Handling Disruptions in Supply Chains:

An Integrated Framework and an Agent-based Model

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to my parents

to Elham

to whom we are waiting for so long

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Delft, December 2012

Behzad Behdani

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1. INTRODUCTION

This chapter introduces the research presented in this thesis. The chapter begins with the motivation and background and subsequently, two research questions are formulated. Next, an overview of research objectives and the contributions are presented. The chapter ends with an outline of the remainder of the thesis.

1.1. Background and motivations

1.1.1. Supply chain

A supply chain is an integrated system of companies involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer (Mentzer et al., 2001; Min and Zhou, 2002).

Despite the term, most supply chains are not linked in a linear and sequential way (Figure 1.1). For instance, a manufacturer might have direct contact with some retailers or final customers. Moreover, more than one actor might be involved in each stage of supply chain; for example, a manufacturer may receive the raw material from different suppliers in different locations and produce many types of products and send them to different distributers. Accordingly, the terms “supply network” or “supply web” can be more accurate to describe the structure of most supply chains (Chopra and Meindl, 2007). Nonetheless, the majority of researchers consider the term “supply chain” as a standard term to describe the network of inter-related entities structured to acquire raw materials, convert them into finished products, and distribute these products to customers (Burges et al., 2006). Similarly, through the whole of this thesis, we indicate the same implication with term *supply chain*.

Managing a supply chain involves numerous decisions about the flow of information, product, and funds which are together termed “Supply Chain Management (SCM)” (Chopra and Meindl, 2007). These decisions mostly span multiple functions in each organization and are usually made in multiple levels (Figure 1.2).

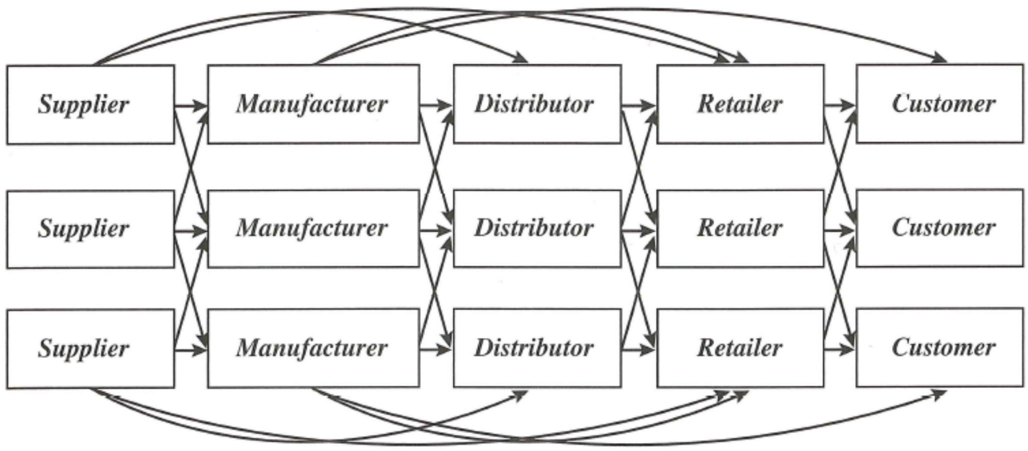

Figure 1.1. A schematic presentation of supply chain (Chopra and Meindl, 2007)

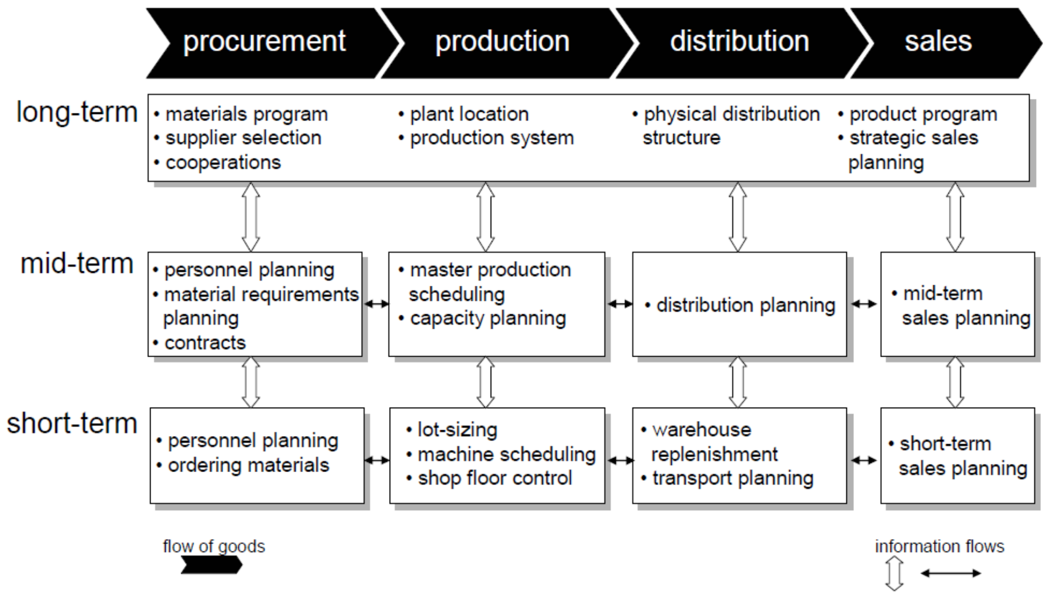

Figure 1.2. Different types of decisions in managing a supply chain (Fleischmann et al., 2002)

At the strategic (or long-term level), a company decides about the design and structure of supply chain over the next several years (Chopra and Meindl, 2007; Fleischmann et al., 2002). These decisions include the location and capacities of production and warehouse facilities, the products to be manufactured or stored at different locations and sometimes the supply channels.

For mid-term decisions, the time frame is a quarter to a year. These decisions are constrained by strategic decisions for a supply chain. For instance, based on the configuration of the network, a supply chain manager must decide which markets will be supplied from which warehouse or production locations, which inventory policies to be followed and how the timing and size of marketing promotions must be aligned with production plans.

In the short-term or operational level the time horizon is weekly or daily. At this level, supply chain configuration and planning policies are already defined. The goal is to fulfill the incoming customer orders in the best possible manner. During this phase, firms allocate inventory or production to individual plans and place replenishment orders for raw materials (Chopra and Meindl, 2007).

The central idea in SCM is that we must have a systemic view about all these decisions and functions and they must be integrated and coordinated in order to improve customer service, cut costs and increase the profit for a company (Chopra and Meindl, 2007). To this aim, a company may possibly collaborate with other actors in the supply chain (e.g., its suppliers).

1.1.2. Four key trends in managing supply chains

Managing supply chains has experienced numerous trends, especially in the last two decades. Globalization of business, outsourcing of internal functions and reducing buffer levels across the chain by Just-In-Time philosophy are examples of typical trends in supply chain management. These trends are concerned with reducing the cost across the entire supply chain and give companies the opportunity to better compete against other players in the market. However, while these trends made supply chains more efficient, they have also made modern supply chains more vulnerable to different disruptions. Some of these important trends and their impact on supply chain risk aspects are discussed in the following sub-sections.

- Just-in-Time

Just-in-Time (JIT) was mainly developed within Toyota manufacturing plants, during the 1970's and it was intended to eliminate all wastes, reduce inventories and increase production efficiency in order to maintain Toyota's competitive edge.

In the JIT philosophy, "waste" results from any activity that adds cost without adding value, such as the unnecessary moving of materials, the accumulation of excess inventory, or the use of faulty production methods that create products requiring subsequent rework. To reduce the waste, the basic premise of JIT is that all materials and products must become available when they are needed (van Weele, 2002). In other words, JIT implies that nothing is produced if there is no demand. The production process

is in fact “pulled” by the demand of downstream customers. The “customer” is actually the organizational entity which is “next-in-line”. It can be another process further along the production line or the external customers, outside the organization.
The other characteristic of JIT is related to the quality aspects. With no buffer of excess parts and smaller batch sizes in JIT, it is necessary to detect the quality defects at an early stage. To achieve this, JIT suggests the “quality at source”; each operator is responsible for the quality of his work and if a particular part does not meet the specifications, the operator immediately notifies the previous link in the production process (Waters-Fuller, 1995).

With JIT, the stock levels for raw materials, work in progress and finished products – and accordingly, the operating costs - can be kept to a minimum. Likewise, storing less material reduces the need for investment in storage space. Therefore, the capital tied up in stock is reduced and the profit and return on investment will be improved. Improving product quality, reducing complexity, preventing over-production and reducing production/delivery lead times are examples of other benefits of JIT (Fullerton and McWatters, 2001). However, in the context of supply chain management, a close relationship with suppliers, effective communication across the supply chain, reliable transportation and logistics and quality/delivery performance of suppliers are some of the main pre-requisites for successful implementation of JIT (Taylor, 2001; Kannan and Tan, 2005). Moreover, JIT exposes businesses to a number of risks, especially those originating from the supply base. With no buffer, a disruption in supplies from just one supplier can force production to shutdown at very short notice (Sodhi and Lee, 2007).

- **Outsourcing**

Outsourcing refers to the strategic decision to shift one or more of an organization’s activities to a third-party specialist (Browne and Allen, 2001).

Traditionally, many companies carried out a wide range of activities internally. This resulted in the development of large, vertically integrated manufacturing and retailing organizations which had the capability to perform all activities with internal resources. However, starting in the 1990’s, a new paradigm emerged emphasizing that an organization should identify its “core competencies”[1] and commit the resources to these competencies. All non-core activities must be outsourced to third party service providers.

[1] “Core competencies” are activities and skills in which the organization has long-term competitive advantage (Tompkins et al., 2005). These competencies are mostly activities that the organization can perform more effectively than its competitors, and which are of importance to customers and tend to be knowledge-based rather than simply depending on owning assets.

For example, there has been a significant trend towards logistics outsourcing in the last two decades and many third party logistics (3PL) companies have been formed that offer a wide range of services from freight transport handling and warehousing services to product and package labeling (Browne and Allen, 2001).

Outsourcing has many benefits for the outsourcer; it helps firms to reduce fixed capital invested in in-house capabilities and decrease operating costs (due to economies of scale, specialization of contractors and lower labour rates for third party operators). In addition, with a focus on core competencies, companies have the opportunity to improve their service level and create better value for their customers. Some other factors like greater flexibility in terms of supply chain reconfiguration and access to latest technology and skilled people without actually employing them might also motivate a company to outsource some of its internal functions (Browne and Allen, 2001; Johnson et al., 2006). However, from a risk perspective, outsourcing creates new risk factors and also influences the resource availability to manage disruptions as will be discussed later in this chapter.

- **Global Sourcing**

To increase the economic competitiveness and in order to seize the opportunities in the global marketplace, an increasing number of companies have started combining domestic and international sourcing as a means of achieving a sustainable competitive advantage (Johnson et al., 2006). This practice is mostly referred to as global sourcing.[1]

The motivations behind global sourcing are many and vary according to specific cases. However, the primary factor and the most frequently cited reason for pursuing a global sourcing strategy is cost saving and access to cheaper resources (Johnson et al., 2006). Meanwhile, unavailability of items domestically, access to technical expertise of local suppliers and exploiting new potential markets might also trigger the sourcing of parts and components from foreign suppliers (Bozarth et al., 1998; Johnson et al., 2006). Moreover, global business helps companies to better handle local trade regulations and restrictions.

Despite its benefits, global sourcing may result in some managerial challenges. Longer lead-times, higher logistics and transport costs, cultural differences and communication/coordination issues are some of the problem areas frequently discussed

[1] Several other terms like ‘global procurement’ and ‘international sourcing’ are also often being used synonymously with global sourcing in the literature (Holweg et al., 2010).

for global sourcing (Johnson et al., 2006; Holweg et al., 2010).[1] Moreover –as discussed later- global sourcing creates new risks in a supply chain.

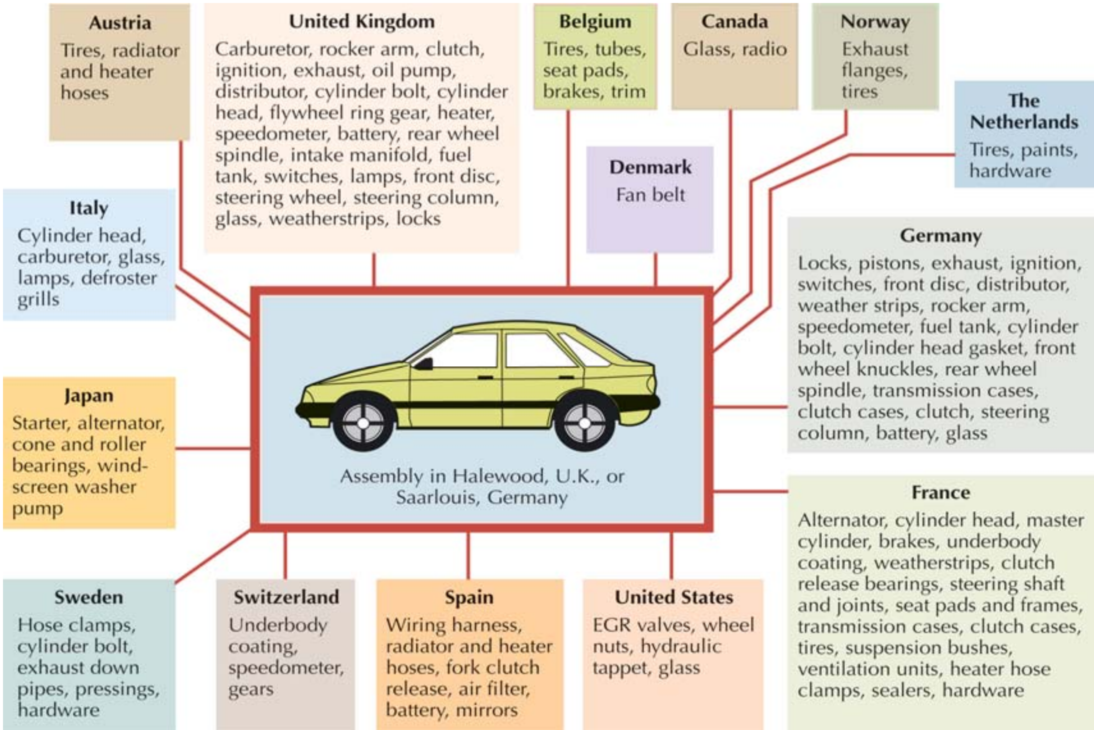

Figure 1.3. An example of global sourcing in supply chain (Daniels et al., 2004)

- Supply-base Reduction

Another trend which has been observed in the last decades is reducing the number of suppliers that an organization utilizes (Ogden, 2006).[2] For example, from 1989 to 1993, Chrysler reduced its production supplier base from 2500 companies to 1114 (Baldwin et al., 2001); similarly, Sun Computer Systems reduced its supplier base from 100 suppliers in 1990 to 20 in 1995 (Goffin et al., 1997).

[1] The other factor that is being discussed as a main challenge is the incompatibility of just-in-time (JIT) and global sourcing (Holweg et al., 2010). The key conflict is because of lack of buyer–supplier proximity, as JIT places the most emphasis on the delivery of small quantities in frequent intervals, whereas the large distance of global sources calls for transportation in large batches (e.g., to achieve the economies of scale in transportation). Moreover, longer transportation roots will impact the reliability of raw material delivery and accordingly the effectiveness of JIT. As an illustration, "Toyota … demands that the main suppliers have production plants within a radius of 30 kilometer!" (van Weele, 2002, p:224).

[2] The issue of supply-base reduction is also discussed as "single vs. multiple sourcing" in the literature (Burke, 2007). The term "supply base rationalization" is also sometimes used interchangeably—and incorrectly—with "supply base reduction". Supply base rationalization mostly consists of two phases: (1) Determination of the optimum size of the supply base and (2) Identification of those who should constitute this base (Sarkar and Mohapatra, 2006). Consequently, rationalization of supply base may result in an expanded or contracted supply base depending on the number of existing suppliers.

Generally, JIT purchasing is seen as a major factor behind supply base reduction (Monczka et al., 2009). By reducing the number of suppliers in the supply base, the buyer can devote its effort to build better and stronger relationships with remaining suppliers. Moreover, having additional suppliers is typically considered as a source of waste incurring more administrative and transaction costs. A reduction in supply base, however, creates several problems. Firstly, the cost savings may not last on the long term, especially because suppliers may increase prices and decrease service as they realize that the buyers are in dependent relationships (Cousins, 1999). In addition, reducing the number of suppliers (and specially, single sourcing) increases the dependency on the supplier's capacity and capabilities (e.g., in developing new products) and reduces flexibility in the supply chain (Choi and Krause, 2006). Consequently, failure in the single source of supply for a critical component may result in the temporary shutdown of manufacturing plants, with severe financial impacts.[1]

1.1.3. Riskier supply chains

The aforementioned trends in supply chain management - no matter how well intended - put most companies in a riskier situation.[2] This is, firstly, because companies have to deal with more risk factors in their supply chains and secondly, due to faster propagation of risk impact in the network.

- **More risk sources in supply chains**

In comparison with the traditional business, supply chain managers face more risk factors. Most of these new risk factors have been triggered by globalization of business and outsourcing.

Before the globalization of economy, some types of risk factors such as exchange rate fluctuations, social instability and even natural disasters were considered as local or regional events. However, with global trade, a disaster in a specific place in the world is not local anymore; it can easily influence many companies working far from the originating regions and countries. Just two recent examples; the terrifying pain of Tōhoku earthquake and the destructive tsunami afterwards, has not only felt by many local Japanese plants but also across supply chains of many international companies (like Toyota, Sony, GM and Apple), even in other continents (Behdani, 2011). Not long after

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[1] As an example, in the well-documented case of "fire in Philips plant in Albuquerque", the major semiconductors supplier for Nokia and Ericsson, Ericsson's single-source strategy caused it to lose over $400 million in potential revenue (Tomlin, 2006).

[2] This challenge is called the "threat of Over-optimized Supply Chains" by World Economic Forum in 2009 (Astley, 2010).

that, the worst flooding in Thailand in more than 50 years hit many global automobile and electronics supply chains including Toyota, Ford, Nissan and Sony among many others (Zolkos, 2011).

Some other significant challenges caused by globalization in managing supply chains stem from communication difficulties and cultural differences. For example, cultural differences and the attitude towards food hygiene in China are blamed as one of the main reasons for the increasing rate of product recalls in recent years (Roth et al., 2008). Another challenge is longer lead-time (and consequently, higher uncertainty) in the extended supply chains which has resulted in a critical role for transportation in the global business. As an explicit consequence, another important class of risk has become highlighted in the risk profile of global companies, i.e. transportation risk.[1]

Besides globalization, outsourcing has created several new types of risks. The possibility of opportunistic behavior for participants with different and even conflicting goals is an example of these new risk factors (Kavčič and Tavčar, 2008). Another risk originating from outsourcing is the "intellectual property risk”. Inadequate regulation in some of the host countries might even intensify the issue (the Economist, 2008).

- **Faster risk propagation in supply chains**

In addition to new types of risks introduced by cost-efficiency trends in supply chain management, disruption in one specific part of a global supply chain can ripple down the chain much faster nowadays. In fact, due to JIT and supply-base reduction, there are very limited buffers in different tiers of supply chains to bear the impact of a disruption. As a result, the adverse effects of an initiating event spread quickly to the downstream of a supply chain and practically, there is little time for the companies to find appropriate response solutions to handle the abnormalities (Sheffi, 2005a). In addition, because of outsourcing and fragmentation of management in the chain, the decision-making process for handling disruptions is slower than before.

- **Less resources to handle risky situations**

Increasing risk factors in supply chains and the rapid propagation of disruption impacts in the network (because of high level of interdependencies and lack of buffer), are not the only undesirable effects of modern trends on supply chain operation; the access to the resources needed to manage the risks has also become more limited due to the aforementioned trends. Firstly, implementing JIT resulted in eliminating many, if not all,

[1] A survey by PRTM found that companies consider on-time delivery of critical products as well as overall product/supply availability as major risks when globalizing their supply chain (Cohen et al., 2010).

Box 1.1- Practitioners' View on Supply Chain Risk

Many reports – which studied the practitioners' point of view on disruptions in supply chains - have confirmed the increase in riskiness of the supply chains for most of companies. Almost two third (65%) of about 3000 executives surveyed in 2006 McKinsey & Co. Global Survey of Business Executives reported that their firm's supply chain risk had increased over the past five years (during the 2001-2006 period) (McKinsey & Company, 2006). In 2008 report, the situation is even worse when 77 % of respondents believe that the degree of risk their companies must face in the supply chain has increased in past five years (McKinsey & Company, 2008).

Another study by Lloyd's in association with the Economist Intelligence Unit in 2006 shows that over a one-year period, one in five companies suffered significant damage from failure to manage risk and more than half experienced at least one near miss (Lloyd's and the Economist Intelligence Unit, 2006).

Finally, in a most recent survey published by Zurich Financial Services Group and Business Continuity Institute (BCI), 85% of companies reported at least one supply chain disruption over the last 12 months (Zurich Financial Services Group and Business Continuity Institute, 2011). Respondents to this survey were from 62 countries and 14 different industry sectors.

types of buffers –in different forms like finished goods, work-in-process and raw materials inventory- in the supply chains. Consequently, when disruptions occur, a company has little resources and alternatives to handle the shocks and abnormalities. Additionally, by outsourcing, most companies have lost the control of the resources and also the visibility[1] across their supply chain (Zsidisin et al., 2005). This loss of control and visibility - that is reflected in the uncertainty about the state of the supply chain - affects the companies' ability to detect disruption and have a full image of the situation. Furthermore, it limits the degrees of freedom which companies have to cope with abnormalities in their supply network.

1.1.4. Solution: *Passively* avoiding the trends or *Actively* managing the risk?

The business for supply chains is riskier nowadays and the resources needed to handle abnormal events are scarce and distributed among different actors; the explicit

[1] Visibility is the ability to see information at different points and track the status of supply chain when required (Mangan et al., 2009). The access to timely, complete and accurate information is a necessity in making decisions in different steps of a supply chain.

consequence of this situation is higher impact on the smooth operation of supply chains.[1] However and despite the influence of disruptions on supply chain performance, customers constantly demand a higher level of service which includes higher reliability and near-instantaneous delivery of products. This puts companies in a challenging position.[2] To handle this challenge in managing supply chains, two options might be considered:

- the *passive* option in which companies avoid the aforementioned supply chain strategies (e.g., JIT, global sourcing or outsourcing) as they have made supply chains increasingly vulnerable; and
- the *active* option in which companies acknowledge the risks imposed by cost-efficiency trends to the supply chain operation; but, at the same time, try to manage the risks in a systematic way.

Despite many criticisms highlighting the growing vulnerability of supply chains, the value of global sourcing, JIT and outsourcing in the daily business of companies – especially in a stable environment and normal conditions- is so significant that for most supply chain managers, the *active* option is the first –and perhaps, the only- choice. In that case, a highly-relevant question is:

> *"How can disruptions be systematically handled in supply chains?"(Research Question 1)*

Companies need a framework that guides them in their efforts to handle disruptions. Such a framework would define the necessary steps that must be followed to identify potential disruptions, define preventive measures and react to a disruption as it happens. Moreover, it must describe how all these steps are inter-related and how they support each other in an organized way.

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[1] The negative effects of a vulnerable Supply chain on the short-term and long term performance of focal companies are also confirmed by empirical studies. Based on a large sample - 519 glitches announcements made during 1989 to 2000- Hendricks and Singhal (2003) underscore the impact of disruptions in supply chains on the shareholder value (Hendricks and Singhal, 2003). The message is alarming: on average "supply chain glitch announcements are associated with an abnormal decrease in shareholder value of 10.28%". In another work, based on a sample of 885 supply chain events announced by publicly traded firms, they showed abnormal events have a significant negative impact on operational performance, and profitability of focal company as well. For example, on average, firms that experience disruptions reported 6.92% lower sales growth and10.66% higher growth in cost (Hendricks and Singhal, 2005).

[2] Based on interviews with nearly 400 supply chain executives worldwide, IBM reported five major challenges with which companies struggle (IBM, 2010). "Supply Chain Risk" is indicated by respondents as the second important challenge which "impacts their supply chains to a significant or very significant extent."

Box 1.2- Practitioners' View: Lack of Formal Frameworks for Supply Chain Disruption Management

A research study conducted in September 2007 by Aberdeen Group from 225 companies with global supply chains shows that 60% of these companies did not have a formal framework for addressing disruptions in their supply chains, despite being highly concerned about supply chain risk (Aberdeen Group, 2008).

Another study of 110 North American risk managers in 2008 by Marsh Insurance Company in cooperation with Risk& Insurance magazine finds that 73% of managers believe their supply chain risk has risen since 2005; however, only 35% considered their companies to be "moderately effective" at managing supply chain risk (Marsh Inc., 2008). Nearly two-thirds (65%) characterized their supply chain risk programs as having "low" or "unknown" effectiveness, or they lacked any formal supply chain risk framework.

Adopting a systematic approach by companies is key to their success in managing disruptions; yet, informed decision-making in handling supply chain disruptions can be very challenging and calls for decision-making tools- as discussed in the next section.

1.1.5. The necessity of modeling and simulation in managing disruptions

Even with a disciplined process in place, managing disruptions in supply chains may face two main difficulties which necessitate developing modeling and simulation tools.

The first difficulty is evaluating the overall impact of disruptions on the supply chain performance. This can be a major challenge as the modern supply chains are highly complex systems, in which many actors with many forms of interdependencies (physical/social/informational) are working in parallel to deliver the right products, in the right quantity, at the right place, at the right time, in a cost effective manner to final customers (Chapman et al, 2002). Because of the high level of dependencies and interactions among different entities in the chain, a disruption in one part of a supply chain is rarely local; it may spread through the system and affect other elements of that network and the system's overall performance. For example, a shutdown in one supplier can affect the production of one manufacturing plant and other customers in the downstream of a supply chain. In addition, if this plant is part of a multi-plant enterprise, this abnormal event would -directly and indirectly- affect other plants and the enterprise as a whole. Defining appropriate policies in managing supply chain disruptions requires an overall understanding of this system-wide impact of disruptions which cannot be captured without appropriate modeling and simulation tools.

The other challenge in managing supply chain risks is that supply chain disruptions can occur for a wide variety of reasons such as industrial plant fires, transportation breakdown and supplier bankruptcy. Likewise, many possible approaches can be used to handle a specific type of disruption. For example, to handle the risk of supplier failure, multiple sourcing (Tomlin, 2006), extra inventory carrying (Wilson, 2007) and demand management (Stecke and Kumar, 2009) are some of the possible actions suggested in the literature. As another example, buffer storage in the supply chain is frequently mentioned as a generic method to reduce the risk of supply chain disruptions, but the amount of buffer and the place in the supply chain to put that buffer is not a trivial issue (Mudrageda and Murphy, 2007). Consequently, although the literature on supply chain risk management is full of different strategies to manage the risk[1], the adoption of those generic methods for specific cases calls for proper decision-making tools and modeling approaches. Subsequently, a company can make a model of its own supply chain, formulate many experiments related to potential disruptions in its own supply chain, study the performance of supply chains under different scenarios and find effective strategies to handle the effects of possible disruptions. The relevant question can be:

> *"How can appropriate models be developed to support better-informed decision-making in handling supply chain disruptions?" (Research Question 2)*

An appropriate model in this thesis is a model which can adequately reflect the main characteristics of a supply chain. These characteristics include the socio-technical complexity of a supply chain – as discussed in detail in Chapter 5 of the thesis. Moreover, the modeling framework must be flexible to model different types of supply chain disruption and disruption management practices.

[1] An overview of different methods presented in managing supply chain disruptions and the important aspects discussed in the literature is presented in the Chapter 4.

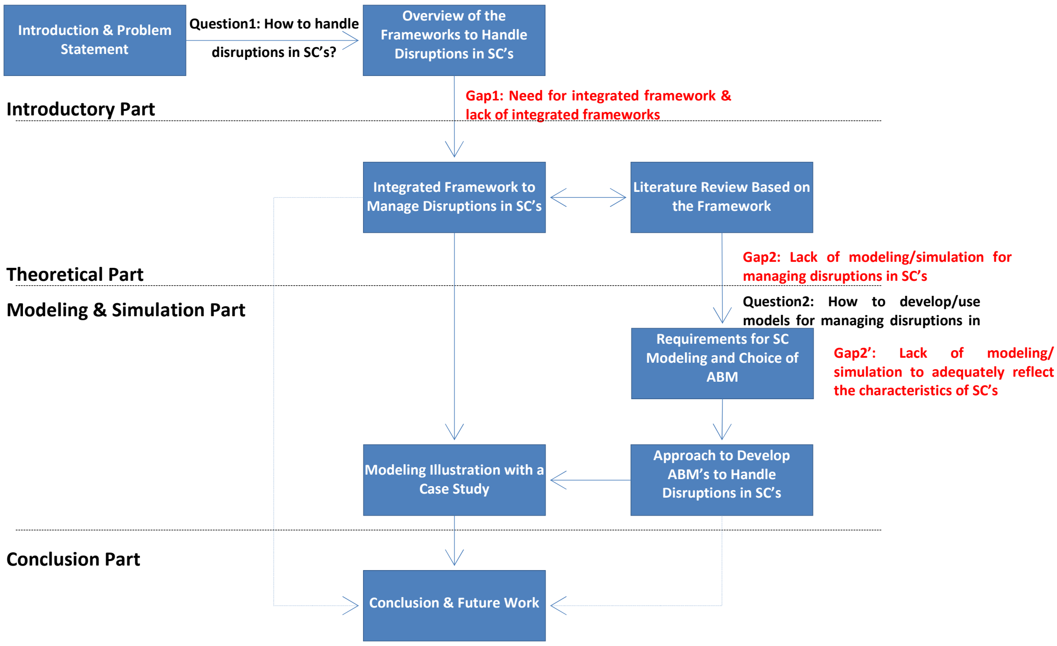


Figure 1.4. The story-line of this thesis

1.2. Research objectives and thesis storyline

This thesis is dedicated to answering two aforementioned questions. Therefore, there are two specific objectives for this research[1]:

RO1: To develop a systematic framework for handling disruptions in supply chains

Handling disruptions in supply chain has been studied form two different perspectives in the literature:

- *Pre-disruption view* which focuses on what must be done before a disruption happens; and
- *Post-disruption view* which focuses on what must be done after a disruption has materialized in the real world[2].

Considering that:

[1] In fact, each research objective is to answer one of research questions.
[2] These two views are discussed in details in Chapter 2 of thesis.

- “in order to systematically handle supply chain disruptions, both views are necessary and important and must be considered together in a comprehensive process for handling supply chain disruptions.”[1]; and
- “currently there are very few frameworks which consider both pre- and post-disruption process to handle supply chain disruptions”[2]

an "Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)" is presented and discussed in this thesis to fulfill the first research objective.

RO2: To develop a modeling approach to support the decision-making process in handling supply chain disruptions

Considering that:

- “there are very few simulation works to support decision-making for handling supply chain disruptions"[3]; and
- “global supply chains are characterized by both technical and social complexity which must be reflected in the supply chain simulation”[4]

an Agent-based Modeling approach to support decision-making for handling supply chain disruptions is presented. This modeling approach describes how different disruptions, possible disruption management responses and also the supply chain entities can be conceptualized in an agent-based model. Subsequently, the developed agent-based model can be used to formulate many what-if scenarios related to different types of disruptions, study the performance of supply chain under different scenarios and find effective strategies to mitigate the effects of possible disruptions and react to real disruptions when they happen.

1.3. Outline of the thesis

The rest of this thesis is organized as follows:

[1] This statement will be discussed with an extensive argument in Chapter 2 and also evaluated based on expert view in Chapter 3 of the thesis.

[2] This statement will be elaborated more and evaluated in Chapter 2 of this thesis.

[3] This statement has been discussed and evaluated in Chapter 4 of the thesis. However, several current studies in the literature also confirm this assumption at this stage of thesis (Buscher and Wels, 2010; Wagner and Neshat, 2011).

[4] This statement will be discussed in Chapter 5 of the thesis.

Chapter 2 discusses the supply chain disruption concept and how it is being handled in the literature. Two main views are described and the importance of both views is elaborated. Moreover, it is also argued that two views in managing disruptions should not be regarded as separate, independent processes. Rather, they must be seen as integrated and interconnected cycles that give feedback to and receive feedback from each other. Then, a review of the existing frameworks for managing supply chain disruptions in the literature is presented. This overview shows that developing integrated frameworks has not received the adequate attention.

Chapter 3 describes the framework presented by this thesis: the "Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)". Firstly, the process of developing framework is discussed. Then, the framework steps and sub-steps are described. The evaluation of framework through expert view is discussed afterward.

Chapter 4 is a review of the literature on the supply chain Risk/Disruption management. The classification scheme is the integrated framework discussed in Chapter 3. Accordingly, for each step in the framework, the key aspects and specific methods are presented. By analyzing the current literature, two main observations are discussed. One of these observations is lack of quantitative approaches to support decision-making in managing disruptions in supply chains. This lack of quantitative methods is the motivation for the rest of thesis which is developing models to support managing supply chain disruptions.

Chapter 5 describes the appropriate simulation paradigm for handling supply chain disruption. Firstly, a supply chain is described from a complex socio-technical perspective. Then, the major simulation paradigms used for modeling supply chains are discussed and critically evaluated. Subsequently, the use of Agent-based Modeling (ABM) is justified for modeling supply chains. Finally, a review on supply chain simulation literature is presented.

Chapter 6 presents an agent-based modeling approach for handling disruptions in supply chain. The conceptualization for the main aspects of research (system, environment, disruption and disruption management practices) is presented.

Chapter 7 provides a case of lube oil supply chain to illustrate the application of modeling framework presented in previous chapter. First, a description of the case is presented. Next, we describe how this case definition can be translated into the model. The developed model, then, will be used in some experimental set-ups to support the decision-making in relevant steps of the InForMDRiSC framework.

Chapter 8 presents the overall conclusion from this research and a discussion of directions for future research.

2. HANDLING SUPPLY CHAIN DISRUPTIONS: TWO DIFFERENT VIEWS

This chapter describes two perspectives on handling supply chain disruptions. The first one focuses on what must be done before a disruption happens (Pre-disruption) and the second view focuses on the necessary steps after a disruption has materialized in the real world (Post-disruption). The importance of both perspectives and the necessity of developing an integrated framework are discussed. Finally, some of main frameworks in the literature are also presented and evaluated.

2.1. Introduction

A supply chain *disruption* is an event that takes place at one point in the chain and can adversely affect the performance of one or more elements located elsewhere in the supply chain and the normal flow of goods and materials within a supply chain (Craighead et al., 2007; Melnyk et al., 2009). The supply chain *risk* is, then, the expected exposure of a supply chain to the potential impact of *disruptions* which is usually characterized by the likelihood of a disruption and the impact of disruption if it occurs (Zsidisin et al., 2005).

Considering a supply chain as a network, a disruption can occur in any node (e.g., a supplier or the manufacturer) or link (e.g., the raw material transportation between supplier and manufacturer) of the chain. The source of disruption may be located inside or outside the chain. For instance, an interruption in the expected flow of materials from a supplier can be because of bankruptcy of the supplier itself or might be caused by catastrophes (e.g., an earthquake) or political events in the supplier's region.[1]

A disruption may impact several performance indicators in a supply chain. The performance of a supply chain is generally analyzed in terms of customer service level (e.g., tardiness, number of late orders), financial aspects (e.g., profit or operational cost) or a combination of both (Beamon, 1999). For example, an emergency shutdown in one of suppliers may delay the order delivery to customers and also reduce the expected profit. The impact of disruption, however, is not always immediate; it sometimes takes

[1] In addition to inside/outside or internal/external classification of disruption sources, some other classifications are presented which are discussed further in Chapter 4.

time for the abnormality to show its full impact on the system performance (Figure 2.1). Besides, a disruption may have a long-term impact on the company. For example, if customer relationship or company reputation is damaged, the impact of disruption can be long-lasting and difficult to recover (Sheffi, 2005a).

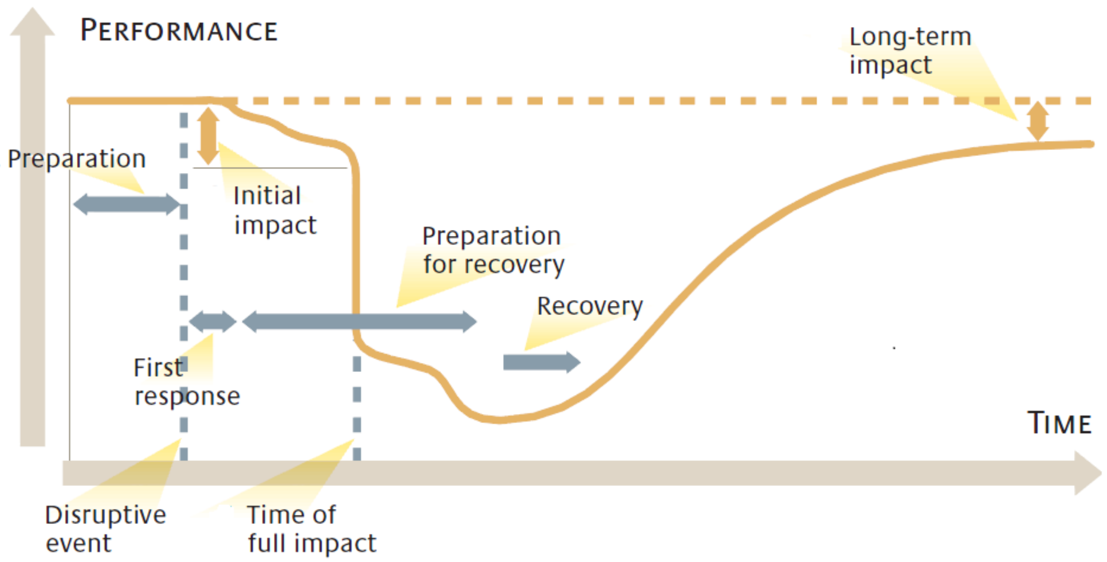


Figure 2.1. The impact of supply chain disruption on the performance (from Sheffi and Rice, 2005)

2.2. Handling disruptions in supply chains- two common perspectives

Handling disruptions in supply chains can take different forms and include different types of activities. From a "time perspective", all these activities can be classified into two major categories: "Pre-Disruption" vs. "Post-Disruption" (Figure 2.2). The two distinctive views on handling disruptions are also called "Prevention" vs. "Response" (Dinis, 2010; Thun and Hoenig, 2011). Some activities and measures are taken by companies to minimize the exposure to potential disruptions. However and despite all the efforts, disruptive events[1] might happen and their impact on supply chain operation must be managed to restore the system to its normal conditions. Another classification used for similar purpose is "Proactive (Predictive)" vs. "Reactive" (Dani and Deep, 2010). In this classification, proactive risk management refers to taking precautionary measures to

[1] Through whole this thesis, we use terms “disruption” and “disruptive event” interchangeably. With both terms we imply the definition presented in section 2.1.

tackle the risk of disruptive events while reactive refers to reacting once an event materializes.[1]

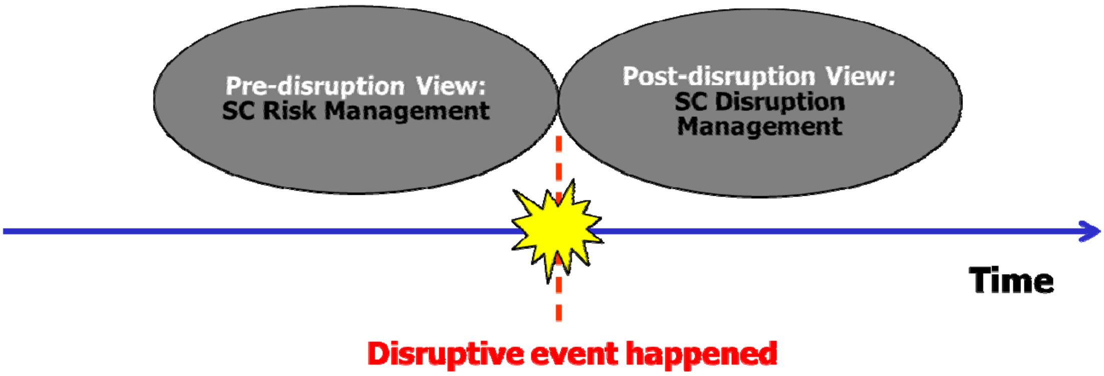


Figure 2.2. Two views on handling disruptions in supply chains

Despite the different classifications, managing supply chain disruptions might be supported by systematic approaches to:

- Identify potential disruptions and recognize/invest in the resources needed to manage them in advance.
- Use the available resources to manage disruptions when disruptions happen.

The former is broadly recognized as *supply chain risk management* (Finch, 2004; Hallikas et al., 2004; Tang, 2006b; Ritchie and Brindley, 2007) or *supply chain risk analysis* (Sinha et al., 2004) which primarily deals with pre-disruption activities (e.g., identification, assessment and mitigation of potential disruptions). The latter is usually called *supply chain disruption management* (Yu and Qi, 2004; Blackhurst et al., 2005) or *abnormal-situation management* (Adhitya et al., 2007a) and focusses on the necessary support in handling an actual disruption after it has materialized.

2.3. Importance of both views in handling supply chain disruptions

For effectively managing disruptions in supply chains, both views are crucial and need to be addressed.

[1] The " Proactive/Reactive" classification can be, however, a confusing classification because as companies might be proactive in eliminating or minimizing the risk in the supply chain, they can also proactively invest in capabilities providing support in handling disruptions after they happen. As an example, a company might proactively design disruption learning procedures which are used solely after a disruptive event happens and it is managed by company. Thus, classifying the activities and capabilities to "Pre-disruption/Post-disruption" or "Prevention/Response" better illustrates the time-related distinction between different activities in managing disruptions.

By investing in risk prevention, many problems can be avoided and companies will face less number of disruptive events. Moreover, without plans and necessary resources the disruption management process – when a disruption happens in the real world - would be very slow.

However, for many reasons, no company can eliminate or even have plans for every possible disruption. First of all, some disruptions are not known beforehand. For example, the ash cloud from an erupting Icelandic volcano, Eyjafjallajökull, in 2010 – and its impact on airport operations in Britain - or the earthquake and tsunami in the Fukushima region of Japan in 2011, is not the kind of event that most companies expected and have included in their risk profile. Even for disruptions that companies expect, they cannot afford to invest in the resources necessary to prevent each one. Consequently, it is neither possible nor economically sensible to invest for every disruption in advance. Of course, for those disruptions that a company can't or don't prevent, more attention must be paid to the response side of the disruption management process. For instance, for rare events like an earthquake, companies would prefer to have a contingency option, as related costs are incurred only in the event of a disruption (Tomlin, 2006).

In addition to the aforementioned issues, having well-designed plans and effectively executing these plans when a disruption occurs are two separate issues and require different sets of capabilities (Xiao et al., 2007). In other words, having response plans and putting resources in place are not necessarily the guarantee for companies' success in handling disruption; companies must also know "when" and "how" to use the available resources and plans. These capabilities - sometimes called predictive intelligence and real-time supply-chain reconfiguration (Blackhurst, et al., 2005) or smart supply chain (Butner, 2010) - support companies to better utilize the available resources to manage disruptions when they happen. Furthermore, the reliance on static plans for managing disruptions that are inherently dynamic events has also been often questioned (Iakovou et al., 2010). Most response plans are developed based on some assumptions that are seldom reviewed. Indeed, when a disruption happens, the capability to gather accurate information about the event and the state of system and also revising the pre-defined plans based on the information are as important as the response plan itself.

