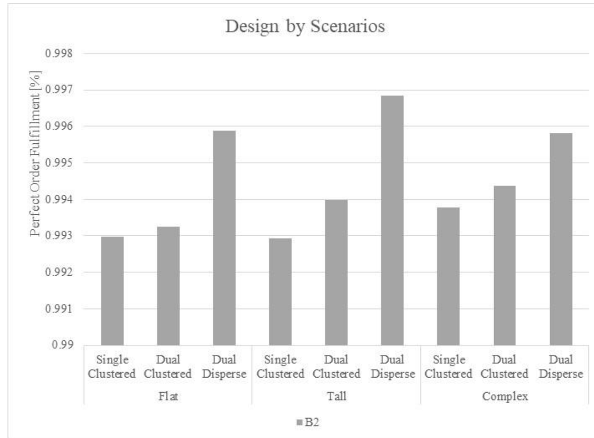
Proposition 2a. *The higher the level of componentization, the larger the impact disperse designs have on the reliability of the network.*

Proposition 2b. *The lower the level of componentization, the more moderate the impact disperse designs have on the responsiveness of the network.*

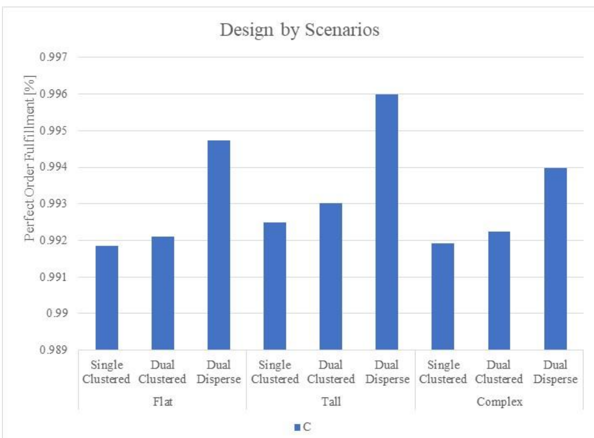
Analysis. Preliminary studies have found network complexity (defined by Choi & Krause [190] as the total number of nodes in the supply network and within-tier material flows) has the highest impact on network reliability [191]. However, network density seems to have a more significant impact on reliability, especially for networks that have higher levels of componentization and experience disruptions other than endogenous at the node level. When the firm opts for disperse design, reliability (as per POF) increases in all the structures Figure 6.3. As per the responsiveness of the network, the benefits of a disperse design are slightly moderate and positive as shown in Figure 6.4. While Choi & Krause [190], in an empirical study, found that the complexity of the supply base is negatively associated with supplier responsiveness (from the perspective of the manufacturer), this research found evidence that a dispersed supplier base has a mild positive impact on the responsiveness of the supplier.



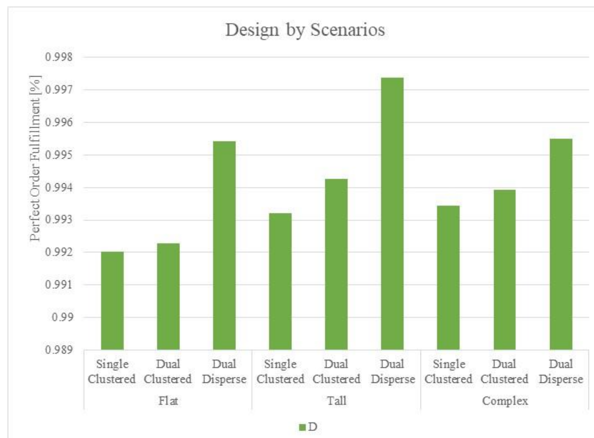
(a)



(b)



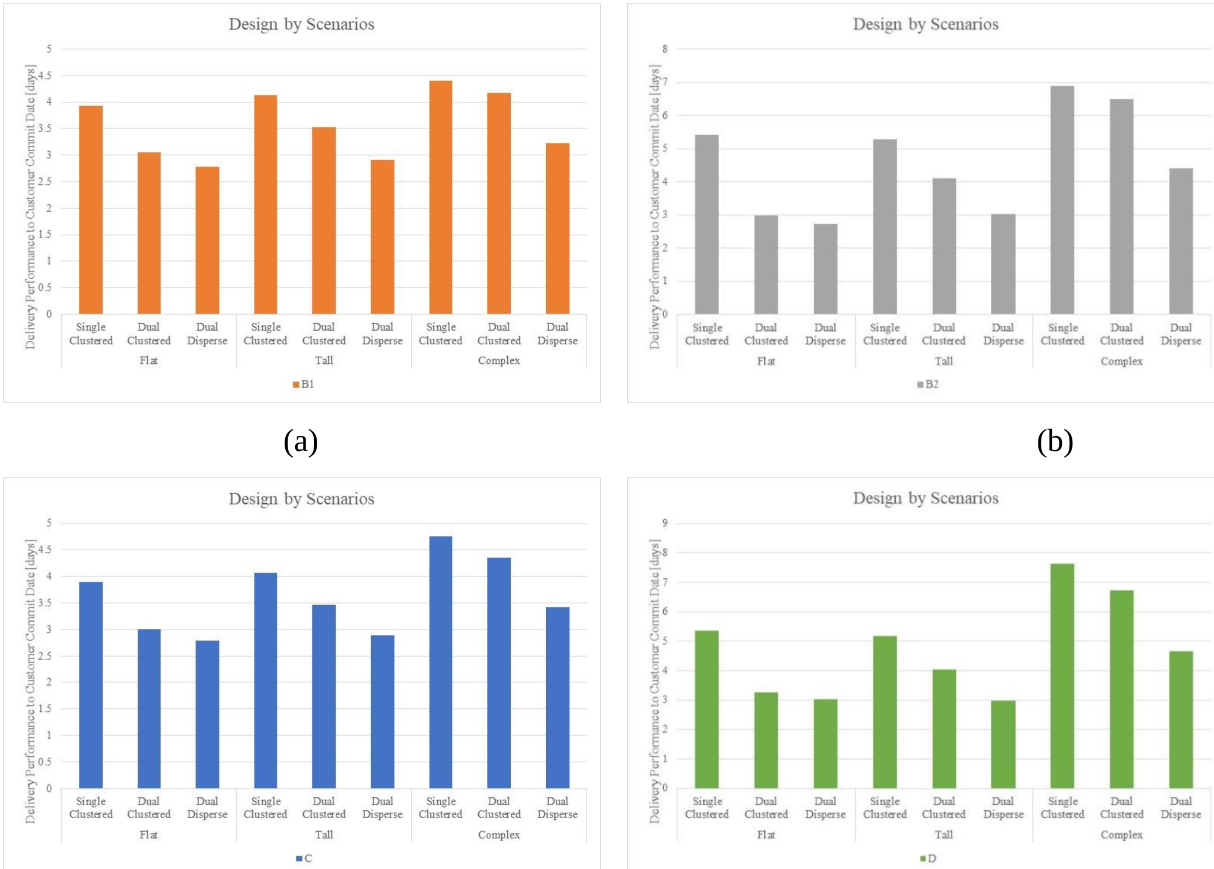
(c)



(d)

Figure 6.3 Network design and network reliability[16]

[16] **Base case:** No disruptions
Scenario A: Operational disruption at the node level
Scenario B1: Operational disruption at the region level
Scenario B2: Strategic disruption at the region level
Scenario C: Operational disruption at both the node and region levels
Scenario D: Operational disruption at the node level and strategic disruption at the region level



(a) (b) (c) (d)

Figure 6.4 Network design and network responsiveness

Table 6.2 through Table 6.5 show the results of the mean comparisons of the POF and for OFCT in a disperse design for the three structures, for scenarios B2 through D. Networks with high componentization, experiencing endogenous disruptions (i.e. short duration, frequent node disruption) have significantly better reliability in a disperse design. Suppliers can easily swap in the early subassemblies to reduce the risk of disruption. Furthermore, this is relevant to companies that have a mass customization strategy. As they delay the customization, the risk of disruption is transferred to the subassemblies. Since these subassemblies can be produced in large volumes in a MTS system, the firm can establish a disperse design for the supplier selection thus implementing a pronged risk hedging strategy. However, a challenge for these companies is related to the required specialization level of the subassemblies as finding suppliers geographically dispersed and with the standards of quality would require tighter control of the firm-suppliers relationships. Additionally, companies could face significant transportation costs that could offset the increment in reliability due to disperse designs.

It is relevant to note that a disperse design affects the reliability of the network very differently across the three structures studied, *only* in the presence of endogenous disruptions. Under exogenous disruptions or a combination of both, the effects of the disperse design are not significantly different for the flat and complex structures but remain significant for the tall structure.

Regarding responsiveness, there are two interesting findings. Complex structures benefit the least from a disperse design when endogenous disruptions occur. While the nodes in MTS systems can adsorb short-lived disruptions, complex structures require a minimum level of coordination between the suppliers of the subassembly components and the firm. Further research could include a coordination mechanism that allows partial visibility of the inventory of components for the suppliers upstream in the network. Also, incentive mechanisms could be incorporated in each agent and be part of the selection criteria used by the nodes to select suppliers. Additionally, an interesting approach would be to create localized incentives, based on the supplier's level in the bill of materials, to yield insights on the relationship between localized performance and network performance.

Table 6.2 Tukey Pairwise Comparisons by design by scenario B1

	Reliability					**Responsiveness**		
Scenario	**Mean**	**Grouping**			**Scenario**	**Mean**	**Grouping**	
TDD-B1	0.996908	A			CDD-B1	5.276	A	
FDD-B1	0.995701		B		TDD-B1	4.110		**B**
CDD-B1	0.994847			C	FDD-B1	3.031		**B**

Table 6.3 Tukey Pairwise Comparisons by design by scenario B2

	Reliability			**Responsiveness**			
Scenario	**Mean**	**Grouping**		**Scenario**	**Mean**	**Grouping**	
TDD-B2	0.996850	A		CDD-B2	4.405	A	
FDD-B2	0.995876		**B**	TDD-B2	3.0307		**B**
CDD-B2	0.995820		**B**	FDD-B2	2.726		**B**

Table 6.4 Tukey Pairwise Comparisons by design by scenario C

	Reliability			Responsiveness			
Scenario	**Mean**	**Grouping**		**Scenario**	**Mean**	**Grouping**	
TDD-C	0.996003	A		CDD-C	3.4200	A	
FDD-C	0.994737		**B**	TDD-C	2.8942		**B**
CDD-C	0.993976		**B**	FDD-C	2.7920		**B**

Table 6.5 Tukey Pairwise Comparisons by design by scenario D

	Reliability			Responsiveness			
Scenario	**Mean**	**Grouping**		**Scenario**	**Mean**	**Grouping**	
TDD-D	0.997372	A		CDD-C	4.667	A	
CDD-D	0.995487		**B**	TDD-C	3.017		**B**
FDD-D	0.995428		**B**	FDD-C	2.9783		**B**

The other finding is the variability in the responsiveness of the network under a disperse structure (see Figure 6.5). Tall structures, operating with a supplier base geographically disperse, experience significantly lower levels of variability in their responsiveness. This phenomenon can be explain by both the flexibility in switching suppliers who are less likely to be impacted by an exogenous disruption and by the reliance on inventory of finished goods of the subassembly suppliers that maintains their performance in the event of endogenous disruptions. This pronged strategy combines a proactive and reactive strategies to mitigate a disruption and yields more consistent network responses. The most variability in responsiveness was carried by the complex structure. While the subassemblies could benefit from flexibility in supplier selection, the lack of a coordination mechanism between component suppliers and the manufacturer negatively impact the consistency of its responsiveness. Of particular interest would be the analysis of coordination mechanisms between subassembly suppliers and their impact on the upstream performance of the network.

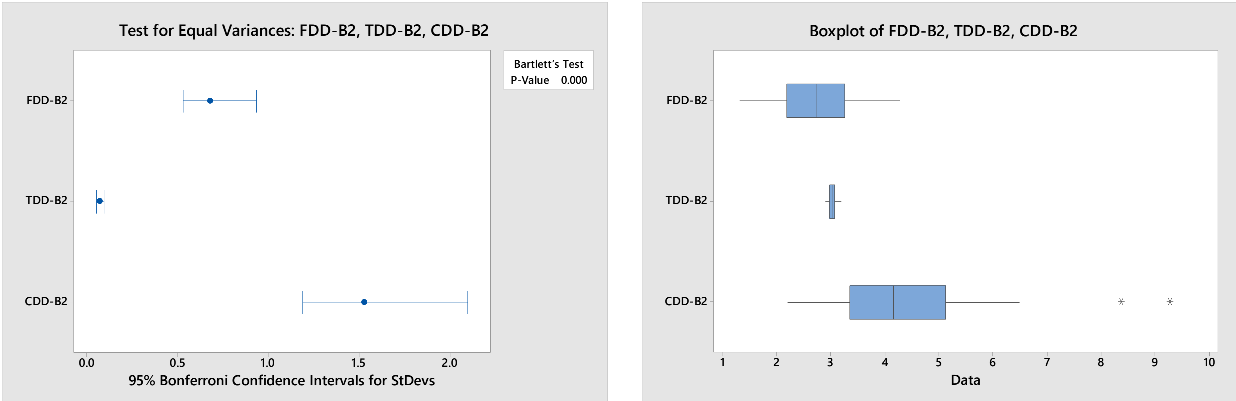


Figure 6.5 Variability of network responsiveness in a componentized structure
Scenario B2: Strategic disruption at the region level

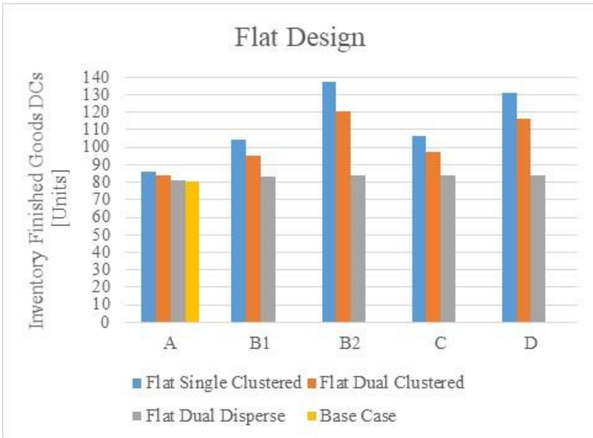
The finding discussed above open several research questions. An analysis of a disperse network with pooled suppliers, lower in the bill of materials, could yield insights on how to improve network responsiveness in complex and flat structures. Furthermore, this type of analysis could expanded to include different safety inventory levels and leverage the cost of reactive vs. proactive strategies. Another interesting analysis would be the impact that pronged mitigation strategies have on the recovery time of a network under different types of disruptions.

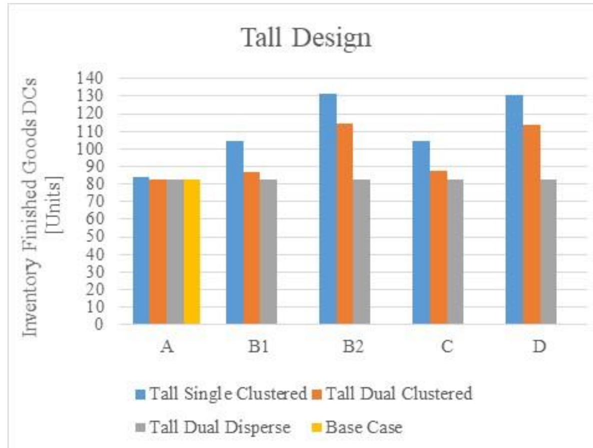
6.1.3 Regarding network structure and downstream disruption impact (statistical analysis of inventory levels)

Proposition 3a. *The higher the level of componentization and the more disperse the network design is, the lesser the impact of the disruption propagating downstream in the network.*

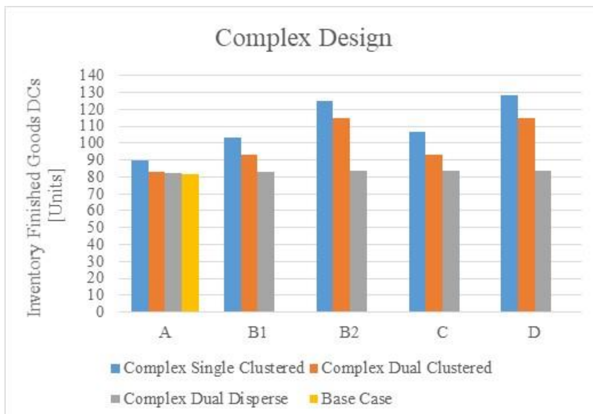
Analysis. As most of the risk is adsorbed by the upstream suppliers and, as the dispersion of the network introduces flexibility, the retailers' inventory levels are experience less fluctuation than the distribution centers. As mentioned before, endogenous disruptions have a marginal impact on the volume of finished goods with the major variances experience when the region of the distributor is impacted by an exogenous disruption.

Figure 6.6 and Figure 6.7 show how the gap between inventory levels for the single and disperse tall structure is significantly larger for the distribution center than it is for the retailer across all scenarios. The Tukey test verifies this finding with a p-value = 0.





(a) (b)



(c)

Figure 6.6 Downstream impact (inventory) – Distribution Center[17]

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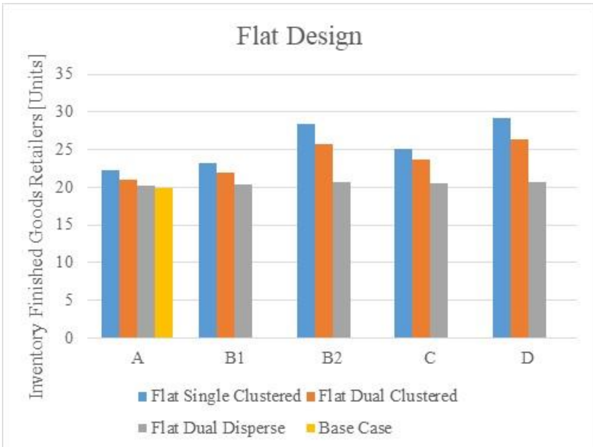
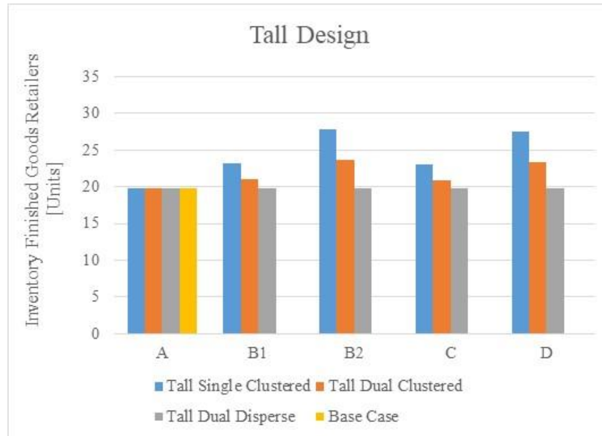
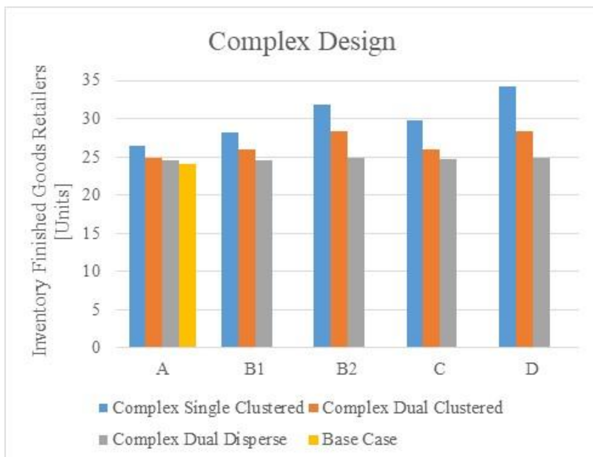
[17] **Base case:** No disruptions
Scenario A: Operational disruption at the node level
Scenario B1: Operational disruption at the region level
Scenario B2: Strategic disruption at the region level
Scenario C: Operational disruption at both the node and region levels
Scenario D: Operational disruption at the node level and strategic disruption at the region level





(a) (b)



(c)

Figure 6.7 Downstream impact (inventory) – Retailer

6.1.4 Regarding network structure and downstream disruption impact (exploratory analysis of recovery time)

While upstream disruptions at the manufacturer level are not felt quickly in the distribution network, their impact is amplified, outlasting the disruptions themselves. Amplification of a regional disruption affects the inventory levels of finished goods downstream for both distribution centers and retailers. Figure 6.8 shows this amplification effect for the three different product structures analyzed. While a more detailed statistical analysis might provide the quantitative measures of this effect (i.e duration in time and decrease in inventory levels), it is important to qualitative describe the nature of the amplification. Distribution centers felt the impact of the regional disruption early and as a consequence, their inventory level decrease first.