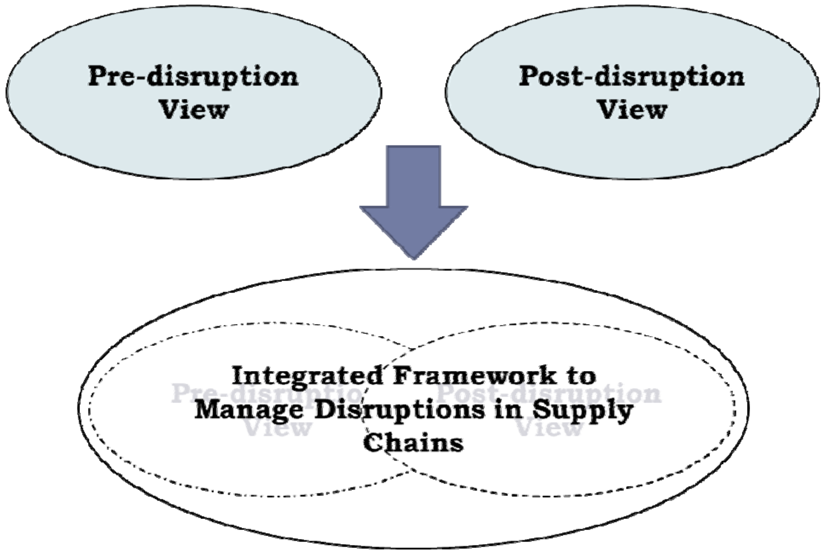


Figure 2.3. From discrete to integrated perspective in managing supply chain disruptions

To sum up, in managing a disruption, what companies do before and after its occurrence are both important. Meanwhile, it is emphasized that these two views should not be considered as mutually exclusive alternatives (Micheli et al., 2008). Instead, both of them should be implemented and coordinated to achieve the best performance in handling disruptions in supply chains. Moreover, two views in managing disruptions should not be regarded as separate and independent processes. Rather, they must be seen as integrated and interconnected cycles that give feedback to and receive feedback from each other (Pyke and Tang, 2010; Dani and Deep, 2010). This necessity calls for frameworks that present an integrated approach to handle pre- and post-disruption activities (Figure 2.3).

2.4. An overview of frameworks to handle disruptions in supply chains

Table 2.1 shows a review of frameworks presented in the literature for managing disruptions in supply chains. As can be seen, the main focus of the literature is on risk management (pre-disruption) process and little works are presented on disruption management (post-disruption) activities. There is also little research discussing the importance of both views and presenting frameworks consisting of all pre- and post-disruption steps.

Table 2.1. An overview of the frameworks to handle disruptions

Perspective	Article	Steps in handling disruptions
Pre-disruption	Adhitya et al. (2009)	Risk identification, consequence analysis, risk estimation, risk assessment, risk mitigation, risk monitoring
	Cigolini and Rossi (2010)[1]	Risk analysis, risk assessment, risk control
	Finch (2004)	Risk identification, risk analysis, risk reduction-transfer and acceptance, risk monitoring
	Harland et al. (2003)	Map supply network, identify risk and its current location, assess risk, manage risk, form collaborative supply network risk strategy, implement supply network risk strategy
	Hallikas et al. (2004)	Risk identification, risk assessment, decision and implementation of risk management actions, risk monitoring
	Knemeyer et al. (2009)	Identifying key locations and threats, estimating probabilities and loss for each key location, evaluating alternative countermeasures for each key location, selecting countermeasures for each key location
	Manuj and Mentzer (2008)	Risk identification, risk assessment and evaluation, risk management strategy selection, implementation of supply chain risk management strategy (s), mitigation of supply chain risks
	Norrman and Jansson (2004)	Risk identification, risk assessment, risk treatment, risk monitoring, incident handling, contingency planning
	Oehmen et al. (2009)	Risk identification, risk assessment, risk mitigation
	Sinha et al. (2004)	Risk identification, risk assessment, risk planning and solution implementation, conducting failure modes and effect analysis, continuously improvement
	VanderBok et al. (2007)	Risk planning, risk identification, risk analysis, risk handling, risk monitoring
	Wiendahl et al. (2008)	Risk identification, risk assessment, risk control
	Wu et al. (2006)	Risk classification, risk identification, risk calculation
Post-disruption	Adhitya et al. (2007a)	Key Performance Indicators (KPI) Monitoring, root cause identification, rectification strategy proposal, rectification strategy selection (optimization), scheduling and coordination
	Blackhurst et al. (2005)	Disruption discovery, disruption recovery, supply-chain redesign
Integrated	Berg et al. (2008)	*Proactive* supply chain risk management processes: risk identification, risk evaluation, risk management, residual risk monitoring and making contingency plans; *Reactive* supply chain risk handling: incident handling, accident handling and execution of contingency plans
	Pyke and Tang (2010)	3R framework: Readiness, Responsiveness and Recovery

[1] One issue in the supply chain risk/disruption literature is the terminology inconsistency. For instance, while “risk analysis” is used by Sinha et al. (2004) to describe the whole process of managing risks, in other papers it has been used for a particular step in the process. With “risk analysis”, VanderBok et al. (2007) imply assessing the risk factors in terms of the likelihood of occurrence and the estimated impact (which is usually called “risk assessment” or “risk quantification”). For Cigolini and Rossi (2010), however, “risk analysis” is the definition of the system’s boundaries and identifying the risky events (equivalent with “risk identification” step).

Despite differences in the terminology in different frameworks, there is an overall agreement on pre-disruption steps in handling disruptions; the risk factors in a supply chain must be identified, their risk level must be assessed and the necessary treatments must be selected and implemented.[1] Some papers also discuss monitoring the risk level to evaluate the effectiveness of risk treatment. For post-disruption process, the disruption discovery is the first step (Blackhurst et al., 2005). This is partly equivalent with "Key Performance Indicators (KPI) Monitoring"[2] in Adhitya et al. (2007a). After discovering a disruption in the supply chain, the next step in Blackhurst et al. (2005) is disruption recovery. In this step, a company quickly reacts to the disruption and implements solutions to manage the impact of the event and recover the supply chain to its normal operation. The recovery from a disruption is described in more detail in the model of Adhitya et al. (2007a); the possible solutions must be listed (rectification strategy proposal), the appropriate option need to be selected (rectification strategy selection) and – if needed – the existing operations must be re-scheduled and the implementation of selected rectification strategies must be coordinated (scheduling and coordination). Finally, after recovery from a disruption, the supply chain can be re-designed to become more resilient in future (Blackhurst et al., 2005).

One of the few studies presenting an integrated approach to handling disruptions is the 3R framework of Pyke and Tang (2010) which is presented for a specific case of product safety risk (Figure 2.4). Pyke and Tang (2010) discuss that the process for managing supply chain operation "before, during, and after" product recall must include three main stages: "Readiness, Responsiveness, and Recovery". Before a potential recall, the company should implement policies - such as TQM practices and statistical sampling inspection- to improve product safety and reduce the likelihood of having a product recall. It should also prepare the necessary channels in case a recall becomes necessary (Readiness). During the recall, the company should create an action plan which allows a quick response to the problems at hand (Responsiveness). After a recall, the company should take steps to restore its supply chain back to normality (Recovery). Moreover, the company must review the recall procedure and take corrective actions (product design, process control, supplier audits, etc.) to prevent or reduce the likelihood of future product recalls. Pyke and Tang (2010) illustrate their framework with three examples of products

[1] The detailed description of different steps in each of these frameworks is presented in Appendix A. These definitions are, in fact, the basis for developing the integrated framework of Chapter3.

[2] In fact, the performance indicators for a supply chain are monitored by comparing the daily values against their pre-specified limits and generating an alarm, when a sustained deviation is detected Adhitya et al. (2007a).

recalls; one example of poor recall management in Ford's Pinto recall case and two successful product recall processes: Black & Decker's recall of Spacemaker Plus Coffeemaker in the late 1980s and Mattel's toy recall in 2007.

Figure 2.4. The 3R framework for mitigating product recall risk (from Pyke and Tang, 2010)

A major strength of the 3R framework is that it offers a full picture – including both perspectives - of what must be done in managing product safety issues. Moreover, it considers the whole process, in an integrated way, as a closed loop and describes the feedback between "Recovery" and "Readiness" stages. Whereas 3R framework presents compelling evidence of benefit for an integrated approach in handling product safety issues, it is yet difficult to operationalize these concepts since this framework does not present the details of each of three stages and the necessary sub-steps. For example, although they discuss "Readiness", a detailed description of how this "Readiness" must be achieved or implemented is lacking in their work. The other drawback of this model is that the feedback is solely considered from Recovery to Readiness. However, in handling disruptions, it is also possible that "Responsiveness" stage provides feedback for "Readiness". For instance, the difficulties in a rapid detection or rapid response to the product safety problem can give insights to improve the procedures and invest in the necessary capabilities to faster detect a safety issue. Finally, the other limitation of this work is its main focus on a specific type of disruption which is "product safety". Of course, three concepts of the framework are generic; nonetheless, the application of model must be shown with cases of other types of disruptions in supply chains. Despite these issues, the 3R framework of Pyke and Tang (2010) is a valuable work in the supply chain risk/disruption literature because it is the first and single effort in the existing supply chain literature which explicitly discussed the benefits of integrated view for a specific disruptive event and presented a model which accommodates the pre- and post-disruption steps and their relations. These two views are, however, implicitly presented in one other study in the literature too. Based on the European Foundation for Quality Management (EFQM) Excellence Model, Berg et al. (2008) has presented a framework for assessing supply chain risk management programs in companies (Figure 2.5). The basic idea in this framework is that to evaluate the success of efforts of one company in supply chain risk management, we must evaluate the "Capabilities" of a company and the "Results" of the risk management efforts. For example, achieving positive outcomes in managing supply chain risks needs the support of senior management in the firm (Risk Leadership). Therefore, risk leadership in a company is considered as a "Capability" which may result in positive "Results". Similarly, enriching "People" and involving them in the risk management process, defining appropriate "Risk Policy and Strategy" and investing on "Supply Chain Partnerships" for managing risks are considered as other capabilities which put companies in the conditions to achieve the excellent results in the supply chain risk management. The last capability considered in this model is the "proactive supply chain risk management processes" which itself includes five sub-processes: "risk identification", "risk evaluation", "risk management", "residual risk monitoring" and "making contingency plans". Berg et al. (2008) believed that having these capabilities help companies to achieve outstanding results in supply chain risk management. These "Results" are categorized in two classes. The first class is termed "reactive supply chain risk handling" which directly defines the success of risk management process and includes "incident handling", "accident handling" and "execution of contingency plans". In other words, how companies handle incidents/accidents[1] (e.g., the time to react) or how well the developed contingency plans are followed, are measures which determine the effectiveness of risk management programs. The second group of results are called "Outputs" and includes there sub-categories of "achievement of business objectives", "cost of risk and risk management" and "health and safety". Examples of what could be measured are Business Interruption Value[2] or the reduction in insurance premiums (resulting from insurance companies' finding that the risks have decreased).

[1] The term "incident" is used to imply an event with potential undesired impact in the system or loss of operability. It is generally consists of "accidents" - an incident that involves some form of loss to an individual, environment, property, and/or process- and "near misses" - the incidents which have the potential to, but do not result in loss (Phimister et al., 2003).

[2] The Business Interruption Value (BIV) is the measure of financial loss because of a disruption and is usually calculated by the product of gross margin and the time a business needs to recover from a disruption plus extra costs such as idle capacity labor and equipment, inventory carrying etc. (Norrman and Janson, 2004).

Box 2.1- The EFQM Excellence Model

The EFQM Excellence Model is introduced by EFQM (European Foundation for Quality Management) in 1992 and is reviewed and refined every three years; the last version published in 2010. This model is the most widely-used Business Excellence Framework in Europe, with over 30,000 businesses using the Excellence Model to improve their performance. This EFQM Excellence Model is based on nine criteria. Five of these are 'Enablers' and four are 'Results'. The 'Enabler' criteria cover what an organization does and include “leadership”, “policy and strategy”, “people”, “partnership and resources”, and “processes, products and services”. The 'Results' criteria cover what an organization achieves and consist of “customer results”, “people results”, “society results”, and “key performance results”. 'Results' are caused by 'Enablers' and 'Enablers' are improved using feedback from 'Results'. The EFQM Excellence Model can be used for self-assessment to evaluate an organization’s progress towards excellence. It helps organizations to identify current strengths and areas for improvement. It is also used as the basis for assessing organizations in the European Quality Award. (Ref: http://www.efqm.org)

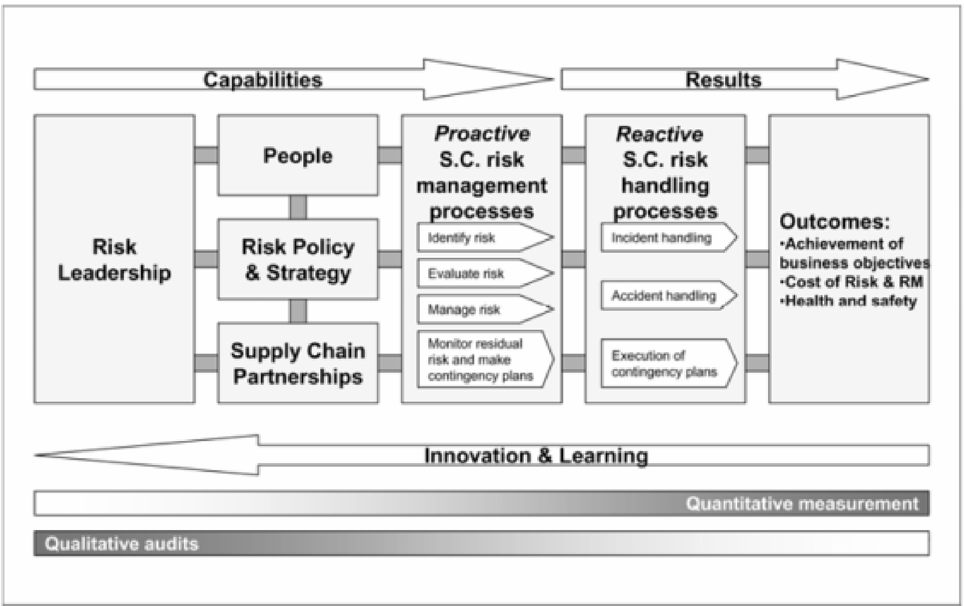


Figure 2.5. Model to assess supply chain risk management programs (from Berg et al., 2008)

Although, the model presented by Berg et al. (2008) explicitly distinguishes between "proactive" and "reactive" aspects, it doesn't go deeply into each step and there is no discussion about the relations and interactions between different parts of the process. This is perhaps because the disruption handling process is only considered as one component in a bigger framework with a basically-different aim – i.e., evaluating the success of supply chain risk management programs in companies. Additionally, the other criticism of work of Berg et al. (2008) is its sole emphasis on pre-disruption "Capabilities"; yet, in the literature many post-disruption "Capabilities" like *Predictive Analysis* – having capability to analyze the available information to perceive when a disruption may happen and how it may impact the supply chain operation - (Blackhurst et al., 2005) or having tools for *KPI Monitoring and Root Cause Identification* (Adhitya et al., 2007a) are discussed for the success of supply chain risk management. These are, in fact, examples of essential capabilities that help companies in achieving significant "Results" in handling supply chain disruptions - like response time reduction or fast reaction to events - and are being ignored by Berg et al. (2008).

2.5. Chapter summary

In this chapter two common perspectives on handling disruption in supply chain are discussed. The first one focuses on pre-disruption activities to prevent disruptions from happening or reduce their risk and the second view highlights the necessary steps for managing an actual disruption when it happens. It is extensively argued that both views are necessary and important and must be considered together in a comprehensive process for handling supply chain disruptions. In summary:

- With investment in risk prevention, companies can reduce the number of disruptions or reduce the severity of their adverse impact.
- Without plans and the necessary resources in place, the disruption management process will be very slow.

However:

- Not all potential disruptions are known to the company and even for known ones, no company can afford to invest enough to mitigate the risk of all possible disruptions.
- Having resources and pre-defined plans does not guarantee success in coping with disruptions; how to use those resources and execute the plans in real-time is also a critical issue.

A review of frameworks for handling supply chain disruptions is also presented in this chapter. This review shows that the current literature on supply chain risk/disruption is mostly about one of above-mentioned views – especially, the pre-disruption view. The first and single effort to integrate pre- and post-disruption views is the 3R framework of Pyke and Tang (2010) which conceptualizes the process of managing product recall in three phases of “Readiness”, “Responsiveness” and “Recovery”. While 3R framework presents compelling evidence of importance of a comprehensive integrated view in managing abnormal situations, the concepts in this framework are difficult to operationalize since no details of each of three stages is presented in their work. Moreover, this framework is primarily developed for a specific type of disruption (i.e., product safety issues). Consequently, a generic framework that incorporates both views and details the pre- and post-disruption steps and their inter-relations is still lacking in the supply chain risk literature. To fill this gap, the "Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)" is presented and discussed in next chapter.

3. HANDLING SUPPLY CHAIN DISRUPTIONS: AN INTEGRATED FRAMEWORK

In this chapter, an integrated framework for handling disruptions in supply chains is presented. This framework incorporates both pre- and post-disruption views on managing disruptions. The integrated framework has been developed based on the existing literature on supply chain risk/ disruption management and evaluated with expert judgement. Different applications for this framework are also discussed in the chapter.

3.1. Introduction

In Chapter 2, the necessity of developing an integrated framework for handling supply chain disruptions has been discussed and some of the efforts to combine pre- and post-disruption management views have been presented. These works demonstrate the significant need and the practical importance of considering both views in handling disruptions in supply chains[1]. Based on the analysis of literature in Chapter 2, this chapter assembles an integrated framework that facilitates a holistic and systematic approach to handle disruptions in a supply chain. This integrated framework, called "Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)", describes the steps which must be followed to handle supply chain disruptions and the relations between different steps. Firstly, the process of developing the framework is discussed. Next, the framework and its steps are described followed by an expert evaluation in section 3.4.

3.2. Framework development process

The integrated framework for handling disruptions in supply chains has been developed based on the existing frameworks as shown in Table 2.1. A detailed description of different steps in each of these frameworks is presented in Appendix A. The frameworks and the definition for each step were carefully studied and the common steps have been combined to derive an initial structure for the integrated framework (Figure 3.1). For the pre-disruption process, *Risk Identification*, *Risk Assessment* and *Risk Control* are the most

[1] Both models presented by Berg et al. (2008) and Pyke and Tang (2010) are developed based on the practitioners' view and the experience of real companies.

prominent steps mentioned in the majority of existing frameworks[1]; the risk factors must be identified, the risk level must be evaluated and the necessary treatments must be chosen and implemented. Two additional steps are also discussed by some authors that were found relevant and included in the framework. Firstly, before starting to recognize the risk factors, we need to define the supply chain boundaries (Harland et al., 2003) and develop an overall plan for the process and actors that might be involved in the process (VanderBok et al., 2007). This is described as "delimitation of scope" by Oehmen et al. (2009) and is considered as part of the risk identification step. Similarly, Wiendahl et al. (2008) suggest that "the first step when identifying risks is to define the system boundary" (Wiendahl et al., 2008, p.426). Hence, in the second revision of the framework, the *Risk Planning* was included as part of the *Risk Identification* step (Figure 3.1). The other step which is discussed by several authors is *Risk Monitoring*[2]. "The company and its environment are not static, and thus also the risk status changes. The recognized risk factors can be monitored to identify the potential increasing trends in their probability or consequences" (Hallikas et al., 2004, p.54). Besides, despite all safeguards to manage disruptive events, a supply chain can never be "totally risk-free" (Harland et al., 2003; Sinha et al., 2004); there is always "Residual Risk" which remains after treatment and must be continuously monitored (Norrman and Jansson, 2004). Considering these arguments, the *Risk Monitoring* step is also an important step and consequently, is included in the revised version of framework. Moreover, by giving feedback to other steps in the framework, the *Risk Monitoring* step makes the pre-disruption process a cyclic and continuous process; by monitoring the environment of business new risk factors might be identified, the risk level for identified risk factors might be updated and the existing risk response plans can be improved (Sinha et al., 2004; Hallikas et al., 2004).

[1] Of course, the exact terminology may differ from one paper to another one.
[2] This step is also termed "continuously improvement" by Sinha et al. (2004).

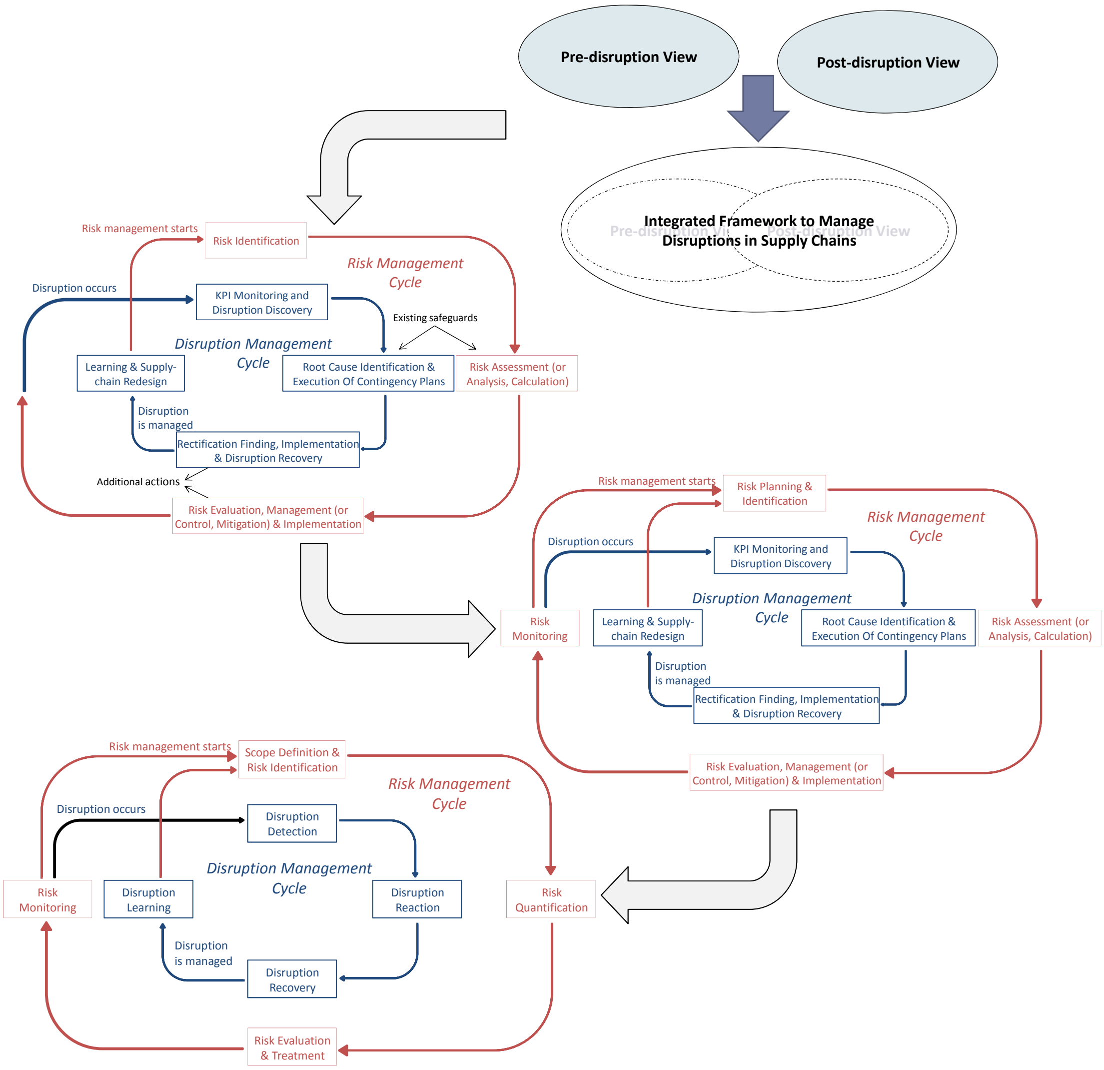


Figure 3.1. The integrated framework development

Similarly, for the post-disruption process, the steps in the available frameworks were studied and incorporated in the initial version of the integrated framework. As a disruption happens in a supply chain, the first step is detecting that disruption as quickly as possible (Blackhurst et al., 2005). For this purpose, “the firm must have in place an effective means of discovering supply-chain disruptions” (Blackhurst et al., 2005, p.4069). This mostly happens by “measure[ing] KPIs and identify[ing] their effect on the supply chain. These KPIs are monitored by comparing their day-to-day values against their pre-specified limits and generating an alarm, when a sustained deviation is detected” (Adhitya et al., 2007a, p.497). Once the disruption is detected in a part of the supply chain, a company must react quickly to manage the impact of disruption and return the system to normal operation (Blackhurst et al., 2005; Adhitya et al., 2007a). The response to a supply chain disruption, may take two different forms. The first response is the execution of response plans which have been pre-defined by the firm (Blackhurst et al., 2005; Berg et al., 2008). For this purpose, the possible cause for a disruption must be identified (Adhitya et al., 2007a). If the first response is found inadequate to control the impact of disruption on the supply chain or if no response plan has been defined for a specific disruption, a "list of corrective actions to rectify the root cause [must be] generated" (Adhitya et al., 2007a, p.497) and the appropriate "rectification strategy [must be] selected" (Adhitya et al., 2007a, p.497) until the system recovers from a disruption (Blackhurst et al., 2005; Pyke and Tang, 2010). After restoring everything back to normal, "management should review the … procedure, so that the company can take corrective actions (product design, process control, supplier audits, etc.) to prevent or reduce the likelihood" of future disruptions (Pyke and Tang, 2010, p.247). This might also include redesigning the supply network to make it more resilient when facing similar disruptions in the future (Blackhurst et al., 2005).

Once the first draft of the framework is created, the main issues in each step are renamed to have the final version of framework as shown in Figure 3.1. The building blocks of this final version are further discussed in the next section.

3.3. Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)

In this section, the structure of InForMDRiSC is discussed. First, a set of definitions which help to better define the framework is presented. Next, the steps of framework are explained in detail.

3.3.1. Some introductory definitions

To discuss the framework, first some introductory definitions and explanations are given.

Definition 1- Supply Chain Disruption: A *Supply Chain Disruption* is an event that might happen in any part of the chain and if happened, it causes undesired impacts on the (achievement of) objective and the performance of supply chain.

As a corollary, if an event has no adverse effect on the achievement of the objectives, it is not regarded as a disruption. This emphasis on the impact on the objectives is essential as it also helps better justify the investment of resources for managing disruptions (Berg et al. 2008).

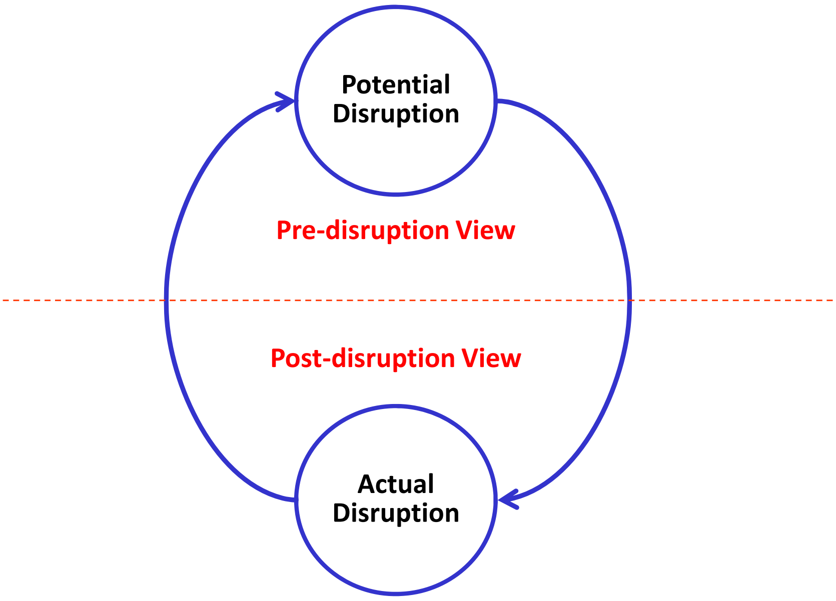


Figure 3.2. Supply Chain Disruption Lifecycle

Definition 2- Disruption Lifecycle: For each disruption in the supply chain, the *lifecycle* with two distinct phases can be considered (Figure 3.2). There is a period of time over which a disruption is latent and only a possibility; it exists basically as a *Potential Disruption*. When an instance of the disruption occurs in reality, it is an *Actual Disruption*.

To best handle a disruption, both phases of the *Lifecycle* must be properly addressed. Each of the two views, which have been already discussed in Chapter 2, focuses on one these two phases; the effort of pre-disruption view are aimed to discover the *Potential Disruptions* and prevent them from becoming *Actual Disruptions*. The main goal of post-disruption view is to handle the *Actual Disruption* once it has occurred and to use that experience to learn so as to avoid, reduce or transfer the risk of happening similar *Potential Disruptions* in the future.

With the definition of *Disruption Lifecycle*, a comprehensive definition for *Supply Chain Disruption Management* can be presented as follows.

Definition 3- Supply Chain Disruption Management: *Supply Chain Disruption Management* is a structured and continuous process to analyze the impact of disruptions across a supply chain on the predefined objectives and to handle these disruptions in their whole *Lifecycle*[1].

Such a systematic process would give insight into the steps that must be followed to better address the capabilities and the resources necessary to handle each *Supply Chain Disruption* in its entire *lifecycle*. For some disruptions, indeed, the main focus might be on pre-disruption capabilities/actions; for others, the main attention might be on the proper response to disruption when it happens.

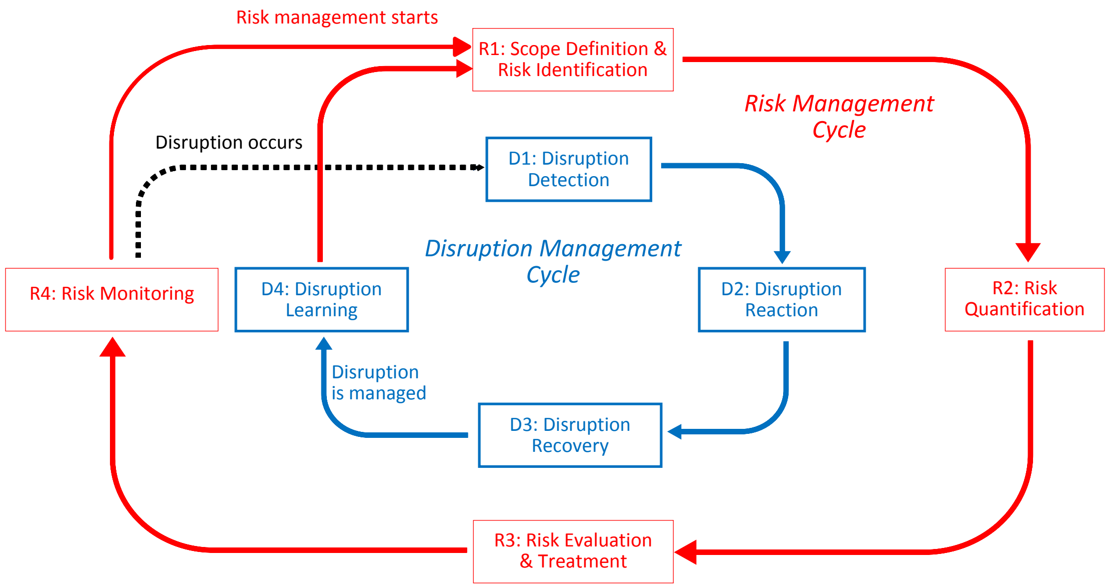


Figure 3.3. The overall structure of InForMDRiSC

3.3.2. The Integrated Framework structure

The overall structure of InForMDRiSC is shown in Figure 3.3. In this framework, managing disruptions is a continuous process with two main cycles. The first cycle – called the *Risk Management Cycle*- is about *Potential Disruptions*. Firstly, the *Potential Disruptions* in the supply chain (or a subset of supply chain that is chosen to study) must be identified; next, for identified disruptions, the risk level is quantified and based on that, the necessary treatments must be provided. When (after treatment) the risks level seems acceptable, supply chain operations proceed. However, the level of risk must be monitored and re-evaluated frequently due to changes in the business environment or within the supply chain.

[1] As can be seen, the main emphasis in this definition is the focus of process on whole *Lifecycle of Disruption*. This point makes the main distinction with traditional definition of disruption management which solely discusses the post-disruption activities.

The second cycle is *Disruption Management Cycle*. Despite enough safeguards, sometime, an *Actual Disruption* will happen. The first step is to detect the event as quickly as possible. The next step is using the resources and pre-defined plans to react to the detected disruption. If the pre-defined plans do not cover the full impact of a disruptive event, alternative solutions should be found to restore the system to normal operation. After recovering from a disruption, lessons should be learned and used in handling similar disruptions in the future. For example, the response plans might be revised or the supply chain might be restructured to reduce the probability or severity of similar disruptions in future.

The steps of the framework are described in more detail in the following subsections.

- **R1: Scope Definition& Risk Identification**

To start the process for handling disruptions, it is important to carefully define the system, delineate its boundaries and give a clear description of the system structure (Wiendahl et al., 2008; Oehmen et al., 2009). The disruption management process might focus on a "Direct Supply Chain" which consists of a company and its immediate suppliers and customers or an "Extended Supply Chain" which includes other tiers in the upstream and downstream of the supply chain (e.g., the suppliers of supplier or the customers of the immediate customer) (Mentzer et al., 2001). For practical reasons, a company may also primarily focus on disruptions happening in a sub-set of the supply chain, e.g., the supply-side or demand-side of the network or the supply chain for some core products. This delineation of the system can be based on the criticality of different parts of the supply chain or the value of different products in the company's portfolio (Norrman and Jansson, 2004).

In addition to the system delineation, the critical objectives and performance indicators must be addressed in defining the scope of study (Oehmen et al., 2009). This is especially important because a supply chain disruption is characterized by its impact on the performance of the supply chain and its objectives. In other words, an event can be included in the list of *Possible Disruptions* if it reasonably impacts one or more performance measures in a supply chain. Profit, cost, market share, order lead-time and customer response time are examples of supply chain performance measures that might be considered in the scope definition. The identified performance measures in this step are the basis for evaluating disruption impact in the next step of the framework – i.e., "Risk Quantification".

When the system of study and the expected consequences are defined, a list of *Potential Disruptions* in the supply chain (or the selected part of it) must be defined for further analysis in the next steps. An extensive list of *Potential Disruptions* can be generated by analysis of past losses, intensive literature review or insurance company checklists. Next, this extensive list might be narrowed down to key *Potential Disruptions* by interviewing employees or meetings with experts (Canbolat et al., 2008; Yang, 2010).

- **R2: Risk Quantification**

For the *Potential Disruptions* identified, the expected impact on the objectives and the performance of the defined system must be evaluated. This evaluation is basically concerned with two main questions; firstly, "how likely a disruption is" (i.e., the frequency/likelihood of disruption) and secondly, "how bad it can be if it occurs" (i.e., severity/impact of disruption) (Harland et al., 2003; Sheffi, 2005a). Moreover, each disruption may influence multiple objectives of a company and consequently, have a range of possible consequences (VanderBok et al., 2007). Determining all these consequences in a complex network of actors and activities can be a challenge for most companies. Accordingly, using modeling and simulation to evaluate the impact of disruption is very much suggested (Wu et al., 2006; Wilson, 2007; Wagner and Neshat, 2010).

Having the likelihood and the expected impact, the risk level for a *Potential Disruption* can be calculated by multiplying these two dimensions (VanderBok et al., 2007). The risk levels calculated for all *Potential Disruptions* are used for deciding whether an identified disruption needs to be treated in the next step of the framework.

- **R3: Risk Evaluation & Treatment**

After the risk levels for all identified *Potential Disruptions* are calculated, the next step is to determine whether the risk level for *Potential Disruptions* is acceptable or mitigation actions and safeguards must be provided. For this purpose, a firm may define a threshold for the acceptable risk level (Harland et al., 2003). For unacceptable disruptions the possible treatment options must be identified. In selecting a safeguard for each of the *Potential Disruptions* several aspects should be taken into account.

First of all, the related costs and gains expected from implementing each treatment action must be carefully evaluated and compared with other options and also with the case of no action (Knemeyer et al., 2009). In addition, investing in risk mitigation measures may provide additional benefits in better managing the day-to-day supply chain mismatches (e.g., protection against demand forecast errors). This impact on the daily operation of the supply chain must be considered in the evaluation of options as well (Sheffi, 2005a).

The second key issue in choosing the appropriate action is the impact of a disruption on other *Potential Disruptions*. Reducing the risk level for one specific disruption may increase the risk level for another one or even introduce new sources of risk. For example, although a deep relationship with suppliers might provide extra resources in the case of an emergency in the chain, it can also increase the exposure of the company to some new types of risk, e.g., intellectual property risks (Choi and Krause, 2006). Another example is carrying extra inventory to reduce the risk of delays, which, on the other hand, incurs much greater inventory-related types of risk such as material out-dating or spoilage (Olson and Wu, 2010). Therefore, the interdependencies among different disruptions can be a crucial factor in making a final decision on selecting the treatment. Moreover, some actions to handle a disruption might change the structure and boundary of the system of study which, consequently, calls for repeating the whole *Risk Management Cycle*. For example, to handle supply-side disruptions, a company may add a new supplier to its supply base; but, this modification changes the system definition and consequently, for the new system –or the parts added to the system- we must start the cycle by identifying new *Potential Disruptions*.

As a last important issue, since some countermeasures may address more than one *Potential Disruption* in a supply chain, it is recommended to consider the whole risk profile of the company – and not single disruptions- in selecting the safeguards (Knemeyer et al., 2009). For instance, carrying extra raw material inventory may reduce the risk of supplier emergency shutdown and also transportation disruption due to a port strike. With this view on risk treatment –that can be called "Holistic Risk Treatment"-, resources invested to mitigate the risk of one specific disruption might be also deployed as alternative solutions for other disruptions.

- **R4: Risk Monitoring**

As *Potential Disruptions* are identified, their expected impact on the system is quantified and the necessary treatments are implemented, a supply chain is ready to continue with its operation. However, for many reasons the risk profile of a company may change over time. Due to changes in the system (e.g., change in customer needs or partner strategies) or in the business environment (e.g., new regulations or new competitors), the likelihood and expected impact of *Potential Disruptions* keep changing (Hallikas et al., 2004; Ravindran et al., 2010). Moreover, the quantification and treatment of identified disruptions can be based on some assumptions that could turn out to be wrong or subject to change. Accordingly, the effectiveness of implemented risk treatment measures must be reevaluated on a continuous basis (Schoenherr et al., 2008). In addition, despite all safeguards to prevent disruptive events, there is always a "Residual Risk" which remains after treatment and must be continuously monitored (Tah and Carr, 2001; Norrman and Jansson, 2004). For all these reasons, a firm must have a dynamic view on managing disruptions in the supply chain and frequently update its risk profile by monitoring the changes in the system and its environment.

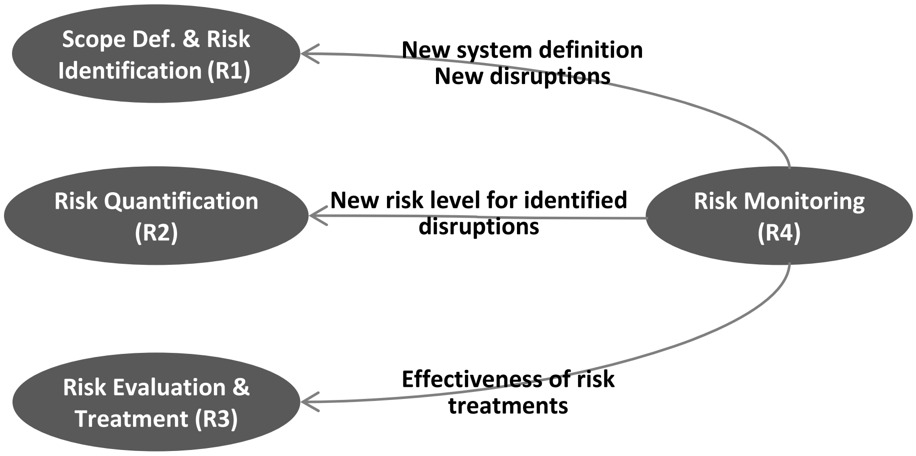


Figure 3.4. The feedback from Risk Monitoring step to other steps in *Risk Management Cycle*

Besides the risk profile, the system boundaries and structure of a supply chain may also change in different ways (VanderBok et al., 2007). For example, a new supplier might be added to the supply base, a new warehouse might be launched or a new set of products might be introduced to the market. As a result of these changes in the supply chain, the system definition –that is the starting point of the whole disruption management process- would change from time to time. Thus, it is imperative to repeat the whole *Risk Management Cycle* by a new definition for the system and identifying the new disruptions. In addition, the risk level for currently-listed disruptions might need to be updated –because of interdependencies between different risk factors.

- **D1: Disruption Detection**

Up to now, the focus of study was on the *Potential Disruptions* in a supply chain but an *Actual Disruption* can occur at any time and impact one or some of the components in the chain. To handle an actual disruption, the first step is detecting the location of disruption, its profile and the expected consequences on the system as quickly as possible.

Detecting a disruption can take two forms. The first case is when an actor can directly observe (or is informed by other partners of) the occurrence of an event in a part of the supply chain (Blackhurst et al., 2005). For example, a supplier may send a message that there is an emergency shutdown in one of its plants which may cause delay in raw material shipment to the manufacturer. After a company is informed about a disruptive event in one part of the supply chain, the first action must be an assessment of the impact disruption on the operation of the supply chain (Blackhurst et al., 2005). This assessment might take two forms. A disruption might push the performance measures out of the acceptable range (Adhitya et al., 2007a; Wilson, 2007) or make the operational plans non-optimal or even infeasible (Qi et al., 2004; Yu and Qi, 2004). Each of these two conditions can be called an *Abnormal Situation* in the supply chain and requires the organization to take response actions to remediate the situation.

In the second type of disruption detection, a firm can see solely the impact of disruptive events on its performance and it needs to explore the cause of deviations observed (Adhitya et al., 2007a). Fining the cause of deviations can be, however, a challenge due to lack of visibility in a supply chain (Christopher and Peck, 2004; Tang, 2006a) and the motives that each player in a supply chain has to hide its internal problems (Williamson, 2008). As an example, there might be frequent delays from a supplier and, with more investigation, the manufacturer may realize that there was an operational problem in one of the plants of a supplier who deliberately hid it. Another example is using banned/unsafe ingredients by suppliers which is traced in the downstream of supply chain which may lead to product recalls (Pyke and Tang, 2010). In such cases, the manufacturer has to test the products to determine which ingredient (and which supplier) may have caused the safety issue.

Once a deviation in the performance is identified, a company must find the main factors that cause that abnormality in the supply chain operation (Adhitya et al., 2007a). The cause of deviation can be one of the *Potential Disruptions* identified in the *Risk Management Cycle* or a new type of disruption which has been overlooked in the *Risk Identification* step.

- **D2: Disruption Reaction**

As the *Actual Disruption* is detected in a part of supply chain, a company must react quickly to manage the adverse effects and return the supply chain to its normal operation[1].

[1] A normal operation for supply chain is characterized when the performance indicators return to the acceptable range.

The primary response to a disruption is on the basis of response plans that are previously defined in the *Risk Evaluation and Treatment* step (Blackhurst et al., 2005). Having a pre-defined plan saves time in reaction to a disruptive event which is a crucial factor in controlling the effects of disruption (Dani and Deep, 2010; Wagner and Bode, 2006). After implementing the response plan, its effectiveness in returning the system to normal operation must be evaluated. If this plan cannot successfully recover the system, it is necessary to continue with the next step – *Disruption Recovery*- to find alternative solutions.