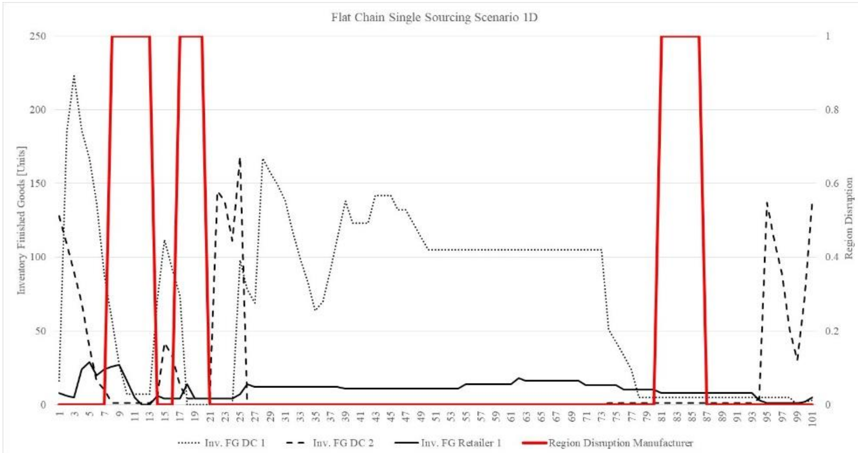
Next, retailers felt the impact also reflected in decreasing levels of inventory. The flat structure (Figure 6.8-(a)) has the lowest amount of inventory decrease while the complex and tall structures (Figure 6.8 (b)) and Figure 6.8 (c)) both have the same amount of inventory decrease. However, for all three structures, the inventory levels of the distribution centers go almost to zero before it recovers again to their pre-disruption levels.

Regardless of the product structure, both distribution centers and retailers can mitigate the impact of a regional disruption by increasing their inventory levels before the occurrence of a regional disruption. However, the difficulty stands in the prediction of the regional disruption. Quantifying the duration and the level of inventory decrease can help distribution centers and retailers to mitigate the impact of the amplification effect at the manufacturing level.

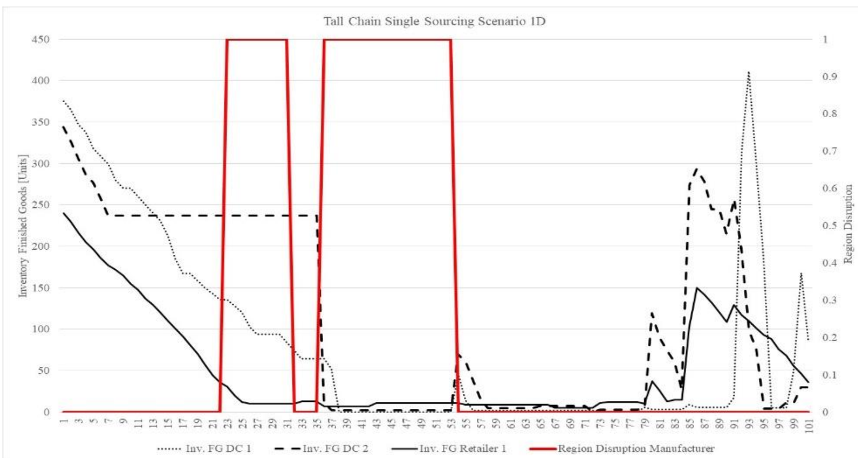
6.2 Summary: A Representation of the tactical and strategic precursors of supply network resilience

Most of the findings regarding the interactions between network and product design, and sourcing decisions have been discussed in the previous sections and were validated with the interaction plots (See Figure 6.9). Each of these finding are summarized below:

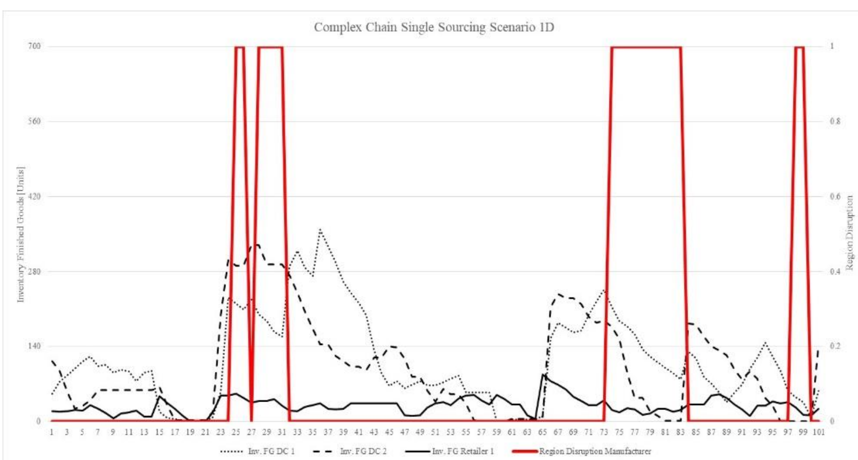
- Product design has the most significant impact on the reliability (POF) of tall structures, i.e., products with high degrees of componentization, when dual sourcing is the chosen strategy. However, when it comes to network responsiveness (OFCT), flat structures benefit slightly better than tall structures from a dual sourcing strategy. Responsiveness for complex structures is significantly lower despite the sourcing strategy. The interaction between product design and network design, as mentioned before, has a significant impact on the reliability of the tall structures as it combines reactive and proactive mitigation strategies. However, the benefits for flat and complex structures, in terms of reliability, are minuscule. These findings are consistent when analyzing the responsiveness of the network.



(a)



(b)



(c)

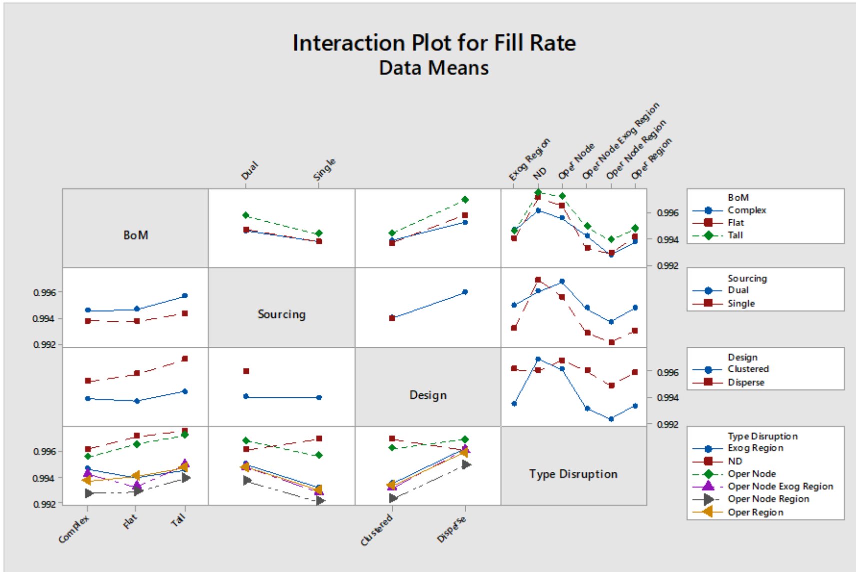
Figure 6.8 Network structure and downstream impact on inventories -Flat

Under different types of disruptions, tall structures perform significantly better than flat and complex designs. However, when the disruptions are limited to the node (endogenous disruptions), the impact is adsorbed by the inventories of finished goods. It is important to note that in the presence of exogenous disruptions at the region level, flat structures tend to perform better in terms of responsiveness.

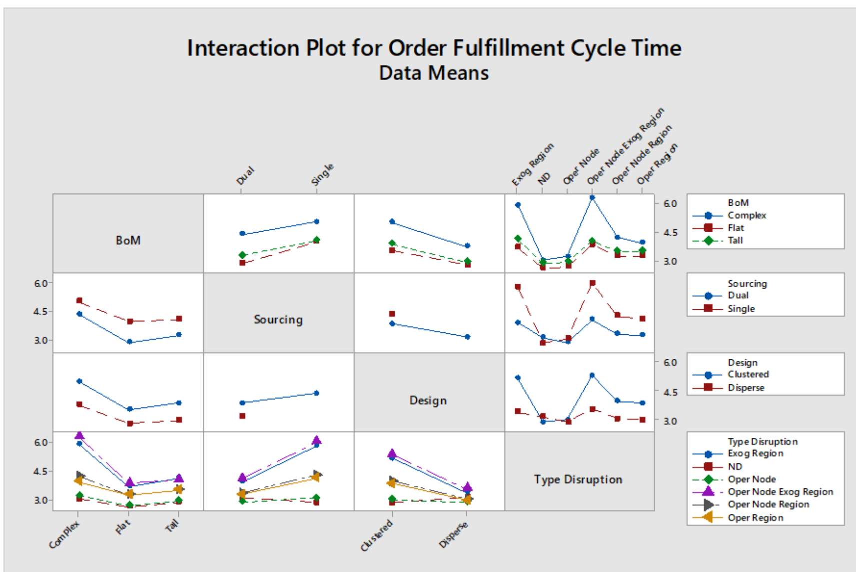
- The impact of sourcing decisions (dual vs. single) on responsiveness is consistent with the literature. Dual sourcing has a more significant impact when the network experiences exogenous disruptions at the region level. While it has been argued that multiple suppliers can mitigate risk, the associate costs of this strategy could offset the benefits when endogenous disruptions occur at the node and region levels.
- Regarding network design, the most interesting finding is related to the low performance of designs that are exposed to endogenous disruptions at both the node and the region level. While a disperse design still outperforms the clustered one, design cannot mitigate risk associated with internal vulnerabilities of the firm or of the region where the firms has its suppliers base. Clustering is common in several industries but the reliability of the regions where clusters of suppliers are set are as important as the reliability of the suppliers themselves. Future studies could analyze in depth the interdependence between of supplier reliability with region reliability.

6.3 Limitations and Further Research

At the methodological level, the research focuses on developing a representation that firms can use to understand the performance of their supply network in the presence of disruptive events. However, the methodological approach is built upon on a firm's decisions regarding product design, sourcing and network design and the complexity derived from the interactions between those factors. While the approach is robust enough to incorporate several product designs, sourcing strategies and network designs (thus representing various firms, potentially belonging to different industries), according to Suh's definition [192], the complexity of a supply network is relative to what a company is interested in achieving or understanding. Thus, as companies redefine what structural and behavioral elements they are interested in analyzing, the framework would have to accommodate those aspects.



(a)



(b)

Figure 6.9 Interactions between precursors of resilience
(a) Perfect Order Fulfillment (POF) (b) Order Fulfillment Cycle Time (OFCT)

While agent based modeling and simulation is a powerful tool for understanding how the complexity of a supply network impacts its performance in the presence of disruptive events, the approach to model the supply network is still dependent on what a firm is interested in analyzing, requiring several iterations over the domain of interest to the firm. Furthermore, by itself, agent based modeling and simulation allows an explicit representation of space and spatial relations.

However, as companies attempt to maximize their performance, the framework proposed in this research analyzes the behavior of a supply network but does not incorporate optimal behaviors at the agent level nor does it include optimization objectives at the network level. Also, as supply networks operate in globalized, competitive markets, the need for a market representation by aggregating global variables would benefit the analysis of competitive forces, industry dynamics and how, individual suppliers, distributors, retailers, etc. react to those external forces. In conclusion, the proposed framework would require enhancements, borrowed from other modeling paradigms such as optimization and system dynamics, to gain better understanding on how supply networks behave in the presence of disruptive events.

At the implementation level, this model assumes deterministic lead times. As disruptions affect the nodes upstream and downstream in the network, it will be interesting to analyze what is the impact of stochastic lead times on the different network structures, designs, and sourcing decisions. Another element that could yield better insights is related to product design. While the structural complexity was found to have a significant effect on the network response to disruptions, other complexity dimensions could be explored. For example, interdependence between the different levels of the bill of materials was not considered in this research. Future extensions could examine how interdependent subassemblies would impact the responsiveness and the reliability of the network.

This research analyzed only the nodes within the same supply network. Market dynamics and other aggregate behaviors were not considered in this analysis and would yield useful insights especially when modeling networks that operate concurrently with other networks, in an international context. Assigning properties and behaviors to the regions (that currently are modeled as a property of the agents) would require inclusion of regions as agents of the network with specific behaviors and properties that could convey sociopolitical and economic conditions.

From a performance evaluation perspective, this research could be extended to include other performance metrics associated with other performance attributes such as agility or cost. For example, it would be interesting to include cost as part of utility based behaviors. Cost associated with disruptive events at the node level such as strikes or quality issues could become behavioral drivers and could yield insights about how the responsiveness of the network changes at different levels of agility (as per the SCOR definition).

Finally, the clustering strategy could be expanded by introducing other metrics beyond geographical dispersion. For example, nodes upstream in the network could be given properties to represent their criticality in the network as a function of their inflows and outflows of materials. If a firm chooses a few small suppliers for its subassemblies in an attempt to delay customization (supplier specialization), it is expected that any disruption impacting them could have severe consequences for the network. Studying different levels of network criticality, based on the number of agents that are critical, could provide insights on the resilience of this type of networks.

6.4 Publications

Conference presentations derived from this research:

- Correa, Y., Seck, M. (2017, May 5-8) An Operational Formulation of the Supply Network Resilience Concept Using Simulation-Based Experiments. Presented at the POMS 28th Annual Conference. Seattle, Washington. https://www.pomsmeetings.org/ConfProceedings/
- Correa, Y., Seck, M. (2018, May 4-7) The Impact of Sourcing Strategies on Supply Network Resilience. Presented at the POMS 29th Annual Conference. Houston, Texas. https://www.pomsmeetings.org/ConfProceedings/

The following publications are expected to be submitted during 2018:

- Correa-Martinez, Y., Seck, M. (2018). The effects of suppliers' location on the resilience of single sourcing supply networks. Manuscript in preparation.
- Correa-Martinez, Y., (2018). A simulation based simulation based analysis of the resilience of MTS supply networks with stochastic lead times. Manuscript in preparation.
- Correa-Martinez, Y., Seck, M. (2018). The effects of product design on the resilience of single sourcing supply networks. Manuscript in preparation.

The following publications are expected to be submitted during 2019:

- Correa-Martinez, Y., (2018). A simulation based analysis of the resilience of MTO supply networks considering different network designs. Manuscript in preparation.
- Correa-Martinez, Y., (2018). A simulation based analysis of the resilience of hybrid MTS/MTO supply networks considering different network designs. Manuscript in preparation.

The following are the targeted journals for dissemination of this research:

- International Journal of Production Research
- Business Logistics
- Journal of Operations Management
- Manufacturing & Service Operations Management
- Production and Operations Management