- **D3: Disruption Recovery**

If the pre-defined response plan is found inadequate to control the impact of disruption on supply chain or if no response plan has been defined for a specific disruption, the firms must look for alternative solutions to restore the normal supply network operations. To define alternative solutions, a company must have the capability to estimate the necessary resources to manage disruption (Charles et al., 2010). Meanwhile, finding alternative resources for the *Disruption Recovery* step can start in parallel with the first response in the *Disruption Reaction* step (Sheffi, 2005a). For example, when rescheduling the orders might be a first response to raw material delay from a supplier, qualifying new suppliers and finding customers that might be willing to re-negotiate their due-dates can follow at the same time.

During the *Disruption Reaction* and *Disruption Recovery* steps, monitoring the event by collecting and analyzing information about the disruptive event and the action of other actors in handling the disruptive event is also extremely important. In fact, a disruptive event is a dynamic phenomenon and its state can change frequently (Blackhurst et al., 2005). In addition, when disruptions occur, the actors in the chain may have little or inaccurate information about the state of disruption. For example, the supplier's estimation of an operational problem in one of its production facilities might be biased. Moreover, it might not be feasible for the firms to have all related information in the early stages of disruption (Chen et al., 2010). Accordingly, a supplier which initially announced a shutdown in one of its plants for one week may give an update on the expected time of returning to normal operation. Considering all these aspects, it is imperative for the company to continuously monitor the event, gather information from different sources and exchange information with other actors in the chain. Moreover, with initial information on the scope of disruption, the first response might seem adequate; however, by gathering more information or by updates from other actors in the chain, looking for additional options might be necessary to cover the full impact of disruption.

- D4: Disruption Learning

After a company can manage the *Actual Disruption* in its supply chain and gets back to the normal operation, it must review the process and extract lessons from its handling the *Abnormal Situation*. Firstly, based on the company's experience with a real disruption, the estimation of likelihood or impact of that type of disruption in the risk profile can be updated. Moreover, during handling a specific disruption, new disruptions might be identified that were not known before or being considered as less significant ones (Cheng and Kam, 2008). In addition to updating the risk profile, an *Actual Disruption* in the supply chain gives a company the opportunity to test and verify the response plans with a real case (Norrman and Jansson, 2004). By reviewing the effectiveness of existing plans to handle an *Actual Disruption*, the weaknesses of an existing response plan can be identified and the strengths can be kept or used as a basis for defining improved response plans. Finally, once the company recovers from a disruption, it may decide to redesign the supply chain with the goal of minimizing the probability or impact of similar disruptions in future (Blackhurst et al., 2005). For example, a new warehouse might be added to the current supply network or a new contract might be signed with a local supplier. These modifications in a supply chain imply changes in the system structure and its boundaries and accordingly, it is a necessity to repeat the *Risk Management Cycle* by identifying new *Potential Disruptions*.

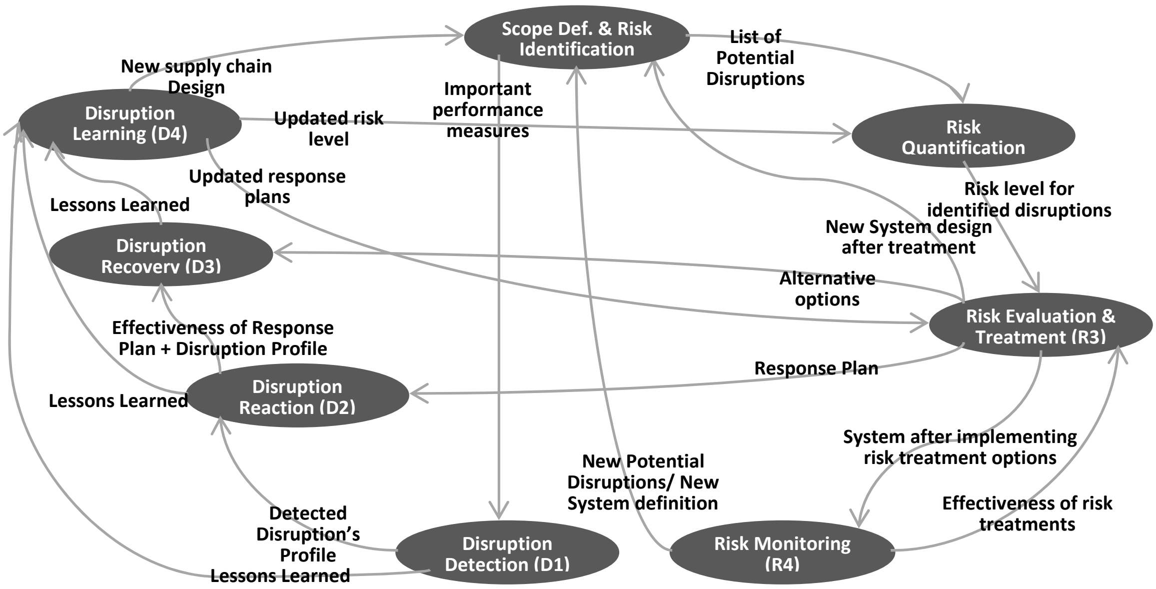


Figure 3.5. The summary of steps and their inter-relations in InForMDRiSC

The steps of the integrated framework and their inter-relations are summarized in Figure 3.5. Moreover, an extended version of the framework in which the description of steps has been formalized and decomposed into several sub-steps is presented and explained with an illustrative case in Appendix C of this thesis.

3.4. Evaluation of framework

To evaluate the structure and applicability of presented framework, we sought domain experts' opinion. Experts in relevant fields -supply chain management, logistics, operations management, warehouse/inventory management and quality control- were asked to assess the integrated framework. The information on background and experience of these experts is presented in the Appendix B and is summarized in Figure 3.6. In total, 33 experts have participated in the evaluation process, sharing their reflections on InForMDRiSC. Most of the experts had experience in more than one field and the majority of them worked in supply chain management, operations management or logistics. Moreover, 77% of the experts had previous experience in managing disruptions in supply chains.

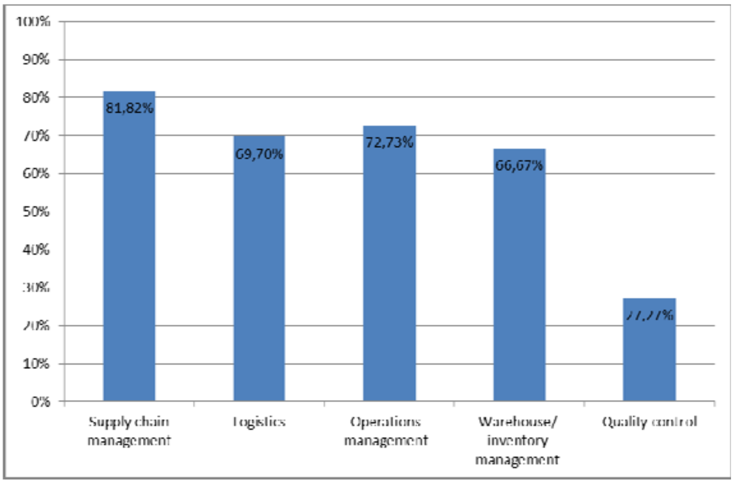


Figure 3.6. The background and experience of experts

To evaluate the framework, a copy of framework description and an illustrative case was sent to experts. In order to reduce the possibility of misunderstandings, we have also conducted meetings (real or Skype meetings) to further clarify the framework structure. Next, the experts were asked to evaluate the 1) clearness and understandability of framework; 2) its usefulness (to give a good understanding of disruption handling process); and 3) its comparative value (in comparison with separate "Risk/Disruption Management" frameworks). These aspects are formalized in a questionnaire and experts were asked to express their view on a 5-point Likert scale:

Box 3.1- Likert scale

Likert scale (named for its inventor, Rensis Likert) is a survey scale which requires respondents to indicate the level of agreement or disagreement with a given statement in an ordinal scale going from most to least agreement (Colburn, 2003). Likert scale is very common in surveys for social science and management studies as it is relatively easy to collect information and the information gathered in the standardized way can be easily compared and analyzed (Taylor et al., 2006). A Likert scale can have any number of response choices; however, an odd number of choices (e.g., 5) leaves respondents the option of choosing a response that is often set up to be neutral. For example, the scale we used in the survey was a 5-point scale with "Strongly Agree", "Agree", "Neither Agree or Disagree", "Disagree" and "Strongly Disagree" scales.

- **Question 1:** Is there a need to have the "Integrated View" (considering pre- and post- Disruption processes together) in managing Disruptions in Supply Chains? (***The necessity of Integrated View***)
- **Question 2:** Is the presented framework clear and understandable for you? (***The clearness of presented framework***)
- **Question 3:** Is this framework useful to you to get a better understanding of disruption handling? (***The usefulness of presented framework***)
- **Question 4:** Does this framework provide a better process to handle disruption than separate "Risk/Disruption Management"? (***The comparative value of presented framework***)

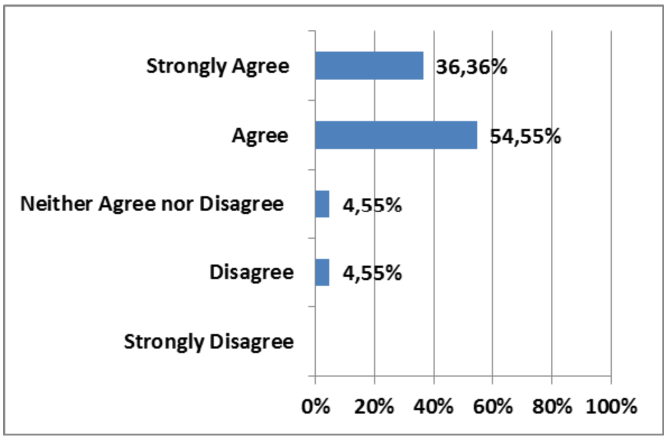
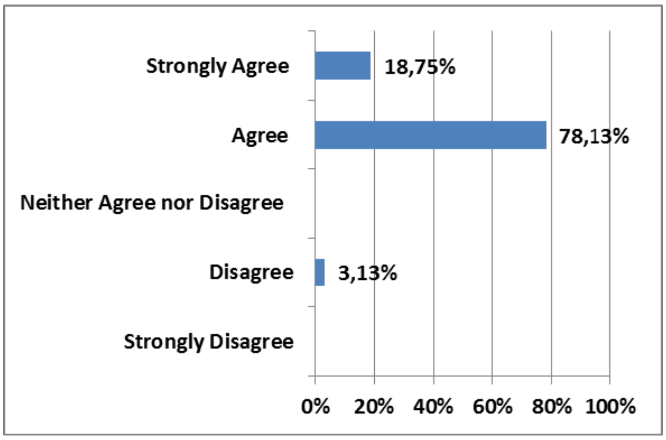
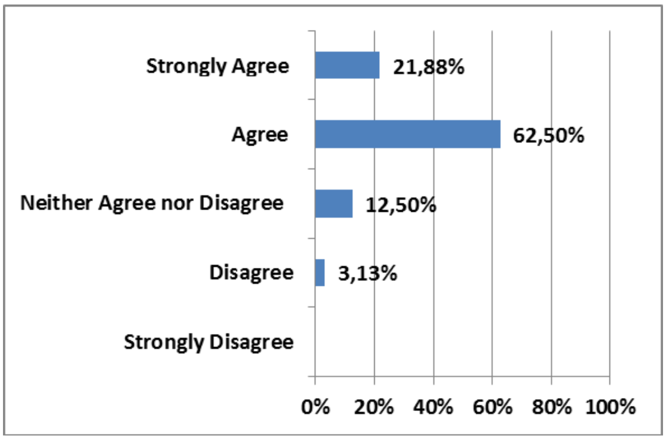


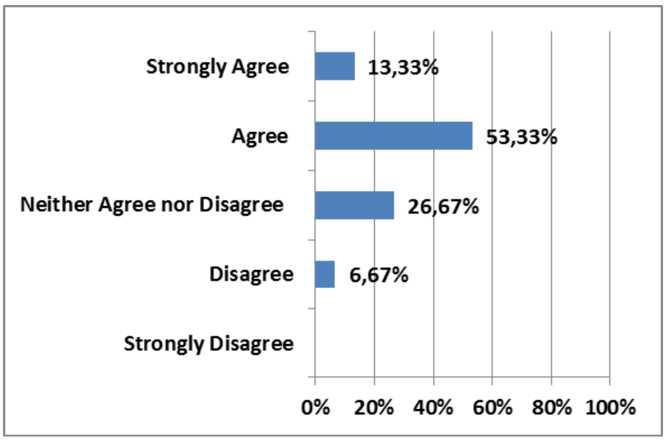
Figure 3.7. The experts' view about the necessity of Integrated View



(a)



(b)



(c)

Figure 3.8. The experts' view about (a) Question 1: clearness of presented framework; (b) Question 2: usefulness of presented framework; (c) Question 1: comparative value of presented framework

The analysis of expert responses shows that:

- The majority of experts (more than 90 percent) believe that an integrated view on managing supply chain disruptions is an important and necessary issue (Figure 3.7). This supports the conclusions in the Chapter 2 of this thesis on the importance of including both views in managing disruptions.
- For more than 96 percent of the consulted experts, the framework was clear and understandable.

  Approximately, 8 out of 10 experts believe that the integrated framework discussed in this chapter is useful to get a better understanding of disruption handling.
- 65 percent of respondents confirmed that this framework provides a better process for handling disruptions than separate "Risk/Disruption Management". 27 percent neither "Neither Agree nor Disagree" with this fact and only 7 percent disagree.

In addition to evaluation of framework, the experts were asked in an open question to inform us about the activities regarding disruption handling in their company (or in the companies they have worked with) that are not addressed in the presented framework. In answering this question, most of experts believe that framework is full complete and no additional step has been suggested to add to this framework. Some experts have also mentioned that the overall concept of InFormDRiSC is a good match with the procedure they follow in their companies. Meanwhile, in the input from experts in answering this open question and also during our meetings, some remarks have been raised which are discussed in detail in the following. These remarks help us to see framework from different viewpoints and reveal potential areas for improving the framework in future research.

- *Difficulty in defining system and disruptions:*

One issue which was raised by some of experts is difficulty in defining the scope for supply chain disruption management. This difficulty can be in defining the boundary for the system of study:[1]

> "Many problems seem to originate in tier 2, 3 or 4 suppliers, and getting visibility into subsequent tiers becomes geometrically more difficult."

---

[1] Quotes in this section are from our discussions with experts or from their answer to open question in our questionnaire.

> "Amongst the major contributors to cause disruptive events are the layers of contractors, subcontractors and sub-subcontractors."
>
> "A supply chain, theoretically, includes all companies from raw material supplier to end customer. Besides, each company may also have multiple products and therefore must manage multiple supply chains. So, defining a boundary to start risk management process seems very difficult in this complicated network."

It might be also difficult to decide which disruptions must be included in the risk analysis process:

> "I found the work interesting and a very good start. In my experience, I found two really driving factors in disruptions. One was "time", in other words, how long will it last? The other, more difficult one to handle is the scope of the disruption. In the example mentioned[1], there was a linear relationship between late vendor and purchasing. This is entirely different from an event that is external and affects either regionally, Area or Globally. It can be as simple as the local prime carrier going bankrupt to a global carrier going bankrupt. The scale of an event causes pressure on the remaining capacity within the entire supply chain. As an example, a local port facility in Rotterdam shutting down is different than the entire port closing, different again if all European ports closed down. This situation is more common for air travel as displayed by the Iceland Volcano and just this past Christmas with less than 10 cm of snow."

To summarize these points:

1- In a complex supply chain with many tiers, defining the system boundary is difficult.

2- Identifying events that may impact the supply chain performance can be a challenge.

We agree that defining the system boundary and identifying supply chain disruptions might be a challenging task. These difficulties are mentioned in some other papers in the supply chain risk management literature as well (for example, see Norrman and Jansson (2004) and Blackhurst et al. (2008)). In most cases, we cannot practically consider an extended supply chain from raw material supplier to final customer in the risk analysis process. Characterizing a disruption based on the impact on the system performance – as

[1] The example we shared with experts to illustrate the framework.

discussed in section 3.3- can be also a challenge since in some cases "the impact of an event may change from time to time or it may be even seen in long future."

However, defining the system boundary and identifying potential disruptions – i.e., Scope Definition& Risk Identification step - is still a critical step in the disruption management process. Without defining the scope of study, disruption management could consume a significant amount of resources and still not deliver the performance improvements as some important parts of the system might be omitted in the risk analysis process. The importance of different segments of a supply chain or the value of different products in the company's portfolio can be guiding factors to define the scope of the disruption management process (Norrman and Jansson, 2004). For example, one company may primarily focus on disruptions in the supply-side of its supply chain and another company may prefer to focus on the whole supply chain for a particular product.

Recognizing the risk factors in the first step is also crucial because it influences all the forthcoming steps in the framework; the risk factors that are not identified will not be included in further analysis in risk quantification and treatment steps. Of course, - as has been raised during one of our interview sessions - we can see the scope definition and risk identification step as an iterative process:

> "We can define a boundary for risk analysis and start with a preliminary list of disruptions and then we can perform a sensitivity analysis on the system boundaries. For instance, a company may primarily start with disruptions happening in a sub-set of supply chain and if there are still resources left for risk mitigation, the boundary of risk analysis can be expanded and include other parts of supply chain."

If some of the potential disruptions are not identified in the Definition& Risk Identification step, they might be found later in the Risk Monitoring step; the cyclic nature of InFormDRiSC allows for adjustment of the system boundary, so that overlooked risk factors may later be included in the risk analysis process.

- *Organizational issues in handling supply chain disruptions:*

There were some other comments by experts about organizational issues in using the framework. In fact, some experts noted that risk management is mostly seen as a strategic subject and handling disruptions – which usually happens on a daily basis at the operational level. The involvement of different departments and different actors in a supply chain may create difficulties in integrating pre- and post-disruption processes for some companies:

> "Most global companies plan for risk prevention centrally but perform event response locally. This certainly impacts the feasibility of the interaction loop you propose between risk management and disruption management."

In addition, one expert suggested that the learning from a disruption can be a network-wise activity as multiple companies can share their experience about a specific disruption:

> "A more complex supply chain would necessitate driving the learning through the supply chain. For instance, if a company uses a number of regional contract packing facilities, what the company has learned would have to be passed on to each of the contract packers so they'd be prepared to react quickly to any future disruption."

These two comments show that the organizational and network-related issues may impact the implementation of integrated framework in a number of industrial cases and must be investigated more in detail in future studies. It is, of course, important to emphasize that InFormDRiSC is primarily about *which steps* must be followed for handling disruptions and not *how* these steps must be followed. Therefore, the way to use this framework can be different for different cases and - based on the size of a company and the complexity of its supply chain - one department, several departments inside the company or even multiple companies might be involved in some or all steps of the disruption management process.

In addition to organizational aspects, one expert mentioned that cultural differences may also impact using framework. A study conducted by MIT Global Scale Risk Initiative in 2010 showed that practitioners from different countries have different attitude toward risk prevention and response (Dinis, 2010). For instance, while practitioners in Brazil, Canada and China mostly leaned toward response, experts from Spain, Switzerland and India believed that prevention should be the focus in handling supply chain disruptions. These cultural differences may especially influence the implementation of framework for a global supply chain spanning multiple countries and consisting of parties with different cultural backgrounds. Studying the cultural and organizational issues in implementing the InFormDRiSC is an important step in implementing this framework in industrial cases and an important direction for future research as discussed in more detail in Chapter 8.

- *Other comments about InFormDRiSC:*

In addition to aforementioned comments some other remarks and suggestions were provided by the experts. One expert pointed out that:

> "In the framework, it seems that the process must necessarily start with the outer cycle [risk management cycle]; however, it is also possible that during operation of a supply chain a disruption happens that has not been faced or considered before. Therefore, it is also possible to start from the internal cycle when a new and unknown disruption is discovered."

We also agree that the framework can be seen both from outer cycle (risk management cycle) and from inner cycle (disruption management). Another expert suggested that models developed in other sectors like infrastructure (railroad, computer network security …) can be compared with InFormDRiSC and the necessary improvement can be made. This can be also a direction for future research as we further discussed in Chapter 8.

3.5. Chapter summary

In this chapter an integrated framework for handling disruptions in supply chain has been presented. In Chapter 2, we discussed two main (but quite separate and isolated) views on handling disruptions in supply chains – i.e., pre- and post-disruption views. Despite the necessity and great importance of both views in handling supply chain disruptions, very few research have been done to combine these two views in one framework. The integrated framework of this chapter (i.e., InForMDRiSC) aimed to fill this gap and present all relevant steps in handling supply chains disruptions - before and after its occurrence - in one framework. Throughout this chapter the structure of this framework and its application for supply chain disruption management has been discussed. Moreover, to evaluate the framework and check its applicability and usefulness, it has been shared with experts in the related fields (supply chain management, operations management, logistics, etc.). The evaluation study largely supports the argument of Chapter 2 on the necessity of including both views in managing disruptions. Experts' reflection on the framework, moreover, showed that the framework is understandable and there is a general agreement that it is useful in handling disruptions.

4. HANDLING SUPPLY CHAIN DISRUPTIONS: A REVIEW OF KEY ISSUES

Considering the framework presented in previous chapter as our classification scheme, in this chapter we will have a review on the supply chain Risk/Disruption management literature. Accordingly, for each of the steps in the framework, we will discuss what is presented in the literature; what aspects are regarded as important; what methods are presented, e.g., for risk identification or risk quantification etc. Finally, two main observations in the existing literature on supply chain risk/disruption management are discussed.

4.1. Introduction

In Chapter 3 an integrated framework for handling supply chain disruptions has been presented. The presented framework determines *which steps* must be followed to handle supply chain disruptions in their whole lifecycle and *how* the steps are *inter-related*. However, *which specific methods* must be used and *which explicit aspects* must be considered for each step are beyond the scope of this framework and might be different for different specific cases. As an example, the framework prescribes that the risk level for potential disruptions must be firstly *quantified before* decisions on necessary *treatments* are made; but the framework does *not* suggest any *specific method* for *quantifying* the risk level. The selection of a method for risk quantification might depend on, e.g., the experience of company or the resources it would like to invest in managing disruptions. One company may use sophisticated quantitative modeling and simulation approaches but another company may prefer to use expert judgment for ranking the risk level of identified disruptions. Likewise, many different aspects of and specific methods for each step of the framework have been discussed in supply chain risk/disruption management literature. This chapter presents an overview of these aspects[1]. The outcome

[1] The papers that are reviewed in this chapter are published in the peer-reviewed journals and are selected from Scopus database with key words “supply chain” + “risk management” and “supply chain”+ “disruption”. With these key words, more than 530 non-repeated articles were found. These papers were carefully scanned based on their abstract and about 150 papers were selected considering the number of steps of frameworks discussed by that paper and number of citations per year. For each of selected papers, the full text was read and a summary sheet was prepared discussing which step(s) of framework is discussed and which aspects (or methods) of that step is presented.

of this chapter can be, therefore, regarded as a guide to operationalize the steps of integrated framework. Meanwhile, with extended review of literature in this chapter we aimed to evaluate if InForMDRiSC steps can adequately reflect the issues raised by supply chain risk and disruption management literature or other steps are necessary to add.

4.2. Risk Identification

The literature on supply chain risk/disruption management has discussed two important issues on risk identification. Firstly, different risk identification methods have been discussed and secondly, different risk classification schemes are presented to support a more structured risk identification process.

4.2.1. Risk identification method

Risk Identification is the first step in managing disruptions in supply chains. This step is especially important because a disruption in supply chain cannot be managed unless it is first identified. To facilitate the risk identification, a wide range of methods are presented in the literature. Some widely-applied methods are presented in Table 4.1.

One of the most frequently used approaches for risk identification in the supply chains is expert view which can be in different forms like survey (Thun and Hoenig, 2011) or brainstorming (Norrman and Jansson, 2004). Historical data for past events and the review of literature or reports of similar companies can support experts in a better-informed risk identification process. It is also recommended to involve a cross-functional team of employees and a diverse group of experts in the process (Hallikas et al., 2004; Norrman and Jansson, 2004). This is beneficial both for the variety of perspectives such a group can provide and to build commitment to the risk management process in the whole company.

Table 4.1. A summary of literature on risk identification method

Reference	Risk Identification Method
Norrman and Jansson (2004)	Personnel brainstorming
Wu et al. (2006)	Literature review and expert interviews
Canbolat et al. (2008)	Literature review and expert interviews
Schoenherr et al. (2008)	Analytic Hierarchy Process (AHP)
Wiendahl et al. (2008)	Ishikawa Diagrams
Thun and Hoenig (2011)	Expert view (survey)
Adhitya et al. (2009)	HAZard and OPerability (HAZOP)
Yang (2010)	literature review, interviews with personnel, and a questionnaire survey
Tuncel and Alpan (2010)	Personnel interview

Among more systematic methods, Schoenherr et al. (2008) used the Analytic Hierarchy Process (AHP) to identify the risk factors related to the offshoring decision in a US

Box 4.1- Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty in the 1970s. For that reason, it is often referred as the Saaty method (Saaty, 2000). This method is generally classified as a group decision-making and also a multi-criteria decision-making method (Ho, 2008). AHP allows a decision maker to structure multi-criterion decision problem into a hierarchy of different levels (Rao, 2007). Usually, this hierarchy contains at least three levels: the goal (which itself can be divided into several main objectives), the attributes (or criteria) for meeting the goal and the alternatives. Next, with a 3-step procedure, AHP prioritizes the alternatives with a quantified judgment:

Step1- Determining the relative importance of attributes with respect to the main objective.

Step2- Rating the alternatives using a pairwise comparison on each attribute.

Step3- Obtaining an overall relative score for each alternative by multiplying the normalized weight for each attribute (from Step1) with its corresponding normalized alternative.

manufacturing company. For this purpose, they have defined three sourcing characteristics related to the product, the partner and the environment as main decision objectives. Next, they subdivided the main objectives into sub-objectives and finally to 17 risk factors (Figure 4.1).

Adhitya et al. (2009) discussed the application of HAZard and Operability (HAZOP) method to supply chain risk identification. The HAZOP method is one of the most widely-used techniques for hazard identification in process plants. Based on the similarities between supply chains and chemical plants, Adhitya et al. (2009) suggested adapting the methods and concepts from chemical process risk management to supply chains. Similar to a HAZOP study for a process plant that is performed around process flow diagrams (PFDs), they defined a supply chain flow diagram (SCFD) and work-flow diagram (WFD) to represent the supply chain structure and the sequence of tasks. Subsequently, the risk identification can be performed by systematically generating deviations in different supply chain parameters and identifying their possible causes, consequences, safeguards, and mitigating actions. For example, the guideword “High” or “Low” can be combined with a flow “Demand” to indicate the deviation “High Demand”

Box 4.2- HAZard and OPerability (HAZOP)

HAZard and OPerability (HAZOP) is a structured and systematic technique for identifying the hazards (Crawley et al., 2000). Hazard in HAZOP studies are characterized by the deviations in the normal/designed operation of a system (e.g., a manufacturing plant). Such deviations are defined by using a group of “Guide Words”. Examples of common HAZOP guide words include "No or Not" (e.g., Not material flow), "Less" (e.g., Less quality of material) and "Part of" (Part of material delivered). The HAZOP guide words are applied to each element of the defined system (which is usually called a "Node") to create different deviations. Subsequently, all possible causes for such deviation and the adverse consequences of this deviation must be determined. Finally, the safeguards which reduce the frequency of the deviation or to mitigate its consequences must be found.

or “Low Demand” respectively and its possible causes and consequences can be identified by tracing the flows in the diagram.

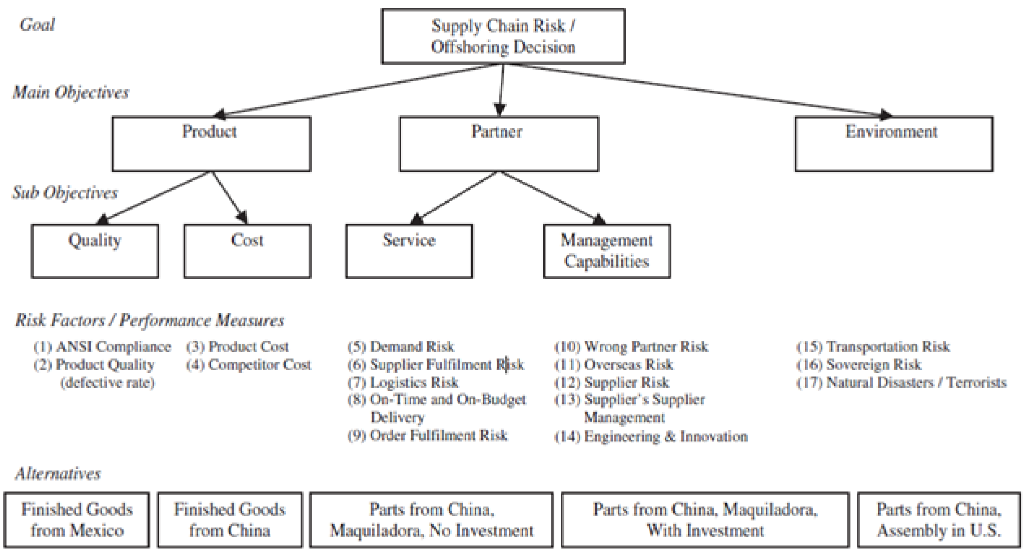


Figure 4.1. An example of AHP application for supply chain risk identification, from Schoenherr et al. (2008)

Another method mentioned in the literature is the Ishikawa Diagram which is used by Wiendahl et al. (2008) to identify the logistic risks for a case study of a forging company. They started with an objective and the possible negative consequences (like “low output rate”) and made a list of possible events that may lead to each adverse effect in five main actuating variables -material, machine, method, human and environment.

Box 4.3- Ishikawa diagram

Ishikawa diagram (also called fishbone diagram or cause-and-effect diagram) is invented by Kaoru Ishikawa in the 1940s (Munro, et al., 2008). The Ishikawa diagram is a graphical analysis tool that supports tracing the causes of a certain event or problem.

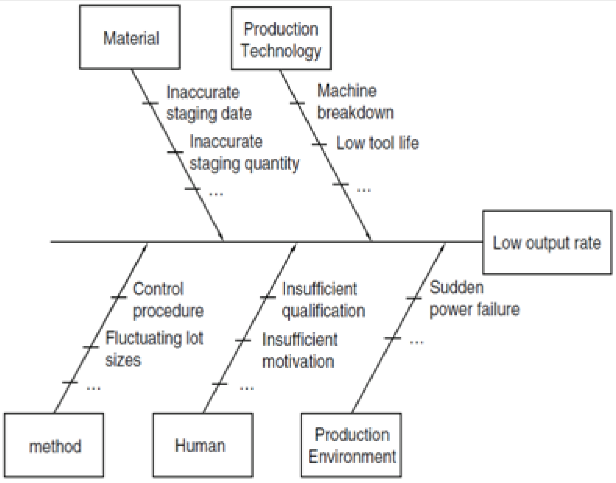


Figure 4.2. An example of Ishikawa diagram for supply chain risk identification, from Wiendahl et al. (2008)

Some other methods discussed for risk identification in the supply chain risk literature are presented in Table 4.1. Although a wide spectrum of methods is available for companies to identify risks, the choice of the risk identification method is different for different cases. Some factors which may influence the chosen method are time, experience availabile and the complexity of supply chain. In general, the basic expert-based methods for risk identification (like brainstorming or risk questionnaire) are fast; however, they need a level of expertise which might not be available inside the company. The other issue with expert-based methods is that for a complicated supply chain with several tiers, they cannot guarantee to provide a full picture of all relevant disruptions. More systematic and disciplined approaches, however, can facilitate a more comprehensive risk identification process. Reproducibility is the other advantage of systematic methods since the results of the risk identification process can be easily evaluated and also extended in future. As a generic recommendation, in most cases, a combination of methods for risk identification may prove to be more useful (Hallikas et al., 2004). As an example, instead of performing AHP by one expert in a company, several experts might use the method and share the output in some meetings to make a final list of potential disruptions.

4.2.2. Risk classification scheme

To facilitate a systematic and comprehensive risk identification process, some classification schemes are presented and discussed in the literature (Table 4.2). Categorizing disruptions also supports a better communication among actors involved in the process (Stecke and Kumar, 2009).

One of the most common risk categorization schemes involves classifying supply chain disruptions based on the location of the source of disruption. Christopher and Peck (2004) considered three main categories of risk sources in the supply chain:

- "Internal to the firm" which are subcategorized into "process risks" - disruptions within the value-adding activities of a company like loss of operating resources- and "control risks" - disturbances in the management systems/procedures that govern how an organization exerts control over the processes, e.g., wrong assumptions or decision rules, misapplication of rules, etc.
- "External to the firm but internal to the supply chain network" which are subcategorized into "demand risk" - potential disturbances to the flow of product, information, and cash between the focal firm and the customers -and "supply risk" – disruptions in the product, information, and cash flows in the upstream of the focal firm.
- "External to the network" or "environmental risks" which are exemplified by natural disasters, terrorist attacks and regulatory changes.

Table 4.2. A summary of supply chain risk categorization literature

Risk Classification	Reference
Location-based classification	Christopher and Peck (2004), Jüttner (2005), Bogataj and Bogataj (2007), Oehmen et al. (2009), Thun and Hoenig (2011), Trkman and McCormack (2009), Kumar et al. (2010), Dani and Deep (2010), Olson and Wu (2010)
Scale-based classification	Kleindorfer and Saad (2005), Gaonkar and Viswanadham (2007), Lodree and Taskin (2008), Knemeyer et al. (2009), Huang et al. (2009), Ravindran et al. (2010)
other	Cavinato (2004), Chopra and Sodhi (2004), Peck (2005), Kleindorfer and Saad (2005), Sheffi (2005a), Tang (2006b), Wu et al. (2006), Matook et al. (2009), Tang and Musa (2010)

Similar classifications have been discussed by many other researchers too (as mentioned in Table 4.2). As another example for location-based classification, Thun and Hoenig (2011) made a distinction between "internal company risks" and "cross-company-based risks". The "cross-company-based risks" are further divided into "purchasing risks (upstream risks)" and "demand risks (downstream risks)". The "external supply chain risks" is the other group which is subcategorized into sociopolitical, economic, technological or geographical disruptions.

Another approach suggested in the literature is categorizing the supply chain disruptions according to the likelihood and impact which is called "scale-based classification" in Table 4.2. In this classification, supply chain disruptions are generally categorized into:

- *Low-probability, high-severity disruptions*: the disruptions with very low probability of occurrence but significant consequences if they occur (for example, labor strike, terrorist attack or natural disaster). This class is also termed Value-at-risk (VaR) type disruptions by Ravindran et al. (2010) and "catastrophes" or "catastrophic events" by Lodree and Taskin (2008), Knemeyer et al. (2009) and Huang et al. (2009).
- *High-probability, low-severity disruptions*: the events that might happen more frequently with less damage to the supply chain operation (for example, late delivery or missing quality requirements). This is frequently called the "operational disruptions" or "day-to-day disruptions" (Kleindorfer and Saad, 2005; Huang et al., 2009). "Miss-the-target (MtT) risks" is also the term which is suggested by Ravindran et al. (2010).

In general, the location-based approach for risk classification has two main advantages over scale-based approach. Firstly, it is clearer and much more straightforward for a supply chain manager because the starting point for classification is different sections (e.g., demand side or supply side) in the supply network. The other difficulty with the scale-based approach is that the quantification of risk mostly happens after identifying the potential disruptions in the chain. Having a precise estimation of the level of risk for a specific disruption is mostly difficult at the start of risk identification step. Therefore, - unless for specific type of disruptions like natural disasters – it might be very difficult to decide whether a disruption is a Low-Likelihood/High-Impact (LL-HI) event or a High-Likelihood/Low-Impact (HL-LI) one. In fact, determining the exact category of a specific disruption requires an assessment of its likelihood and the expected impact which is done in the next step of framework – i.e., Risk Quantification step.

Besides location-based and measure-based classifications, several other approaches for categorizing supply chain disruptions can be found in the literature. From these works, the multi-level classification of Peck (2005) has received more attention. In Peck's classification, the sources for supply chain abnormality are presented in four main levels of “value stream/product or process”, “assets and infrastructure dependencies”, “organizations and inter-organizational networks” and “environment”. With a similar idea, Cavinato (2004) discussed that identifying risks and uncertainties in supply chains must focus on five sub-chains/networks in every supply chain: Physical, Financial, Informational, Relational and Innovational networks.

Table 4.3. A list of mostly-discussed supply chain disruptions in the literature

<table>
<tr><th colspan="3">Disruption</th><th>Reference</th></tr>
<tr><td colspan="2" rowspan="3">Company Level</td><td>Production facility failure</td><td>Sodhi and Lee (2007), Stecke and Kumar (2009)</td></tr>
<tr><td>Quality problems in End Product</td><td>Pyke and Tang (2010), Dani and Deep (2010)</td></tr>
<tr><td>Human resource problems (e.g., strike)</td><td>Stecke and Kumar (2009)</td></tr>
<tr><td rowspan="9">Network Level</td><td rowspan="2">Demand Side</td><td>Distribution network breakdown</td><td>Canbolat et al. (2008), Stecke and Kumar (2009),</td></tr>
<tr><td>Demand volatility</td><td>Tang and Tomlin (2008), Buscher and Wels (2010)</td></tr>
<tr><td rowspan="3">Supply Side</td><td>Quality problems in Raw Material</td><td>Chopra and Sodhi (2004), Wu et al. (2006), Tang (2006a), Schoenherr et al. (2008), Buscher and Wels (2010)</td></tr>
<tr><td>Supplier delay</td><td>Tang (2006a), Wu et al. (2006), Tang and Tomlin (2008), Schoenherr et al. (2008), Buscher and Wels (2010)</td></tr>
<tr><td>Supplier bankruptcy</td><td>Sodhi and Lee (2007),</td></tr>
<tr><td rowspan="4">Transportation</td><td>3PL bankruptcy</td><td>Stecke and Kumar (2009)</td></tr>
<tr><td>Shipping delay</td><td>Wilson (2007), Schoenherr et al. (2008)</td></tr>
<tr><td>Transportation Infra. Congestion</td><td>Schoenherr et al. (2008), Yang et al. (2009)</td></tr>
<tr><td>Port strike</td><td>Stecke and Kumar (2009), Yang et al. (2009)</td></tr>
<tr><td colspan="2" rowspan="2">Environment</td><td>Natural catastrophes</td><td>Schoenherr et al. (2008), Knemeyer et al. (2009), Stecke and Kumar (2009),</td></tr>
<tr><td>Regulatory and legal risk</td><td>Chopra and Sodhi (2004), Stecke and Kumar (2009)</td></tr>
</table>

A list of possible disruptions which are frequently discussed in the literature is shown in Table 4.3.[1] In this table, the potential disruptions are classified in three main groups of company level, network level and environmental disruptions.

[1] This table will be used in Chapter 6 when we discuss how different disruptions can be translated into a model in our modeling approach.

4.3. Risk Quantification

Risk quantification is the process for evaluating the disruptions that have been identified and developing the basis for making decisions on the relative importance of each disruption. The risk level of disruptions is mostly quantified in two dimensions; the likelihood (or frequency) of the disruption occurring and the impact of disruption on the performance of the supply chain.

4.3.1. Likelihood estimation methods

Appropriate methods to estimate the probability of supply chain disruptions have received little attention in supply chain management research so far. An exception is the work of Knemeyer et al. (2009) in which some approaches for probability estimation of catastrophic events are discussed. For some types of catastrophic events, such as aircraft accidents, the historical data is available and can be used for estimating the transportation disruption likelihood. Simulation is another approach for likelihood estimation. This method can be used when the factors that cause a disruption are well-known. As an example, Knemeyer et al. (2009) discussed a hurricane (or tropical cyclone) simulator which uses input (like, central pressure, maximum wind radius, etc.) from government and private sources to generate probability distributions for the number, intensity and location of hurricane activity. The simulation results, subsequently, can be used for making decision about the location of production and warehousing facilities.

Probability assessment scale

Rank	Subjective estimate	Description
1	Very unlikely	Very rare event
2	Improbable	There is indirect evidence of event
3	Moderate	There is direct evidence of event
4	Probable	There is strong direct evidence of event
5	Very probable	Event recurs frequently

Figure 4.3. An example of assessment scale for qualitative probability estimation, from Hallikas et al. (2004)

In addition to these methods, expert judgment is also used by literature for evaluation of disruption likelihood. For example, Hallikas et al. (2004) suggested a five-class scale for qualitative estimation of disruption probability by experts. Similarly, Yang (2010) used 5-point Likert scales for rating the risk frequency in a questionnaire to evaluate the risk factors in container security.

4.3.2. Impact estimation methods

Systematic methods for assessing the disruption impact have gained more attention in the supply chain risk management literature. Table 4.4 presents some of these methods. Among the most-commonly-used methods is the Analytic Hierarchy Process (AHP). Gaudenzi and Borghesi (2006) applied the AHP method in two phases to identify supply chain risk factors and evaluate the intensity of each risk factor. Firstly, the supply chain objectives (e.g., on-time delivery, order completeness, order correctness, and damage-free delivery) have been prioritized. Subsequently, the relative importance of identified risk factors regarding each of these objectives was assessed. Similarly, Wu et al. (2006) have used AHP to analyze the risk factors in the supply base of companies. For this purpose, they firstly classified the supplier-oriented risk factors into six categories (e.g., Internal Controllable, Internal Uncontrollable, External Controllable, etc.). Then, they applied AHP technique to calculate the weight of risk factors in two steps. In the first step, it is used to rank how important one category is over another category. Next, the pair-wise comparison of risk factors was done in each category. Multiplying these two weights and the probability of occurrence for each risk factor, an overall risk index was calculated.

Some of other recent applications of AHP for assessing the risk factors in supply chain can be found in Schoenherr et al. (2008) and Enyinda et al. (2010).

Table 4.4. A summary of supply chain impact estimation methods

	Reference	**Risk Quantification Method**
Qualitative/semi-quantitative	Wu et al. (2006)	AHP
	Gaudenzi and Borghesi (2006)	AHP
	Schoenherr et al. (2008)	AHP
	Levary (2008)	AHP
	Enyinda et al. (2010)	AHP
	Matook et al. (2009)	Expert group rating
	Norrman and Jansson (2004)	Expert group rating and historical data
	Thun and Hoenig (2011)	Expert opinion (survey)
	Blackhurst et al. (2008)	Multi-criteria scoring and historical data
	Yang (2010)	Expert opinion (survey)
Quantitative (Modeling and Simulation)	Appelqvist and Gubi (2005)	Discrete event simulation
	Wu et al. (2007)	Petri net
	Tuncel and Alpan (2010)	Petri net
	Wilson (2007)	System dynamics
	Munoz and Clements (2008)	Discrete event simulation
	Wei et al. (2010)	Inoperability input-output modeling (IIM)

Besides AHP, some other efforts for qualitatively assessing the impact of disruptions are discussed in the literature. Table 4.4 gives an overview of these qualitative methods

Box 4.4- Petri Nets (PN)

Petri Nets (PN) – which were firstly proposed by Carl Adam Petri in 1962- is a graphical tool for the formal description of the processes and flow of events in a system (Diaz, 2009). It also offers a mathematical network model to analyze the behavior of dynamic systems.

The basic elements in PN include "places" – which are the states and conditions of the system and are mostly shown with circles- , "transition" – which are the actions in the system and are drawn as bars or boxes - "tokens" – which are resources responsible for the changes in the system and are usually shown with black (or colored) dots - and "directed arcs" – which indicate the direction of token (resources) travel (Cortellessa et al., 2011). When the number of token in a place meets the minimum requirements for firing (or executing a transition), some of tokens are moving from one place to another place. This rule – which is called firing rule- is the basis for the simulation of dynamic behavior of system (Cortellessa et al., 2011).