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APPENDIX A: NETLOGO CODE

```
extensions [ array csv matrix nw]
breed [prodnodes prodnode]
breed [distnodes distnode] ;***** FOR MULTIECHELON
breed [workorders workorder]
breed [orders order]
breed [prodmgrs prodmgr]
globals
[
  aggregated-demand boms mfg dcslist depth echelon GGG impact Retailers-Customer-ID
  Demand-to-Manufacturer multiplier orders-delayed product-demand DC-Order-Size
  product-demand-history product-distdemand-history regions sourcing-regions time-
todisruption-regions disrupted-regions time-disrupted-regions workorders-delayed
wordersaccum
  working-days-year my-list-co-filled-rate-manufacturer days-to-recover my-list-
avg-delayed-days my-list-avg-total-days
]
prodnodes-own
[
  assembly-node
  cap
  co-filled-ontime
  co-fill-rate
  co-issued
  commercial-orders
  compmult
  components
  customer
  date
  demand
  demand-met-on-time
  dcs ;Added on 01/02/2018 to check plan procedure for retail part of the supply
chain
  disrupted
  eoq
  fill-rate
  forecast-history
  forecast-vector
  lead-time
  lot2m
  myminatm
  myminatmstock
  myminatmincord
  my-list-workorders
  myregions
  mydistances
  mysuppliers
  node-demand-history
  number-children
  number-orders
  workorder-vector
  planning-horizon-forecasts
  prob-disruption
  projected-stock-components
  projected-stock-fg
  q-forecast
  q-delivered
  q-produced
  qworder-after-atmstock
  qworder-after-incord
  region
  safety-stock
  stock-fg
```

```
  stock-components
  stock-incord
  stockout
  temptotaldistribute
  time-between-orders
  time-disrupted
  time-todisruption
  wo-filled-ontime
  wo-fill-rate
  wo-issued
]
distnodes-own ;***** FOR MULTIECHELON
[
  distco-filled-ontime
  distco-fill-rate
  distco-issued
  distcommercial-orders
  distdisrupted
  disttemptotaldistribute
  disttime-disrupted
  disttime-todisruption
  customer
  diststock-fg
  distdemand
  distdemand-history
  distdemand-met-on-time
  distforecast-history
  distlead-time
  distnode-demand-history
  distplanning-horizon-forecasts
  distprob-disruption
  distprojected-stock-fg
  distq-delivered
  distq-forecast
  mydcs
  mydcslist
  myregions
  mydistances
  mysuppliers
  projected-stock

  region
  stock-out
  distsafety-stock
  supplier
  dcs
]
prodmgrs-own
[
  my-list-of-prodnodes
  my-list-of-distnodes
]
orders-own
[
  customer
  date
  date-created
  delayed-sup
  delayed-cust
  delayed-time
  fulfilled
  delivered
  processed
  qorder
```

```
  supplier
]
workorders-own
[
  date
  date-created
  delayed
  delayed-time
  processed
  qwork-order
  in-production
  supplier
  upstream
  qwork-order-tobeproduced
  planned
]
directed-link-breed [ dirlinks dirlink ]
directed-link-breed [direct-links direct-link] ;***** FOR MULTIECHELON
to setup
  clear-output
  clear-all
  loadBoM
  create-echelon
  ;create-prodmgrs  1 [ht]
  reset-ticks
end
to go
  generate-demand
  generate-forecasts
  if Node-Disruption [create-node-disruptions]
  if Region-Disruption [create-region-disruptions]
  plan-production-retailers
  plan-production-141
  explodeBoM-141
  distribute
  receive
  make
  receive-retailers
  distribute-retailers
  tick
end
to loadBoM
  let bomcsv csv:from-file "C:/Model/Base Case Complex Chain/bomverif.csv"
  let bom matrix:from-row-list bomcsv
  let bommultcsv csv:from-file "C:/Model/Base Case Complex Chain/bommultverif.csv"
  let bommult matrix:from-row-list bommultcsv
  let dimvct matrix:dimensions bom
  set depth item 1 dimvct
  set boms bom
  set regions n-values no-regions [ i -> i ]
  set time-todisruption-regions n-values no-regions [ i -> int (random-exponential
disruption-occurrence-region) ]
  set time-disrupted-regions n-values no-regions [ i -> int (random-exponential
disruption-duration-region) + 1 ]
  set disrupted-regions n-values no-regions [ 0 ]
  set sourcing-regions n-of no-sourcing-regions regions
  set my-list-co-filled-rate-manufacturer (list 1)
  set my-list-avg-delayed-days (list 1)
  set my-list-avg-total-days (list 1)
  nw:set-context prodnodes dirlinks
  nw:load-matrix "bomverif.txt" prodnodes dirlinks
  nw:save-matrix "bomverif1.txt"
  ask prodnodes
    [
```

```
      set label who
      setxy random-xcor random-ycor
      set region item 0 n-of 1 sourcing-regions
      let id who
      let capacitycsv csv:from-file "C:/Model/Base Case Complex
Chain/capacityverif.csv"
      set cap matrix:get matrix:from-row-list capacitycsv id 0
      let leadtimescsv csv:from-file "C:/Model/Base Case Complex
Chain/leadtimesverif.csv"
      let leadtimes item id leadtimescsv ; creates lead times vector
      set lead-time first leadtimes
      set number-children count in-link-neighbors
      set size 1
      set shape "square"
      set assembly-node ifelse-value (number-children != 0) [1] [0]
      set components matrix:submatrix bom 0 who depth (who + 1)
      set compmult matrix:submatrix bommult 0 who depth (who + 1)
      let stockcompcsv csv:from-file "C:/Model/Base Case Complex
Chain/initialstockcomp.csv"
      let stockcomp matrix:from-row-list stockcompcsv
      set stock-components matrix:submatrix stockcomp 0 who depth (who + 1)
      set mfg max [who] of prodnodes
      set planning-horizon-forecasts n-values (planning-horizon)[0]
      set forecast-history (list)
      ;let forecasth csv:from-file "C:/Model/Integrated/forecasthistory.csv"
      let demandh csv:from-file "C:/Model/Base Case Complex
Chain/demandhistory.csv"
      let initialstockfg csv:from-file "C:/Model/Base Case Complex
Chain/initalstockfg.csv"
      ;let fh item id forecasth set forecast-history fh
      let dh item id demandh set node-demand-history dh
      let sfg item id initialstockfg set stock-fg item 0 sfg
      set myregions [region] of [in-link-neighbors] of self
      set mysuppliers [who] of [in-link-neighbors] of self
      set time-todisruption int (random-exponential disruption-occurrence-node)
      set time-disrupted int (random-exponential disruption-duration-node) + 1
      set projected-stock-components stock-components
      set mydistances n-values (no-regions) [ 0 ]
      let my-calc-proximity 0
      foreach regions
        [
          set mydistances replace-item my-calc-proximity mydistances abs (region -
item my-calc-proximity regions)
          set my-calc-proximity my-calc-proximity + 1
        ]
    ]
end
to create-echelon  ;***** FOR MULTIECHELON
  create-distnodes  no-dcs + no-retailers
  create-prodmgrs  1 [ht]
  set Retailers-Customer-ID 100
  ask distnodes [setxy random-xcor random-ycor]
  set echelon matrix:make-constant (no-dcs + no-retailers + 1) (no-dcs + no-
retailers + 1) 0
  ask prodmgrs
    [
      set my-list-of-distnodes sublist sort-by <  distnodes 0 no-dcs
      ;output-show my-list-of-distnodes
      foreach my-list-of-distnodes [ [ag] ->
        ask ag [ set dcs 1]]]
  ask distnodes
    [
      let id who
      set region item 0 n-of 1 regions
```

```
      let leadtimescsv csv:from-file "C:/Model/Base Case Complex
Chain/leadtimesverif.csv"
      let leadtimes item id leadtimescsv ; creates lead times vector
      set distlead-time first leadtimes
      set distplanning-horizon-forecasts n-values (planning-horizon)[0]
      set distforecast-history (list)
      let demandh csv:from-file "C:/Model/Base Case Complex
Chain/demandhistory.csv"
      let dh item id demandh set distnode-demand-history dh
      let initialstockfg csv:from-file "C:/Model/Base Case Complex
Chain/initalstockfg.csv"
      let sfg item id initialstockfg set diststock-fg item 0 sfg
      set disttime-todisruption int (random-exponential disruption-occurrence-node)
      set disttime-disrupted int (random-exponential disruption-duration-node) + 1
      set mydistances n-values (no-regions) [ 0 ]
      let my-calc-proximity 0
      foreach regions
        [
          set mydistances replace-item my-calc-proximity mydistances abs (region -
item my-calc-proximity regions)
          set my-calc-proximity my-calc-proximity + 1
        ]
    ]
  ifelse no-retailers < no-dcs
    [show (word "No. of retailers has to be greater or equal than the number of
distribution centers")]
    [
      ask distnodes
        [
          ifelse dcs = 1
            [
              set label who
              create-direct-links-to distnodes with [dcs = 0]
              create-direct-links-from prodnodes with [who = mfg]
            ]
            [
              set label who
            ]
        ]
      ask distnodes
        [
          set myregions [region] of [in-link-neighbors] of self
          set mysuppliers [who] of [in-link-neighbors] of self
          ;set dcslist list [region] of [in-link-neighbors] of self [who] of [in-
link-neighbors] of self

        ]
    ]
end
to generate-demand
   ask distnodes
     [
       let id who
       if dcs = 0
         [
          hatch-orders No-Orders
            [
              ht
              set supplier id
              set qorder int (random-normal mean-demand stdev-demand); * demand-
multiplier) 0; quantity to fullfil
              show (word "qorder retailers " qorder)
              set date ticks ; sets the date for the order  WHAT DATE
              set date-created ticks
```

```
              set customer Retailers-Customer-ID
;user-message (word " Order of: " qorder ", with a date of " date ", to be supplied
by: " id " generated atosp " ticks)
             ]
         ]
     ]
end

to generate-forecasts
  ask prodnodes
    [
      let id who
      let ph 0
      while [ph < planning-horizon]
        [
          if forecast-method = "AR (1)"
            [
              let lag-1 but-last node-demand-history
              let ar matrix:forecast-linear-growth lag-1
              ;if id = 0 [set q-forecast 28] if id = 1  [set q-forecast 14] if id =
2 [set q-forecast 14] if id = 3  [set q-forecast 14] if id = 4 [set q-forecast 14]
              set q-forecast precision (item 0 ar ) 0;precision (item 1 ar + ph *
item 2 ar) 0
              set planning-horizon-forecasts replace-item ph planning-horizon-
forecasts q-forecast
            ]
          if forecast-method = "MA(n)"
            [
              let ma-list sublist node-demand-history max list 0 (length node-
demand-history - n-for-MA) (length node-demand-history)
              ;if id = 0 [set q-forecast 28] if id = 1  [set q-forecast 14] if id =
2 [set q-forecast 14] if id = 3  [set q-forecast 14] if id = 4 [set q-forecast 14]
              set q-forecast precision (mean ma-list) 0
              set planning-horizon-forecasts replace-item ph planning-horizon-
forecasts q-forecast
            ]
          set ph ph + 1
        ]
      set forecast-history lput first planning-horizon-forecasts forecast-history
    ]
  ; Add on 01/02/2018 for generating forecasts for Distibution nodes
  ask distnodes
    [
      let distid who
      let distph 0
      while [distph < planning-horizon]
        [
          if forecast-method = "AR (1)"
            [
              let lag-1 but-last distnode-demand-history
              let ar matrix:forecast-linear-growth lag-1
              ;if distid = 3 or distid = 4  [set distq-forecast 14]
              set distq-forecast precision (item 0 ar) 0;precision (item 1 ar +
distph * item 2 ar) 0
              set distplanning-horizon-forecasts replace-item distph distplanning-
horizon-forecasts distq-forecast
            ]
          if forecast-method = "MA(n)"
            [
               let ma-list sublist distnode-demand-history max list 0 (length
distnode-demand-history - n-for-MA) (length distnode-demand-history)
               ;if distid = 3 or distid = 4  [set distq-forecast 14]
               set distq-forecast precision (mean ma-list) 0
```

```
              set distplanning-horizon-forecasts replace-item distph distplanning-
horizon-forecasts distq-forecast
            ]
          set distph distph + 1
        ]
      set distforecast-history lput first distplanning-horizon-forecasts
distforecast-history
    ]
end
to plan-production-141
  ;;; To calculate the service level according to the probability of no stock-out
per replenishment cycle, service levl P1, (one simulation period in the Lot-4-Lot
model) for each node ;;;
  let z-value 0
  ifelse Desired-Service-Level = "99.5%" [set z-value 2.5758]
     [ifelse Desired-Service-Level = "99%" [set z-value 2.3263]
         [ifelse Desired-Service-Level = "98%" [set z-value 2.0537]
             [ifelse Desired-Service-Level = "95%" [set z-value 1.6449]
                 [set z-value 1.2816]]]]

  ask prodmgrs
    [
      set my-list-of-prodnodes sort-by >  prodnodes
      foreach my-list-of-prodnodes [ [ag] ->
      ask ag
        [
      let id who
      let id2 who
      let ph 0
      let leadtime lead-time
      ;;; Procedure to calculate the safety stock based on the probability of no
stockout per replenishment cycle, service levl P1 ;;;
      let my-node-mean-demand mean (node-demand-history)
      let my-node-sd-demand standard-deviation (node-demand-history)
      set safety-stock 0 ; floor (my-node-sd-demand * z-value)
      ;;; End of the procedure.  It will update the value based on the variability
of the demand for each node
      set projected-stock-fg stock-fg
      let qt-mps 0
      ;set projected-stock-components stock-components
      let my-safety-stock safety-stock
      while [ph < planning-horizon];
        [
          set commercial-orders sum [qorder] of orders with [supplier = id and
ticks - date + ph = 0 and delayed-sup = 0]; includes all orders (delayed or not)
because the
          ifelse commercial-orders = 0
            [set qt-mps 0]
            [set qt-mps max (list item ph planning-horizon-forecasts commercial-
orders)]
;user-message (word " workorder " [who] of workorders with [supplier = id and ticks
- date + ph - leadtime = 0 and planned = 1])
          let already-scheduled sum [qwork-order] of workorders with [supplier = id
and ticks - date + ph - leadtime = 0 and planned = 1] ;***
          set projected-stock-fg projected-stock-fg + already-scheduled
;user-message (word "Real D of: " commercial-orders ", Max D or F: " qt-mps ",
already scheduled: " already-scheduled ", Proj. Inv of FG: " projected-stock-fg ",
for R Node: " id ", atbopp " ph)
          ifelse projected-stock-fg >= qt-mps
                [
                  let predicted-stockout 0
                  set projected-stock-fg projected-stock-fg - qt-mps
                  ask orders with [supplier = id and ticks - date + ph = 0]
                    [
```

```
                      set processed 1 ; why here???  These are orders acknowledged
by the supplier WHEN it has enough FG to satisfy them
                    ]
                ]
                [
                  let tempprojected-stock-fg projected-stock-fg
                  let tempqt-mps qt-mps
;user-message (word "qt mps "  qt-mps)
                       foreach sort-on [qorder] orders with [supplier = id and
ticks - date + ph = 0]
                         [ corder -> ask corder [
                           if qorder <= tempprojected-stock-fg
                             [
                               set processed 1
                               set tempprojected-stock-fg tempprojected-stock-fg -
qorder
;user-message (word "qorder "  qorder " of order " who)
                               set tempqt-mps tempqt-mps - qorder
                             ]]]
                       set projected-stock-fg tempprojected-stock-fg
                       set qt-mps tempqt-mps
                       let predicted-stockout qt-mps
                    ifelse assembly-node != 1
                      [
                        hatch-workorders 1
                          [
                            ht
                            set date-created ticks
                            set supplier id
                            set upstream 0
                            set planned 1
                            set qwork-order predicted-stockout + my-safety-stock ;
*** SAFETY STOCK BY ORDER???? INVENTORY LEVEL??? PERIOD????
                            ifelse  ph < leadtime [set date ticks + ph + leadtime
set delayed 1 set delayed-time delayed-time + leadtime] ;WILDDDD
                              [set date (ticks + ph - leadtime)]
                            set processed 1
show ( word "work order no. AA" who " quantity " qwork-order " to be manufactured
by " supplier " with a date-created of " date-created "and due date of " date "
processed " processed " upstream " upstream "ph " ph)
                        ]
                      set wo-issued wo-issued + 1
                    ]
                    [
                       let j 0
                       let auxlist (list)
                       while [j < depth]
                         [
                           if matrix:get compmult j 0 > 0
                             [
                               let aux matrix:get compmult j 0 * matrix:get
projected-stock-components j 0
                               set auxlist lput aux auxlist
                             ]
                             set j j + 1
                         ]
                            ifelse min auxlist = 0
                              [
                                 set myminatmstock 0
                              ]
                              [
                                 set myminatmstock min auxlist
                              ]
                       ifelse predicted-stockout > myminatmstock
```

```
                    [
                      set projected-stock-components matrix:minus projected-
stock-components matrix:times components myminatmstock
                      set predicted-stockout max list (predicted-stockout -
myminatmstock) 0
                      set qworder-after-atmstock matrix:times components
predicted-stockout
                      ask in-link-neighbors
                        [
                          let id3 who
                          if any? orders with [customer = id and supplier =
id3 and ticks - date + ph - leadtime = 0 and processed = 1]
                            [
                              let incoming-orders sum [qorder] of orders with
[customer = id and supplier = id3 and ticks - date + ph - leadtime = 0 and
processed = 1]
                              ask prodnode id
                                [
                                  let temp matrix:get projected-stock-
components id3 0

                                  let temp1 temp + incoming-orders
                                  matrix:set-row projected-stock-components
id3 (list temp1)
                                ]
                            ]
                        ]
                      let k 0
                      let auxlist1 (list)
                      while [k < depth]
                        [
                          if matrix:get compmult k 0 > 0
                            [
                              let aux1 matrix:get compmult k 0 * matrix:get
projected-stock-components k 0
                              set auxlist1 lput aux1 auxlist1
                            ]
                            set k k + 1
                        ]
                      ifelse min auxlist1 = 0
                        [
                          set myminatmincord 0
                        ]
                        [
                          set myminatmincord min auxlist1
                        ]
                      set projected-stock-components matrix:minus projected-
stock-components matrix:times components myminatmincord
                      set predicted-stockout max list (predicted-stockout -
myminatmincord) 0
                      let temp components matrix:set-row temp id [1]
                      set qworder-after-incord matrix:times temp predicted-
stockout
                      if (myminatmstock + myminatmincord) != 0
                        [
                          hatch-workorders 1
                            [
                              ht
                              set supplier id
                              set date-created ticks
                              set upstream 0
                              set planned  1
                              set qwork-order ([myminatmstock +
myminatmincord] of prodnode id + my-safety-stock) ; *** SAFETY STOCK
```

```
                                    ifelse  ph < leadtime [set date ticks + ph +
leadtime set delayed 1 set delayed-time delayed-time + leadtime] ;LEATIME OF
SUPPLIERS!!!!
                                    [set date (ticks + ph - leadtime)]
                                    set processed 1
show ( word "I have and/or have scheduled components to arrive on time ==> work
order no. BB" who " quantity " qwork-order " to be manufactured by " supplier "
with a date-created of " date-created "and due date of " date " processed "
processed " upstream " upstream)
                                  ]
                                set wo-issued wo-issued + 1
                              ]
                            if matrix:get [qworder-after-incord] of prodnode id id 0
!= 0
                              [
                                let My-WOQ matrix:get [qworder-after-incord] of
prodnode id id 0
                                let No-WO-Upstream int (My-WOQ / cap) + 1
                                hatch-workorders 1
                                  [
                                    ht
                                    set supplier id
                                    set date-created ticks
                                    set upstream 1
                                    set qwork-order (int (My-WOQ / No-WO-Upstream) +
1 + my-safety-stock)  ; *** SAFETY STOCK
                                    ifelse  ph < leadtime [set date ticks + ph +
leadtime set delayed 1 set delayed-time delayed-time + leadtime]
                                    [set date (ticks + ph - leadtime)]
                                    set processed 1
show ( word "I am ordering components for the remaining of the stockout from
supplier to avoid stockout ==> work order no. CC" who " quantity " qwork-order " to
be manufactured by " supplier " with a date-created of " date-created "and due date
of " date " processed " processed " upstream " upstream)
                                  ]
                                set wo-issued wo-issued + 1
                              ]
                          ]
                          [
                            set projected-stock-components matrix:minus projected-
stock-components matrix:times components predicted-stockout  ;myminatmstock changed
because I will produce only what I need
                            if [predicted-stockout] of prodnode id != 0
                              [
                                hatch-workorders 1
                                  [
                                    ht
                                    set supplier id
                                    set date-created ticks
                                    set upstream 0
                                    set planned 1
                                    set qwork-order ([predicted-stockout] of
prodnode id  + my-safety-stock)
                                    ifelse  ph < leadtime [set date ticks + ph +
leadtime set delayed 1 set delayed-time delayed-time + leadtime]
                                    [set date (ticks + ph - leadtime)]
                                    set processed 1
show ( word "I have enough components to produce ==> work order no. DD" who "
quantity " qwork-order " to be manufactured by " supplier " with a date-created of
" date-created "and due date of " date " processed " processed " upstream "
upstream)
                                  ]
                                set wo-issued wo-issued + 1
                              ]
```

```
                              ]
                        ]
                  ]
          set ph ph + 1
;user-message (word " planning horizon = " ph)
        ]
  ]]]
show (word "End of Production Planning ")
end
to explodeBoM-141
  ask prodmgrs
    [
      set my-list-of-prodnodes sort-by >  prodnodes
      foreach my-list-of-prodnodes [ [ag] ->
      ask ag [
      let id who
      let leadtime lead-time
      let ph 0
      while [ph < planning-horizon]
        [
            if any? workorders with [supplier = id and ticks + ph - date = 0 and
upstream = 1 and processed = 1 and planned = 0]
            [
              let temp sum [qwork-order] of workorders with [supplier = id and
ticks + ph - date = 0 and upstream = 1 and processed = 1 and planned = 0]
              ask workorders with [supplier = id and ticks + ph - date = 0 and
upstream = 1 and processed = 1 and planned = 0]
                [
                   set planned 1
                ]
              let basicprodvector [components] of prodnode id
              let prod-vctr matrix:times basicprodvector temp
              set workorder-vector prod-vctr;
              ask in-link-neighbors
                [
                  let id2 who
                  let oleadtime lead-time
 ;                 show (word "YYYY Order created from workorders in the quantity
of: " matrix:get [workorder-vector] of prodnode id id2 0 " for supplier " id2 "
with customer " id)
                  if matrix:get [workorder-vector] of prodnode id id2 0 > 0
                    [
                      hatch-orders 1
                        [
                          ht
                          set customer id
                          set supplier id2
                          set date-created ticks
                          set qorder matrix:get [workorder-vector] of prodnode id
id2 0
                          set date ticks + ph
                          set processed 1 ;New Addition on March 7, 2018
show ( word "commercial order no. EE" who " quantity " qorder " to be delivered by
" supplier " to " customer " with a date-created of " date-created "and due date of
" date )
                        ]
                    ]
                ]
            ]
         set ph ph + 1
        ]
            ]
                                ]
  ]
```

```
show (word "End of Explosion of BoM ")
end
to distribute
   ask prodmgrs
    [
      set my-list-of-prodnodes sort-by <  prodnodes
      foreach my-list-of-prodnodes [ [ag] ->
      ask ag
        [
      let id who
      let mleadtime lead-time
      let total-to-distribute 0
      set co-filled-ontime 0
      set co-issued count orders with [supplier = id and date-created = ticks and
date = ticks] ;"WHY DATE IS SAME
      if any? workorders with [supplier = id and ticks - date - mleadtime = 0 and
planned = 1 and in-production = 1 ] ; Work orders to finish manufacturing at the
beginning of the current simulation period
        [
          let myproduced sum [qwork-order] of workorders with [supplier = id and
ticks - date - mleadtime = 0 and planned = 1 and in-production = 1]
          set stock-fg stock-fg + myproduced
          ask workorders with [supplier = id and ticks - date - mleadtime = 0 and
planned = 1 and in-production = 1] [die]
        ]
      let current-stock-fg stock-fg
      ifelse Dispatching-Rule = "Smallest Order Quantity (SOQ)"
        [foreach sort-on [qorder] orders with [supplier = id and ticks - date = 0
and processed = 1]
          [ corder -> ask corder [
            let id2 customer
            let region-supplier 0
            let region-customer 0
            ifelse qorder <= current-stock-fg
              [
                ask prodnode id [set region-supplier region]
                ifelse id2 > mfg [ask distnode id2 [set region-customer
region]][ask prodnode id2 [set region-customer region]]
                ifelse item region-supplier disrupted-regions = 1 or item region-
customer disrupted-regions = 1; MAKE SURE TO INCLUDE INTENSITY
                  [
                    set date ticks + 1
                    set delayed-time delayed-time + 1
                    set delayed-sup 1
                  ]
                  [
                    set fulfilled 1
                    ;let my-status delayed
                    set current-stock-fg current-stock-fg - qorder
                    set total-to-distribute total-to-distribute + qorder
                    ask prodnode id
                      [
                        set temptotaldistribute total-to-distribute
                        set co-filled-ontime co-filled-ontime + 1
                        ;if my-status = 0 [set co-filled-ontime co-filled-ontime +
1]
                      ]
                  ]
              ]
              [
                set date ticks + 1
                set delayed-time delayed-time + 1
                set delayed-sup 1
              ]
```

```
                              ]
         ]
        ]
      [foreach sort-on [date-created] orders with [supplier = id and ticks - date =
0 and processed = 1]
          [ corder -> ask corder [
            let id2 customer
            let region-supplier 0
            let region-customer 0
            ifelse qorder <= current-stock-fg
              [
                ask prodnode id [set region-supplier region]
                ifelse id2 > mfg [ask distnode id2 [set region-customer
region]][ask prodnode id2 [set region-customer region]] ;fix for a general case
                ifelse item region-supplier disrupted-regions = 1 or item region-
customer disrupted-regions = 1
                  [
                    set date ticks + 1
                    set delayed-time delayed-time + 1
                    set delayed-sup 1
                  ]
                  [
                    set fulfilled 1
                    ;let my-status delayed
                    set current-stock-fg current-stock-fg - qorder
                    set total-to-distribute total-to-distribute + qorder
                    ask prodnode id
                      [
                        set temptotaldistribute total-to-distribute
                        set co-filled-ontime co-filled-ontime + 1
                        ;if my-status = 0 [set co-filled-ontime co-filled-ontime +
1]
                      ]
                  ]
              ]
              [
                set date ticks + 1
                set delayed-time delayed-time + 1
                set delayed-sup 1
              ]
                              ]
         ]
      ]
      set stock-fg current-stock-fg
      if any? orders with [supplier = id and ticks - date = 0 and processed = 1 and
delayed-sup = 1 and fulfilled = 0]
      [set orders-delayed orders-delayed + count orders with [supplier = id and
ticks - date = 0 and processed = 1 and delayed-sup = 1 and fulfilled = 0]]
      set demand sum [qorder] of orders with [supplier = id and ticks - date = 0
and processed = 1]; and fulfilled = 1]
      set demand-met-on-time sum [qorder] of orders with [supplier = id and ticks -
date = 0 and processed = 1 and fulfilled = 1]
      set node-demand-history lput demand node-demand-history
      set co-filled-ontime count orders with [supplier = id and date-created = date
and processed = 1 and fulfilled = 1]
      ifelse co-issued = 0 [set co-fill-rate 1][set co-fill-rate co-filled-ontime /
co-issued] ;QUESTION What if I did not get any co??? set co-filled-rate = 0 OR 1
      if id = mfg and co-issued != 0
        [
          set my-list-co-filled-rate-manufacturer lput co-fill-rate my-list-co-
filled-rate-manufacturer
        ]
]]]
show (word "End of Distribute ")
```

```
end
to receive
 ask prodmgrs
    [
      set my-list-of-prodnodes sort-by <  prodnodes
      foreach my-list-of-prodnodes [ [ag] ->
      ask ag
        [
      let id who
      if assembly-node = 1 ;SHOULD IT BE AND ELSE stock components of prodnode 0 2
4
        [
          ask in-link-neighbors
            [
              let id2 who
              let mylead-time lead-time
              if any? orders with [customer = id and supplier = id2  and ticks -
date = 0 and fulfilled = 1]; removed processed = 1 because if order has been
fulfilled by default it must have been processed
                 [
output-show (word " incoming components from node " id2 " is equal to" sum [qorder]
of orders with [customer = id and supplier = id2  and ticks - date = 0 and
fulfilled = 1] )
                   set q-delivered sum [qorder] of orders with [customer = id
and supplier = id2  and ticks - date = 0 and fulfilled = 1]; removed processed = 1
because if order has been fulfilled by default it must have been processed
output-show (word " stock components of prodnode "  [stock-components] of prodnode
id)
                  let temp matrix:get [stock-components] of prodnode id id2 0
                  let temp1 temp + sum [qorder] of orders with [customer = id and
supplier = id2  and ticks - date = 0 and fulfilled = 1]; ; removed processed = 1
because if order has been fulfilled by default it must have been processed
                  matrix:set-row [stock-components] of prodnode id id2 (list
temp1)
                  ask orders with [customer = id and supplier = id2  and ticks -
date = 0 and fulfilled = 1] [ die]; and processed = 1] [die]
                 ]
            ]
        ]
  ]]]
show (word "End of Receive" )
end
to make
  ask prodmgrs
    [
      set my-list-of-prodnodes sort-by <  prodnodes
      foreach my-list-of-prodnodes [ [ag] ->
      ask ag
        [
      let id who
      let mleadtime lead-time
      let totalworkorders 0
              ifelse assembly-node = 1
            [
              set myminatm 0
            ]
            [
              set myminatm 10000
            ]
            if assembly-node = 1
              [
                let j 0
                let auxlist (list)
                while [j < depth]
```

```
                  [
                    if matrix:get compmult j 0 > 0
                      [
                        let aux matrix:get compmult j 0 * matrix:get stock-
components j 0
                        set auxlist lput aux auxlist
                      ]
                    set j j + 1
                  ]
                ifelse min auxlist = 0
                  [
                    set myminatm 0
                  ]
                  [
                    set myminatm min auxlist
                  ]
              ]
            if cap <= myminatm
              [
                set myminatm cap
              ]
      if disrupted = 1
        [
          set myminatm int myminatm * impact
        ]
      ;  This accounts for impacts on the performance of the system due to
disruption
      output-show (word "===============>my min atm " myminatm "and I am prodnode "
id)
      output-show (word "number of workorders to make " count workorders with
[supplier = id and ticks - date = 0 and planned = 1 and in-production = 0] " of
prodnode " id)
      foreach sort-on [date-created] workorders with [supplier = id and ticks -
date = 0 and planned = 1 and in-production = 0] ; it was [date-created] before
        [ worder -> ask worder
          [
            ifelse qwork-order <= [myminatm] of prodnode id
              [
              set in-production 1
              ask prodnode id
                [
                  set myminatm myminatm - [qwork-order] of myself
                  set wo-filled-ontime wo-filled-ontime + 1
                ]
              set totalworkorders totalworkorders + qwork-order
              ]
              [
              set date ticks + 1
              set delayed-time delayed-time + 1 ;average delayed time (orders die,
how to calculate)
              set delayed 1
              ]
          ]
        ]
        set lot2m totalworkorders
;user-message (word "lot2m " lot2m)
        let temp matrix:times components lot2m matrix:set-row temp id [0]
        set stock-components matrix:minus stock-components temp
        set stock-fg stock-fg + lot2m ; new line
        if any? workorders with [supplier = id and ticks - date = 0 and delayed =
1]   [set workorders-delayed workorders-delayed + 1]
        set wo-fill-rate wo-filled-ontime / max (list 1 wo-issued)
   ]]]
show (word "End of Make ")
```

```
end
to plan-production-retailers; it is assumed that retailers deliver instantaneously
to their customers (lead time = 0)
  ;;; To calculate the service level according to the probability of no stock-out
per replenishment cycle, service level P1, (one simulation period in the Lot-4-Lot
model) for each node ;;;
  let dist-z-value 0
  ifelse Desired-Service-Level = "99.5%" [set dist-z-value 2.5758]
     [ifelse Desired-Service-Level = "99%" [set dist-z-value 2.3263]
         [ifelse Desired-Service-Level = "98%" [set dist-z-value 2.0537]
             [ifelse Desired-Service-Level = "95%" [set dist-z-value 1.6449]
                 [set dist-z-value 1.2816]]]]

  ask prodmgrs
    [
      set my-list-of-distnodes sort-by >  distnodes
      foreach my-list-of-distnodes [ [ag] ->
      ask ag
        [