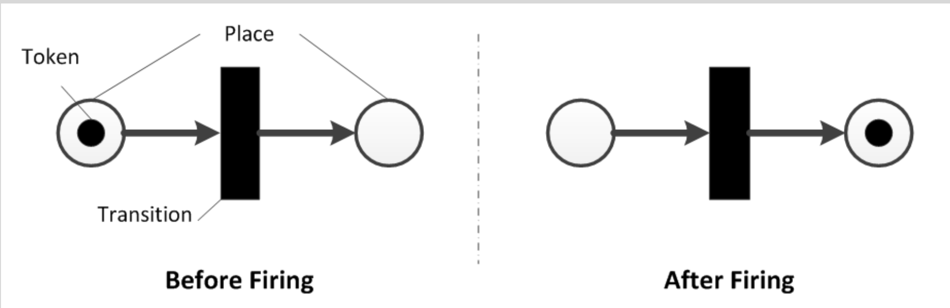


Figure 4.4. The main elements of PN model

which mainly rely upon experts' judgment and experience. A few quantitative approaches have been also proposed. Wu et al. (2007) presented a Petri net-based (PN) modeling approach, termed Disruption Analysis Network (DA_NET), to model how disruption effects propagate through a supply chain. Another application of Petri net (PN) based simulation for risk management in supply chains is presented by Tuncel and Alpan (2010). They used Petri net (PN) to evaluate the impact of multiple-disruption scenarios (disruptions in demand, transportation and quality) and possible mitigation actions on the supply chain performance.

To study the impact of transportation disruptions on the supply chain performance, Wilson (2007) presented a system dynamics model for a supply chain which contains five echelons: retailer, warehouse, tier-1 supplier, tier-2 supplier and raw material supplier.

Box 4.5- Inoperability Input-Output Model (IIM)

The Inoperability Input-Output Model (IIM) is a modeling approach to analyze how perturbations in one part of a system propagate to other parts through the exchange of input and output that link them. This modeling approach is developed by Yacov Haimes and his colleagues in University of Virginia – based on the Leontief's Input-Output (I-O) Model which describes the indirect ripple effects among the industry sectors of the economic system - to evaluate the impact of a disruption in one infrastructure and the cascading effects on all other interconnected and interdependent infrastructures (Haimes, 2009). This effect is mainly evaluated with "inoperability" measure which represents the gap between planned or business-as-usual level and current levels of operation caused by a disruptive event. For example, if the major evaluating metric of a system is the production level, then the inoperability can be defined as the unrealized production (Wei et al., 2010).

Different possibilities for a transportation disruption – which might occur between adjacent echelons - are modeled and their impact on customer orders fulfillment rate and inventory fluctuations are evaluated. As a result, they concluded that the greatest impact occurs when transportation is disrupted between the tier 1 supplier and warehouse.

Among more recent quantitative methods for supply chain risk assessment, Wei et al. (2010) have introduced the application of Inoperability Input-output Modeling (IIM) to analyze the ripple effects caused by disruption at a particular node. The IIM simulation results can be used to prioritize nodes for planning potential actions to manage the impact of disruptive events. To illustrate the application of the model, they discussed an example of a Chinese white alcohol manufacturer. A potential disruption in one of the suppliers was modeled and increasing the number of suppliers as a possible risk mitigation strategy has been studied.

4.4. Risk Evaluation & Treatment

Once the risk factors have been identified and assessed, the appropriate response must be selected and implemented in the supply chain.

In general, the possible response to a disruption can fall within four main categories.

Table 4.5. A summary of risk treatment methods

Risk Treatment Method			Reference
Risk Acceptance			Tomlin (2006), Khan and Burnes (2007)
Risk Reduction	**Flexibility**	**Flexible Supply Base**	Choi and Krause (2006), Tomlin (2006), Babich (2006), Tan and Enderwick (2006), Tang (2006a-b), Tang and Tomlin (2008), Deane et al. (2009), Thun and Hoenig (2011), Yang et al. (2009), Wang et al. (2010), Iakovou et al. (2010)
		Flexible Product Configuration (Postponement)	Sheffi (2005a-b), Tang (2006a-b), Babich (2006), Tang and Tomlin (2008), Manuj and Mentzer (2008), Wagner and Bode (2008), Ji (2009), Yang and Yang (2010)
		Flexible Manufacturing	Sheffi (2005a-b), Tomlin (2006), Sodhi and Lee (2007), Tang and Tomlin (2008), Stecke and Kumar
		Flexible Transportation	Tang (2006a), Stecke and Kumar (2009), Knemeyer et al. (2009), Colicchia et al. (2010)
	Redundancy	**Extra Inventory (Redundant Stock)**	Chopra and Sodhi (2004), Sheffi (2005a), Hale and Moberg (2005), Tomlin (2006), Tang (2006a), Khan and Burnes (2007), Mudrageda and Murphy (2007), Wilson (2007), Ratick et al. (2008), Knemeyer et al. (2009), Stecke and Kumar (2009), Schmitt and Snyder (2010)
		Backup Supplier	Tomlin (2006), Wilson (2007), Sodhi and Lee (2007), Deane et al. (2009), Knemeyer et al. (2009), Yang et al. (2009), Xu and Nozick (2009), Schmitt and Snyder (2010)
		Overcapacity	Chopra and Sodhi (2004), Goh et al. (2007)
	Control/ Incentives	**Security Improvement**	Manuj and Mentzer (2008), Stecke and Kumar (2009), Knemeyer et al. (2009)
		Demand Management	Tang (2006a-b), Tang and Tomlin (2008), Stecke and Kumar (2009), Ji (2009)
		Supplier Qualification Screening	Sheffi (2005a-b), Sodhi and Lee (2007), Roth et al. (2008), Wagner and Bode (2008), Manuj and Mentzer (2008), Yang et al. (2009), Sanchez-Rodrigues et al. (2010)
		Organizational Aspects	Sheffi (2005a-b), Knemeyer et al. (2009)
	Cooperation	**Resource Sharing**	Hale and Moberg (2005), Tuncel and Alpan (2010)
		Collective Response Planning	Hallikas et al (2004), Tan and Enderwick (2006), VanderBok et al. (2007), Knemeyer et al. (2009), Stecke and Kumar (2009), Butner (2010)
Risk Avoidance			Tang (2006b), Tomlin (2006), Wu and Olson (2008), Levary (2008), Manuj and Mentzer (2008), Stecke and Kumar (2009), Xu and Nozick (2009), Knemeyer et al. (2009)
Risk Transfer			Giannoccaro and Pontrandolfo (2004), Manuj and Mentzer (2008), Wagner and Bode (2008), Stecke and Kumar (2009), Knemeyer et al. (2009)

4.4.1. Risk acceptance

The consequences and likelihood of a particular disruption might be accepted if the risk level is less than a specific threshold. Moreover, for cases where the problem owner cannot find a reasonable response or the cost of available solutions outweighs the anticipated disruption risk, the risk acceptance might be considered a default action (Tomlin, 2006).

4.4.2. Risk reduction

For disruptions with unacceptable level of risk, appropriate actions must be taken to reduce the risk to the acceptable threshold. The risk of disruption can be reduced by reducing the likelihood of its occurrence or reducing the severity of disruption (Zsidisin et al., 2005; Tang and Tomlin, 2008). For this purpose, many different approaches are discussed in the literature.

- **Flexibility**

One way for managing disruptions is to create flexibility in the supply chain. Flexibility is the ability to take different positions to better respond to an abnormal situation and rapidly adapt to significant changes in the supply chain (Lee, 2004). The necessary condition for flexibility in the supply chain is having multiple interchangeable resources (Ji, 2009). For example, by having different manufacturing plants in different locations - with the capability to produce a similar set of products- a company can move the business among them should one fail because of disruption in its supply chain.

Different types of flexibility strategies are suggested in the literature to handle the risk of supply chain disruptions.

- **Flexible supply base:** One method for mitigation of risk in a supply chain is establishing a flexible supply base. To have a flexible supply base, two main tactics are commonly discussed in the literature. One is to diversify the material supply through multiple-sourcing (Tang, 2006a; Tomlin, 2006; Thun and Hoenig (2011); Iakovou et al., 2010), so that, when the supply from one supplier is disrupted (as a result of, e.g., supplier failure or transportation disruptions), the company can temporarily shift the orders (or at least some part of its demand) to another supplier.

  Another element of a flexible supply base is flexible contracting with suppliers (Tang and Tomiln, 2008; Tang, 2006b). In flexible supply contracts, the ordering

Box 4.6- An example of product postponement: HP DeskJet printer

To satisfy certain country-specific requirements, Hewlett-Packard (HP) has to develop multiple versions for each model of their printers to serve different geographical regions (Asia-Pacific, Europe, or Americas). For example, HP printers in North American and the European market have different power supplies and instruction manuals in different languages.

Previously, the manufacturing was done in the North America factories and finished products were shipped to the three distribution centers in Asia-Pacific, Europe and US (Johnson and Anderson, 2000). However, due to uncertain demand in each region, HP could end up with more printers than it required in one area (overstocking) and less printers in the other regions (under-stocking) (Tang and Tomlin2008). To solve this problem, HP redesigned the process for producing its DeskJet printers by delaying the point of product differentiation. Specifically, HP first produces the generic printers and ships them to the distribution centers in different regions. These generic printers are then customized for specific markets in the last stage of process by distributers. This postponement strategy has enabled HP to respond to the demand changes quickly and more accurately as the printer is customized only when HP sees the demand for printers in a certain region. Moreover, transportation cost is decreased because printers are shipped in bulk and the final reconfiguration is done in the destination.

firm can adjust the agreed quantity or time of delivery[1]. Thus, with disruption in one supplier, a manufacturer has the immediate option to increase the order size from other suppliers (Wang et al., 2009; Babich, 2006). Flexible supply contracting is also beneficial to cope with demand risks (Tang and Tomlin, 2008). In fact, the buyer can change the supply orders (increase or decrease volumes and change delivery timing) with fluctuations in demand in the downstream supply chain.

- **Flexible product configuration (Postponement):** Postponement - also known as "delayed differentiation" (Anand and Girotra, 2007) or "late product differentiation" (Wagner and Bode, 2008) - is a frequently discussed method to handle demand risks in supply chains (Sheffi, 2005a; Tang and Tomlin, 2008). The main assumption in this strategy is that the production process can be divided

[1] In a flexible contract, the adjustment in the order quantity is mostly restricted to a few percent of original quantity and must be announced to the supplier in a specific period of time before order delivery (Tang and Tomlin, 2008).

into two sub-processes of "general production" and "customization". Based on postponement strategy, the product customization must be made at a point in the supply chain which is closer to the customer and the uncertainty in the demand of specific products is less (Ji, 2009). Consequently, postponement reduces the demand risk, because the product will stay in an undifferentiated state as long as possible allowing to respond to unexpected market shifts (Manuj and Mentzer, 2008; Wagner and Bode, 2008; Yang and Yang, 2010).

- **Flexible manufacturing process:** In a flexible manufacturing process, different types of products can be manufactured in the same plant at different volumes (Tang and Tomlin, 2008) and the production can be moved easily among different plants (Sheffi, 2005a-b). With a flexible process, companies can shift to other products when the demand for some specific products is disrupted (e.g., because of new safety regulations) or if a disruption in the supply base impacts the normal rate of production for some products. It is also possible to shift the demand to other plants when the production in a specific plant is impacted by a disruptive event.
- **Flexible transportation:** Flexibility in transportation is a critical issue for smooth operation of supply chains, especially for companies that source globally and supply different markets in different places around the world. Flexibility in transportation can be achieved by multi-modal logistics strategy (Tang, 2006a; Knemeyer et al., 2009; Colicchia et al., 2010); to prevent supply chain breakdown due to disruptions in one mode of transportation, some companies may prefer to utilize multiple modes of transportation including air, ground, and sea shipping. Other options such as working with multiple logistics companies and defining alternative routes for the case of disruption are also important to better handle transportation disruptions (Tang, 2006a; Stecke and Kumar, 2009).

- **Redundancy**

One way to manage the risk of potential disruptions is creating redundancies across the supply chain. In general, redundancies are considered as expensive options for handling disruptions because they are put to use only when certain unanticipated events occur (Sheffi, 2005b). For example, contracting with a local backup supplier to supply the needed material (or a part of it), when the main global supplier is disrupted, can be a costly decision. More administrative cost might be imposed to find and monitor the secondary supplier and higher unit prices might be paid for low-volume material delivery from a secondary supplier. However, as a disruption occurs (e.g., an emergency in the main supplier facilities), the secondary supplier can be used to ensure a steady flow of materials across the chain. The disruption reaction process is also faster as lots of hours needed to find (and set) alternative resources will be saved.

Redundancy in a supply chain can take different forms as discussed in the following.

- **Extra inventory (redundant stock):** One of possible approaches to handle disruption is keeping buffer stocks in different parts of the supply chain. A company might carry extra inventory for finished goods to handle fluctuations in market demand (demand risk) or have a buffer in the raw material storage to cope with potential disruptions in the supply base (e.g., late raw material order delivery). Despite its advantage to prevent production shutdown and avoiding stock-outs, carrying additional inventory can result in increased costs and reduced quality (Sheffi, 2005a). Thus, this strategy is mostly advised for items that have a low holding cost and will not be outdated (Wilson, 2007).
- **Backup supplier:** Contracting with a backup supplier helps companies to insure the raw material stream against possible disruptions in the main supplier (Tomlin, 2006; Sodhi and Lee, 2007). This is usually materialized with a "capacity reservation contract" in which a secondary supplier guarantees any amount of delivery up to the reserved capacity (Xu and Nozick, 2009). Therefore, comparing with buffer stock, a company can mitigate the risk in the supply base without incurring the cost of keeping excess inventory.

  One aspect in selecting extra suppliers is avoiding "share of similar disruption risk" among different suppliers (Wilson, 2007). For example, sourcing from two suppliers in the same region would impact the material supply when a disaster (e.g., an earthquake) happens in that region. Likewise, when suppliers deliver their materials through similar transportation routes, (e.g., they use similar same ports), a disruption in that route (e.g., closure of port because of strike) might leave the company with no option to supply its needed material.
- **Overcapacity:** Another method that ban be beneficial in mitigating the supply chain risk is designing/installing a certain level of excess capacity in some key nodes of the network (Chopra and Sodhi, 2004; Goh et al., 2007). Consequently, the disruption impact can be partially absorbed in the chain. For example, an emergency shutdown in one of the production plants in a multi-plant enterprise can be handled for a period of time by over-production in other plants if they have

excess manufacturing capacity. The excess capacity can also be used to manage the daily variations in customer demand, i.e., demand risk (Chopra and Sodhi, 2004).

- **Control/ Incentives**

The potential disruptions in the supply chain might be reduced with a higher level of control and supervision. Moreover, some incentives might be created to involve different actors in managing disruptive events in the supply chain.

- **Security improvement:** One method for risk mitigation, especially when intentional threats are concerned, such as terrorism attacks, thefts or piracy risk, is enhancing the security (Manuj and Mentzer, 2008; Stecke and Kumar, 2009). Stecke and Kumar (2009) have enumerated three types of security initiatives in the supply chain: physical security (e.g., in ceasing security personnel or implementing camera systems), information security (e.g., firewalls, antiviruses) and freight security (e.g., cargo inspections before shipping and Tracking the track cargo movements by RFID and GPS systems).
- **Demand management:** Demand management is suggested as a contingent response supply chain disruptions by some authors. This might happen in two main ways (Ji, 2009); firstly, shifting the demand across product portfolio which is also termed “responsive pricing” or “flexible pricing” by Tang and Tomlin (2008). Thus, when a disruption (e.g., delayed supply of certain components) interrupts manufacturing of some specific products, a firm can use the price mechanism and promotions to temporarily change the demand pattern and shift customer choices to available products. A classic example of this form of demand management is the Dell response to the Taiwan earthquake in 1999 (Tang, 2006a).

  The second form of demand management is shifting demand across time. Thus, facing a disruption, a company may start negotiating with the customers or offer discounts to change their orders’ due date or accept a delayed shipment.

Box 4.7- An example of demand management: Dell response to Taiwan earthquake

In 21st of September 1999, the 7.6 earthquake hit the Chi-Chi region in Taiwan. Because of extensive power outages and damaged plants, the supply of PC components to numerous companies was disrupted for several months. To handle the disruption, Dell immediately deployed a contingency plan by offering special “low-cost upgrade” options to customers if they chose similar computers with components from other suppliers (Tang, 2006a). The ability of Dell to steer customers to where Dell wants them by selling the available configurations, increased its third quarter earnings by 41% over the same period of previous year in spite of disaster in Taiwan (Tang, 2006a).

At the same time, the other main PC producer in market, Apple, – that had announced the launch of some new products and received thousands of order- faced product backlogs due to component shortages and inability to alter product configurations. The abnormal situation in Apple's supply chain resulted in many cancelled orders and consumer complaints (Sheffi, 2005b; Tang, 2006a).

- **Supplier qualification screening:** A well-established quality control process decreases the exposure to supply chain risks in several ways. Firstly, it allows better/faster identifying the possible cause of disruptions, reducing their frequency and also avoiding the propagation of trouble to the downstream supply chain (Sanchez-Rodrigues et al., 2008). This is especially important for customer-related disruptions such as product recalls due to safety and product quality issues (Roth et al., 2008; Pyke and Tang, 2010). Moreover, regular auditing of suppliers might reduce supply chain risks by giving suppliers an incentive to improve their internal weaknesses (Yang et al., 2009).

Organizational aspects:

One other issue which might impact the success of disruption management is increasing the knowledge of employees with training programs (Stecke and Kumar, 2009). A training program must inform workers about how to avoid potential risks (which consequently reduces the probability of disruption in the plant) and also better handle abnormalities when they occur (which, in fact, reducing the expected impact of disruption). Moreover, the response plans that are developed for specific disruptions must be regularly rehearsed and, if necessary, modified (Knemeyer et al., 2009). Sheffi (2005a-b) call all these aspects “creating the corporate security culture".

- Cooperation

In contrast with unilateral control actions, co-operative responses to supply chain disruptions involve joint agreement/action by several actors in the chain (Jüttner et al., 2003). Two possible cooperative strategies are discussed here.

- **Collective response planning:** Planning for supply chain disruption management might involve other actors in the chain (Hallikas et al., 2004; Vanderbok et al., 2007)[1]. This is especially important as modern supply chains are complex systems and no one actor has all the necessary information for identifying and mitigating the possible risks in the system (Butner, 2010). Additionally, in a joint risk management process, the options that might be too expensive to be implemented by a single partner can be discussed and agreed upon (Hallikas et al., 2004). One of these methods is investing in shared resources as discussed further below.
- **Resource sharing:** In some cases, the necessary capital might be a significant barrier to implement a specific risk mitigation option, particularly, for those disruptions of which the likelihood is not so high but the expected impact on supply chain operation can be significant (Hale and Moberg, 2005). In these cases, collaboration would help companies to pool resources and share the expenses of disruption response. Tang (2006a) discussed the cases of Toyota and Sears in which these companies keep certain inventories at some locations in their supply chains so that all retailers in the nearby region share these inventories for the case of disruption or demand fluctuation. In the same view, Hale and Moberg (2005) presented an optimization-based decision process to design a network for shared Just-In-Case resources. Firstly, an estimation of the necessary resources must be made. Next, the decision about the maximum time it should take for each facility in the supply chain to gain access to shared resources must be made. Finally, a mathematical programming model is used to determine the number and locations of storage areas for shared resources.

4.4.3. Risk avoidance

For some disruptions, the risk level is so high that even with partial reduction in the likelihood or impact of disruption, the risk level is still unacceptable. For these disruptive events, the decision is to avoid the risk and eliminate the possible causes, might be the only reasonable decision. Moving the production facilities to safe locations (e.g., places

[1] As an example, Stecke and Kumar (2009) mentioned cases of auto manufacturers such as GM that these companies help their suppliers develop certain strategies to mitigate disruptions.

with less probability of earthquake) or working with suppliers located in safe areas (Stecke and Kumar (2009), focus on secure markets or products with constant demand (Thun and Hoenig, 2011) and dropping troublesome suppliers from the supply base (Manuj and Mentzer, 2008) are examples of risk avoidance in the supply chain.

4.4.4. Risk transfer

Another method that can be used to control risk is shifting the negative consequences of a risky factor to another entity inside or outside the supply chain. The classic example of risk transfer is insurance (Lodree and Taskin, 2008). Different parts of the supply chain such as facilities, transport, and labor can be insured against natural disasters, accidents, and theft (Stecke and Kumar, 2009).

Contracting is also frequently discussed as a form of risk transfer or risk sharing in the supply chain. A contract defines the way in which the risk arising from different sources of uncertainty (like demand and price) is shared among different actors in the supply chain (Giannoccaro and Pontrandolfo, 2004). Accordingly, with a fair contracting, certain risks can be allocated to the parties who are in the best position to manage those risks.

4.5. Risk Monitoring

Supply chain risks change constantly. The likelihood and severity of disruption may change; some risks can be reduced or even eliminated, while new risk factors may appear. A necessary part of supply chain risk management process is monitoring changes in the network, customer needs, technology, partner strategies and competitors and updating the risk assessment correspondingly (Hallikas et al., 2004; Pyke and Tang, 2010). However, despite its profound importance, there is very little rigorous research presenting the methods, tools and procedures for supply chain risk monitoring. Two fairly recent papers that discuss risk monitoring methods are Blackhurst et al. (2008) and Schoenherr et al. (2008). For a case of an automotive manufacturer, Blackhurst et al. (2008) presented a multi-criteria scoring procedure for measuring, tracking and analyzing supplier and part specific risk indices over time to identify trends towards higher risk levels. With this method, the focal company can better recognize the potential risky parts of the supply base. In a similar way, Schoenherr et al. (2008) presented an AHP-based decision-making tool which was used to assess risk factors and alternatives in an international sourcing context. They also discussed that the evaluation must be a continuous process; the selected alternatives need to be reevaluated regularly, and risk factors must be reassessed as changes occur in the market environment.

4.6. Disruption Detection

An effective response to a disruption requires detecting quickly the location and nature of disruption. With faster detection of disruption in the chain, corrective actions can be started sooner, the escalation of the disruption impact can be avoided, and consequently, the impact of the disruption can be reduced.

To quickly detect a disruption, several aspects are regarded as important issues and some capabilities are listed in the literature.

4.6.1. Visibility and information access

One of the issues frequently discussed in the literature is improving the "end-to-end" visibility in the supply chain (Christopher and Lee, 2004; Glickman and White, 2006). Supply chain visibility is the ability to track the status of the supply chain (e.g., the health of different parts of chain, the material in transit in the network, etc.) from suppliers to end customers (Christopher and Lee, 2004). It is primarily achieved by collaborative relationships and real-time sharing of correct information among actors in the chain (Blackhurst et al., 2005). The information sharing – which may include the actual or forecast demand, inventory levels (excess, shortage), and processing capacities (Stecke and Kumar, 2009; Tang, 2006) - helps companies to faster discover an abnormal situation in the network and also have a better understanding of the available resources to handle disruptions (Li et al., 2006).

The other issue which improves the visibility in the supply chain –and accordingly, faster detection of disruption- is investing in performance monitoring and early warning systems (Stecke and Kumar, 2009). For instance, a firm may have various IT systems for monitoring the material flows (inventory level, quality, product delivery and sales) or information flows (demand forecasts, production schedule …) along the supply chain. These monitoring systems would reduce the detection time by tracking the deviations in the performance of supply chain (Huang et al., 2009). Moreover, the implementation of technologies like RFID that will increase the speed of information flow throughout a supply chain can assist to minimize the time of detection of disruption (Munoz and Clements, 2008).

4.6.2. Information analysis tools

In addition to information availability, developing tools for analyzing the information is an important issue in disruption detection. Such tools support decision makers in better understanding the disruption profile, how far disruptions propagate through a supply chain and which parts of the system may be affected more by the event (Blackhurst et al., 2005). Some of the tools to analyze real-time information on disruptions are presented in recent literature on supply chain disruption management. Wu et al. (2007) discussed a network-based modeling methodology – termed “DA_NET”- to determine how disruptions propagate in supply chains and how these disruptions affect the supply chain operation. Accordingly, the user can assess which areas of the supply chain and which performance measures (such as cost or lead-time) might be affected by the disruption.

Among more recent works, Huang et al. (2009) described a dynamic system model and used it to check if a disruption (like demand shock) can be absorbed by a supply chain without affecting the expected order delivery performance. Tuncel and Alpan (2010) also proposed a Petri net (PN) based decision support tool for tracking material and information flows in the supply network.

4.6.3. Disruption causal analysis

The other key aspect - which is somewhat related to the previous issue of information analysis - is searching for the real cause or causes for an abnormal event (Adhitya et al., 2007a; Gaonkar and Viswanadham, 2007). This is especially important when the triggering event cannot be directly observed and only the deviation in the supply chain performance can be detected.

The causal analysis might also investigate the causal relations among disruptions as one disruptive event might cause another set of events in the supply chain (Gaudenzi and Borghesi, 2006). For example, a problem for a 3PL service provider, which is responsible for managing the material delivery for a focal company and its supplier, would directly and indirectly impact the company’s performance.

Finding the main cause of disruptions and the interdependencies among different disruptions help decision makers in choosing the corrective actions in disruption reaction and recovery steps.

4.7. Disruption Reaction & Recovery

Once a disruption is detected, a company must quickly react and restore the normal operation of the supply chain. Some key issues are discussed in the literature for better reaction to disruption in supply chains.

4.7.1. Resource finding and (re-)allocation

Disruptions in the supply chain may lead to a shortage of resources and efficient use of available resources is a crucial issue in handling the event (Dani and Deep, 2010).

For example, an earthquake in a specific region might impact the supply of some specific materials to the manufacturing plants. Consequently, the firm must look for alternative supplies. Moreover, because of new resource constraints, the pre-defined plans for supply chain operation may no longer be optimal or even feasible and should be revised according to the new situation (Xiao et al., 2005; Huang et al., 2006).

The search for resources to handle a disruption should start with an evaluation of needs and resource requirements (Charles et al., 2010). Subsequently, a company should determine the remaining resources after disruption and also look for alternative resources to cover the needs. Some of necessary resources to react to a disruptive event can be previously-planned/invested in the risk treatment step. For example, carrying extra inventory, investing in flexible supply contracts or flexible transportation will provide some degrees of freedom in handling disruptions in real-time (Stecke and Kumar, 2009; Tomlin, 2006). Moreover, some actions like product redesign or demand shifting can provide extra resources to manage the impact of the event (Sheffi, 2005b). Multiple partners in a supply chain may also decide to temporarily share some of their resources to better handle an event (Mudrageda and Murphy, 2007).

Based on the available/found resources, possible reactions to a disruption can be defined and the appropriate options must be implemented (Adhitya et al., 2007a). In some situations, finding the appropriate option can be a challenge as many (and, sometimes, conflicting) objectives might be considered in managing disruptions. To better handle this difficulty, simulation and modeling can provide a sound basis to better analyze the reaction to the disruption (Adhitya et al., 2007a; Tuncel and Alpan, 2010).

4.7.2. Communication and information sharing

The other factor that would influence an effective disruption reaction is the continuous sharing of information among different actors in the supply chain (Dani and Deep, 2010). Generally, an abnormal situation in the supply chain is characterized by a high degree of uncertainty and lack of accurate information (Chen et al., 2010); for example, the supplier's estimation of its trouble might be biased. Moreover, for most actors in the chain, it might not be feasible to make reasonable estimates of the disruption profile, especially in the early stages. The uncertainty about the extent of the disruption and the lack of knowledge can impact the resource allocation across the supply chain and might delay the disruption recovery.

4.7.3. Coordination of activities and actors

Proper coordination is usually a key requirement for managing disruptions in a supply chain; because, in many cases, disruption management is a cross-functional and even cross-company process and requires close involvement of several actors in the chain (Blackhurst et al., 2005; Braunscheidel and Suresh, 2009; Hendricks et al. 2009).

Moreover, collaboration among different actors by sharing the existing resources calls for an effective coordination scheme. For example, managing a disruption in one manufacturing plant in a multi-plant enterprise might necessitate sharing the resources among the plants. In these cases, lack of coordination and inter-functional conflicts may slow down the efforts to manage disruption and worsen the disruption effects (Stecke and Kumar, 2009).

4.8. Learning & SC Redesign

Once a supply chain recovers from a disruptive event, it is necessary to capture the lessons learned from the disruption management process (Dani and Deep, 2010). This step is generally ignored in the literature. One exemption is the description of Norrman and Jansson (2004) of Ericsson’s proactive supply chain risk management approach after a fire at its supplier plant (Philips microchip plant in Albuquerque) in March 2000. After this disruptive event, Ericsson developed new processes and tools to “minimize risk exposure in the supply chain”.

Pyke and Tang (2010) also described cases of product safety recalls in which the impacted companies have designed new plans to prevent safety problems in the future and reported these plans to their stakeholders to rebuild confidence.

4.9. The analysis of literature and identified gaps

A detailed analysis of papers in this review is presented in Appendix D of thesis. For each paper we have shown which steps of the framework are discussed. The methods that are used by in each paper are also presented. Based on this analysis, two observations – and subsequently, two gaps in the research – have been identified and discussed in the following.

- *The literature on supply chain risk/disruption is not uniform; some parts of the framework have received detailed attention and some parts are mostly overlooked.*

One of the most evident observations to emerge from our review is that the literature has not uniformly discussed different parts of the InForMDRiSC (Figure 4.5). Some steps of the framework have been explored extensively in the supply chain disruption/risk management literature. Some other steps, however, have not been adequately investigated. Overall, the steps of the disruption management cycle (i.e., disruption detection, disruption reaction and recovery and disruption learning) have received less attention than the risk management cycle (i.e., scope definition and risk identification, risk quantification, risk evaluation& treatment and risk monitoring). Different steps of the risk management cycle have also received different levels of attention. For example, although the literature on risk identification and risk treatment steps is very rich, the risk monitoring step, with a few exceptions, is generally overlooked in the literature. Moreover, comparing with risk identification and treatment, only a small fraction of the literature presents rigorous approaches or well-documented methods for risk quantification in supply chains.

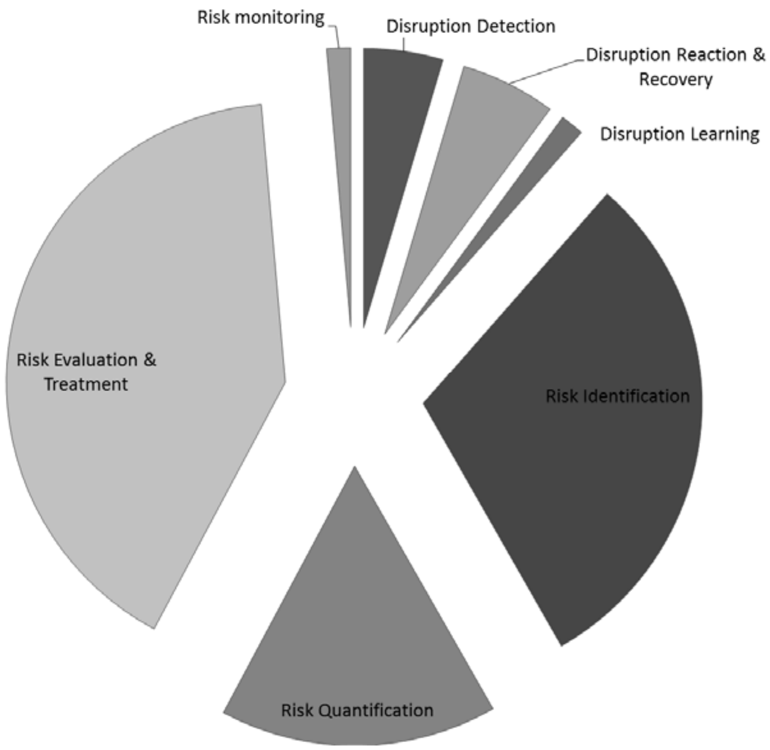


Figure 4.5. The focus of papers on different parts of InForMDRiSC

- *The review evidences a lack of quantitative efforts for handling supply chain disruptions.*

Another finding from the literature analysis is the relative lack of quantitative modeling and simulation works to support the decision makers in better handling supply chain disruptions[1]. As can be seen in Figure 4.6, qualitative methods like survey, interview and case study dominate. Very few papers have used quantitative methods for supply chain risk analysis. Moreover, flexible simulation frameworks to support decision-making in specific cases are lacking in the existing literature. The lack of simulation studies implies that although the literature on some parts of the framework – e.g., risk identification or treatment - is informative, the issues are mainly addressed from a general and high-level perspective. There is a vast body of knowledge presenting general recommendations for possible risk treatments; however, providing appropriate simulation frameworks for adopting these generic methods in specific real cases has not received adequate attention. This, actually, reduces the practical value of those generic recommendations since in any real application – to implement a specific risk treatment option- the detailed supply chain structure, procedures and circumstances for a specific company must be dealt with.

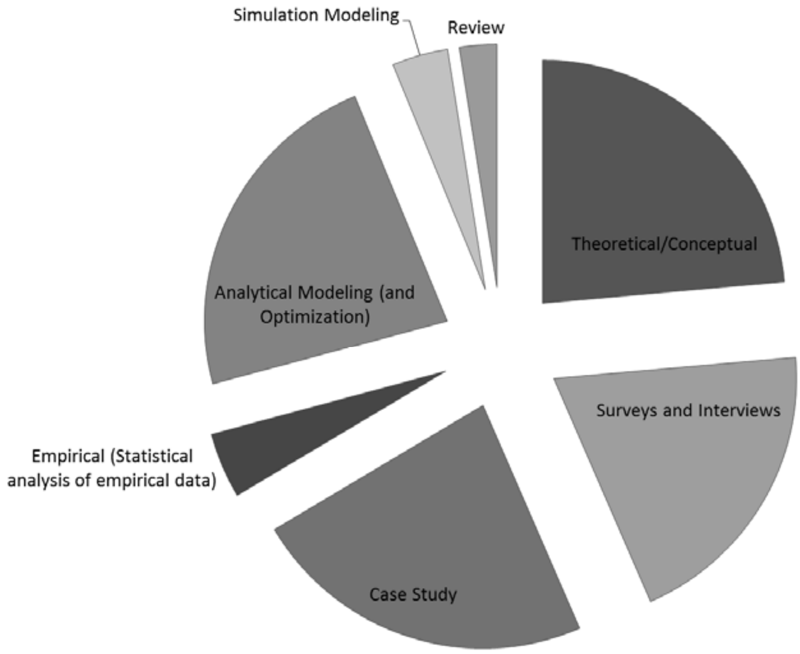


Figure 4.6. The research methods used in supply chain risk/disruption literature

A more detailed analysis of available simulation studies for supply chain risk is presented in Table 4.6. As can be seen, the focus of simulation works presented in the literature is

[1] This lack of quantitative efforts has been reported by several other recent studies, e.g., Buscher and Wels (2010) and Wagner and Neshat (2011).

on the pre-disruption steps (i.e., risk quantification and risk treatment steps). Moreover, a modeling & simulation framework which can support all steps of integrated process is lacking in the existing literature. In addition, in most cases the application of simulation methods for supply chain disruption management is solely discussed for a specific case and the approach presented in the paper cannot be generalized to other cases.

Table 4.6. Simulation studies for managing supply chain disruptions

Reference	Model Application for	Generalizable	Simulation Approach
Appelqvist and Gubi (2005)	Risk Treatment step	-	Discrete event simulation
Wu et al. (2007)	Risk Quantification step	+	Petri Net
Wilson (2007)	Risk Quantification and Treatment steps	-	System Dynamics
Munoz and Clements (2008)	Risk Treatment step	-	Discrete event simulation
Tuncel and Alpan (2010)	Risk Quantification and Treatment steps	-	Petri Net
Wei et al.(2010)	Risk Quantification step	+	Inoperability input-output modeling

4.10.Chapter summary

In this chapter, the integrated framework of Chapter 3 was used to structure a review of the literature on supply chain disruption/risk management. The review aimed to identify the important approaches and a set of key issues which have been discussed by researchers for each step of InForMDRiSC. Therefore, the content of this chapter can be considered as a guide to operationalize different steps of integrated framework. In the analysis of the literature, it turns out that the supply chain risk/disruption has been very much focused on some specific steps of the framework, especially on the pre-disruption steps. Different steps of risk management cycle have also received different levels of attention. Risk identification and risk treatment have been explored extensively whereas risk monitoring and risk quantification steps have been relatively neglected.

The review furthermore reveals a lack of simulation and modeling studies to support the decision makers in handling supply chain disruptions in different steps of framework. The lack of modeling and simulation is more obvious for post-disruption steps and considerably more work needs to be done in this area. Moreover, a modeling &

simulation framework which can support all steps of the integrated disruption management process is missing in the existing literature. [1]

The motivation for the rest of this thesis is the development of a modeling framework that enables a decision maker to create models of its own supply chain and experiment with different issues that may impact the supply chain disruption management in different steps of InForMDRiSC.

[1] The need for developing decision making tools is also discussed from practitioners' perspective (Kinaxis, 2009). These tools, additionally, must include both pre-disruption (risk prevention) and post-disruption (response) as emphasized by Kinaxis (2009): "To have an effective supply chain risk management strategy, companies need a tool that addresses risk assessment and mitigation as well as event response. This tool must support:

- Visibility and analytics capable of modeling the entire supply chain
- Simulation combined with the ability to compare resolution alternatives
- Event detection and alerting to instantly notify of supply disruptions – and their impact to the business
- Collaboration among knowledge experts in the company to develop the most robust mitigation strategies and event responses."

5. MODELING FOR DISRUPTION MANAGEMENT: CHOICE OF SIMULATION PARADIGM

This chapter is the first of three consecutive chapters in which a simulation framework for supply chain disruption management is presented. To select an appropriate paradigm, we start by describing the major challenges in disruption management process and the main characteristics of a supply chain as a complex socio-technical system. Based on these features, then, the major simulation paradigms for modeling supply chains are discussed and critically evaluated.

5.1. Introduction

In Chapter 4, we discussed that the literature on supply chain disruption/risk management provides ample support in identifying potential disruptions and possible strategies to manage disruption. However, the detailed dynamic analysis of supply chain behavior in order to understand the suitability of different strategies over time and under different scenarios is generally ignored by the literature.

The ability to assess the potential impact of disruptions on supply chain performance as well as the effectiveness of possible responses are critical components of the supply chain disruption management process. For the Risk Management Cycle (Pre-disruption process), it is necessary to evaluate the probability and expected severity of disruptions in the Risk Quantification step before *making decisions* on which disruptions have higher priority in the risk profile and, therefore, need treatment. In the Risk Evaluation & Treatment step, the expected costs/benefits of implementing disruption management strategies must be carefully estimated prior to the *decision* on the most suitable treatment for a disruption. Similarly, for the Disruption Management Cycle (Post-disruption process), a crucial element for fast disruption detection is assessing the potential future consequences of a triggering event; there is a need to examine the different disruption responses to determine the appropriate option. And finally, in the Disruption Learning step, it is necessary to evaluate different alternatives to reduce the probability or severity of similar disruptions in the future. *Making decisions* in all these steps can be very challenging and calls for appropriate decision support tools (Figure 5.1), due to the following reasons:

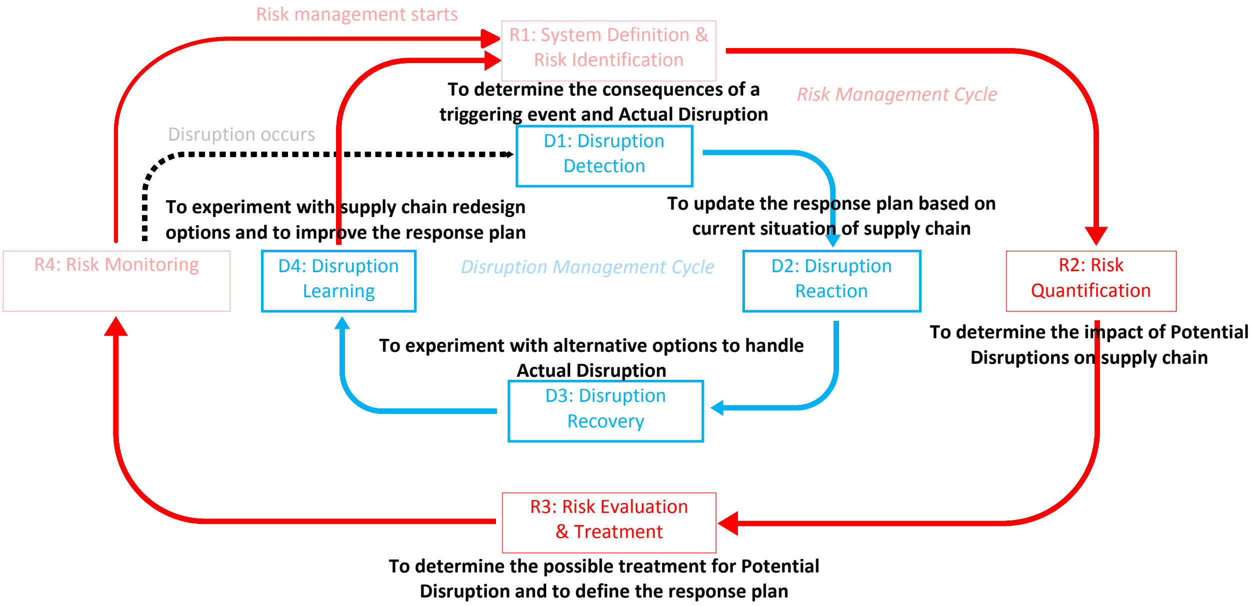


Figure 5.1. Modeling and simulation to support decision-making in different steps of INForMDRiSC

- **A supply chain is a dynamic system.** The behavior of a supply chain dynamically changes over time either as a result of interactions between the decisions at various levels inside each company or as a consequence of interactions with other parties (Swaminathan et al, 1998). Moreover, the (exogenous) parameters which influence the operation of the chain are continuously changing and are mostly uncertain (Puigjaner et al., 2009); the market demand fluctuates; the raw material availability and the price of material vary over time; even supply chain structures keep changing with new customers and suppliers (Fine, 2000). When a disruption happens, the disruptive event has also a dynamic impact on the supply chain with a rippling effect throughout multiple companies (Liberatore et al., 2012). A detailed analysis of disruption impacts on a supply chain and the definition of appropriate policies to manage supply chain disruptions need an overall understanding of this dynamic behavior which is, in most cases, beyond the cognitive capability of decision makers (Eysenck and Keane, 2005).

- **Decision-making for managing supply chain disruptions needs different trade-offs.** To handle a supply chain disruption, the related costs and gains expected from implementing each alternative treatment action must be carefully evaluated and compared (Sheffi, 2005a). Moreover, selecting an appropriate treatment for a disruption requires a trade-off among different performance measures (Jüttner et al., 2003). Faster delivery of raw material from a local reliable supplier might impose higher operational cost to a company; however, it can reduce the number of late orders to customers. An enterprise might also decide to rank different customers and treat them differently in the case of a disruption. Relying on personnel's expertise is mostly inadequate to make judgment about these trade-offs; models and simulations, however, can support the decision makers to arrive at well-informed conclusions.

- **Disruption in supply chains is characterized by resource scarcity and calls for effective coordination.** Disruptions in supply chains may lead to a *shortage of resources* and efficient use of available assets is crucial for disruption management (Dani and Deep, 2010). It might even be essential that the existing resource for each actor be known and shared with others and this requires coordination across a network of stakeholders (Blackhurst et al., 2005; Braunscheidel and Suresh, 2009). Accordingly, proper coordination is a key requirement for managing disruptions in supply chains. However, how to effectively use the available resources and how to design the coordination structures and evaluate their effectiveness in managing disruptions is a challenging issue.
- **Decision-making for disruption management is time critical.** The *speed* and *accuracy* of decision-making, especially in Disruption Reaction and Recovery steps are critical issues and have great impact on operational loss (Kinaxis, 2009). A delay in the selection of an appropriate response can be caused by late detection of disruption and the vast amount of information that needs to be processed.

Because of these issues, making well-informed decisions in managing supply chain disruptions can be very difficult and needs flexible simulation frameworks enabling decision makers to explore a range of what-if scenarios and experiment with different disruption management strategies. The rest of this thesis explores how simulation models can be developed and used to support decision makers in managing disruptions in supply chains.

5.2. How to develop a simulation model: an overview of main steps

To develop simulation models, many approaches are presented and discussed in literature (examples can be found in Law and Kelton (2007) and Heath et al. (2009)). Robinson (2004) and Robinson (2008) review these simulation development methods and explain that despite some differences, all methods are basically very similar, outlining a set of processes that must be performed. The differences, however, are mostly related to the naming of steps or the number of sub-steps for each main step. By analyzing these methods, Robinson (2004) presents a systematic approach for simulation studies with four main processes (Figure 5.2), which are briefly described below.

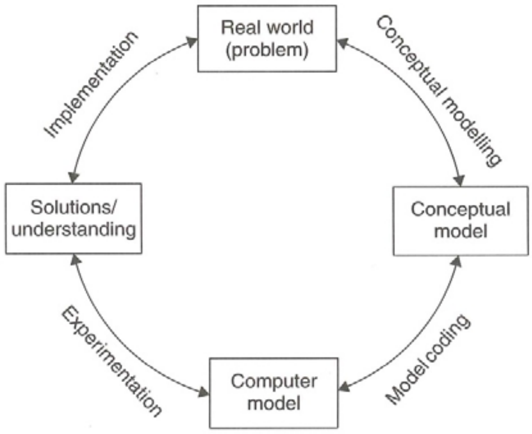


Figure 5.2. Key stages in simulation studies (Robinson, 2004)

Conceptual modeling:

The starting point in any simulation design is to identify the system of study and define the problems observed in the real world. From the understanding of the system and problem situation the “Conceptual Model” can be derived. This model is only a partial description of the real world, however it is sufficient to address the problem situation (Robinson, 2008). The conceptual model generally consists of four main components: the *objectives* of modeling, *inputs* (experimental factors), *outputs* (responses) and *model content* (Figure 5.3). The *inputs* are those elements of the model that can be altered to effect an improvement in, or better understanding of, the problem situation. Meanwhile, the *outputs* report the results from a run of the model. Inputs and outputs are determined by the *objectives*, which, in our case, is the application of simulation modeling for managing disruptions in supply chains. Therefore, the inputs of the model are different potential disruptions and disruption management practices. The expected output of simulation is the impact of disruptions or different disruption management strategies on the performance of supply chains.

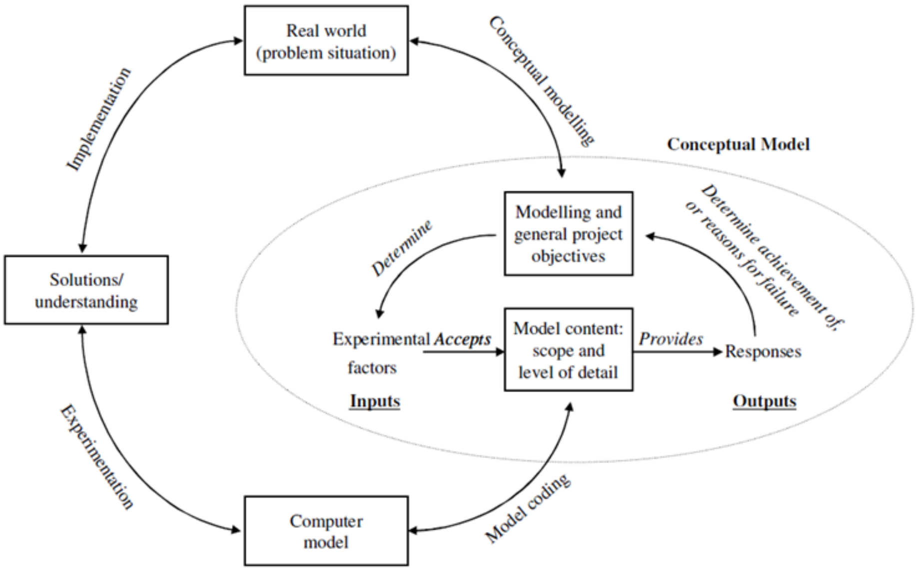


Figure 5.3. Conceptual modeling (Robinson, 2008)

The most important part of a conceptual model, however, is the *model content*, which consists of the components that are represented in the model and their interconnections. While making decisions about the content of the model, various *assumptions* and *simplifications* are normally introduced. While assumptions are needed when there are uncertainties or different beliefs about the real world being modeled, the simplifications are different ways of reducing the complexity of the model. Part of these assumptions and simplifications are imposed by the choice of simulation paradigm. Each paradigm is characterized by a set of core – or fundamental - assumptions and some underlying concepts (Lorenz and Jost, 2006) or, as Meadows and Robinson (1985, p. 17) explain, “every modeling discipline depends on unique underlying assumptions; that is, each modeling method is itself based on a model of how modeling should be done”. For example, when a modeler selects System Dynamics as a simulation paradigm, he explicitly assumes that “the world is made up of rates, levels and feedback loops” (Meadows, 1989). The types of assumptions brought by selection of a particular modeling and simulation paradigm are also called “heroic assumptions” by North and Macal (2007). The existence of these assumptions in each simulation paradigm implies that selection of a modeling paradigm is part of the conceptualization process in a simulation study.

Model Coding:

Once a “Conceptual Model” for the problem and system of study is created, we must implement the model in an appropriate modeling and programming environment. The output of this process is called "Computer Model" (Robinson, 2004).

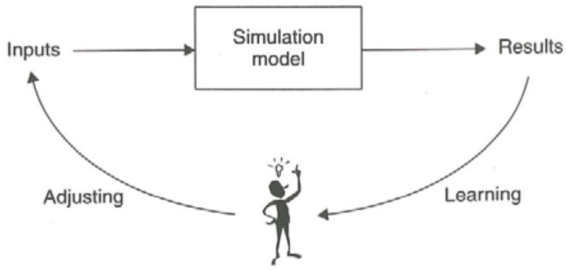


Figure 5.4. “What-if” analysis with simulation (Robinson, 2004)

Experimentation:

Following Model Coding, experiments are performed with “Computer Model" in order to obtain insight into the nature of the system and find solutions to problems (Robinson, 2004). This is mostly an iterative “what-if” analysis process in which different changes in model “inputs” are made, then the simulation is run, the “outputs” are analyzed and –if necessary- new modifications to the inputs are made and so on (Figure 5.4). The outcome of this experimentation process is described as "solution/or understanding". In fact, the simulation models are not necessarily aimed at finding concrete solutions for specific problems; they rather provide a better understanding of the system and real world. In both cases, simulation can support actors to make better-informed decisions.

Implementation:

Finally, the Implementation stage represents the idea of putting the outcomes of a simulation study into practice. Sometimes, the study might have led to an improved understanding and, subsequently, those outcomes cannot be implemented immediately; they can solely impact future decisions to be made about the system. In other situations, the simulation result itself is implemented. For instance, a simulation model might be used to generate a production schedule. In this case, the output of simulation can be immediately implemented in the real world.

These four are the main steps in each simulation study. Two other points, however, are also discussed by Robinson (2004). Firstly, despite the fact that the movement through the process generally goes from conceptual modeling towards the implementation, the simulation process is not linear and might involve *iterations*; a modeler can start with a primary model with partial understanding about the problem and, based on this understanding, he improves the conceptual model and develops a new computer model.

Another important point in Robinson's (2004) methodology is the fact that model testing (verification and validation) is not considered as a single explicit process in the simulation modeling, but it is a continuous process performed throughout the model development and use.

The Robinson's methodology is the basis for developing simulation models in this thesis. We start with the description of the system which is a supply chain. Two well-established theories are used to describe a supply chain. Firstly, supply chains are described from socio-technical systems theory perspective. Afterwards, they are described as complex adaptive systems. In each of these two parts, we also discuss the specific implications for supply chain disruption management. Based on the system description, major characteristics of supply chains are derived. These characterizations have two implications for conceptual modeling of supply chains. Firstly they provide a basis for selecting the appropriate simulation paradigm[1]. The description of system presented here provides also a basis for the conceptual model which is presented in Chapter 6.

5.3. Supply chains as socio-technical systems

Socio-technical systems are "systems that involve both complex physical-technical systems and networks of interdependent actors" (de Bruijn and Herder, 2007). The key contribution of the socio-technical theory is that the system behavior can be analyzed (and improved) only by considering both social and technical subsystems and the interdependencies between them (Otten et al., 2006). In other words, the structure and behavior of both social and technical sub-systems gives rise to the overall behavior of a socio-technical system (Figure 5.5). Modern supply chains – whose characteristics were described in Chapter 1 – can be typically viewed as socio-technical systems.

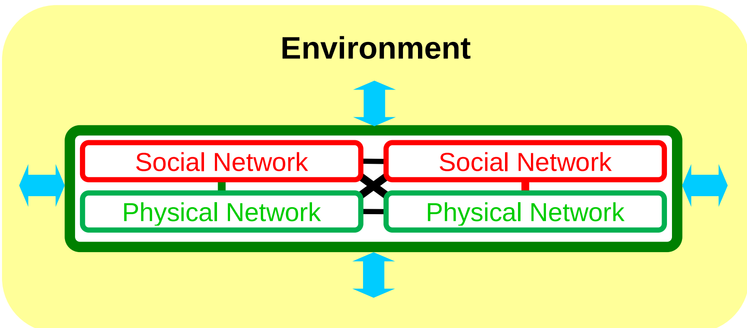


Figure 5.5. The structure of a socio-technical system (after van Dom, 2009)

[1] As mentioned before, part of the assumptions and simplifications in a conceptual model is reflected in the choice of simulation paradigm.

On the one hand, the supply chain is a network of technical elements (e.g., manufacturing facilities, warehouses, etc.) which are physically connected to each other: the material flows by trucks or ships from suppliers to manufacturers; components and semi-finished parts are produced in manufacturing centers and finished goods are assembled at different assembly plants; the final product is then shipped to Central Distribution Centers (CDC) and Regional Distribution Centers (RDC) and finally to retailers and final consumers in different locations (Figure 5.6). Each of the physical nodes and links in this extended network may itself comprise several other physical subsystems. For example, manufacturing plants contain production lines, storage facilities and material handling equipment, while the transportation link between assembly plants and distribution centers may include large scale vessels, cargo terminals and material handling equipment in ports, train or road infrastructures.

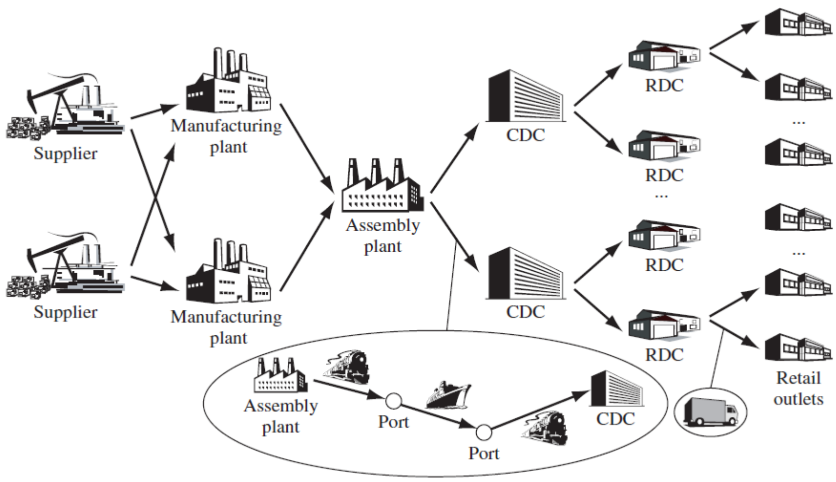


Figure 5.6. A schematic model of a supply chain (Ghiani et al., 2004)

On the other hand, in a supply chain, suppliers, manufacturers, retailers and customers form a social network with many formal and informal interactions. The most formal interaction among actors is through contracts specifying the commitments and terms of transactions between different parties. In addition, information flows among actors influence the decision-making process for the operation and development of physical entities. For example, sharing Point-of-Sale (POS) information between retailers and manufacturers can influence the production planning in manufacturing plants and also reduce the risk of stock-outs and improve on-shelf availability in retailer shops (Zhao et al., 2002). Different types of interactions in the chain might also directly or indirectly depend on each other. For instance, sharing information between supply chain parties can be influenced by formal interaction (e.g., the terms of contract) or informal social factors (e.g., the trust between parties) in the chain. The decisions in the social network are also influenced and constrained by characteristics of physical components. For instance, the rate of producing different products in a manufacturing plant is not only determined by customers' orders and contract setting (e.g., the requested product by customer or the time of order delivery) but also controlled by the characteristics of production facilities (e.g., production capacity or the cost/speed of switching from one product to another on a production line). Consequently, the overall behavior of a supply chain is the output of behavior of both the social and physical networks and the interactions and interdependencies among these networks.

Describing a supply chain as a socio-technical system has specific implications for the disruption management process. Firstly, disruptions can happen in both the physical and social networks. For example, the material delivery from a supplier to a manufacturer might be delayed because of machine breakdown and emergency shutdown in one of the supplier's production lines (disruption in physical sub-system) or the bankruptcy of supplier because of financial issues (disruption in social sub-system). Similarly, possible strategies to handle disruptions can be defined and implemented in both physical and social sub-systems. For instance, to handle late raw material delivery from suppliers, a manufacturer might look for alternative sources of raw material or change the production recipe (response in physical level). He can also start negotiating with customers to extend the delivery date for orders (response in social level). Moreover, the performance of the disruption recovery process is determined by restrictions in the physical and social sub-systems. For example, a quantity-flexible contract[1] between manufacturer and suppliers gives the opportunity to rapidly change the order quantity when a disruption halts the material delivery from one of the suppliers. Similarly, the start-up conditions for production facilities (e.g., the time and costs of plant startup) determine the speed of recovery from an emergency shutdown. Consequently, the capabilities for response to a disruption are determined by characteristics of both the social and physical networks.

Based on all these aspects, an appropriate model for supply chain disruption management must necessarily capture the social and physical characteristics of the supply chain and allow alterations in both networks.

[1] In a flexible contract, the ordering firm (buyer) can adjust the agreed quantity or time of delivery. Of course, the adjustment is mostly restricted to a few percent of original quantity and must be announced to the supplier in a specific period of time before order delivery (Tang and Tomlin, 2008).

5.4. Supply chains as Complex Adaptive Systems

Complexity has been discussed in a wide range of literatures, including philosophy, physical sciences, psychology, engineering and management, among others (Bozarth et al., 2009). With this broad attention, a wide range of definitions regarding what constitutes a Complex Adaptive System (CAS) can be found. A widely accepted description of complex adaptive systems comes from Holland:

> "A complex adaptive system is a system that *emerges* over time into a coherent form, and *adapts* and *organizes itself* without any singular entity deliberately managing or controlling it" (Choi et al., 2001, p. 352).

In another definition, he discusses some other properties of complex adaptive systems, which consist of:

> "...a dynamic network of *many agents* (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly *dispersed* and *decentralized*. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a *huge number of decisions* made every moment by many individual agents" (Waldorp, 1992, p. 144).

Another definition from the psychology domain, Tetlock and Belkin (1996) states that:

> "A complex adaptive system is an *adaptive network* exhibiting aggregate properties that *emerges* from *local interactions* among many agents mutually constituting their own environment" (Tetlock and Belkin, 1996, p. 206).

Plsek (2003) also describes a complex adaptive system as:

> "A *collection* of *individual agents* that have the *freedom* to act in ways that are not always predictable and whose actions are *interconnected* such that one agent's actions *change* the *context* for other agents".

Although these definitions are presented in different domains and from different perspectives, several common features have been discussed for complex adaptive systems. All these features can be generally classified into "Micro-level" and "Macro-level" characteristics.[1] Micro-level characteristics are about the building blocks of the system - which are commonly called “Agents” (Holland, 1996) - and describe the internal structure of a complex system. The macro-level properties, on the other hand, describe how a complex system behaves if we observe it at the whole system level. The micro- and macro-level characteristics of complex adaptive systems are described in the following sub-sections.[2] We also argue that a supply chain has most of these features and accordingly, it needs to be treated as a complex adaptive system.

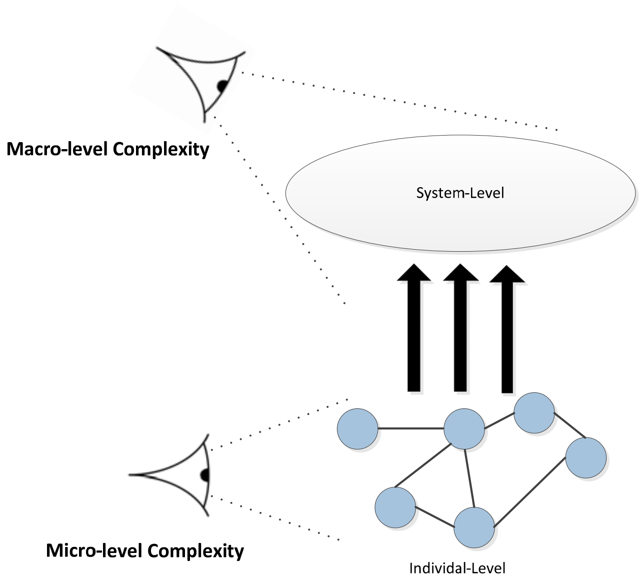


Figure 5.7. Micro-Level vs. Macro-Level Complexity

5.4.1. Micro-level properties of complex adaptive systems

The micro-level features describe the structure of a complex adaptive system and properties of its constituting components. Consequently, the terms “Structural Complexity” (Senge, 1990; Daft, 2004) or “Microstructure” of complex system (Yolles, 2006) can be also used to refer to these properties.

Numerousness and heterogeneity:

[1] It is frequently discussed in the literature that a comprehensive understanding of a complex system needs studying both the macro- and micro-level features of these systems (Chen and Stroup, 1993; Mittleton-Kelly, 2003; Squazzoni, 2008; McDonald and Kay, 2010). Chen and Stroup (1993) describe this with “[t]he ability to understand the world on more than one level is important for engaging complexity. We believe large and complex systems need to be analyzed at both the individual (micro) and collective (macro) levels” (Chen and Stroup, 1993, p. 457).

[2] It must be emphasized that there is no general agreement on the specific characteristics of a complex system in each of these two levels. The features which are presented here are those attributes of a complex adaptive system which are mostly described in literature.

Numerousness is one of well-established attributes of complex systems in the literature (Simon, 1962); a complex system consists of many elements. In addition, these elements normally differ in their characteristics. This property is frequently called “Diversity” (Page, 2011), “Heterogeneity” (Miller and Page, 2007) or “Differentiation” (Foster and Hölzl, 2004). For instance, a supply chain consists of a variety of actors (suppliers, customers, etc.) with different needs, objectives and decision-making behaviors. They are located in different geographic locations (with unique cultures and local business environment), possess different type of technologies and ask for specific types of products. Therefore, the numerousness and diversity can be seen in both physical and social sub-systems of a chain. The number of products (and their differentiation), the number of production lines (with different level of flexibility to produce different range of products) and the number of parts which are needed in producing the final products are examples of supply chain complexity at the physical level. The greater number of suppliers in the upstream of supply chain with diverse characteristics (e.g., delivery performance) and more customers with different preferences in terms of product features and order delivery expectations are examples of social-level issues that increase the supply chain complexity (Choi and Krause, 2006, Bozarth et al., 2009).

Local Interactions:

Another key feature of complex systems is local interactions and interdependencies of the system elements (Bar-Yam, 2003). In general, higher interactions among system components increase the system complexity (Daft and Lengel, 1984; Robinson, 2007).

Like system components themselves, the interactions can be seen in both social and physical levels of the system. For instance, in the physical level, the technical entities of a supply chain are connected through material and energy flows. In the social level, however, interactions are usually in the form of contracts and information flows among different actors.

The other key point is that interactions in complex systems are local (Lane, 2002); two components in the system (in social or physical level) are either connected to each other or not[1]. Therefore, each component in a complex system is connected only to a small number of other components and assuming an average value for sub-systems’ interactions is not acceptable (Finnigan, 2005). For instance, in analyzing the cooperation among

[1] When the local interactions become important we will come to the concept of “Network” to represent the structure of complex systems.

actors, the results with local interactions will differ from the results for well-mixed populations where everyone can potentially contact everyone (Helbing et al., 2011).

The other important issue about interactions in complex systems is that – as the system components are numerous and heterogeneous - the interactions between two components can be also numerous and heterogeneous. For example, a manufacturer may have different contracts for different materials with different terms of delivery with one specific supplier (i.e., multiple social connections). For shipping the raw material from a supplier to its plants, the manufacturer may also consider different routes and modes of transportation (i.e., multiple physical connections). The multiple interactions among two agents are also usually interdependent. For instance, the material flow from supplier storage facilities to the manufacturing plants is dependent on the flow of information between these two actors.

The complexity of a system due to the nature of interactions and relations among its components is often referred to as Interconnection Complexity or Relationship Complexity (Boisot and Child, 1999).

Nestedness:

Another characteristic of complex systems is that the internal organization of the system displays some type of hierarchical organization which is usually termed “Nestedness” (Allen and Starr, 1982). In other words, complex systems are built up from other complex systems and we can call them “systems of systems” (Eisner, 2005). For example, as in a supply network, suppliers, manufacturers, retailers and customers form a complex adaptive system; each of these actors (e.g., the manufacturer) has also several production plants in different locations and each of these plants has some internal departments that are responsible for some internal activities. The interaction and behavior of internal departments determine the behavior of each plant; the collective behavior of plants gives rise to the behavior of each company in the network; and the interactions among different companies and their individual behavior define the behavior of a supply network as a whole. The nestedness of a complex system is also sometimes called Organizational Complexity in the literature (Baccarini, 1996).

Adaptiveness:

Adaptiveness refers to the ability of components of a complex system to change their behavior as a result of their interactions with the other components and the environment (Kauffman and MacReady, 1995; Macal and North, 2010). For example, customers in a supply chain change their opinion and perception about the manufacturer after each transaction. The manufacturer also adapts its policies (e.g., raw material ordering policy) based on the history of interactions with other actors (e.g., the history of order delivery from a specific suppliers). The interaction with the environment can also adaptively influence the behavior of actors (Surana et al., 2005); suppliers define their acceptable range for raw material price according to the average market price for a specific product and new international or national regulations to ban some materials in specific products may force a company to redesign its whole supply chain.

5.4.2. Macro-level properties of complex adaptive systems

In this section several important features of a complex system which are observable at the system-level will be presented. These features include emergence, self-organization, path dependency and co-evolution. Emergence and self-organization can be called "scale-related" features of a system as they describe the relation between micro-structure of the system and system-level behavior. (Co-)evolution and path dependency are, however, "time-related" or dynamic features and describe the changes in the structure and state of the system over time.

Emergence:

The "system-level" behavior in a complex system emerges from the behavior of individual components (both social and physical) and their interactions (Holland, 1999). The delivery performance of a supply chain – e.g., the customer order cycle time - and the robustness of a supply chain to cope with abnormal events are examples of emergent properties. None of these properties can be assigned to one specific individual entity but they emerge from the micro-structure of the system and all individual behaviors.

Self-organization:

Emergence is a property of every system; in every system the system-level properties are the result of sub-system behavior and their interactions. But what is specific about a complex adaptive system is that the emergent behavior arises without any external influence or a central controller[1]; it is the result of interactions of local autonomous decision makers (Finnigan, 2005). This property is called self-organization (Kauffman, 1993), self-governance (Berkes, 2006) or distributed decision-making (Schneeweiss, 2003). To illustrate, complicated artifacts like cars also have emergent features in the sense that the overall functioning of a car is the output of interactions among different parts of the car. However, contrary to a car in which the properties are pre-designed and

[1] In a simple and intuitive definition, Dempster (1998) defines self-organization of a system as the system's capability to organize itself without external direction, manipulation, or control.

imposed by an external designer, in a complex system like a supply chain, there is no one external controller or planner and the overall system behavior emerges from interactions of local autonomous and heterogeneous actors.

Co-evolution:

The components of a complex adaptive system change over time. The social entities learn and adapt to the changing environment and the actions of other actors. Likewise, the physical components might change with time; new production lines may be installed at some of the production plants, new products might be designed to fulfill new needs of final customers and new transportation modes and routes are being selected by manufacturers or suppliers. As a result of all these changes, the system structure and content change and evolve over time making the supply chain a dynamic system (Choi et al., 2001).

The changes in the system are co-evolutionary in two perspectives. Firstly, the constituents of a complex (socio-technical) system are evolving together in a complimentary way (Mittleton-Kelly, 2003). Changes in one component in the system alter the context for all other entities. For instance, a supplier's switch to a new production technology (e.g., with faster production rate) would influence all its customers downstream in the supply chain. Similarly, if a manufacturer likes to introduce a new product, it might need suppliers to adapt their technologies to provide some specific parts for new products. Therefore, all entities within a complex system mutually co-evolve.

Moreover, the structural changes in a complex system cause the co-evolution of the system and its environment (Choi et al., 2001). As an example, when a buying firm switches to a new supplier for a specific material, this action in turn creates a whole new set of second- and third-tier suppliers who will now deliver parts to this new supplier. Moreover, changing the supplier puts the supply chain in a new business environment with new cultural, economic, social and regulatory issues.

Path dependency:

Path-dependency means that current and future states and decisions in a complex system depend on the path of previous states, actions, or decisions, rather than simply on current conditions of the system (Choi et al., 2001; Page, 2006).[1] Path-dependency is also reflected in the decision-making of each of the actors at the micro-level of the system as

[1] Antonelli describes path-dependency by "[the] past narrows the scope of possible outcomes" (Antonelli, 2011, p.48).

past decisions made by that actor (and other actors in the system) constrain the current options. For example, in a supply chain, the decision to install a specific physical setting influences all operational decisions and possible states of the system in the future. A flexible multi-product production line gives the opportunity to better adapt to demand volatility and changes in customer taste. Another example in a supply chain is the order acceptance process; the decision for accepting a new order from a customer highly depends on the previously-accepted orders waiting for processing in the production plants.

5.5. Modeling requirements for disruption management in supply chain

Supply chains as described in sections 5.4 and 5.5 can be considered as "Complex Socio-technical Systems" with micro-level characteristics, summarized as follows:

- *Numerousness* and *diversity*: a supply chain consists of many heterogeneous constituents both in the technical (physical) and social level.
- *Local Interactions*: the constituents of a supply chain are interconnected and interact with each other in different ways. These interactions are in both social and technical levels; they are local and also interdependent.
- *Nestedness*: a complex supply chain may be nested; the components of the system may themselves be complex systems.
- *Adaptiveness*: the social components of a supply chain are adaptive; they change their behavior as a result of their interactions with the other components and the environment.

These four features describe the ***micro-level complexity*** of supply chains and must be adequately reflected in supply chain modeling.

A fairly good representation of micro-level complexity in a supply chain is especially important for analysis of disruptions in the chain as "[a]n unplanned event that disrupts a complex supply chain would be more likely to be severe than the same supply chain disruption occurring within a relatively less complex supply chain" (Craighead et al., 2007, p. 141) and "[a]n unplanned event that disrupts one or more complex portions of a supply chain would be more likely to be severe than the same supply chain disruption affecting relatively less complex portions of the supply chain" (Craighead et al., 2007, p. 142). These two statements show that the number of entities, the way they are connected to each other and the location of the disruption in a supply network are among the determinant factors of the impact on supply chain performance and accordingly the decision-making for supply chain disruption management.

The supply chain modeling approach must (be capable to) capture the ***macro-level complexity*** of a system as well. At the macro-level, a supply chain has four basic features:

- *Emergence*: the structure and behavior of a supply chain as a whole emerge from the behavior of individual components (both social and physical) and their interactions.
- *Self-organization*: in a supply chain, there is no external controller or planner and the overall system behavior emerges from the interaction of local autonomous and heterogeneous actors.
- *Co-evolution*: the structure and behavior of a supply chain are not fixed; they evolves over time together with its environment.
- *Path-dependency*: in a supply chain the current and future state of the system and the decision of actors depend on previous states and decisions.

In addition to the important features of the system (i.e., supply chain), the simulation approach must adequately support the decision makers in handling the problem of study (i.e., disruption management). Different disruptions occur in a supply chain and a variety of mitigation and response strategies might be necessary to evaluate – before implementing them in the real world; therefore, a successful model needs to be ***flexible*** enough to perform experiments with disruptions and disruption responses in different parts of the system – both in the social and technical networks.

The three mentioned criteria – capability to capture the micro-level complexity, capability to capture the macro-level complexity and flexibility to model different disruptions and disruption management practices – are the basis for selecting the appropriate simulation paradigm. Of course, we might not necessarily model a whole supply chain at once. However, the chosen paradigm must have the capability to capture the characteristics of the system and the problem domain.

5.6. Overview of simulation paradigms for complex socio-technical systems

Three main paradigms have been frequently discussed for simulation of complex systems: System Dynamics (SD), Discrete-Event Simulation (DES) and Agent-Based Modeling (ABM). Each of these paradigms comes along with a set of (implicit or explicit) assumptions regarding the key aspects of the world (Borshchev and Filippov, 2004; Lorenz and Jost, 2006). In the following sub-sections the assumptions of the three competing simulation paradigms will be discussed. Subsequently, in section 5.7, we will discuss which paradigm is more compatible with the criteria that are derived from system and problem description as mentioned in section 5.5.

5.6.1. System Dynamics (SD)

System Dynamics is a field of study that Jay Forrester developed at the Massachusetts Institute of Technology (MIT) in the 1950s. Forrester called this new field “Industrial Dynamics” and defined it as: “the study of information feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise” (Forrester, 1961, p. 13). To capture the complexity of a system, Forrester suggested the “feedback loop” concept and discussed that a “complex system has a multiplicity of interacting feedback loops” (Forrester, 1969, p. 9). In other words, the feedback loop is the basic building block of a complex system and the existence of multiple feedback loops is the driver of complex dynamic behavior in a system (Richardson, 1991). Intuitively, a feedback loop exists when information resulting from one action travels through a system and eventually returns in some form to its point of origin, potentially influencing future action (Sterman, 2000). If the tendency in the loop is to reinforce the initial action, the loop is called a positive or reinforcing feedback loop; on the other hand, if the tendency is to oppose the initial action, it is called a negative or balancing feedback loop. Balancing loops can be characterized as goal-seeking, equilibrating, or stabilizing processes. Reinforcing loops are sources of growth and destabilization in the system (Sterman, 2000).

All feedback loops identified for a system from the Causal Loop Diagram (or also called the Influence Diagram (Coyle, 1996)). As an example, Figure 5.8 shows the causal loop diagram for the operation of a production plant.

Causal loop diagrams aid in visualizing a system’s structure and behavior and analyzing the system qualitatively. However, the overall net effect of all the feedback loops in a very complex system cannot be determined merely by inspecting the causal loop diagram. The same system element can belong to several feedback loops, some negative and some positive, and it may not be instantly obvious which loop dominates and drives system behavior (Heath et al., 2011). To determine this, a detailed quantitative analysis of system behavior is necessary. For this purpose, a causal loop diagram needs to be transformed to a *stock-flow diagram* (Forrester, 1968) which consists of two fundamental types of variables: Stocks (or levels) and Flows (or Rates). Stocks are the accumulations of rates of flow, which themselves are the output of decision rules. The process of accumulation is mathematically expressed by integrating the net difference between inflow and outflow over time (Forrester, 1968). Therefore, the state of a system at any specific point in time is solely described by the level variables. This explicitly means that the system dynamics paradigm models the systemic problems at an aggregate level over time. Moreover, system dynamics models are typically formulated in continuous time and assume continuous variables, though most simulators discretize the time to solve the set of differential equations describing the system behavior (Brailsford and Hilton, 2001).

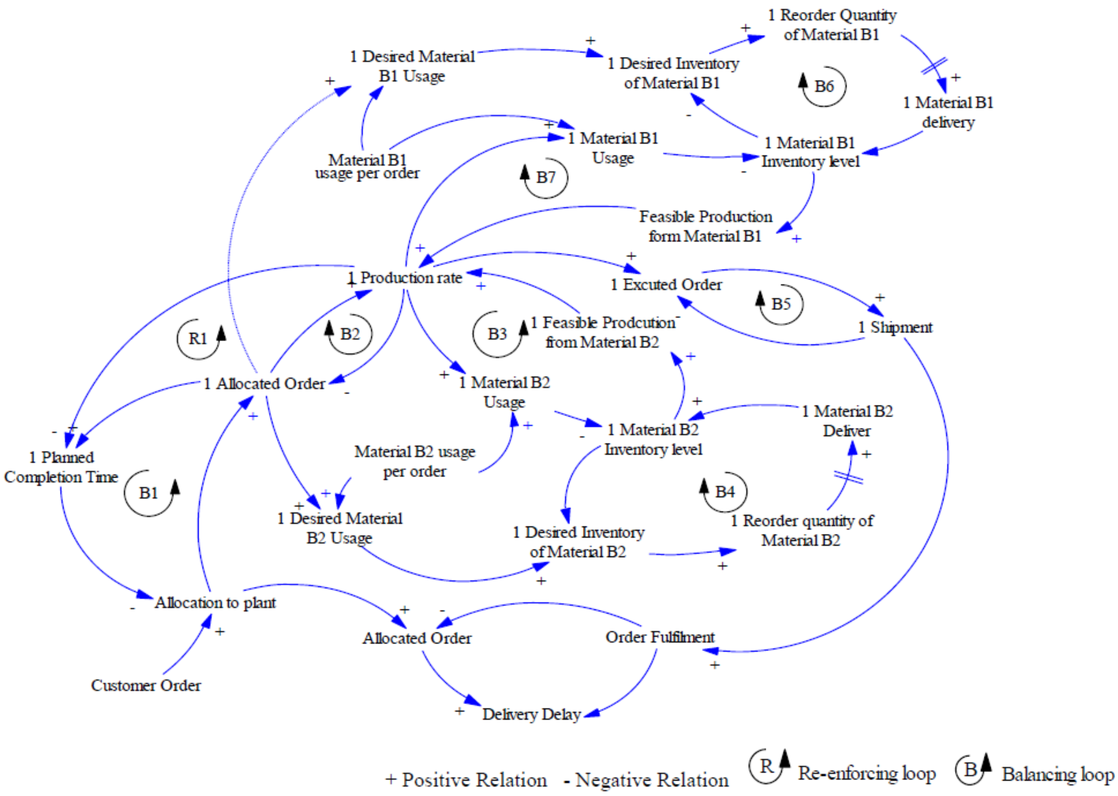


Figure 5.8. Causal relation diagram for the operation of a production plant (Mussa, 2009)

As an example of a stock-flow diagram, Figure 5.9 shows the inventory management for a raw material in a production plant.

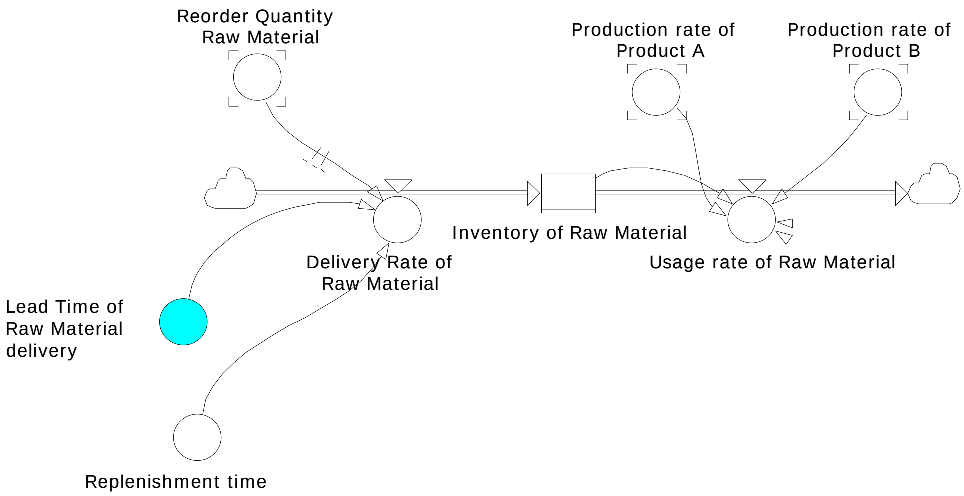


Figure 5.9. Stock-flow diagram for inventory management in a plant (Mussa, 2009)

In summary, system dynamics is a feedback-based simulation paradigm. The feedback concept is at the heart of system dynamics; diagrams of information feedback loops and circular causality are tools for conceptualizing the structure of complex systems (Forrester, 1961; Richardson, 1991). The feedback loops are, then, represented in stock-flow diagrams in order to formalize the whole structure of a complex system in terms of stocks, the flows between these stocks, and information that determines the value of these flows. This structure is finally represented as a set of differential and algebraic equations which are solved numerically to describe the dynamic behavior of the system over time.

5.6.2. Discrete-Event Simulation (DES)

The greater majority of processes around us appear to be consisting of continuous changes. However, when analyzing those processes, in many cases it makes sense to abstract from their continuous nature and consider only some important events and moments in the system lifetime. This is particularly the case for many dynamic processes in industrial contexts (e.g. manufacturing, transportation and inventory management). In most of these systems the state of the system changes at discrete points in time (i.e. at events), rather than through a continuous state of fluctuation. For example, suppose we simulate the operation of a warehouse. Purchase orders come in and are fulfilled. Consequently, the inventory level is reduced; however, it is replenished from time to time. Here, considering the number of items in stock for a given product (or "inventory level") as a typical variable to describe the system states, the events -decreases and increases in the inventory—are occurring in a discrete manner. The modeling paradigm that suggests approximating the real-world processes with such events is called Discrete Event Simulation (Altiok and Melamed, 2007). In this simulation paradigm, the system possesses at any point in time a *state* whose change over time is triggered by discrete *events*. In other words, the simulation state remains unchanged unless an event occurs, at which point the model undergoes a state transition. The model evolution is governed by a *clock* and a chronologically ordered *event list*. A simulation run starts by placing an initial event in the event list, proceeds as an infinite loop that executes the current most imminent event (the one at the head of the event list), and ends when an event stops or the list becomes empty.

In addition to this formalization for DES –which is usually termed "Event-Scheduling (ES)" (Cassandras and Lafortune, 1999) or "Event-Oriented Modeling" (Silver et al., 2010) - a number of other methods and formalizations for carrying out discrete-event simulation have been discussed in the literature (Pidd, 1998). Two important formalizations are "Activity Scanning (AS)" and "Process-Interaction (PI)". These different formalisms are usually called different "worldviews" (Altiok and Melamed, 2007) or different "simulation strategies" (Martinez, and Ioannou, 1999) in DES literature. In the activity scanning approach, the model focuses on activities and their preconditions. An activity consists of a pair-event (a start and an end event) and is preformed when its preconditions become true (Silver et al., 2010). For instance in the Petri-Nets approach - which is classified as an activity scanning method-the model consists of two types of nodes, "transition" and "place", and a "transition" will fire if there are enough "tokens" at each of its input "places" (Miller et al., 2004). The Process-Interaction approach focuses on processes which describe the life cycle of one entity in the system (Banks et al., 2010). PI assumes that entities in the system will progress through a set of steps and each step requires one or more resources and takes a certain (usually stochastic) amount of time (Silver et al., 2010). The process view is the most-commonly-used formalism for DES and most of commercial DES software such as GPSS, SIMAN, SIMSCRIPT and SLAM are based on this approach. Because of the popularity of this method, DES is also sometimes termed the "process-centric" simulation paradigm (Salamon, 2011).

Besides these three classical worldviews, there are other popular modeling approaches which are usually classified as DES. State-Transition models (e.g., Markov Chains) whose focus is on identifying the system states, determining which of the states are linked and describing the transitions, is one example (Miller et al., 2004).

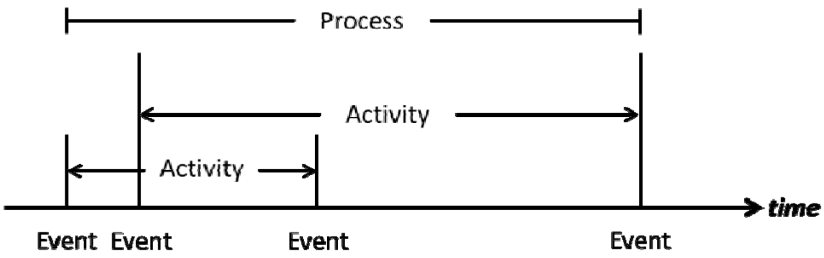


Figure 5.10. The main building blocks of DES: Event, Activity and Process (Page, 1994)

As can be seen, whereas SD has a more-commonly-accepted conceptualization for a system, DES has many different forms to conceptualize a system. However, in all these approaches, the entities that describe the structure of system (events, activities and processes) are passive 'objects' (Siebers et al., 2010); they are pre-defined by the modeler. The main strength of DES, however, is its capability to model distinctive entities with heterogeneous characteristics.

5.6.3. Agent-based Modeling (ABM)

Agent-based modeling is a type of modeling in which the focus is on representing the individual decision makers in the system – which are termed "Agents" - (such as people or companies) and their interaction with each other and their environment (North and Macal, 2007).The global (system-level) behavior then emerges as a result of agents' individual behaviors and their interactions.

To describe an "Agent" –as core element of ABM- a wide range of properties have been discussed in the literature. There is a general consensus that the agent needs to be autonomous but there is little agreement beyond this because the potential properties vary in their importance in different domains and different applications (Wooldridge, 2002). The following characteristics are, however, among the features which are usually mentioned for an agent in agent-based modeling (Wooldridge and Jennings, 1995; North and Macal, 2007):

- *Autonomy*: agents have a certain level of autonomy; they can take decisions without a central controller or commander. To achieve this, they are driven by a set of rules that determines their behavior.
- *Reactivity*: agents are capable of reacting to their environment; they are able to perceive the changes in the environment in which they are immersed and respond to those changes with their own actions whenever necessary.

- *Pro-activeness*: agents have proactive ability; they do not just act in response to changes that have occurred in their environments but they have their own goals.
- *Social ability*: agents have social ability to interact and communicate with each other.
- *Adaptiveness*: agents may have memory and learn and adapt their behaviors based on experience.

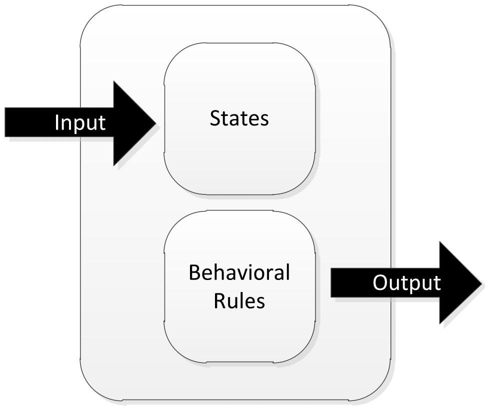


Figure 5.11. A simple structure for an Agent in ABM (after Nikolic, 2009)

Developing an agent-based model typically starts by defining the internal *states* (or attributes) and *behavioral rules* of different types of agents (Figure 5.11). The behavioral rules describe, e.g., how an agent changes state or selects an action to do, how agents interact with each other and how the agents interact with the environment. The agents - states and behavior- and the environment are next structured in a simulation program. ABM programming can be done in any language, but “Object-Oriented Programming” is the most appropriate programming paradigm because of similarities between the concepts of “object” and “agent” (Gilbert and Terna, 2000).