          let id who
          let ph 0
          let leadtime distlead-time
          ;;; Start of procedure to select closest supplier
          let my-distance 100
          let mysupplierid 1000
          let mysupplierregion 1000
          let myregiondistances mydistances
          ask in-link-neighbors
             [
              set mysupplierid who
              set mysupplierregion region
              ;user-message (word " My supplier " mysupplierid " located in region
" mysupplierregion)
              if my-distance > item mysupplierregion myregiondistances
                 [
                  set my-distance item mysupplierregion myregiondistances
                  ;user-message (word " My supplier " mysupplierid " located in "
mysupplierregion " far from me " my-distance " units.")
                 ]
             ]
          ;;; End of procedure to select closest supplier
          ;;; Procedure to calculate the safety stock based on the probability of
no stockout per replenishment cycle, service levl P1.  IT NEEDS TO BE UPDATED ONCE
THE WHOLE NETWORK IS IN PLACE ;;;
          let my-distnode-mean-demand mean-demand ;mean (distdemand-history) ;mean-
demand mean (distdemand-history)
          let my-distnode-sd-demand 0;stdev-demand ;standard-deviation (distdemand-
history) ;stdev-demand ;standard-deviation (distdemand-history)
          set distsafety-stock floor (my-distnode-sd-demand * dist-z-value)
          ;;; End of the procedure.  It will update the value based on the
variability of the demand for each node
          set distprojected-stock-fg diststock-fg
          let qt-distorder 0
          let my-distsafety-stock distsafety-stock
          while [ph < planning-horizon];
            [
             set distcommercial-orders sum [qorder] of orders with [supplier = id
and ticks - date + ph = 0 and delayed-sup = 0]
             set qt-distorder max (list item ph distplanning-horizon-forecasts
distcommercial-orders)
             ;***CHECK THIS PIECE IT NEEDS TO BE UPDATED WITH THE ORDERS ALREADY
ISSUED BASED ON THE LEADTIME OF MY SUPPLIER***
             let distalready-scheduled sum [qorder] of orders with [customer = id
and ticks - date + ph - leadtime = 0 and processed = 1] ;*******************
```

```
              set distprojected-stock-fg distprojected-stock-fg + distalready-
scheduled
;user-message (word "Real D of: " distcommercial-orders ", Max D or F: " qt-
distorder ", already scheduled: " distalready-scheduled ", Proj. Inv of FG: "
distprojected-stock-fg ", for R Node: " id ", atbopp " ph)
              ifelse distprojected-stock-fg >= qt-distorder
                [
                  let predicted-diststockout 0
                  set distprojected-stock-fg distprojected-stock-fg - qt-distorder
                  ask orders with [supplier = id and ticks - date + ph = 0] ;
dispatch orders as we can, based on inventory whether they are delayed or not
                    [
                      set processed 1 ; why here???  ORDERS ARE ACKNOWLEDGED BY THE
NODE THAT WILL SATISFY THEM
                    ]
                ]
                [
                  ;let predicted-diststockout max list (qt-distorder -
distprojected-stock-fg) 0
                  let tempdistprojected-stock-fg distprojected-stock-fg
                  let tempqt-distorder qt-distorder
;user-message (word "qt distorder "  qt-distorder)
                       foreach sort-on [qorder] orders with [supplier = id and
ticks - date + ph = 0]
                         [ corder -> ask corder [
                           if qorder <= tempdistprojected-stock-fg
                             [
                               set processed 1
                               set tempdistprojected-stock-fg tempdistprojected-
stock-fg - qorder
;user-message (word "qorder "  qorder " of order " who)
                               set tempqt-distorder tempqt-distorder - qorder
                             ]]]
                               set distprojected-stock-fg tempdistprojected-stock-
fg
                               set qt-distorder tempqt-distorder
                               ask turtle mysupplierid ; be careful with this.  Can
it be done
                                 [
                                   let id2 who
                                   let dleadtime 0
                                   ifelse dcs = 1
                                     [set dleadtime distlead-time]
                                     [set dleadtime lead-time]
                                     if qt-distorder > 0
                                       [
                                         hatch-orders 1
                                           [
                                             ht
                                             set customer id
                                             set supplier id2
                                             set date-created ticks
                                             set qorder (qt-distorder + my-
distsafety-stock) ; *** Is safety stock added to each order??? or by period??? or
for inventory level???
                                             ifelse  ph < dleadtime [ set date
ticks + ph + dleadtime set delayed-cust 1 set delayed-time delayed-time +
dleadtime]
                                                                           [set date
(ticks + ph - dleadtime)]
;user-message ( word "commercial order no. FF " who " quantity " qorder " to be
delivered by " supplier " to " customer " with a date-created of " date-created "
and due date of " date " atbopp " ph)
                                           ]
```

```
                                          ]
                                    ask orders with [supplier = id and ticks - date
+ ph = 0 and processed = 0]
                                        [
                                          ifelse  ph < dleadtime [ set date ticks + ph
+ dleadtime set delayed-sup 1 set delayed-time delayed-time + dleadtime]
                                                                [set date (ticks +
ph - dleadtime)]
                                        ]
                                    ]
                 ]
              set ph ph + 1
            ]
        ]
      ]
    ]
show (word "End of Sourcing Planning for Retailers")
end
to distribute-retailers
   ask prodmgrs
    [
      set my-list-of-distnodes sort-by <  distnodes
      foreach my-list-of-distnodes [ [ag] ->
      ask ag
        [
      let id who
      let mleadtime distlead-time
      let disttotal-to-distribute 0
      set distco-filled-ontime 0
      let distcurrent-stock-fg diststock-fg
      let stock-check 0
      ifelse distdisrupted = 0
        [
;          set distcurrent-stock-fg diststock-fg
          set stock-check 1
        ]
        [
          set distcurrent-stock-fg int distcurrent-stock-fg * impact
        ]
      ifelse Dispatching-Rule = "Smallest Order Quantity (SOQ)"
        [foreach sort-on [qorder] orders with [supplier = id and ticks - date = 0];
and processed = 0]
          [ corder -> ask corder [

            let id2 customer
            let region-supplier 0
            let region-customer 0

          ifelse qorder <= distcurrent-stock-fg
            [
              ask distnode id [set region-supplier region]
              ifelse id2 = Retailers-Customer-ID [set region-customer region-
supplier][ask distnode id2 [set region-customer region]]; the region of the
customer of the retailer is the same as the retailer.
              ifelse item region-supplier disrupted-regions = 1 or item region-
customer disrupted-regions = 1; Regardless the region where both supplier and
customer are located, a disruption in the region prevent any delivery of
productregion
                [
                  set date ticks + 1
                  set delayed-time delayed-time + 1
                  set delayed-sup 1
                ]
                [
```

```
                  set processed 1 ;MAYBE because they are not label processed
anywhere else
                  set fulfilled 1
                  set distcurrent-stock-fg distcurrent-stock-fg - qorder
                  set disttotal-to-distribute disttotal-to-distribute + qorder
                  let myqorder qorder
                  ask distnode id
                    [
                      set disttemptotaldistribute disttotal-to-distribute
                      set distco-filled-ontime distco-filled-ontime + 1
                    ]
                  if customer != 100
                    [
                      ask distnode customer
                        [
                          set diststock-fg diststock-fg + myqorder
                        ]
                    ]
                ]
            ]
            [
              set date ticks + 1
              set delayed-time delayed-time + 1
              set delayed-sup 1
            ]
      ]]]
      [foreach sort-on [date-created] orders with [supplier = id and ticks - date =
0]; and processed = 0]
          [ corder -> ask corder [
;user-message (word "Fulfilling order in a Q of " qorder ", for order # " who ",
with a date of " date ", and customer " customer ", and processed " processed ",
and delayed status " delayed-sup ", with a current Inv. FG of " distcurrent-stock-
fg )

            let id2 customer
            let region-supplier 0
            let region-customer 0

          ifelse qorder <= distcurrent-stock-fg
            [
              ask distnode id [set region-supplier region]
              ifelse id2 = 100 [set region-customer region-supplier][ask distnode
id2 [set region-customer region]]; the region of the customer of the retailer is
the same as the retailer.
              ifelse item region-supplier disrupted-regions = 1 or item region-
customer disrupted-regions = 1; Regardless the region where both supplier and
customer are located, a disruption in the region prevent any delivery of
productregion
                [
                  set date ticks + 1
                  set delayed-time delayed-time + 1
                  set delayed-sup 1
                ]
                [
                  set processed 1  ;MAYBE because they are not label processed
anywhere else
                  set fulfilled 1
                  set distcurrent-stock-fg distcurrent-stock-fg - qorder
                  set disttotal-to-distribute disttotal-to-distribute + qorder
                  let myqorder qorder
;user-message (word " customer" customer)
```

```
;user-message (word "Order " who " fulfilled with a Q of " qorder " with customer "
customer ", and supplier " supplier ", leaving Inv FG of supplier in " distcurrent-
stock-fg )
                  ask distnode id
                    [
                     set disttemptotaldistribute disttotal-to-distribute
                     set distco-filled-ontime distco-filled-ontime + 1
                    ]
                  if customer != 100
                    [
                      ask distnode customer
                        [
                          set diststock-fg diststock-fg + myqorder
                        ]
                    ]
                ]
            ]
          [
            set date ticks + 1
            set delayed-time delayed-time + 1
            set delayed-sup 1
;user-message (word "Order " who " NOT fulfilled with a Q of " qorder " with
customer " customer ", and supplier " supplier ", leaving Inv FG of supplier in "
distcurrent-stock-fg )
          ]
      ]]]
      ifelse stock-check = 1 [set diststock-fg distcurrent-stock-fg] ; to keep
inventoty as it was before if there is a disruption in the node
                             [set diststock-fg (1 - impact) * diststock-fg +
distcurrent-stock-fg]
      if any? orders with [supplier = id and ticks - date = 0 and processed = 1 and
delayed-sup = 1 and fulfilled = 0]
      [set orders-delayed orders-delayed + count orders with [supplier = id and
ticks - date = 0 and delayed-sup = 1] ]; processed = 0 and  fulfilled = 0 removed
because of redundancies
          set distdemand sum [qorder] of orders with [supplier = id and ticks -
date = 0]; and processed = 1]; and fulfilled = 0] removed fulfilled because real
demand includes orders that were or were not fulfill ontime
      set distdemand-met-on-time sum [qorder] of orders with [supplier = id and
ticks - date = 0 and processed = 1 and fulfilled = 1]
      set distnode-demand-history lput distdemand distnode-demand-history
      ifelse distco-issued = 0 [set distco-fill-rate 1][set distco-fill-rate co-
filled-ontime / distco-issued] ;QUESTION What if I did not get any co??? set co-
filled-rate = 1
      ask orders with [supplier = id  and ticks - date = 0 and processed = 1 and
fulfilled = 1][die]
  ]]]
show (word "End of Retailers Distribute ")
end
to receive-retailers
  ask distnodes with [dcs = 1]
    [
      let id who
      let my-new-stock-fg 0
      ask in-link-neighbors
        [
          let id2 who

          let region-supplier 0
          let region-customer 0

          let mylead-time lead-time
```

```
          if any? orders with [customer = id and supplier = id2  and ticks - date =
0 and processed = 1 and fulfilled = 1]
              [
                ask distnode id  [set region-customer region]
                ask prodnode id2 [set region-supplier region]
                ifelse item region-supplier disrupted-regions = 1 or item region-
customer disrupted-regions = 1; Regardless the region where both supplier and
customer are located, a disruption in the region prevent any delivery of
productregion
                  [
                    set q-delivered 0

                    set date ticks + 1
                    set delayed-time delayed-time + 1
                    ifelse item region-supplier disrupted-regions = 1 [set delayed-
sup 1][set delayed-cust 1]
                  ]
                  [
                    set q-delivered sum [qorder] of orders with [customer = id and
supplier = id2  and ticks - date = 0 and processed = 1 and fulfilled = 1]
                    set my-new-stock-fg my-new-stock-fg + q-delivered
                    ask orders with [customer = id and supplier = id2  and ticks -
date = 0 and processed = 1 and fulfilled = 1]
                      [
                        if delayed-time > 0
                          [set my-list-avg-delayed-days lput delayed-time my-list-
avg-delayed-days]
                        set my-list-avg-total-days lput (delayed-time + mylead-
time) my-list-avg-total-days
                        die
                      ]
                  ]
              ]
        ]
      set diststock-fg diststock-fg + my-new-stock-fg
    ]
show (word "End of Retailers Receive" )
end
to create-region-disruptions
  let mycounter 0
  foreach regions
    [
      ifelse item mycounter disrupted-regions = 0
        [
          ifelse item mycounter time-todisruption-regions > 0
            [
              set time-todisruption-regions replace-item mycounter time-
todisruption-regions (item mycounter time-todisruption-regions - 1)
            ]
            [
              set disrupted-regions replace-item mycounter disrupted-regions 1
              set time-disrupted-regions replace-item mycounter time-disrupted-
regions (item mycounter time-disrupted-regions - 1)
              set time-todisruption-regions replace-item mycounter time-
todisruption-regions int (random-exponential disruption-occurrence-region)
            ]
        ]
        [
          ifelse item mycounter time-disrupted-regions = 0
            [
              set disrupted-regions replace-item mycounter disrupted-regions 0
              set time-todisruption-regions replace-item mycounter time-
todisruption-regions int (random-exponential disruption-occurrence-region)
```

```
              set time-disrupted-regions replace-item mycounter time-disrupted-
regions (int (random-exponential disruption-duration-region) + 1)
              if item mycounter time-todisruption-regions > 0
                [
                  set time-todisruption-regions replace-item mycounter time-
todisruption-regions (item mycounter time-todisruption-regions - 1)
                ]
            ]
            [
              set time-disrupted-regions replace-item mycounter time-disrupted-
regions (item mycounter time-disrupted-regions - 1)
            ]
        ]
      set mycounter mycounter + 1
    ]
end

to create-node-disruptions
  ifelse disruption-intensity = "low" [ set impact  0.80] [ifelse  disruption-
intensity = "medium" [set impact 0.51] [set impact 0.20]]
  ask prodnodes
    [
      ifelse disrupted = 0
        [
          ifelse time-todisruption > 0
            [
              set time-todisruption time-todisruption - 1
            ]
            [
              set disrupted 1
              set time-disrupted time-disrupted - 1
              set time-todisruption int (random-exponential disruption-occurrence-
node)
            ]
        ]
        [
          ifelse time-disrupted = 0
            [
              set disrupted 0
              set time-todisruption int (random-exponential disruption-occurrence-
node)
              set time-disrupted int (random-exponential disruption-duration-node)
+ 1
              if time-todisruption > 0
                [
                  set time-todisruption time-todisruption - 1
                ]
            ]
            [
              set time-disrupted time-disrupted - 1
            ]
        ]
    ]
  ask distnodes
    [
      ifelse distdisrupted = 0
        [
          ifelse disttime-todisruption > 0
            [
              set disttime-todisruption disttime-todisruption - 1
            ]
            [
              set distdisrupted 1
              set disttime-disrupted disttime-disrupted - 1
```

```
              set disttime-todisruption int (random-exponential disruption-
occurrence-node)
            ]
        ]
        [
          ifelse disttime-disrupted = 0
            [
              set distdisrupted 0
              set disttime-todisruption int (random-exponential disruption-
occurrence-node)
              set disttime-disrupted int (random-exponential disruption-duration-
node) + 1
              if disttime-todisruption > 0
                [
                  set disttime-todisruption disttime-todisruption - 1
                ]
            ]
            [
              set disttime-disrupted disttime-disrupted - 1
            ]
        ]
    ]
end
```