ABM is a relatively new simulation paradigm. However, some specific features of ABM make it a popular paradigm for modeling complex systems in different domains. First, it is easy to model heterogeneous agents in an agent-based model. The heterogeneity can be expressed in the behavioral (decision-making) rules of agents and their attributes (Gilbert, 2007). Second, learning mechanisms and adaptive behavior can be easily represented in an agent-based model. This is especially important in the domains in which an explicit representation of human decision-making is necessary to model the system behavior. Examples include economics (Tesfatsion, 2006), crowd simulation (Shendarkar et al., 2006) and traffic management (Helbing, 2001). The other particular feature of ABM is its ability to model spatial aspects. In some cases, like ecological problems (Heckbert et al., 2010), land use modeling (Valbuena et al., 2010) or urban systems planning (Crooks et al., 2008), an explicit spatial representation may be required for the analysis. Finally, an agent-based model can be easily extended or used for other purposes. For instance, it is easy to add more agents to a previously-developed model or change the level of detail by "tuning the complexity" of agents, e.g., in terms of degree of rationality and rules of interactions (Bonabeau, 2002b). This is especially useful when the appropriate level of description or complexity is not known ahead of time and finding it requires some tinkering. Moreover, it gives the opportunity to develop agent-based models in an iterative process in which the modeler may start out with an idealized and general model and make the underlying structure of the model more complicated by iteratively adding details (Epstein, 2006).

5.7. Choice of simulation paradigm

Three main paradigms for modeling complex systems have been discussed in section 5.6. As mentioned, each of these paradigms has specific features, considers different building blocks for describing the system structure/behavior and has some key assumptions about the world. A summary of the main characteristics of these approaches is presented in Table 5.1.

Table 5.1. Summary of main characteristics of three simulation paradigms

System Dynamics (SD)	Discrete-event Simulation (DES)	Agent-based Simulation
System-oriented; focus is on modeling the system observables	Process-oriented; focus is on modeling the system structure and behavior in detail	Individual-oriented; focus is on modeling the behavior of entities and interactions between them
Homogenized entities; all entities are assumed have similar features; working with average values	Heterogeneous entities	Heterogeneous entities
No representation of micro-level entities	Micro-level entities are "passive objects" (with no intelligence or decision-making capability) that move through a system in a pre-specified process	Micro-level entities are "active entities (agents)" that can make sense of the environment, interact with others and make autonomous decisions
Driver for dynamic behavior of system is "feedback loops".	Driver for dynamic behavior of system is "event occurrence".	Driver for dynamic behavior of system is "agents' decisions & interactions".
Computer formalization of system is in "Stock & Flow"	Computer formalization of system is with "Event, Activity and Process".	Computer formalization of system is by "Agent and Environment"
Handling of time is continuous (and discrete)	Handling of time is discrete	Handling of time is discrete
System structure is fixed	The process is fixed	The system structure is not fixed

In this section, we discuss which simulation paradigm can better meet the three criteria mentioned in section 5.5. In fact, we would like to examine which paradigm is "naturally"[1] more capable to capture the micro- and macro-level characteristics of a supply chain as a complex socio-technical system. Moreover, we would like to select a paradigm which provides flexibility in modeling disruptions and disruption responses in the social and physical sub-systems. Of course, it might be impossible for one model to accommodate all the complexities of a specific supply chain and model every possible disruption; nonetheless, the challenge is to select a paradigm which best fits the system characteristics and does not constrain developing a model with the necessary level of detail.[2]

5.7.1. Capturing micro-level complexity

ABS, DES and SD modeling paradigms take fundamentally different perspectives when modeling the micro-level complexity of supply chains. SD basically belongs to a class of modeling approaches which are usually labeled "top-down modeling", i.e., focusing on system observables and modeling the system components with aggregated state variables (Heath et al., 2011). In contrast, DES and ABM have a "bottom-up" perspective in modeling; they start with a detailed representation of individual parts of the system and their interactions.

This top-down approach and high aggregation level in SD could be problematic for modeling complex system. Firstly, SD is unable to model the heterogeneity and numerousness in a complex system. The discrete entities which compose a complex supply chain (people, firms, products, etc.) are modeled homogenously and represented by their quantities (described as system's observables) in SD models (Rahmandad and Sterman, 2008). To put it another way, instead of working with distinctive entities with different characteristics, SD works with an "average individual" which represent a population of entities (Scholl, 2001). Similarly, SD has an aggregative view of the interactions in a complex system and assumes perfect mixing within compartments of the

[1] The emphasis on "natural-representation" is important because – as described in the text- some aspects of a complex supply chain cannot be modeled by a specific paradigm; however, there are aspects which can be modeled with all paradigms but might be easier to model with a specific one. Moreover, sometimes a modeling paradigm needs to relax some of its core assumptions to be able to model a specific feature of complex supply chains.

[2] Parunak et al. (1998) discuss that understanding the capabilities of modeling approaches is of ethical and practical importance for system modelers and simulators. It is important ethically because the duty of simulators ought to be first of all to the domain being simulated, not to a given simulation paradigm, and the choice of technology should be driven by its adequacy for the modeling task. Selection of the appropriate paradigm is also important practically because the available resources for modeling and simulation must be used to deliver the best possible results.

system where everybody is connected to everybody else (Rahmandad and Sterman, 2008). Assuming uniform distribution for the interactions among agents in the system is a challenging issue because –as mentioned before- the interactions in a complex system are local and we cannot define an average value to represent them in a model (Finnigan, 2005).

Although there is general agreement among scholars that the aggregate philosophy in SD limits modeling the basic micro-level features of complex system, there is still much debate on the importance of these features on the dynamic behavior of system and also on which specific issues can/cannot be captured by a SD model. In an effort to evaluate the impact of aggregation assumptions, Rahmandad and Sterman (2008) developed agent-based and SD models for a case of contagious disease epidemic in a classic SEIR model[1]. Experimenting with different network topologies- including fully connected, random, scale-free and lattice networks – they concluded that the effect of network representation on the results are small except for lattice networks. They also evaluated the impact of heterogeneity and claimed that in their case the effect of heterogeneity assumption on the results was small and negligible. However, they also believed that "AB models enable analysts to examine questions not easily modeled in the DE [Differential Equation] paradigm[2], e.g., creating and removing nodes and links to simulate random failures or targeted attacks" (Rahmandad and Sterman, 2008, p. 1012).

In another study, Demirel (2007) compared two models of SD and ABM for a case of a three-level supply chain consisting of retailers, wholesalers, and manufacturers. Many different issues including different ordering policies, shadow ordering[3], dynamic pricing and the impact of supplier prices and loyalty in supplier selection are modeled and analyzed with both models. Based on the analysis of the two models, Demirel (2007) made some general conclusions regarding the comparison of aggregated (SD) and disaggregated (AB) modeling approaches. Some factors are shown to be difficult or

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[1] The susceptible-exposed-infectious-recovered (SEIR) model is a model for diffusion of disease in which all members of a population are categorized in are categorized as susceptible, exposed, infected, or recovered (Zhang, and Ma, 2003; Rahmandad and Sterman, 2008). Contagious individuals can infect susceptible ones before they are "removed" (i.e., recover or die). The exposed state captures latency between infection and the emergence of symptoms. Depending on the disease, exposed individuals may become infected. Typically, such individuals have more contacts than those in later stages because they are asymptomatic.

[2] The DE paradigm implies system dynamics in Rahmandad and Sterman (2008).

[3] When the supply is scarce in the market and accordingly the delivery time is high, there is a competition among the firms to gather the supplied goods and each firm might show its demand more than its original need. This attitude of firms is usually term "shadow (or phantom) ordering" (Demirel, 2007). This phenomenon especially can be seen in cases that customers can cancel their orders at any time of production or even during the delivery process (Sterman, 2000).

impossible to define with a system dynamics model at an aggregate level. For instance, when the interactions between agents is impacted by discrete factors – e.g., considering the price in the selection of supplier- SD cannot capture this detail as there is no distinction among individual agents and individual entities in the model. Consequently, there may be factors which significantly affect the supply chain behavior, but the dynamics generated by these factors cannot be captured by the SD model at an aggregate level. In addition, Demirel (2007) showed that assuming the heterogeneity among the agents can result in a different dynamic behavior for the system which cannot be captured in a SD model. Based on his study, Demirel (2007) concluded that "there are factors, the effects of which can be captured by System Dynamics at an aggregate level; however … System Dynamics may miss the dynamics at [a] more detailed level resulting from the emerging heterogeneity among individual agent behaviors in these cases. There are also cases where System Dynamics cannot capture the dynamics generated by ABM, even at an aggregate level."

In addition to numerousness, heterogeneity and interconnectedness, the aggregated view in SD makes it difficult to model the nestedness and multi-level characteristics of complex supply chains (Mussa, 2009; Yang et al., 2012). There are, however, several efforts in the literature to model the nestedness of complex systems; one of them is the work of Mussa (2009) in which a SD model for a chemical enterprise with multiple levels of decision-making is presented. In this case, the enterprise consists of several plants and each of the plants has some departments. The behavior of each department is described with a stock-flow diagram. The behaviors of departments give rise to the behavior at the plant-level and plants together form the behavior at the enterprise-level.

Probably the main strength of SD is in modeling the adaptiveness in a complex system; because, feedback loops is the key driver of dynamic behavior in a SD model (Sterman, 2000). This fact, however, can be challenged as in a complex system the individual agents learn or adapt (Holland, 1999). In other words, the learning and adaptiveness for a complex system happen at the individual-level and not at the system-level.

All in all, the general conclusion is that SD is not capable –in nature- to capture most of the micro-level features of a complex adaptive system and this would influence the validity of results of SD for a complex system like a supply chain. In contrary, discrete event and agent-based simulations have the capability to model the micro-level of a system in details. There are, however, basic differences between these two paradigms. Firstly, in DES the events are the atomic part of the model and the occurrence of events is triggered by previous events or timing rules (Figure 5.12). In ABM, the atomic part is the agent and all events and activities are triggered by decisions of agents (actors) in the system (Heath et al., 2011). This difference in the micro-level components of two approaches is described in Siebers et al. (2010) as “Passive vs. Active”. In event-driven simulation, the contents of model are “Passive” objects, on which in some sequence some set of operations is performed. In ABM, the entities themselves can take on the initiative to do something; they are “Active” entities. This explicitly indicates that modeling the social-level behavior in a complex socio-technical system is not straightforward in a DES model (Becker et al., 2006). The knowledge sharing and change of opinion among different actors in the system about each other are examples of challenging aspects to capture with a DES model. This is especially an issue as the social interaction in a supply chain is a main driver of dynamic behavior of the system. Customers might share their experience with a manufacturer or specific brand and this sharing of information may impact the attitude of other customers for transaction with that manufacturer or towards that brand. Moreover, the adaptiveness of actors is not usually modeled in a DES model as entities in the system are considered as passive. Modeling these aspects is solely possible in an ABM.

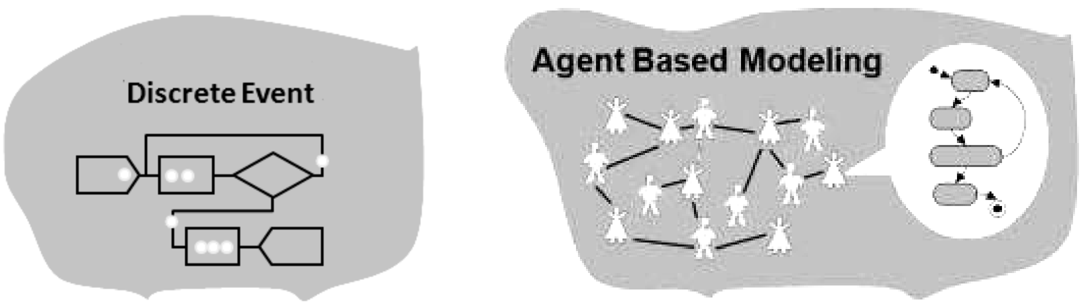

Figure 5.12. The difference in event occurrence in DES vs. ABM (from: www.anylogic.com)

Altogether, DES is an appropriate paradigm for modeling the details of physical components of a complex system; however, it is not usually considering the social entities and the social-level complexity in supply chain modeling.

5.7.2. Capturing macro-level complexity

Similar to micro-level complexity, the three modeling paradigms -i.e. SD, DES and ABS – are distinct in the way that they capture the macro-level complexity of supply chains.

At the first look, one may think the ***emergence*** in complex system can be addressed in every simulation approach; in all cases the simulation outputs are emerging from model components and their interaction. But, the capability of SD to produce the emergent properties in a complex system has been challenged by several authors. In their book – Simulation for Social Scientist - Gilbert and Troitzsch (1999) argue that as the emergent properties are the "system properties" resulting from "individual-level" behavior and interactions, "A technique capable of modeling two or more levels is required to investigate emergent phenomena" (Gilbert and Troitzsch, 1999, p. 12). In other words, the necessary condition for emergent properties in a system is existence of hierarchy of system level.[1] Therefore, since SD models the behavior of system in an aggregate level, Gilbert and Troitzsch (1999) explicitly deny the ability of SD approach to display emergence in a complex system. With similar reasoning, Bonabeau (2002a) claimed that the only way to analyze and understand emergent phenomena is to model them from the bottom up.

Similar to SD, some authors also criticized modeling emergence in DES. They argued that in DES, the "macro behavior is modeled" by the programmer and it is not emerging in the system level (Siebers et al., 2010). This is in contrast with ABM in which "macro behavior is *not* modeled; it emerges from the micro decisions of the individual agents" (Siebers et al., 2010, p. 207). The programmer only models the behavior of individuals in the ABM and the system behavior emerges collectively from the interactions of individuals (Garcia, 2005).

Despite these arguments, the main drawback of SD and DES in modeling macro-level behavior is not in capturing the emergence but it is about the ***self-organization*** characteristics of complex systems. The decentralized decision-making is not (adequately) modeled in either one of these two simulation paradigms. As mentioned before, SD is not individual-based modeling in nature. Likewise, DES models also ignore the self-organization in the system as system-level rules govern the movement and behavior of entities and these entities do not have any intelligence or decision-making capability within them (Siebers et al., 2010; Heath et al., 2011). This is, however, basically different in ABM in which agents – as autonomous decision makers- have rules and can alter the interactions with other agents and the environment (Heath et al., 2011).

[1] The emergence phenomenon in complex systems is frequently described by two main necessary conditions. Firstly, the system must show nonlinearity in its behavior (Goldspink, 2002). This, in fact, implies that the system observables cannot be decomposed to properties of its constituents. Gilbert and Troitzsch (1999) explain this with "a phenomenon is emergent if it requires new categories to describe it that are not required to describe the behavior of the underlying components. For example, temperature is an emergent property of the motion of atoms. An individual atom has no temperature, but a collection of them does" (Gilbert and Troitzsch, 1999, p. 11). The second necessary condition to show emergence is the existence of at least two levels for system (or in conceptualizing the system) (Goldspink, 2002; Gilbert and Troitzsch, 1999). In other words, emergence is regarded as a macro phenomenon that results from interactions of components on a lower level.

Both SD and DES have also difficulty to capture the ***evolution*** of complex adaptive systems; because in both paradigms, the system structure is assumed fixed. In a System Dynamics model, the structure of system – in form of causal diagrams and stock-level diagrams- has to be defined before starting the simulation (Schieritz and Grobler, 2003). This structure is constant and cannot be modified throughout the course of the simulation (Schieritz and Milling, 2003). Similarly, in DES, the process must be well-defined beforehand (Siebers et al., 2010). On the contrary, for an agent-based model the underlying processes are not fixed; but, based on its decision-making rules and the interactions with other agents and with environment, an agent may select a different course of actions and follow a different process. Consequently, the network structure is modified dynamically (Achorn, 2004).

About ***path-dependency***, in comparing three simulation approaches, we need to explicitly differentiate between two main issues. As mentioned, path-dependency means that the *current* and *future* states of a complex system depend on previous states and decisions (Page, 2006). This firstly implies that a small change in the initial condition or the early stages is exacerbated over the course of time and results in a basically-different present state for the system (Choi et al., 2001). This aspect of path-dependency can be captured by all three simulation paradigms: in every model, any event which alters one of previous states of the system can be a critical determinant of current state of the system and any change in the path of events would result in a different final state and configuration for the system (Sterman and Wittenberg, 1999). The path-dependency in a complex system, however, has an added implication which is in the transition from current state to the next state of the system, the path of events and states –and not solely the current state of system- is influential and must be taken into account (Schieritz and Milling, 2003). With this aspect of path-dependency, there is a basic difference between ABM and two other paradigms. Actually, the future behavior of a system in a SD or DES model only depends on the current state of system. For example, for a SD model, the state of system at time “t” is calculated based on the state variables at previous time and the “Net Rate” at time “t” (i.e., $S_t = f(S_{t-1}, R_t)$ or in the simplest form $S_t = S_{t-\Delta t} + R_t * \Delta t$) and no explicit dependence on the past states is usually reflected in the model.[1] For DES, however, the path-dependency can be captured in the model because models mostly have queues with a certain length which represent a history of arrivals and the decisions are made based on the queues (and not solely one specific job or order). In an Agent-based Simulation model,

[1] In fact the behavior of system in SD is modeled as a “Memoryless System”, meaning that the future state of the system depends only on its present state and not the history of system states (Zeigler et al., 2000).

also, individual agents possess internal memory of past events (e.g., the history of interactions with other agents) which impacts every future decision of that agent and consequently, the next state of the system (Schieritz and Milling, 2003; North and Macal, 2007).

5.7.3. Flexibility in modeling for disruptions management in supply chains

To support decision makers in handling supply chain disruptions, flexibility in modeling approach is desired to allow for experimentation with different types of disruptions and disruption management practices at both social and physical sub-systems. In comparing simulation paradigms to capture the micro-level complexity of system, we argued that some aspects of the system are hard to grasp with SD and DES models. SD has difficulty in modeling the distinctive entities (at social and physical level) as well as the decision-making of individual actors. Modeling a supply chain in DES is also normally focused on the physical network and generally ignores the social level and individual decision-making. This explicitly means that some disruptions in the physical and social levels of system are very difficult, if not impossible, to represent in SD or DES models. ABMs, however, offer a good way to include different aspects of complex socio-technical systems (van Dam, 2009; Chappin, 2011). This is primarily because ABM - in terms of software implementation - naturally follows the object-oriented software paradigm (Gilbert, 2005). The physical components of technical sub-systems in a supply chain, both nodes (e.g., storage and production facilities) and links (e.g., the raw material pipes between storage and production facilities) can be presented by separate objects in an agent-based model. In addition, the social actors in the system can also be represented as agents making decisions about the operation and development of the technical network. With this flexibility in modeling socio-technical systems, various types of disruptions can be modeled in the social or physical dimension of the system. Moreover, ABM is very flexible to define and encode different behavioral settings for agents and experiment with possible disruption management strategies. This is an important feature of ABM as in most cases the disruption management practices are basically defined by change in the behavior of actors at the individual-level of system and their way of interaction. For instance, faster response to an initial event by an actor can be a determining factor for the degree of disruption impact on the supply chain. As another example, the disruption response plan may describe which actor must interact with which actor and which resources should be shared. Representing these disruption management practices is very difficult in a simulation paradigm – like SD - which cannot adequately capture the micro-level structure of supply chains. Likewise, modeling some issues such as information exchange, resource sharing and coordination mechanisms to manage disruptions are not in the standard procedures for developing discrete event models and require complicated modules.

The natural representation of complex socio-technical systems in ABM has another important advantage too; ABM's are easier to translate back into practice (Parunak et al., 1998). Because an agent-based model is expressed and modified directly in terms of behaviors, implementation of its recommendations is simply a matter of transcribing the modified behaviors of the agents into task descriptions for the represented entities in the real world.

The other important feature of ABM is ease of extending the model. The model structure can be adjusted by adding more agents or revising the behavioral rule for current agents. This is very challenging in other simulation paradigms. For example, changing the structure of the system by adding new entities may take a lot of time in a system dynamic model; because in SD the structure has to be determined before starting the simulation (Schieritz and Grobler, 2003). So, to introduce new variables, the implications for all current system variables and the overall (feedback) structure of the model have to be checked. This makes the task of extending a system dynamic model more difficult and time-consuming as compared to agent based modeling (Mussa, 2009).

5.8. Choice of agent-based modeling as simulation paradigm

Based on the discussion of section 5.7, Table 5.2 summarizes how alternative simulation paradigms are fitting with system and problem features.

The main difficulty with SD paradigm is its inability to capture the distinctive entties – in the socil and technical level of a supply chain - and their interactions. Likewise, the focus of DES is on technical entities and their interactions. However, ABM is the modeling approach which can capture the properties of supply chains as complex socio-technical systems and also provides the greatest flexibility in experimenting with different settings in a disruption management problem. Therefore, it is chosen for the model development in the next chapters of this thesis. For two other simulation paradigms, capturing some characteristics of a supply chain is difficult – if not impossible. Indeed, the need for a model to grasp all key system features is also dependent on the problem and the necessary interventions. For instance, with a system dynamic model, it is possible to model the impact of variations in market demand on the manufacturing performance (e.g., in Beer Game (Sterman, 2000)); but, the intervention to steer customer and change the demand pattern needs to include the individual customers' decision-making in the conceptual model which is not straightforward in SD. Likewise, DES might be very well-suited if the focus lies on the logistics of order fulfillment and delivery. However, modeling the information exchange between customers about a brand or sharing their transaction experience with a particular company is impossible with the fundamental concepts and standard procedure of discrete modeling.

Table 5.2. Comparison of simulation paradigms for supply chain disruption modeling

		System Dynamics (SD)	**Discrete-event Simulation (DES)**	**Agent-based Simulation**
micro-level complexity	Numerousness and heterogeneity	No distinctive entities; working with average system observables (homogenous entities)	distinctive and heterogeneous entities in the technical level	distinctive and heterogeneous entities in both technical and social level
	Local Interactions	Average value for interactions	Interactions in technical level	Interactions in both social and technical level
	Nestedness	Hard to present	Not usually presented	Straightforward to present
	Adaptiveness	No adptiveness at individual level	No adptiveness at individual level	Adaptiveness as agent property
macro-level complexity	Emergence	Debatable because of lack of modeling more than one system level	Debatable because of pre-designed system properties	Capable to capture because of modeling system in two distinctive levels
	Self-organization	Hard to capture due to lack of modeling the individual decision-making	Hard to capture due to lack of modeling the individual decision-making	Capable to capture because of modeling autonomous agents
	Co-evolution	Hard to capture because system structure is fixed	Hard to capture because processes are fixed	Capable to capture because network structure is modified by agents interactions
	Path dependency	Debatable because of no explicit consideration of history to determine future state	Capable to capture because current and future state are explicitly defined based on system history	Capable to capture because current and future state are explicitly defined based on system history
Flexibility in modeling		Difficulty in modeling disruptions and disruption management at social/technical level	Difficulty in modeling disruptions and disruption management at social level	Flexible to model disruptions and disruption management at social/technical level

It is noteworthy to mention that the arguments for suitability of ABM for supply chain simulation in this chapter are for the conceptualization step; ABM can help to better conceptualize the complexity features of a supply chain. However, at software implementation and model coding stage, several issues may limit the applicability of ABM. The first issue is that using ABM is justified solely as long as a fairly good description of micro-level behavior of system – i.e., Agents – is available or can be discovered by some sort of observation. The usefulness of this approach is largely challenged when a good theoretical basis or adequate information to describe the actors' behavior does not exist for developing a simulation model. The other barrier that impacts the application of ABM for every industrial case is difficulty in the model development and coding agent-based models. Developing an agent-based model mostly needs a good knowledge of (object-oriented) programming languages (especially, Java). Meanwhile, although several academically-developed tools for ABM (like Repast or NetLogo) are available for researchers, the commercial software tools with "drag and drop" features are generally lacking for managers who like to easily model a system and solve their problems. The story is completely different for other simulation paradigms, like DES, for which several user-friendly software tools are available. Because of availability of software tools, DES is usually seen as an accepted simulation approach unless some social factors involved the system and must be reflected in the simulation model.

As a final point, it must be emphasized that although the focus of this chapter was on choice paradigm for supply chain modeling, the arguments of section 5.7 and Table 5.2 can be generalized for modeling any complex socio-technical system.

5.9. Analysis of supply chain simulation literature

In this section, an analysis of supply chain simulation literature is presented and discussed. The literature search was done in Scopus (2012), using the "supply chain" and "simulation" terms in the abstract, title and keywords. Moreover, the search was limited to articles or reviews that have been published before 2012.[1] A first search in Scopus resulted in about 1510 papers. To confine the literature analysis, we next did a quick scanning of abstract of these papers (and the full text, if needed) to check if they really present a simulation model for supply chains. In fact, despite inclusion of simulation or supply chain terms in the abstract, not all papers were about supply chains or have presented a simulation model that can be used to solve specific supply chain problems or define experiments and answer "what if" questions. In addition, in some cases, the paper was about analytical modeling for supply chains. Moreover, for cases that the abstract did

[1] The Scopus query *TITLE-ABS-KEY("supply chain" AND "simulation") AND DOCTYPE(ar OR re) AND PUBYEAR < 2012* was used for our literature analysis.

not verify the relevance of paper and the full text could not be accessed for the evaluation, the paper was excluded from further analysis. With this refinement, total number of 855 papers has been selected for the next stage of analysis. For this set of papers, the simulation method is identified and subsequently presented in Figure 5.13. As can be seen, the number of publications on supply chain simulation has been constantly growing in last two decades. Moreover, Discrete Event Simulation (DES) has been the preferred method used for supply chain simulation in the literature[1]. System Dynamics (SD) is the second mostly-used method. There are also papers which have used other approaches like graph theory, Inoperability input-output modeling (Wei et al., 2010) or Bayesian networks to model supply chains (Chen et al., 2010). There have also been some efforts on Agent-based Modeling (ABM) in the literature. However and despite its high relevance - as described in this chapter - ABM has not yet become the mainstream method for supply chain simulation. Moreover, it does not seem that there has been a specific change in the tendency towards using ABM in last few years. For example, although the papers using SD or DES have steadily increased from 2009 to 2011, the number of papers using ABM is almost unaltered. This lack of using ABM for supply chain simulation might be because of difficulties in implementing agent-based models. In fact, although ABM is a suitable paradigm to capture the main characteristics of a supply chain in the conceptualization step, at the software implementation stage developing an agent-based model mostly needs a profound knowledge of (object-oriented) programming languages (especially, Java). Moreover, although some academically-developed tools for ABM (like Repast) are available for researchers, commercial easy-to-use software tools are mostly lacking. The story is completely different for other simulation paradigms, especially DES, for which many user-friendly software tools are available for application in the industrial practices. Such a wide availability of software applications, in fact, has facilitated the acceptance of DES as a simulation paradigm. In addition to these issues, ABM is not yet adequately known to practitioners and even researchers and more research is needed to demonstrate the full capabilities of ABM in modeling complex systems like supply chains.

[1] In total, about 66 % of papers have used DES for SC simulation, 14 % used SD and about 5 % were ABM.

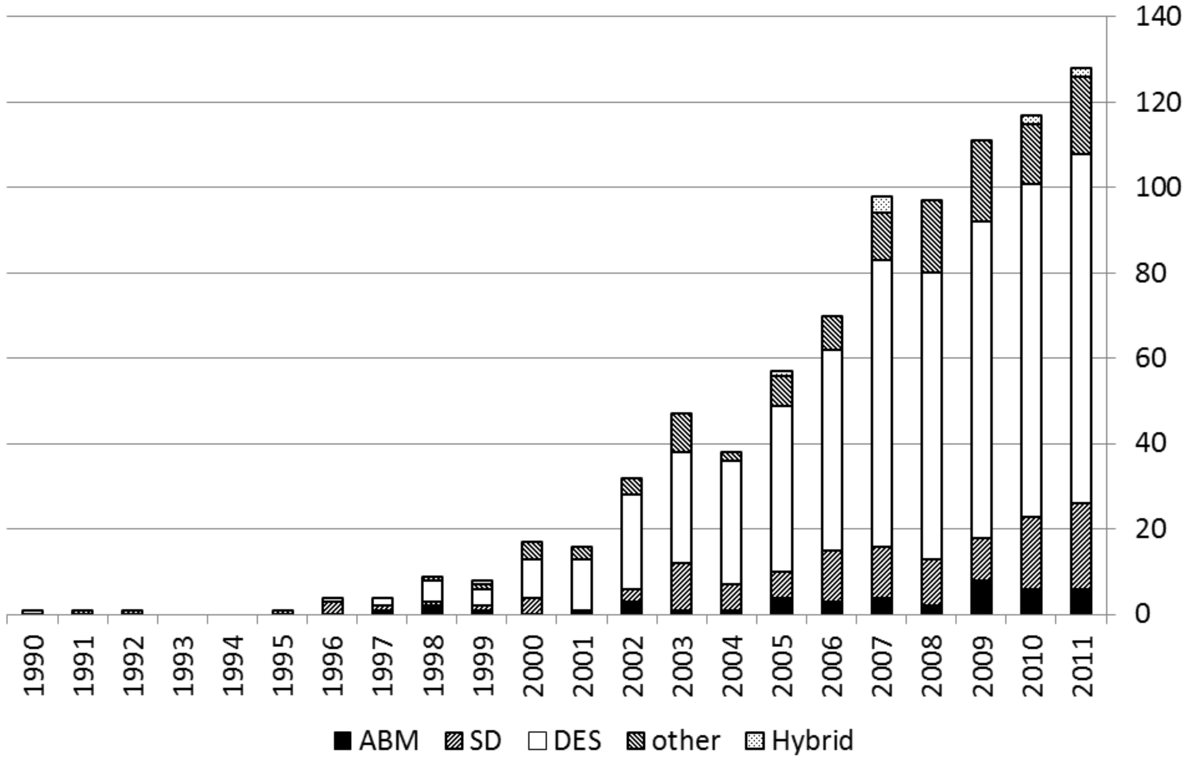

Figure 5.13. Supply chain simulation literature analysis: application of different methods

Continuing the analysis of supply chain simulation literature, we next focused on the papers using ABM as simulation method. A list of these papers is presented in Appendix E. For each paper the aim and specific problem that is studied together with a more detailed study of following attributes is presented:

- **Socio-technical view**: is the supply chain modeled as a socio-technical system in the paper?
- **Generalizable**: Can the approach presented in the paper be generalized to other cases or does it present a simulation model (or results of simulation) for a specific case?

As can be seen, ABM has been used to study different types of supply chain problems. However, the majority of these papers have not used a socio-technical representation of supply chain in developing the model. Two exemptions are the work of van Dam et al. (2009) and Behdani et al. (2010a) which are extensively discussed in chapters 5 to 7 of this thesis. Some of these papers have solely focused on the social issues in a supply chain. For example, Lin et al. (2005) and Tykhonov et al. (2008) have presented models to analyze the effect of trust on supply-chain performance; Hofstede et al. (2009)

modeled the cultural aspects in the behavior of agents; Giannoccaro and Pontrandolfo (2009) studied the conditions in which revenue sharing contracts may form between different actors. Other papers are mostly concerned with modeling the technical aspects of supply chains. The majority of these papers are looking at the logistical issues and flow of material in the supply chain. For instance, the order fulfillment process in supply chain networks is modeled by Lin et al. (1998) and different strategies for improving this process are analyzed. As another example, managing reverse flows of material in an automotive supply chain is modeled by Golinska and Kawa (2011). There are also some papers that - although do not explicitly model supply chains from a socio-technical perspective- consider some elements of social level together with some elements in the technical level in developing agent-based models. See for example the work Garcia-Flores and Wang (2002), who presented an agent-based simulation framework to study the dynamic behavior and support the management of chemical supply chains. In their modeling approach, they made a distinction between two types of agents; functional and information agents. Functional agents are those through which there is a material flow (retailers, warehouses, plants and raw material suppliers), whereas information agents refer to those that support the activities of functional agents through taking decisions or facilitating certain operations (logistics and purchasing departments). Functional agents carry inventories of raw materials (if they are located in the supply side of the chain, i.e. suppliers and plants) or finished products (if they are located in the demand side of the chain, i.e. warehouses and retailers) and are assigned a physical location. There is no material flow through information agents, so no physical locations are considered for them. Figure 5.14 shows the class relationships and main concepts in the model of Garcia-Flores and Wang (2002). As can be seen, althoygh Garcia-Flores and Wang (2002) have not used an explicit socio-technical representation of supply chains, they implicitly consider some social elements and some technical elements in the conceptual model for a supply chain. Similarly, some other papers like Allwood and Lee(2005), Labarthe et al. (2007) and Forget et al. (2009) have considered separate social and technical elements in their modeling approach.

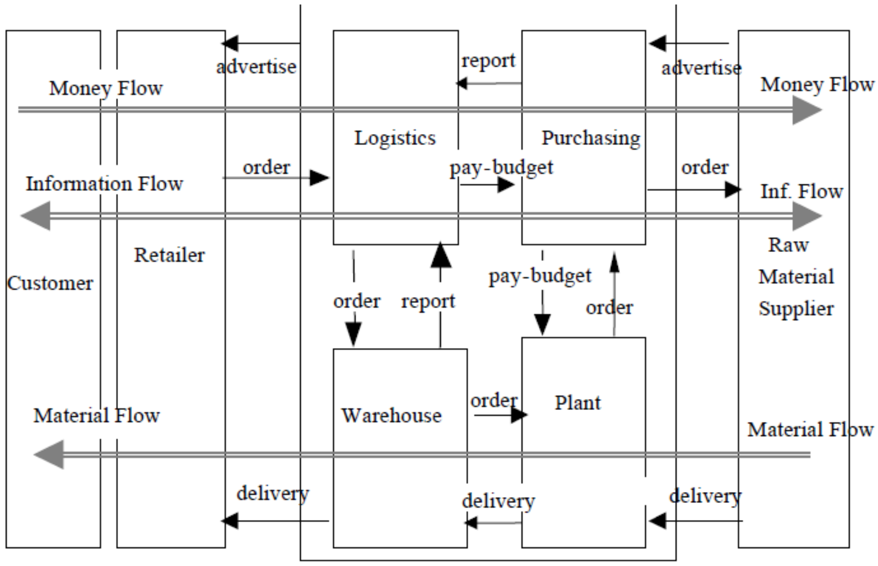

Figure 5.14. The main classes of concepts in Garcia-Flores and Wang (2002) modeling framework

To sum up, the analysis of supply chain simulation literature shows that:

- Despite its relevance and capability to capture the socio-technical complexity of supply chains, ABM has not been the mainstream simulation paradigm in the existing literature. More research is needed to demonstrate the capability of ABM for supply chain simulation.
- A simulation approach to model supply chains from a socio-technical perspective and capture both the physical and social reality of a supply chain and their interactions with one another is lacking in the existing literature.

5.10.Chapter summary

In order to select an appropriate simulation paradigm, this chapter has described a supply chain from two perspectives: a socio-technical system perspective and a complex adaptive systems perspective. This study gives a set of features for supply chains as complex socio-technical systems which is subsequently used to compare three simulation paradigms – namely, system dynamics, discrete-even simulation and agent-based modeling. Comparing these three paradigms, we conclude that agent-based modeling is the preferred simulation paradigm as it is able to capture the properties of supply chains as complex socio-technical systems and also provides the greatest flexibility in experimenting with different settings in a disruption management problem.

In this chapter, a review of literature on supply chain simulation has also been presented and discussed. From literature analysis, we can conclude - despite its high relevance - ABM has not yet become the mainstream method for supply chain simulation and other simulation paradigms (especially, DES) are used more often for supply chain modeling. Additionally, developing a supply chain model for a complex socio-technical perspective – in which the explicit distinction between social and technical elements and their interactions in the model is made - has not been addressed in the existing literature.

6. MODELING FOR DISRUPTION MANAGEMENT: AN ABM FRAMEWORK

This chapter presents an agent-based modeling framework for handling disruptions in supply chains. This framework includes the conceptualization for the main aspects of supply chain disruption management (i.e., supply chain, disruption and disruption management practices). We also discuss how this framework is implemented in the software environment and how it can be customized to develop computer models for specific cases. Such a computer model can be used to experiment with different aspects that impact the operation of supply chain. Meanwhile, it provides support for the decision-making process in handling disruptions at different steps of the integrated framework of Chapter 3.

6.1. Introduction

In Chapter 5, the Robinson process for simulation studies has been discussed. In this process, the simulation study is arranged in four main phases: Conceptual Modeling, Model Coding, Experimentation and Implementation. We started the simulation process in Chapter 5 by discussing the main issues in disruption management as well as describing supply chains as complex sociotechnical system. Based on that, we have chosen Agent-based Modeling (ABM) as an appropriate simulation paradigm for this research. Meanwhile, as each simulation paradigm depends on some underlying assumptions, the choice of ABM can be considered as the starting point for the conceptual modeling step.

The conceptual modeling for supply chain disruption management will be further discussed in this chapter. To develop the conceptual model we will use the existing knowledge on modeling socio-technical systems. Meanwhile, proven supply chain management theories and existing literature on supply chain disruption/risk management are used to define the factors that need to be reflected in the conceptual model.[1]

Besides conceptual modeling, we discuss how the conceptual model is implemented in a programming environment and how the experiments can be performed with the model.

[1] The application of proven theories in developing agent-based model is discussed extensively by Gilbert (2005).

These two aspects will be elaborated in more details and illustrated with a case study in Chapter 7.

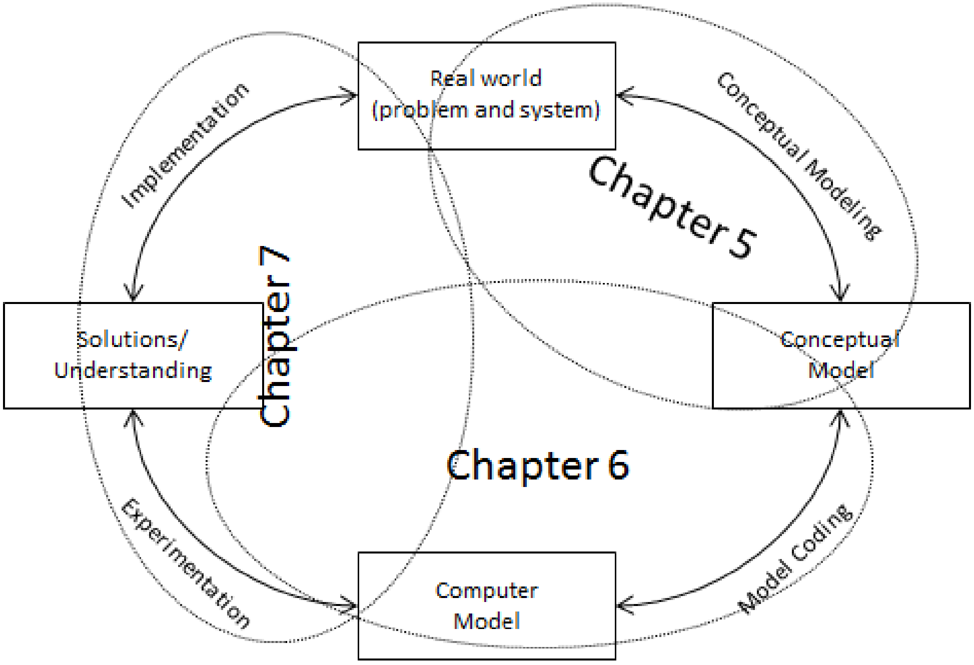

Figure 6.1. The structure of chapters based on Robinson' simulation process

6.2. A framework for supply chain disruption modeling

To define the concept of "Supply Chain Risk Management" Jüttner et al. (2003) has presented a theoretical framework as shown in Figure 6.2. In this framework – which is widely accepted as a reference definition for supply chain risk in the literature- they distinguish four basic constructs for supply chain risk management: 1) supply chain risk sources (or disruptive events), 2) supply chain structure, 3) risk mitigating strategies and 4) risk consequences.[1] In fact, the level of impact and the *consequences* of each supply chain disruption are the result of *supply chain structure*, the magnitude and profile of *disruptive event* (or risk source) and also the *coping and mitigation strategies* that are in place. Consequently, the same event, e.g. the supplier's plant emergency shutdown, would have a different impact on supply chains with different structures and with different resources and strategies to handle disruption.

[1] A similar approach to define supply chain risk has been discussed by Wagner and Bode (2008).

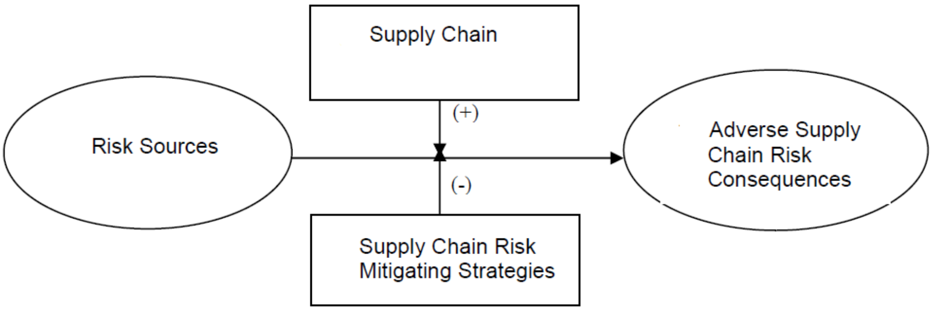

Figure 6.2. Basic constructs of Supply Chain Risk Management (Jüttner et al., 2003)

Based on this theoretical framework, the conceptual model for supply chain disruption management is developed in three following steps (Figure 6.3):

- "Supply chain modeling" which defines the structure and behavior of a supply chain.
- "Disruption modeling" which describes the characteristics of disruptive events.
- "Disruption management modeling" which outlines how different disruption management practices can be modeled.

Among three components in the conceptual model, the system conceptualization is central and other two modeling components are constructed based on the model for supply chain. Therefore, we start with "supply chain modeling" in section 6.3, followed by "supply chain disruption modeling" and "supply chain disruption management modeling" in sections 6.4 & 6.5 respectively.

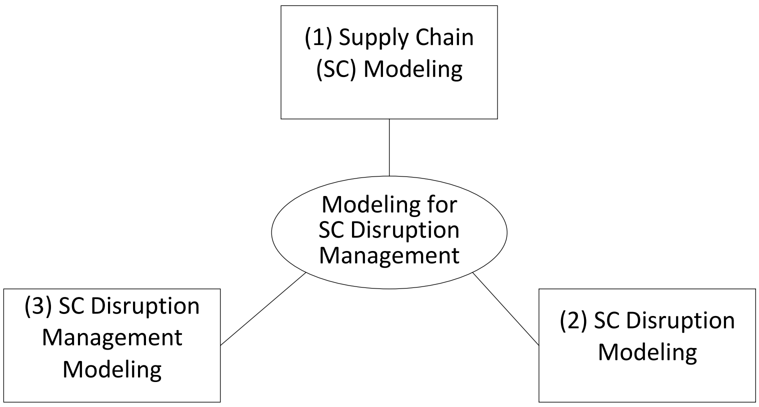

Figure 6.3. Main steps in developing supply chain disruption modeling framework

Box 6.1- Ontology: one concept with many applications

Ontology is the "formal explicit description of concepts in a domain of discourse (classes, sometimes called concepts), properties of each concept describing various features and attributes of the concept (slots, sometimes called roles or properties), and restrictions on slots (facets, sometimes called role restrictions)" (Noy and McGuinness, 2001). An ontology is usually used to make explicit the knowledge within software applications for a particular domain (Gruber, 2008; Muñoz et al., 2011; Muñoz et al., 2012); however, for simulation and modeling, it is also found useful to define the conceptual model of a system (Silver et al., 2007; Turnitsa et al., 2010; Muñoz et al., 2010). Meanwhile, in multi-agent systems, the ontology is a formal language, used for agents' communication (Hadzic et al., 2009); therefore, FIPA agent specification (IEEE Foundation for Intelligent Physical Agents, 2012) is requiring defining an ontology for every multi-agent system.

6.3. Supply chain modeling

To develop a supply chain model, we primarily make a distinction between system and environment. The system sub-model describes the supply chain entities, their interactions and behavior. The environment sub-model includes all the aspects that are outside the supply chain boundaries but influence its operation.

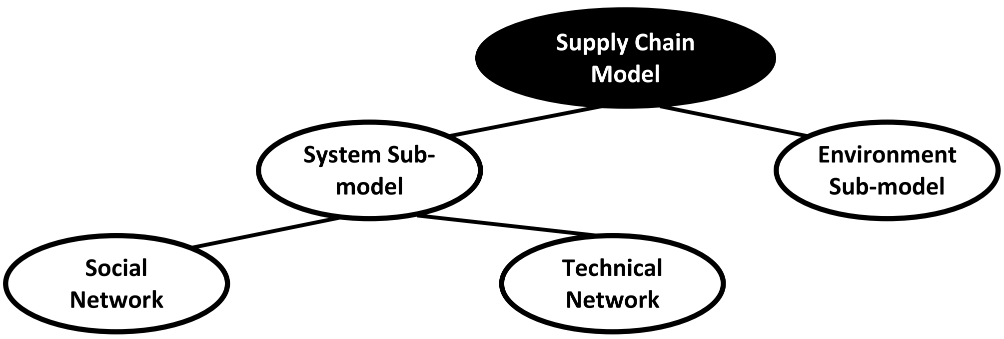

Figure 6.4. The overall structure of supply chain model

6.3.1. System sub-model

Designing an agent-based model for a system consists of two main steps (Gilbert, 2005). Firstly, the types of objects to include in the simulation need to be defined. Defining these objects is much "easier if there is already a body of theory to draw on" (Gilbert, 2005- p. 9). These theories are, in fact, the basis to determine what factors are likely to be important in the model. Meanwhile, the other function of theory is to clearly identify the assumptions on which the model is built (Gilbert, 2005). The types of object that are found useful to reflect in the model are finally shown in a class hierarchy (or ontology). For each object, the set of attributes must be defined and the relationship between objects is clearly described. The ontology which is created in this way is basically the conceptual model for the system of study (Silver et al., 2007; Turnitsa et al., 2010).

As the main objects in the system are conceptualized, "[t]he next step is to add some dynamics, that is, to work out what happens when the model is executed" (Gilbert, 2005, p. 10). In other words, we must define how the concepts in the ontology are used in describing the behavior of Agents and how this leads to the dynamic behavior of system as a whole.

These two steps to define the "system sub-model" are discussed in following subsections.

6.3.1.1. Static representation of system

In Chapter 5 we extensively argued that ABM is the appropriate modeling paradigm to capture the main characteristics of a supply chain. Selecting ABM as simulation paradigm explicitly means that a supply chain must be modeled by defining the individual building blocks of the system – i.e., Agents- and their interactions. However, as a supply chain is also a socio-technical system, we must explicitly consider the technical sub-system in conceptual modeling as well. Meanwhile, in developing the conceptual model, we distinguish between components that describe the structure and the operation of a supply chain (Figure 6.5). This distinction is frequently discussed and emphasized in modeling and simulation literature (Maria, 1997; Thierry et al., 2008). In fact, a modeler must define both structural/operational constituents of system.

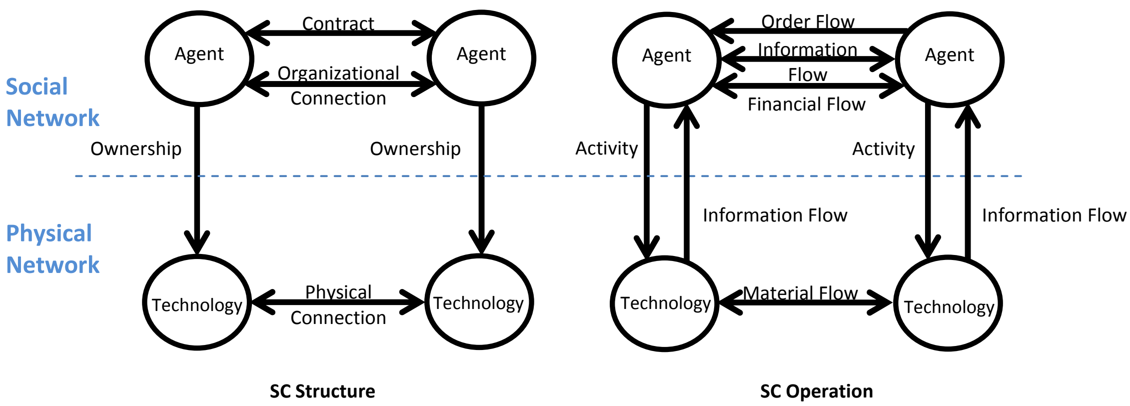

Figure 6.5. The distinction between structure and operation of supply chain model

To support the model development process for socio-technical systems, van Dom (2009) has presented an ontology which is the starting point for developing a conceptual model

Box 6.2- Rules for Naming Conventions

For concepts (or classes) in the ontology, we use CamelCase (also known as Upper CamelCase) naming convention. That is, the first letter is capital and if compound words are used for naming, they are joined without spaces, with each element's initial letter capitalized (e.g., PhysicalConnection). The Attributes for each class follow the Lower CamelCase format in which the first letter is in lower case (e.g., physicalProperties). These naming rules are consistent with the overall-accepted naming convention in Java programming language in which class names are in Upper CamelCase format and properties and methods are in Lower CamelCase (Sun Microsystems, 1997).

for supply chains in this section. The central concepts in this ontology are two types of nodes: SocialNode[1] or Agent is the building block of social sub-system and PhysicalNode or Technology is the main building block for technical sub-system modeling. Agent represents the actors which make decisions about other entities in the system. Technologies describe the technical elements of system and are owned/ operated by Agents. Each Technology is characterized by OperationalConfiguration that defines which set of Goods is needed as input and which Goods are produced as output. Of course, for some technical artifacts, like storage facilities, the operational inputs and outputs can be the same. Based on the current situation of system and environment, Agents make decisions about the current OperationalConfiguration and other properties of Technology like production throughput[2].

The Nodes in the system are connected through Edges. Just like Nodes, the Edges in the system are either social or physical. The link between two technologies is represented by a PhysicalConnection. It describes the infrastructure - such as a pipeline or road- which is used to transport the material in a supply chain. A social Edge, however, is aimed to describe the social network connections as well as the link between social network and physical network. The social Edges in a supply chain are:

- Contract which defines the formal connection between two companies in the supply chain;
- OrganizationalConnection which describes the link between two Agents inside a company;

[1] The convention for naming can be found in Box 6.2.
[2] These properties are presented in Table 6.1.

- Ownership which connects an Agent to a Technology or a PhysicalConnection. In fact, every technical artifact in the system must be owned and operated by an Agent. An Ownership can be also defined between two Agents. For instance, the relation between a company and its departments is described by Ownership.

The Ownership and OrganizationalConnection help us to model the nestedness and multi-level characteristics of a supply chain (Figure 6.6). For instance, a supply chain may include several enterprises; each enterprise may have different plants and each of plants may have several departments that are responsible for internal activities. The relation between departments is described by OrganizationalConnection; the link between plants and their departments is defined by Ownership and the connection between enterprises is presented by Contract.

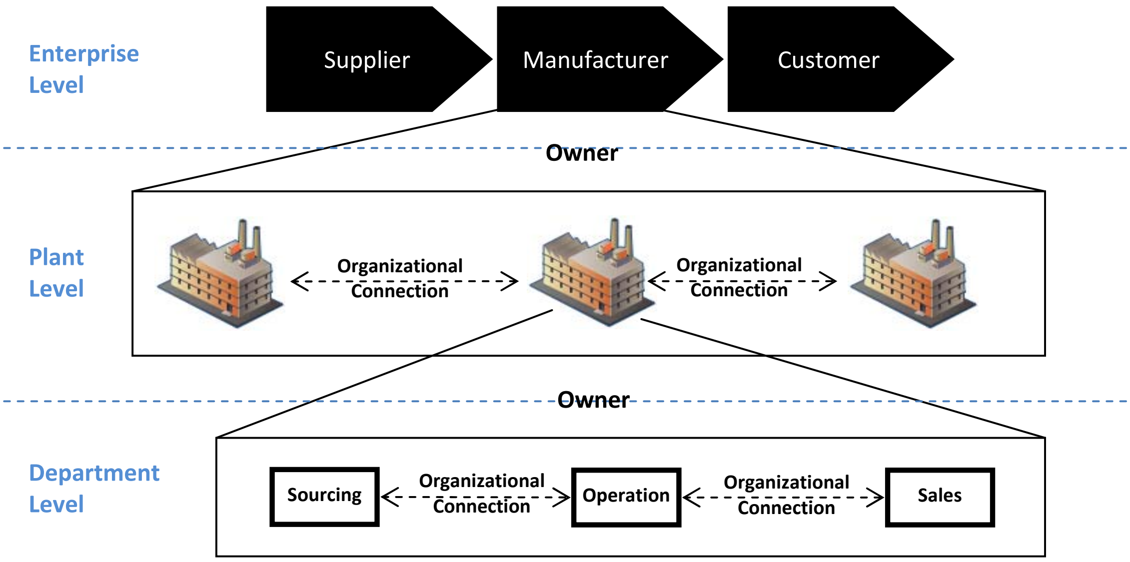

Figure 6.6. Using different types of Edges to describe nestedness in supply chain

Agent, Technology, PhysicalConnection, Contract, OrganizationalConnection and Ownership are the main concepts to represent the *structure* of a supply chain as a sociotechnical system. To describe the *operation* of supply chains, we need some additional concepts (Figure 6.5). Two main concepts are Activity and Flow. The Activity is the unit of behavior of Agent and causes changes in the state of Agent and Technology – as will be discussed in next subsection. Flow represents the movable items in the supply chain.[1] Four main flows are usually considered in a supply chain (Lambert and Pohlen, 2001; Mentzer et al., 2001):

[1] Looking at a supply chain in the operational level, supply chain management is generally defined as the integration of different activities and actors in a supply chain through these flows to achieve supply chain objectives (Lalonde and Pohlen, 1996; Towill, 1997; Mentzer et al., 2001; Coyle et al., 2008; Sehgal, 2009).

- MaterialFlow which is the Flow of physical Goods in a supply chain. For instance, raw material flows from suppliers to manufacturers and final products move from manufacturers to customers.
- InformationFlow which is the Flow of Data. Examples of Data are actual or forecast demand, inventory levels and processing capacities. With these data the MaterialFlow can be more accurately planned and controlled by an Agent.
- FinancialFlow which is the Flow of Money. This includes both the Flow of cash from downstream actors as they receive the MaterialFlow and also the Money that upstream actors in the supply chain must pay as a penalty of not fulfilling their commitments.
- OrderFlow which is the Flow of Order. An Order describes the request for purchasing Goods and is usually from upstream actors to downstream actors in a supply chain.

Among these four Flows, MaterialFlow is defined in the technical level; it is between two Technologies. FinancialFlow and OrderFlow are flows of entities between two Agents. InformationFlow can be between two Agents or between an Agent and a Technology. For example, the point-of-sale information might Flow from a retailer to manufacture. On the other hand, the Data on the level of inventory might Flow from storage facilities (as one type of Technology) to Agent.

During operation of a supply chain, an Agent constantly monitors the current situation of Environment[1], other Agents and Technologies and based on that, makes decision and performs Activities. Performing an Activity by Agents may directly change the state of a Technology or may trigger a Flow to other Agents or between Technologies. Subsequently, the dynamic behavior of the supply chain emerges. This dynamic behavior will be discussed further in next subsections.

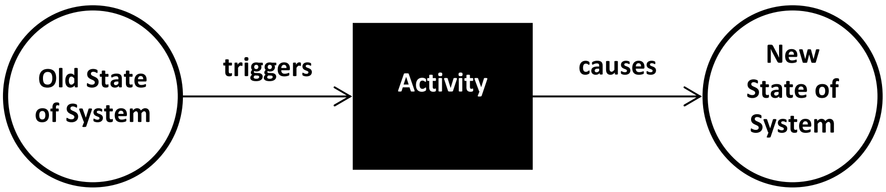

Figure 6.7. Activity as the main driver of changes in the system

All elements to describe the conceptual model for a supply chain are represented in the ontology of Figure 6.8. This ontology contains the formalized concepts and how they are

[1] The interaction of Agent with Environment is discussed in section 6.3.2.

related to each other. The relation is shown with arrows in the figure. As a general rule, the existence of operational elements of the model depends on the structural elements. As an example, for MaterialFlow between two Technologies there must exist a PhysicalConnection. The behavioral elements are also constrained by structural elements. For instance, the time of delivering Order to customers is constrained by Contract specifications or the amount of MaterialFlow is bounded by the capacity of PhysicalConnection.

For each concept in the ontology a set of attributes are defined and presented in the Table 6.1. The naming for attributes follows the naming convention of Box 6.2. Each attribute has a value type which is either primitive (e.g., String) or an instance (or set of instances) of other concepts in the ontology. The properties for classes in Table 6.1 are, of course, the necessary properties to model that entity and it is possible to include other properties as we use the ontology for specific cases.

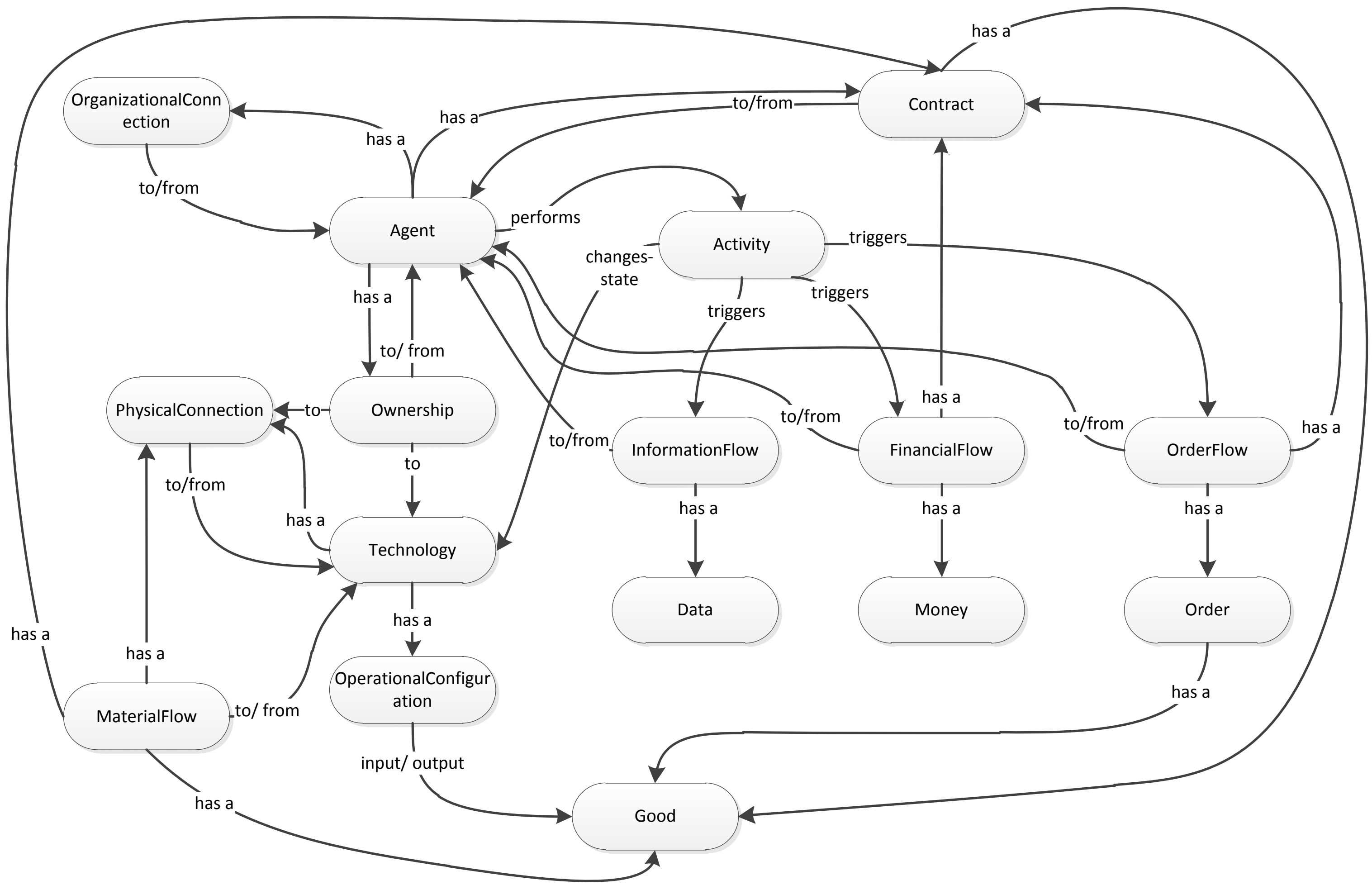

Figure 6.8. The main concepts and relations in supply chain ontology

Table 6.1. Summary of classes and their attributes in ontology

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
Agent	Represents actors which make decisions about other entities in the system	label	primitive	String	The tag to be identified by others
		status	primitive	String	The tag to describe if this entity is disrupted (see section 6.4 for more details)
		physicalProperties	instances	Property*	Properties to define the physical aspects of Agent (e.g., location)
		economicProperties	instances	Property	Properties to define the economic aspects of Agent (e.g., profit)
		operationalProperties	instances	Property	Properties that are related to the operation of an Agent or the physical systems that each Agent owns (e.g., number of late orders)
		inEdges	instances	Ownership/ OrganizationalConnection / Contract	Connections with other Agents or Technologies coming into this Agent
		outEdges	instances	Ownership/ OrganizationalConnection / Contract	Connections with other Agents or Technologies going out of this Agent
		inFlows	instances	InformationFlow/ FinancialFlow/ OrderFlow	Flows coming into this Agent from other Agents or Technologies
		outFlows	instances	InformationFlow/ FinancialFlow/ OrderFlow	Flows going out of this Agent to other Agents
		performingActivities	instances	Activity	Set of Activities must be executed by this Agent
		currentActivity	instance	Activity	The current Activity that Agent is performing
		ownedComponents	instances	Agent/ Technology/ PhysicalConnection	The entities that are owned by this agent including other Agents (e.g., departments of a plant),

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
					Technologies (e.g., production lines) or PhysicalConnection (e.g., vessels owned by a shipper)
Technology	Represents the technical elements of system which are owned/operated by Agents	label	primitive	String	The tag to be identified by others
		status	primitive	String	The tag to describe if this entity is disrupted.
		disruptedAttribute	instance	Property	Describes which characteristics of entity is disrupted; e.g., the production rate of plant may become half because of disruption (see section 6.4 for more details)
		physicalProperties	instances	Property	Properties to define the physical aspects (e.g., location)
		economicProperties	instances	Property	Properties to define the economic aspects of Technology (e.g., cost of operation)
		designProperties	instances	Property	Properties related to the design of a physical system (e.g., capacity or maximum production rate)
		operationalProperties	instances	Property	Properties that are related to the operation of a physical system (e.g., current production rate) and are set by Agent (see section 6.3.1.2 for more details); operationalProperties are constrained by designProperties.
		possibleOperationalConfigurations	instances	OperationalConfiguration	Set of possible OperationalConfigurations for a Technology
		currentOperationalConfiguration	instance	OperationalConfiguration	Describe the current OperationalConfiguration for a

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
					Technology
OperationalConfiguration	Describes the production recipe by defining the input-output specification	label	primitive	String	The tag to be identified by others
		operationalInputs	instances	Good	The input requirements for a Technology
		operationalOutputs	instances	Good	The produced materials as output of a Technology
Good	Describe the material that is handled in different parts of supply chain	label	primitive	String	The tag to be identified by others
		amount	primitive	Float	The quantity of Good
		amoun tUnit	primitive	String	The unit in which the amount is expressed
		price	primitive	Float	The price of each amountUnit of Good
		priceUnit	primitive	String	The unit in which the price is expressed
		physicalProperties	instances	Property	Properties to define the physical aspects of Good (e.g., quality of material)
Ownership	Describes the link between a Technology (or Agent) and Agent (as its owner)	label	primitive	String	The tag to be identified by others
		from	instance	Agent	Defines the owner
		to	instance	Agent/ Technology/ PhysicalConnection	The entity that is owned by "from" Agent
OrganizationalConnection	Describes the link between two Agents inside a company	label	primitive	String	The tag to be identified by others
		from	instance	Agent	By convention, we define "form" for the Agent in the upstream (closer to supplier)
		to	instance	Agent	By convention, we define "to" for the Agent in the downstream (closer to customer)
Contract	Describes the link between two companies in a	label	primitive	String	The tag to be identified by others
		status	primitive	String	The tag to describe if this entity is disrupted; for example if a

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
	supply chain				Contract suddenly terminated by one Agents
		disruptedAttribute	instance	Property	Describes which characteristics of entity is disrupted
		from	instance	Agent	Agent in the upstream of supply chain
		to	instance	Agent	Agent in the downstream of supply chain
		startTime	primitive	Float	The starting date of Contract
		endTime	primitive	Float	The date until which Contract is valid
		contractedForMaterial	instances	Good	The material that this Contract is signed for
		economicProperties	instances	Property	Properties to define the economic aspects of Contract (e.g., cost per unit of material or penalty for late delivery)
		commitments	instances	Property	Defines the commitments of Agents (e.g., accepted delay time)
PhysicalConnection	Describes the link between two Technologies	label	primitive	String	The tag to be identified by others
		status	primitive	String	The tag to describe if this entity is disrupted
		disruptedAttribute	instance	Property	Describes which characteristics of entity is disrupted
		from	instance	Technology	The Technology that the flow of material is originating from
		to	instance	Technology	The Technology that the flow of material is going to
		physicalProperties	instances	Property	Properties to define the physical aspects (e.g., location)
		economicProperties	instances	Property	Properties to define the economic

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
					aspects of this connection (e.g., cost of operation)
		designProperties	instances	Property	Properties related to the design of a physical system (e.g., capacity or maximum transferring rate)
		operationalProperties	instances	Property	Properties related to the operation of a physical system (e.g., current transferring amount); operationalProperties are constrained by designProperties
		transportModality	primitive	String	The modality of the transport going through this connection, such as pipe, road or sea
		content	instance	MetrialFlow	The MaterialFlow going through this PhysicalConnection
MaterialFlow**	Describes the flow of Good in a PhysicalConnectio n	label	primitive	String	The tag to be identified by others
		from	instance	Technology	The Technology that the flow of material is originating from; by flow of material, the operationalProperties of this Technology change (see section 6.3.1.2 for more details)
		to	instance	Technology	The Technology that the flow of material is going to; by flow of material, the operationalProperties of this Technology change.
		content	instances	Good	The set of Goods that flow
		potentialCarrier	instances	PhysicalConnection	The PhysicalConnection that could carry this MaterialFlow; more than one PhysicalConnection might be

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
					available and possible for a MaterialFlow
		actualCarrier	instances	PhysicalConnection	The PhysicalConnection that carries this MaterialFlow
		materialContract	instance	Contract	The Contract for material delivery between Agents own the "from" and "to" technologies; this contract defines the terms of material delivery
		shipmentContract	instances	Contract	The Contract between owner of “to”/ “from” Technology and the Agents which own the potentialCarrier
		sendingTime	primitive	Float	The date of starting the flow from "from" Technology
		receivingTime	primitive	Float	The date of receiving flow by "to" Technology
FinancialFlow	Describes the flow of Money between two Agents	label	primitive	String	The tag to be identified by others
		from	instance	Agent	The Agent that sends the Money and consequently its economicProperties change (decreases); this Agent is usually in the downstream of supply chain
		to	instance	Agent	The Agent that receives the Money and consequently its economicProperties change (increases); this Agent is usually in the upstream of supply chain
		contract	instance	Contract	Each FianancialFlow is defined based on economicProperties of a Contract

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
		content	instance	Money	The cash that flows between two Agents
		sendingTime	primitive	Float	The date of sending Money by "from" Agent
		receivingTime	primitive	Float	The date of receiving Money by "to" Agent
Money	Describe the cash that is transferred between supply chain entities	label	primitive	String	The tag to be identified by others
		moneyAmount	primitive	Float	The amount of Money
		moneyUnit	primitive	String	The unit in which the Money is expressed
InformationFlow[***, ****]	Describes the flow of Data between two Agents	label	primitive	String	The tag to be identified by others
		from	instance	Agent	The Agent that sends the Data
		to	instance	Agent	The Agent that receives the Data
		content	instances	Data	Data cover any type of information that can be transferred between two Agents; it is one of properties of Agents, Technologies, Edge or Flows that is accessible to one Agent ("form Agent") and sends it to other Agent
Data	Describes the piece of information that is transferred between two entities	label	primitive	String	The tag to be identified by others
		value	primitive	Float/ Boolean/ String	The value of one property of an entity in the system
OrderFlow	Describes the request for purchasing material which is usually from upstream actors to	label	primitive	String	The tag to be identified by others
		from	instance	Agent	The Agent that sends the Order; this Agent is usually in the upstream of supply chain
		to	instance	Agent	The Agent that receives the Order: this Agent is usually in the

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
	downstream actors in a supply chain				downstream of supply chain
		contract	instance	Contract	The Contract that defines the terms of order delivery between two Agents
		content	instances	Order	The specifications for material delivery
		sendingTime	primitive	Float	The date of sending Order by "from" Agent
		receivingTime	primitive	Float	The date of receiving Order by "to" Agent
Order	Describe the characteristics of order for one or more materials	label	primitive	String	The tag to be identified by others
		orderAmount	primitive	Float	The amount of material that is ordered
		orderedMaterial	instances	Good	The order can be for one or more Goods
		fulfillingActor*****	instance	Agent	The Agent which fulfills the Order
		timingConditions	instances	Property	The requested timing conditions for Order (e.g., order due date)
		operationalConditions	instances	Property	The requested operational conditions for Order (e.g., type of packaging)
		fulfillmentState	primitive	String	Determines the state of an Order which can be "fulfilled", "pending" or "cancelled"
		fulfillmentProperties	instances	Property	The properties of order that is fulfilled (e.g., time of delivery)
Actvitiy	Describes the unit of behavior of actors in the system; each Activity triggers a	label	primitive	String	The tag to be identified by others
		performingActor	instance	Agent	The Agent who performs the Activity
		triggeredFlow	instances	MetrialFlow/ InformationFlow/	The flows that are activated when this Activity is ended

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
	Flow or changes the state of a Technology			FinancialFlow/ OrderFlow	
		affectedArtifact	instances	Technology/ PhysicalConnection	The state of this Technology/ PhysicalConnection would change when Activity is ended
		precedingActivity	instances	Activity	Activities need to be finished before starting this Activity
		followingActivity	instances	Activity	Activities must be done after this Activity is ended
		temporalCondition	primitive	Float	The constraint for time to start performing this Activity
		initiationTime******	primitive	Float	An Activity begins at this time
		completionTime	primitive	Float	An Activity ends at this time
Property	Defines the features of entities in the system	label	primitive	String	The tag to be identified by others
		propertyValue	primitive	Float/ Boolean/ String	The value of a Property
		propertyUnit	primitive	String	The unit in which the Property is expressed

* The Property items can be defined differently for each specific case. Examples are presented in Chapter 7.

** For a MaterialFlow between companies in a supply chain, two types of Contacts are needed: materialContract which is, e.g., between a supplier and manufacturer and shipmentContract which is between a shipping company (or 3rd party logistics provider) and sender/receiver of material (In different cases, one of buyer or seller is responsible for material delivery and subsequently, must have a contract with shipping company).

*** Unless other Flows, we assume that flow of Information happens instantly. Therefore, we do not consider sendingTime and receivingTime for InformationFlow.

**** InformationFlow is the only Flow that does not need a Contract. It is basically defined between each two Agents in the system. Other Flows need a Contract to be available.

***** The fulfillingActor is not necessarily the actor which receives the order. For example, sales department may receive the Order but operations department fulfills the Order. Similarly, the supplier may sub-contract the order to other agent.

****** By default, the initiationTime and completionTime of an Activity are the same unless the opposite is mentioned in the description of Activity.

6.3.1.2. System's dynamic behavior

In the last section, the main elements to conceptualize a supply chain as a complex socio-technical system are presented. Here, we discuss how these concepts are used in a simulation model to describe the dynamic behavior of a supply chain. As for all agent-based models, the main driver for dynamic behavior of system is the agent's behavior (Gilbert, 2007). However, in a socio-technical system, the state of technical artifacts might also change because of physical rules which can influence the dynamic behavior of the system as described in the following.

- ***Social sub-system dynamics***

Agents in an agent-based model are usually described by "State" and "Behavioral Rules" (Epstein, 1999; Gilbert, 2007; North and Macal, 2007). The State of Agent includes the Agent's Attributes – which are the set of properties to define the identity of agent at each moment - and Agent's Memory. The Agent's attributes in an agent-based model function like variables in a mathematical model (Gilbert, 2005). They change during simulation; they decrease or increase. For instance, the profit of a company is an attribute which dynamically changes based on transactions with other companies. The Memory of agent represents the history of Agent States and the history of interactions with external world[1]. Finally, the behavioral rules of Agent[2] describe how an Agent behaves based on its current state and the memory of past states. This usually happens in three steps (Sterman, 2000; Joslyn and Rocha 2000); firstly an Agent must monitor the situation of world. Next, it must decide what to do based on the available information and take one action subsequently (Figure 6.9). As an example, a manufacturing company *monitors* the level of inventory for different products in the storage facilities and based on the inventory level (*current state*) – and also considering the demand pattern of previous periods (*memory*)-*makes a decision* about which products must be produced at which moment of time and how much of these products need to be processed. When the decision on type of product, timing of production and the quantity of products are made, company can *take action* and start the production.

[1] The external world in our modeling approach includes technical artifacts, other Agents and the Environment.

[2] The behavioral rules of agent are also term its "Schema" by Anderson (1999).

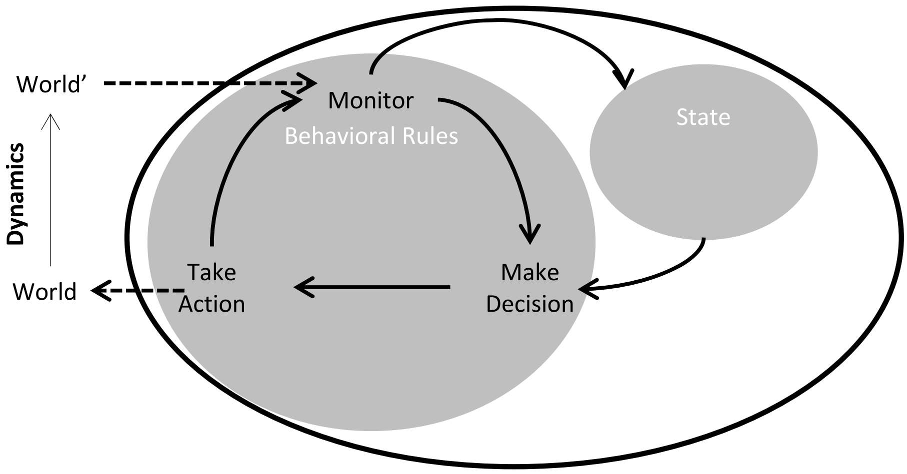

Figure 6.9. A generic structure for Agent in ABM (after Joslyn and Rocha 2000)

Considering all these, Figure 6.10 shows the internal structure of Agent in our modeling approach.

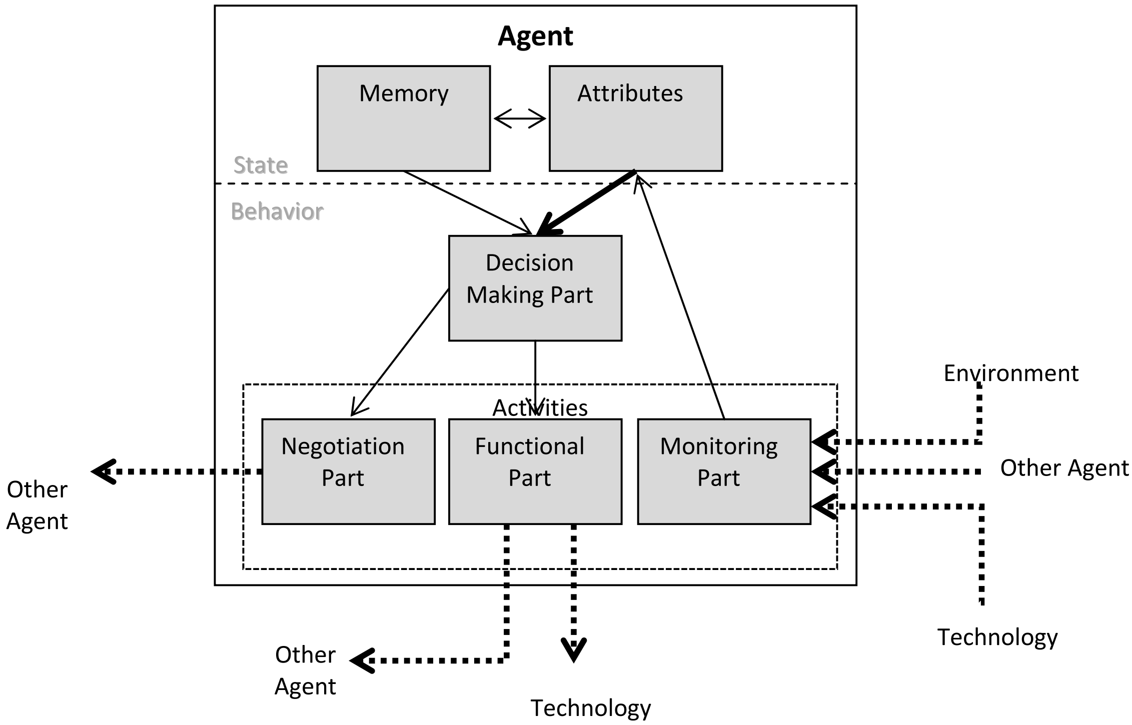

Figure 6.10. The structure of Agent in the model

The Agent's Attributes are the properties we have described in Table 6.1. For an Agent, these Attributes are physicalProperties, economicProperties, inEdges, outEdges, inFlows, outFlows, perfromingActivties, currentActivity and ownedComponents. The attributes of Agent in the model work as variables in the equation-based modeling. They, by definition, can change during simulation runs. To model the supply chain operation, however, some of these properties might be assumed fixed at the start of simulation. For instance, the ownedComponents of an agent are considered fixed when we model a supply chain at the operational level.[1]

The Memory of Agent includes the history of Agent's attributes and the state of technical artifacts – i.e., Technologies or PhysicalConnection - that are owned by this Agent. Although, Agent has access to all characteristics of its owned technical components, it does not necessarily monitor all those characteristics and record them in the memory. Therefore, to start modeling, it must be clearly described which aspects of technical sub-system is monitored by an Agent and which of them is used in its decision-making process. In the Memory, Agent also has a record of past interactions in OrderList (list of OrderFlows received or sent by Agent), FinancialList (list of FinancialFlows that are paid or received by Agent), InformationList (list of InformationFlows) and MaterialFlowList (list of MaterialFlows that are received or sent by Technologies which are owned by Agent). Finally, Memory may include a history of past States of Environment, e.g. the market price for raw material for a period of time.

The behavioral part of Agent has three main components (Figure 6.10). The Monitoring Part of Agent reads the inFlows to Agent or technical artifacts that are owned by Agent. These inFlows are from other Technologies (i.e., MaterialFlow) or from Technologies owned by this Agent (i.e., InformationFlow), from other Agents (i.e., InformationFlow/ FinancialFlow/ OrderFlow) or from Environment (i.e, InformationFlow/ FinancialFlow)[2]. These Flows change the State of Agent and its Technologies. For instance, the Money received from other Agents in the FinancialFlow increase the Agent's revenue (as one of economicProperties) or new data about the inventory level (as an InformationFlow) from a storage tank (as a Technology) is stored in the Memory of Agent. Similarly, receiving the raw material (as a MaterialFlow) from a supplier increases the inventory level (as one of operationalProperties) of storage facilities (as a Technology). Therefore, at each time step of simulation, the Monitoring Part monitors the inFlows and subsequently, updates the State of Agent and the Technologies owned by Agent.

With the updated State for Agent and Technologies, next, the agent must decide how to react and make changes in the State in the next time interval. The specific tool for this

[1] As a general rule we assume that the structural elements are fixed when we model the supply chain at the operational level. More specifically, all inEdges/outEdges –like contracts or ownership – and ownedComponents must be set before we start modeling the supply chain. Of course, to model the supply chains tactical and strategic issues (e.g., the design of distribution network) the structural elements (e.g., terms of contracts or type of technologies) must also be considered as varying attributes in the simulation.

[2] The interaction of Agent with Environment will be discussed in more details in section 6.3.2.

aim in the model is Activity. In fact, performing an Activity is the driver for change of state of Agent and Technology throughout the simulation. Deciding about next Activity at each time step of simulation happens in two phases by decision-making part of Agent. Firstly, it must be determined which Activity has to performed next. In order to do that, two aspects have to be evaluated:

1. *If previous Activity is completed?* This can be checked by completionTime of currentActivity of Agent.
2. *What is the next Activity in thread of activities?* Each agent has one or more thread of Activities to do. At each point of time, the Activity with the highest priority in each thread must be investigated for execution. Such an investigation entails checking "preconditions". The pre-conditions to activate an activity are one or more of following requirements:
   - *The temporal conditions*: an Activity might be triggered by time; for example, a company might place an order for raw material in specific time intervals (e.g., once in a month).
   - *The availability of the required inputs to define the characteristics of an Activity*: the execution of one Activity may require receiving a Flow or performing some Activities by other Agents. For instance, starting production in the manufacturing plants depends on the information of inventory in warehouses of distribution centers. Without this information, a manufacturer cannot decide about the type/amount of product that must be produced next. The availability of these inputs in Agent/Technology State has to be checked before execution of Activity. When we model a real case, these types of "preconditions" can be shown by flowcharts or Activity Diagrams as further discussed in section 6.6.

As next Activity is determined, the decision-making part of Agent must define the Activity's characteristics. These characteristics are, in fact, a set of decision variables which must be adjusted for the next time interval. Part of these variables is about the timing of an Activity (i.e., initiationTime and completionTime) and some others are about characteristics of impactedArtifacts (Technology or PhysicalConnection) and triggeredFlows. For instance, a manufacturer must decide about the type of Good to produce. This basically implies a new value for currentOperationalConfiguration and "rate of production" – as one of operationalProperties – for production facility (as a Technology). As another example, the manufacturer must define the orderAmount and order due date (as one of timingConditions) for a raw material OrderFlow before sending to supplier.

Making a decision about characteristics of each Activity is usually done by one actor in the system. There are, however, cases in a supply chain in which multiple actors might be involved in the decision-making process. For example, the specification of raw material order (e.g., delivery timing or price) might be defined beforehand in a contract between actors in the chain. It is also possible that one actor (mostly, the buyer) makes the timing and quantity decisions and subsequently, sends the orderFlow to its supplier. As another alternative, the timing and price of raw material Order can be defined by joint decision-making of both buyer and seller. In other words, decisions are being made from the viewpoint of more than one decision entity (Raiffa et al., 2002). In these cases, the involved actors need to have the capability to negotiate.

In following sub-sections we discuss how single- and multi-actor decision-making are represented in the system model.

Single-actor decision-making:

For cases in which decisions on features of Activities are made by one Agent, four options are possible to include in the model:

1. The values of decision variables are previously defined and agreed by Agents in the chain (i.e., in the terms of Contract or Orders). For instance, the Money that a manufacturer must pay for late delivery in a FinancialFlow to its customers is defined in the Contract. As another example, when a manufacturer selects one customer Order to produce at this moment of time, the “current product” and the “batch size” (as instance of operationalProperties for production facility) are previously defined in the Order specification from customers.
2. The decision-making style of Agent can be defined by some policies that are selected for operation of the supply chain.
3. The Agent has a set of heuristic rules to define the value for decision variables.
4. Agent might have a utility which defines the value for decision variables.

Last three options are illustrated in the following with an example of storage department which is responsible for raw material inventory management in a production plant. Two main decisions must be made about inventory management in the plant:[1]

1. When the raw material Order must be placed (i.e., initiationTime for "order placement" Activity)?
2. How much material is needed (orderAmount for raw material Order)?

A policy can determine both of these two aspects for an Agent. For instance, the (s, S) policy defines when the inventory reaches a specified reorder point, "s", sufficient units must be ordered to bring up the inventory to a pre-determined level "S" (Wisner et al., 2009). The inventory policy can also determine the period of monitoring. For instance, (R, s, S) policy implies checking inventory position every "R" time units.

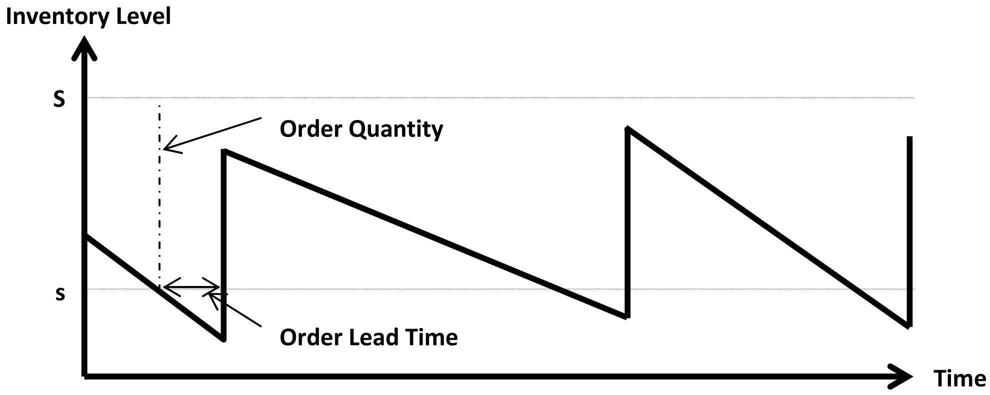

Figure 6.11. (s, S) policy for inventory management

Instead of having a policy, the storage department can make the two aforementioned decisions based on some heuristic rules. For example, it may order in fixed periods – e.g., every one month- and to determine the inventory, it may assume that next period's demand will remain equal to current period's and based on material requirement to produce this demand pattern, it determines the raw material order size. These heuristics for decision-making can be presented in a flowchart as shown in Figure 6.12.

[1] The decisions that are mentioned here are decisions at the operational level of a supply chain. At the tactical level, other decisions must be made for material sourcing in a plant – e.g., who must be the supplier and how the contract terms must be set? Likewise, at the strategic level other types of decisions are important – e.g., how much capacity must be considered for storage facilities?