APPENDIX B: MATLAB CODE FOR MSRE-5[18]

```
% Read Raw Data of Simulation output with a text file
output = fopen('dataMSER.txt');
check = fscanf(output, '%f');
% Batch Mean Generation
dataLength = length(check); %Find out the run length of a replication
b = 5; %Batch Size is five
batchSize = b;
batchNumber = floor(dataLength/batchSize); %Batch Number Calculation
batchMean = zeros(batchNumber); %initialize zero vectors to hold batch means
for i = 1:batchNumber
 batchMean(i) = sum(check(((i1)*batchSize+1):(i*batchSize)))/batchSize;

end
% MSER-Statistic
sampleMSE = zeros(0, batchNumber);
sampleMean = zeros(0, batchNumber);
batchMean2 = batchMean.^2;
for d = 1:batchNumber
 sampleMean(d) = mean(batchMean(d:(length(batchMean))));
 sampleMSE(d) = (sum(batchMean2(d:length(batchMean)))-(batchNumber -
d)*(sampleMean(d)^2))/((batchNumber - d)*(batchNumber - d - 1));
end
% Find a truncation point whose MSER statistic is minimum except the last
% few output series. Consider one or two points to compute sample variance.
% Thus, we need to exclude those erratic points.
trun = find(sampleMSE == min(sampleMSE(1:(batchNumber-batchSize))));
% Add a graph showing the trend of MSER statistics
% Match dimensions between x and y axis
plot(1:(batchNumber-batchSize), sampleMSE(1:batchNumber-batchSize));
title 'Truncation Point with Batch Mean';
xlabel 'Batch Numbers';
ylabel 'MSER Statistic';
hold all;
```

[18] This code was adapted from S. N. Hwang, "MSER Exploratory Research: Implementations, Virtual Laboratory Development, and Parameterization Analysis," PHD (Doctor of Philosophy) Dissertation, Department of Systems and Information Engineering, University of Virginia, Charlottesville, 2017.

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