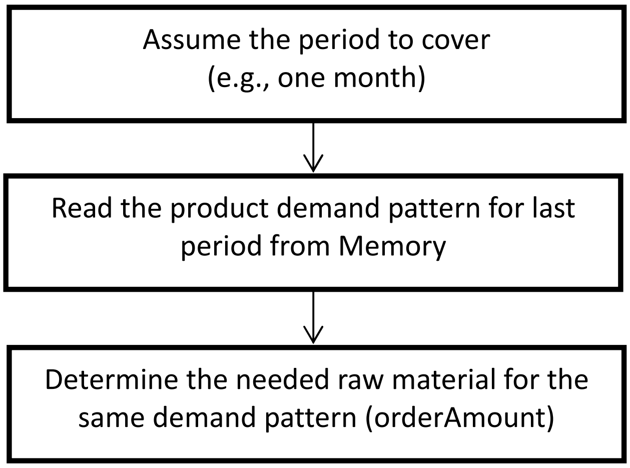

Figure 6.12. A heuristic rule to determine Order amount

As a third option, the storage department might define a total cost function for material handling as:

Total Cost = Material ordering costs +Inventory costs + Warehousing costs +Transport costs

Each cost term in this equation can be defined as a function of time and material quantity and by minimizing this total cost, the orderAmount and time of order placement can be determined.

The logic to value decision variables is implemented in each Activity when we develop the computer model in programming environment (this is discussed in more details in section 6.6). Meanwhile, this logic can be updated during simulation by Agent learning. For instance, in above-mentioned example, the procedure for defining the orderAmount can be changed by storage department learning. To define the first estimation for orderAmount, the Agent may use historical data for product demand. This amount, however, can be improved considering the real demand data and material stock-out in the last period of time (Figure 6.13). Other examples of Agent learning can be found in Chapter 7.

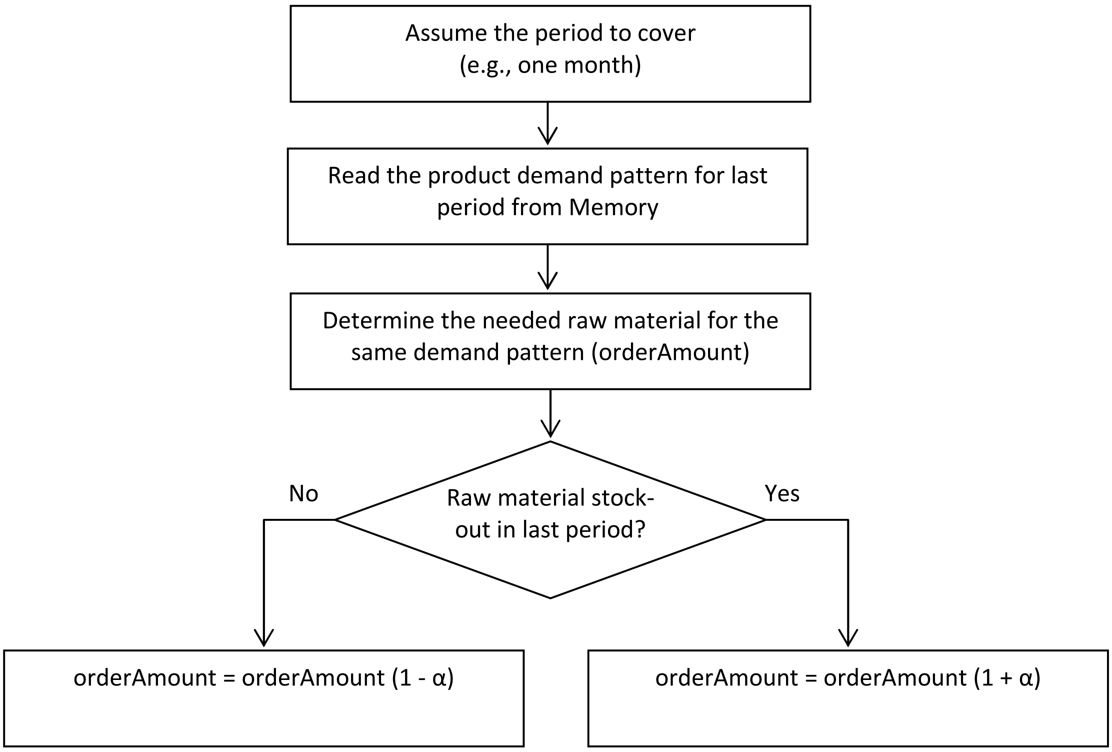

Figure 6.13. An example of learning in inventory management process

All four mentioned methods are to set the value of decision variables by one Agent. However, there are cases in which more than one Agent is involved in determining the value for one or more decision variables. For these cases, agents must be able to negotiate the case as further described in following sub-section.

Multi-actor decision-making[1]:

Negotiation is a type of interaction between two or more self- interested actors (each with its own objectives, needs and viewpoints) seeking to find a common ground and reach an agreement to settle a matter of mutual concern or resolve a conflict (Raiffa et al., 2002). Negotiation challenges researchers and practitioners from many disciplines including psychology and sociology (Bazerman et al., 2007; Francis, 2008), political sciences (Zartman and Rubin, 2002; Slantchev, 2004), economics (Kremenyuk and Sjostedt, 2000; Tollison and Willett, 2009) and law (McMains and Mullins, 2001). Supply chain management literature is also informative about different negotiation-related topics (an overview can be found in Tsay et al., 1999 and Monczka et al., 2009).

[1] This sub-section is partly based on Mobini (2010) – title: "An Agent-Based Model to Support Negotiation-Based Order Acceptance in a Multi-Plant Enterprise" -, Behdani et al. (2011a) – title: "Negotiation based approach for order acceptance in a multi-plant specialty chemical manufacturing enterprise"- and Mobini et al. (2011) - title: "An Agent-Based Model to Support Negotiation-Based Order Acceptance in a Multi-Plant Enterprise".

The majority of work in supply chain management, however, is focused on buyer-seller negotiation where two or more parties negotiate on terms of transactions like price or delivery time (Talluri, 2002). On the basis of activities and their sequence that form the interaction between parties, negotiation processes are usually categorized as auction or bargaining (Wong and Fang, 2010). In auctions, the auctioneer – buyer or seller - initiates an auction with an initial offer and monitors the auction process while bidders send their own bids in response to the initial offer or bids from other offers. The auctioneer follows a certain auction protocol to pick the final partner. In a bargaining case, however, the bargainers try to solve the conflicts by alternating offer and counteroffer round by round until an agreement is reached. This process is referred to as Rubinstein's bargaining model in the literature (Rubinstein, 1982). There are also several variations of bargaining: bilateral bargaining (one-to-one), multilateral bargaining (one-to-many, many-to-one and many-to-many), single-issue bargaining and multi-issue bargaining (Wong and Fang, 2010). Multi-issue bargaining, according to the order of issues bargained, can further be divided into two categories: bargaining in-bundle over multiple issues and bargaining issues one by one. In the former, there is bargaining on multiple issues simultaneously and it is possible to make trade-offs among different issues, but the negotiation space is more complex. The issue-by-issue approach has a simpler computation, but an important question that arises is the order in which the issues are bargained (Fatima et al. 2004). Based on the order of exchanging offers, in some bargaining situations parties submit offers simultaneously. In contrast, there are some other situations in which iterative exchange of offers is possible.

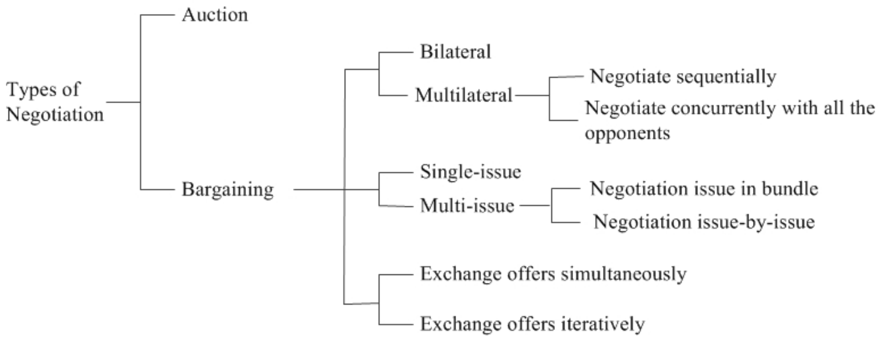

Figure 6.14. Different types of Negotiation (adapted from Wong and Fang (2010))

As it can be observed from the mentioned literature, there are various types of negotiation processes based on set of activities, number of actors involved and negotiation rules that govern the process. However – and without considering the details of different cases - several concepts are common in each negotiation problem; a number of *parties* with different objectives and behavior are involved in the negotiation *process* negotiating on a negotiation subject that can be described by several *issues* such as price, lead time and quality.

All relevant concepts can be formalized in the negotiation ontology as shown in Figure 6.15. In brief, a number of NegotiationParties with diverse characteristics participate in the NegotiationProcess. The NegotiationProcess is governed by a NegotiationProtocol which defines the rules of interaction between parties (i.e., NegotiationRules). The NegotiationProcess also consists of a set of NegotiationActivities which are performed by the NegotiationParties. NegotiationActivities deal with OfferFlows which contain an Offer that itself is described by several NegotiationIssues (e.g., price). A successful negotiation eventually defines the Agreement between NegotiationParties which is a type of Offer (it contains the agreed value for NegotiationIssues). Each of the concepts of the ontology is further characterized by a set of attributes as described in Table 6.2.

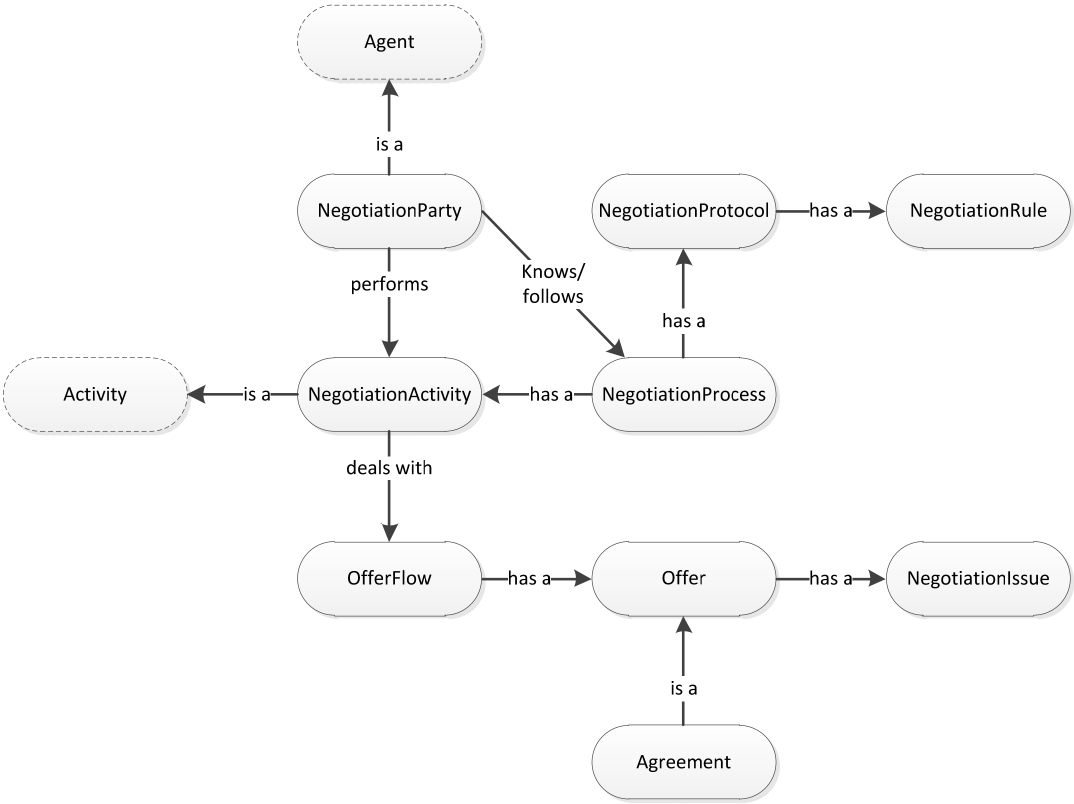

Figure 6.15. Concepts and relations in the negotiation ontology

Table 6.2. Summary of classes and their attributes in Negotiation ontology

Concept	Description	Attributes			
		Name	**Value type**	**Allowed classes**	**Description**
NegotiationParty	Describes the participants in the negotiation. The NegotiationParty is a subclass of Agent and extends its properties; In fact, the Agent with negotiation capability has this set of additional properties.	negotiationFeatures	instances	Property	describes the negotiation attributes of NegotiationParty (e.g., Step limit which is the maximum number of negotiation rounds for each party).
		perfromingNegActivties	instances	NegotiationActivity	Set of Activities must be executed during negotiation
		negotiationProtocol	instance	NegotiationProtocol	NegotiationParty knows/ follows this set of rules during the NegotiationProcess.
NegotiationProcess	Defines the allowed activities and terms of negotiation between NegotiationParties	label	primitive	String	The tag to be identified by others
		allowedActivties	instances	NegotiationActivity	Set of Activities are allowed during negotiation; for instance if the negotiation is an Auction or a Bargaining case, the set of activities would be different
		negotiationProtocol	instance	NegotiationProtocol	Set of rules must be followed by NegotiationParties during negotiation
NegotiationActivity	Defines the activities that are done by Negotiation Parties in a Negotiation Process. The NegotiationActivity is a sub-class of Activity. It has all properties of Activity but triggeredFlow is over-written.	triggeredFlow	instances	OfferFlow	The flows that each NegotiationActivity must deal with

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
OfferFlow[*]	Describe the flows of Offers between Agents during NegotiationProcess	label	primitive	String	The tag to be identified by others
		from	instance	Agent	The Agent that sends the Offer
		to	instance	Agent	The Agent that receives the Offer
		content	instance	Offer	The offer that is exchanged between NegotiationParties
Offer	Consists of a number of NegotiationIssues and an assigned value for each of them	label	primitive	String	The tag to be identified by others
		composingIssues	instances	NegotiationIssue	Each offer consists of a number of Negotiation Issues and an assigned value for each of them.
NegotiationIssue	Is an issue under negotiation between the parties during the NegotiationProcess	label	primitive	String	The tag to be identified by others
		negotiationObject	instance	Thing	Defines the component in the model that NegotiationParties are negotiating about. In general, this can be any entity in the model like an Order or properties of Technology.
		issuesUnderNegotiation	instance	Property	The specific properties of negotiationObject which are under negotiation.
Agreement	Defines the agreed value for NegotiationIssues at the end of NegotiationProcess; Agreement is a sub-class of Offer.	see Offer			

Concept	Description	Attributes			
		Name	Value type	Allowed classes	Description
NegotiationProtocol	Defines the rules and restrictions must be followed in the NegotiationProcess	label	primitive	String	The tag to be identified by others
		consistsOf	instances	NegotiationRule	Defines the content of NegotiationProtocol
		initiatingAgent	instance	NegotiationParty	The NegotiationParty that must start the negotiation process
NegotiationRule	Describes any restriction in the NegotiationProcess	label	primitive	String	The tag to be identified by others

* We assume that flow of offers happens instantly. Therefore, we do not consider sendingTime and receivingTime for OfferFlow.

During simulation runs, if the decision-making for a specific decision variable calls for involving multiple Agents, a negotiation session must be started. This negotiation occurs in one or more rounds (based on the NegotiationProcess that is defined for Agents[1]).[2] In each round of negotiation, one NegotiationParty must select a NegotiationActivity to perform. Eight sub-classes of NegotiationActivity have been defined in the model: "PrepareOffer", "SendOffer", "ReceiveOffer", "EvaluateOffer", "AcceptOffer", "RejectOffer", "ContinueNegotiation" and "QuitNegotiation". Negotiation starts by one of Agents (i.e., the initiatingAgent of NegotiationProtocol) by PrepareOffer Activity. The prepared offer must be sent to other NegotiationParty by SendOffer with an OfferFlow. The counterparty receives offer and evaluates the Offer in EvaluateOffer Activity. After evaluation, the second party must choose next activity. There could be three situations:

(a) If Offer is acceptable, it performs the AcceptOffer Activity which activates an InformationFlow with acceptance message.

(b) The terms of Offer is rejected and the NegotiationParty breaks off the negotiation (e.g., because of time limitation[3]). In this case, NegotiationParty performs QuitNegotiation Activity which triggers an InformationFlow with quitting message.

(c) The offer is rejected but the second party sends a counter-offer. Preparing a counter-offer is done by PrepareOffer Activity and finally, SendOffer triggers an OfferFlow to other party.

The negotiation is terminated when the parties end in agreement (the Offer of one party is accepted by counter- party) or disagreement (when one of them quits the negotiation). Throughout the whole NegotiationProcess, the NegotiationRules constrain the interactions between Agents. For instance, there might be a "response time limit rule" which defines for each party to respond to the offer of its counter-party. After this time, one of parties can quit the negotiation. Similarly, there can be a NegotiationRule for the number of negotiation rounds as no negotiation can continue forever.

To prepare and evaluate the Offers, each NegotiationParty has a utility function (Russell and Norvig, 2002). This utility function assigns a single number to express the

[1] Clearly, if the NegotiationProcess is an auction, there is no iteration in the negotiation. One side is allowed to propose counter-offers but the other side can only accept/reject the opponent's counter-offers.
[2] We assume that all rounds of negotiation occur in one simulation step unless the opposite is definite in the description of a case. This means that when negotiation starts, it continues until an agreement is reached. Then, the time step can change to next simulation tick.
[3] This is defined as negotiationFeatures of NegotiationParty.

desirability of each Offer in the negotiation. The objective of a party in the negotiation would be to maximize its utility function. A widely used type of utility function is the type of linear additive utility function in which the contribution of every issue to the utility is linear and does not depend on the values of other issues (Keeney and Raiffa, 1993). The value of each issue in a specific offer can be assessed using "evaluation functions". These evaluation functions map the value of issue to a single number indicating its desirability.[1]

As an illustration, consider price as an issue for negotiation between a buyer and a seller. The buyer prefers to purchase with the lowest possible price. So, the evaluation function of price for the risk-neutral buyer could have the decreasing form (similar to what is presented in Figure 6.16). Similarly, a Trapezoid evaluation function can represent the desirability of different delivery dates for buyer. In fact, the order delivery in a period between an earliest due date and a latest due date is acceptable. The utility function for the buyer is then the sum of evaluation functions for each issue which is multiplied by a weight representing the importance (sensitivity) of that particular issue from the buyer viewpoint. Assuming the buyer is price sensitive and has more interest to buy at a low price, the utility function would be:

$$Utility = w_1\, f(price) + w_2\, f(delivery\ time)$$

In which w_1 and w_2 are the weights for price and delivery time respectively. Evaluation functions are denoted by f(price) and f(delivery time). For a price sensitive buyer, w_1 has a higher value compared to w_2 (e.g. 0.7 for w_1 and 0.3 for w_2).

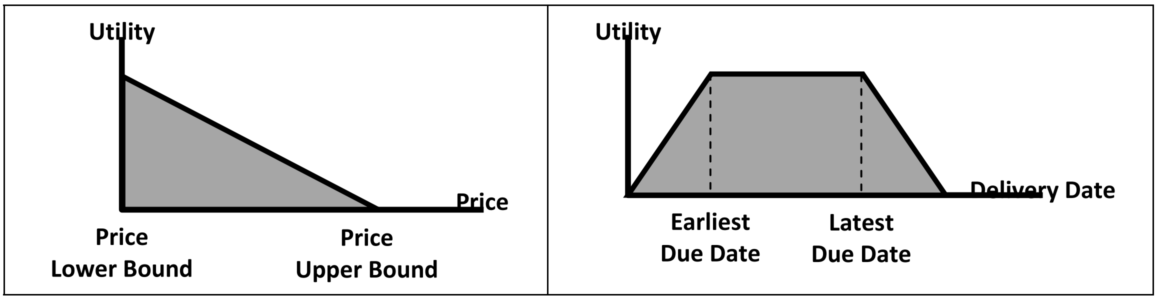

Figure 6.16. Examples of evaluation function for price and delivery time

Four types of evaluation functions are widely used in the literature (Chen and Huang, 2007; Tykhonov, 2010):

- *Downhill function*: minimal issue values are preferred over other values of issue.

[1] A utility function is used to evaluate the desirability of an offer as a whole, while an evaluation function is utilized to assess a single issue.

- *Uphill function*: maximal issue values are preferred over other issue values.
- *Triangular function*: a specific issue value somewhere in the issue range is valued most and issues to the right and left are valued less.
- *Trapezoid function*: a specific range of values somewhere in the issue range is valued most and issues to the right and left are valued less.

Based on its utility function, NegotiationParties PrepareOffer and EvaluateOffer of their counter-parties. There could be also some limitations for each party during the negotiation. These limitations are defined in the negotiationFeatures of each NegotiationParty. An example is the time limitation for an actor to continue negotiation.[1] The involved actors may also have different constraints regarding different NegotiationIssues. For example, a seller or a buyer may have different acceptable ranges for price or due date of an order and they are not willing to accept or negotiate the values beyond those ranges. Meanwhile, each party has an option outside the negotiation (Raiffa et al, 2002). In case negotiation fails, the outside option would be the alternative for that party. This is called Best Alternative to the Negotiated Agreement (BATNA). As an example, BATNA for a buyer could be, purchasing the desired product from the spot market.

To sum-up, each NegotiationParty makes decisions about the NegotiationActivity by its utility function in different rounds of negotiation. This, basically, drives the negotiation progress until an Agreement is reached, one of NegotiationParties quits the negotiation or a termination rule is imposed by NegotiationProtocol. In that case, the final Agreement or BATNA defines the value for decision variables (or NegotiationIssues) of negotiationObject.

- *Technical sub-system dynamics*

Similar to Agents, the Technologies are also modeled with two distinctive parts: the state and the behavior (Figure 6.17). The state is described by a set of properties as discussed in Table 6.1. During simulation, these properties are constantly altered by acts of Agents or by technical (behavioral) rules. For example, the decision for the product that must be produced at each time step is made by Agent and subsequently, the state of technology is being changed. The properties of technical artifacts can also be updated by technical behavioral rules which are defined based on engineering principles. An example is the

[1] This limitation is important as Muthoo (1999) claimed that the parties will reach an agreement if and only if time is valuable to at least one of the two parties in a bilateral situation.

dynamics of producing goods in a chemical reactor or the dynamic degradation of raw material quality in the storage tanks. In both cases, the physical rules are defined by algebraic equations and functions. Therefore, at each time step, the value of properties needs to be re-assessed before Agent starts monitoring the technical artifacts' State.

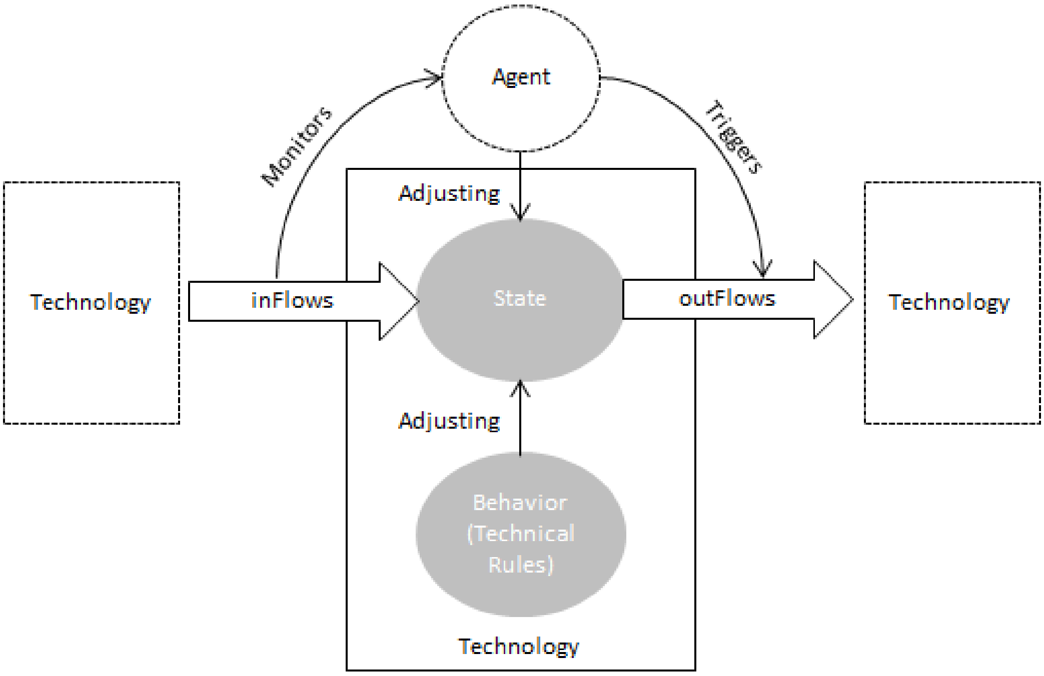

Figure 6.17. The structure/ behavior of Technology

The Technology's state changes through interaction with other technical artifacts as well. The interaction at the technical level is modeled by MaterialFlow. At each time step, the inFlows to each Technology are monitored by Agent. In addition, the outFlows from each Technology are triggered by Agent's decisions and Activities. Monitoring the inFlows and triggering outFlows, subsequently, cause changes in the state of technical entities during simulation runs. An example is when the production agent activates the flow of material from production facility to storage facility. By this flow, the level of material in the production facility decreases and the level at the storage facility increases.

To sum up, the technical artifacts in the model are also defined by state and technical behavioral rules. At each time step of simulation, the state of these entities is updated by direct acts of Agents or indirectly through triggering MaterialFlows from/to each Technology. The state of Technology might also change because of physical rules.

6.3.2. Environment sub-model

The definition of the supply chain model concludes by describing the Environment "sub-model" in this section. The Environment is used in the model for two purposes: firstly, Environment is the *Source* of resources that are consumed by Agents but are not produced by actors inside the supply chain. For example, when we model a supply chain with supplier, manufacturer and customer as shown in Figure 6.18, the external resources for supplier are modeled with MaterialFlow from Environment. In other words, the Environment provides the resources which are outside the boundaries of system.[1] This interaction basically occurs between technical subsystem (i.e., Technology) and Environment and is modeled with MaterialFlow. We assume that the resources in the environment are unlimited unless there is an explicit constraint defined for specific real cases.

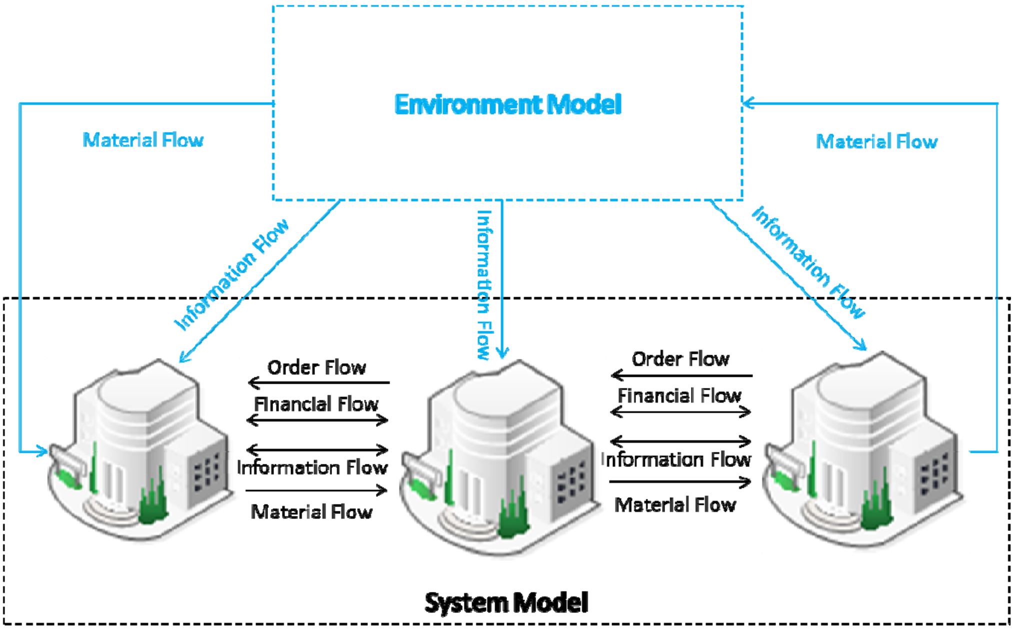

Figure 6.18. The interaction of system and environment in the model

The second role of the Environment sub-model is to define the exogenous variables in each simulation. These variables are, in fact, those aspects of reality which are not part of the system or influenced by Agents, but can affect Agents' behavior. The prices of goods or the demand pattern for final products are examples of exogenous variables. The values for these variables are usually set as an assumption or sampled from a trend function which is given before starting the simulation. For this purpose, we assume that

[1] The Environment might also work as a *Sink* of resources when we focus on a sub-set of supply chain. For instance, when we do not model the final customer and just model the supplier, manufacturer and retailers, the Environment can be the sink for receiving the final product.

Environment has also a State/Behavior structure. State is defined by the set of exogenous variables (e.g., price of goods) and behavior represents how this state changes over time. This is shown by algebraic equations which, for instance, describe the relationship between time and material price during the simulation horizon. The value of exogenous variables is updated at each time step and it is read by Agents through InformationFlow. Next, Agents use this information in their decision-making process in that time step of simulation.

As different kinds of information are important for different Agents in the system, we define two types of Environment in each simulation model. There is a Global Environment which is accessible by all Agents. However, each Agent in the model may have its own Local Environment too. For example, in modeling a multi-plant enterprise, the raw material price or demand pattern might be different in different geographical locations and subsequently they are represented in the local Environment of each production plant.

6.4. Disruption modeling

The “Disruption Modeling” component in the framework of Figure 6.2 describes the characteristics of a disruptive event in the simulation model. Different features have been discussed in the literature to define a supply chain disruption (Table 6.3).

Table 6.3. A summary of main feature to describe supply chain disruption in the literature

Reference	Disruption Feature
Erhun and Deleris (2005)	Failure time, Duration of Disruption, Location of Disruption
Losada et al. (2010)	Duration of Disruption, Recovery Profile
Jin and Zhuang (2010)	Failure time, Duration of Disruption
Schmitt and Singh (2009)	Duration of Disruption, Location
Sheffi and Rice (2005)	Failure Time, Recovery Profile, Length of Disruption
Adhitya et al. (2007a)	Detection Time, Disrupted Object, Disruption Duration
Falasca et al. (2008)	Location of Disruption, Recovery Profile, Duration of Disruption

These features can be classified in three main dimensions (Figure 6.19):

- **Locational dimension:** In general, a supply chain disruption might occur in each of the structural components of the system model - which is termed “disruptedObject” – and subsequently one of the attributes of that entity – which is called “disruptedAttribute” – would be changed. Therefore, the disruptedObject can be:

1. A *Technology*: for example, the production rate (disruptedAttribute) of a plant can be reduced to a fraction of its nominal production capacity because of machine breakdown.
2. An *Agent*: for instance, the logistics service provider might stop its business temporarily or permanently.
3. A *Connection*: as an example, the physicalConnection between supplier and production plant might be temporarily disrupted because of a strike in the main delivery port.[1]

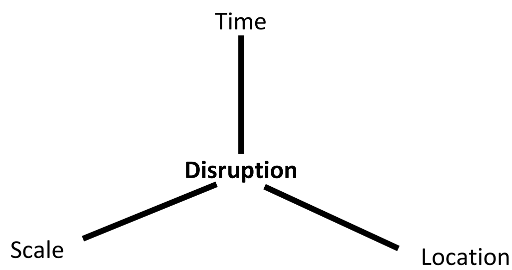

Figure 6.19. Three main dimensions in disruption definition

- **Time-related dimension**: Some other features of disruption are time-related aspects of disruption. Two specific features are “disruptionOccurenceTime” - which describes the time that a disruption starts - and “disruptionDuration” - which determines the length of time that is needed to return the “disruptedAttribute” to “normalValue”[2].
- **Scale-related dimension**: The scale of disruption defines the level of impact on “disruptedObject”. This can be simply defined as a percentage of “normalValue” – which is itself one of properties of disruptedObject. For instance, the “production capacity” –as one of designProperties of a Technology - can be reduced to 50% because of machine breakdown or “material transferring capacity” – as one of designProperties of a PhysicalConnection – may be reduced due to port strike and subsequently, material shipment can be delayed. We can also consider more sophisticated profiles for disruption with gradual recovery as shown in Figure 6.20. In that case, a “rateOfRecovery” needs to be also defined in the Disruption description.

[1] As can be seen, a disruption can occur in both physical and social networks of a supply chain.
[2] NormalValue is the value of disruptedAttribute before disruption.

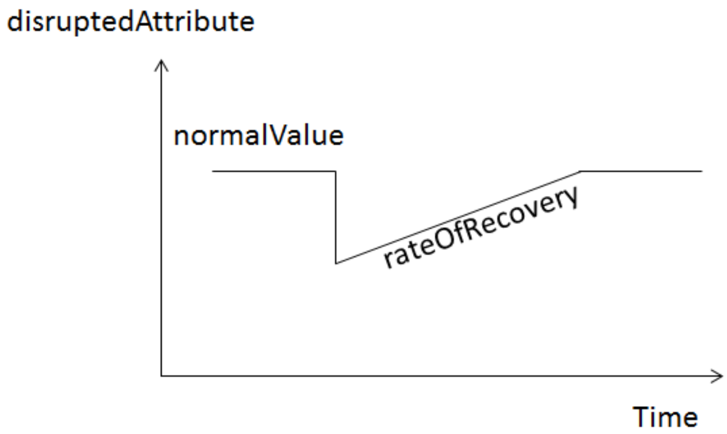

Figure 6.20. Disruption profile with gradual recovery

All characteristics of a supply chain disruption are represented in the SupplyChainDisruption class (Table 6.4). Of course, the complete description is not necessarily considered in every simulation and – as discussed further in Chapter 7 – for specific case, we may just consider some of these features.

Table 6.4. Properties of SupplyChainDisruption class

Attributes			
Name	**Value type**	**Allowed classes**	**Description**
disruptedObject	instance	Agent/ Technology/ PhysicalConnection	Defines the component in the model which is disrupted
disruptedAttribute	instance	Property	Describes which characteristics of disruptedObject is disrupted
disruptionOccurenceTime	primitive	Float	The disruption occurs at this time
disruptionDuration	primitive	Float	Describes the length of disruption period
normalValue	primitive	Float	The value of disruptedAttribute before disruption
disruptedValue	primitive	Float	The value of disruptedAttribute after disruption
rateOfRecovery	primitive	Float	Describes the rate of recovery of the recovery profile is gradual

During the simulation, SupplyChainDisruption is the means by which we can create the disruptive events based on disruption scenarios or disruption inputs (more details can be found in section 6.6). More specifically, when the simulation time equals disruptionOccurenceTime, the disruption model changes the disruptedAttribute of disruptedObject to disruptedValue and its Status to “disrupted”. The disruptedObject returns to normalValue when the simulation time equals “disruptionOccurenceTime + disruptionDuration”. If disruption has a gradual recovery profile, at each simulation time step, the disruption class must update the disruptedValue for disruptedAttribute.

6.5. Disruption management modeling

The model of the system which is presented in section 6.3 describes the normal operation of supply chain entities. To handle a disruption, Agents in the model must have the capabilities to *detect* and *react* to disruption. These capabilities are in fact areas for improving the supply chain disruption management process in the system.

Detection of disruption can be implemented in the model in two ways. Firstly, the disrupted Agent or the Agent that owns the disruptedObject sends a message with an InformationFlow to other Agents. The logic for this process has to be designed and implemented inside the Agents beforehand.[1] For this purpose, each Agent has the necessary AnnounceDisruption Activity in its performingActivities which describe that as disruption happens, the “disruption occurrence message” must be sent in an InformationFlow to other relevant Agents.

The second possibility for disruption detection by an Agent is through monitoring the “Status” (see Table 6.1) of technical artifacts and other Agents in the system. This monitoring is done through a CheckStatus Activity. This Activity has a temporalCondition which defines the interval of checking. As an example, the Agent may check the “Status” of a PhysicalConnection every time step or every two time steps. *Which Agents or technical artifacts are monitored* and *how frequently this monitoring occurs* are important factors to define the disruption detection capability of Agent and impact the performance of the disruption management process (Blackhurst et al., 2008).

The second issue in the disruption management is defining the disruption responses. As disruption is detected, Agents can go forward and take the necessary actions to handle disruptions. The responses to a disruption are defined by changes in the **Structure** or **Behavior** of system. The former is modifying the structural elements of system. These modifications might be at the technical level (changing the technology/physical connection’s attributes) or social level of the system (change of agent/social connection states). For instance, as a SocialNode, the financial state of an Agent can be improved by a loan and consequently the money level for agent will increase. Similarly, the capacity of a storage facility (as a TechnicalNode or Technology) might be increased by a few percent to better handle the unexpected delays in raw material delivery.

[1] In real world this can be a part of obligations in the contract settings in the supply chain. For example, a manufacturer may legally oblige its suppliers – in the contract setting – to notify any disruption that leads to late delivery of material in less than 24 hours after disruption occurrence.

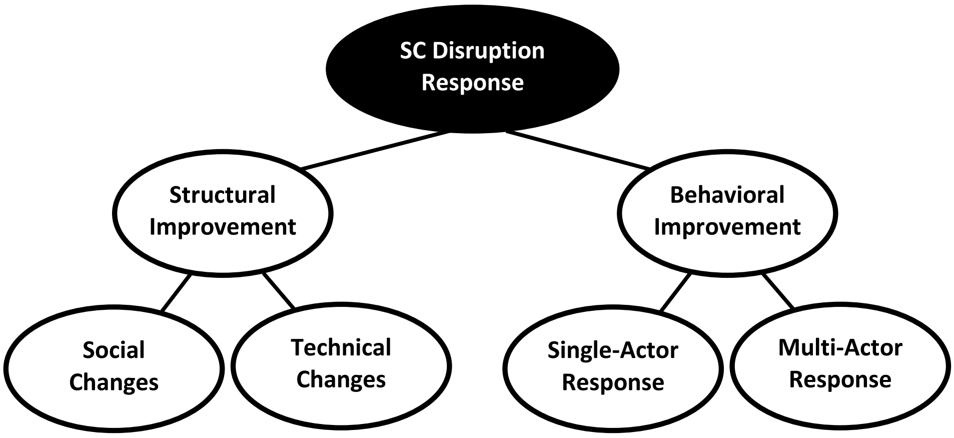

Figure 6.21. Possible disruption responses to implement in the model

The behavioral changes in the system can happen in two different ways; firstly, it might involve one Agent. This class is termed “Single-Actor Response” in Figure 6.21. In this case, the disruption management practice is described by a set of Activities that must be performed when a disruption is detected by Agent.

The second class of behavioral changes in the system involves multiple actors in the system. To describe the disruption management in this case, we need a coordination scheme (Figure 6.22). This coordination scheme must describe which Agents are involved in the disruption process, which activities must be done by each Agent and which temporary Flows must be defined among them (Malone and Crowston, 1994; Behdani, et al. 2011c). For example, the production plants in an enterprise might exchange their orders or raw material with each other when there is a disruption in the supply chain of one of them. This implies that a new pattern of information and material Flows must be defined for the case of disruption.

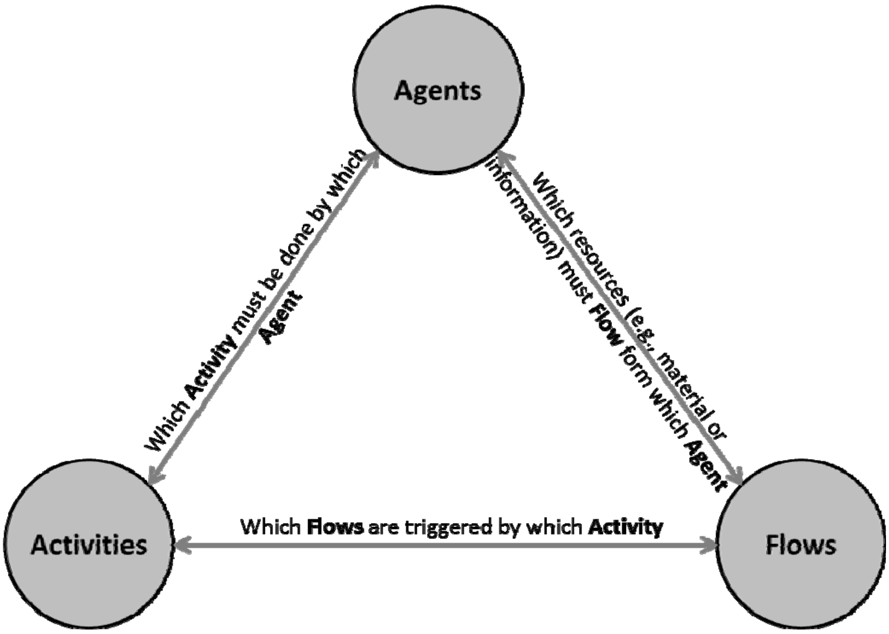

Figure 6.22. Coordination scheme to define multi-actor disruption response

6.6. Software implementation

All concepts that are presented in sections 6.3, 6.4 and 6.5 together provide us with a framework to conceptualize disruption management in the supply chain. With framework we imply the definition of Gamma et al. (1995) who describes a framework as “a set of cooperating classes that make up a reusable design for a specific class of software.” Each concept in the conceptual model is, in fact, a class of entities and the ontology is basically the class structure for software implementation.

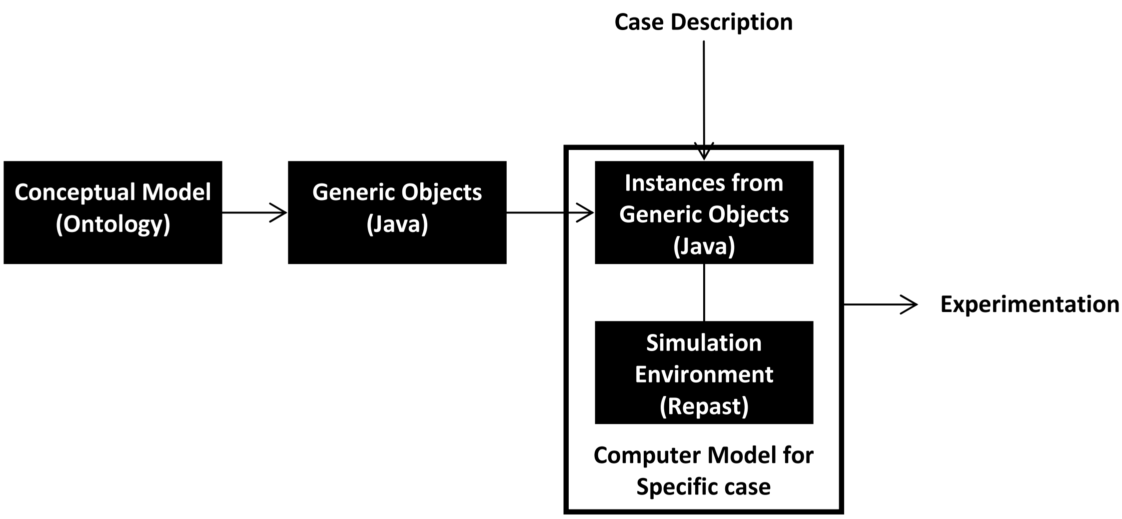

Figure 6.23. Procedure from conceptual model to computer model for specific case

The concepts in the framework are coded in Java programming language. For each concept, the properties are considered as *fields* in the java class and behavior is presented as *methods*. Consequently, a set of generic objects are developed in Java which can be customized for specific cases by sub-classing and composing instances (Gamma et al., 1995). For example, for the case study of Chapter 7, twelve different instances of Agent are defined to describe various actors involved in the operation of supply chain (Figure 6.24). Of course, from these instances, further sub-classes can also be defined to more concretely specify a given case (e.g., sub-classes of each department are defined for each plant). Because of inheritance, each sub-class has the properties of super-class in the model. For instance, all defined Agents have label, status, inEdges, outEdges, etc. Meanwhile, each lower-level class (instance) can extend the set of properties or specify properties further. Moreover, the object-oriented environments like Java are flexible enough to define new concepts (classes) for specific cases if needed.

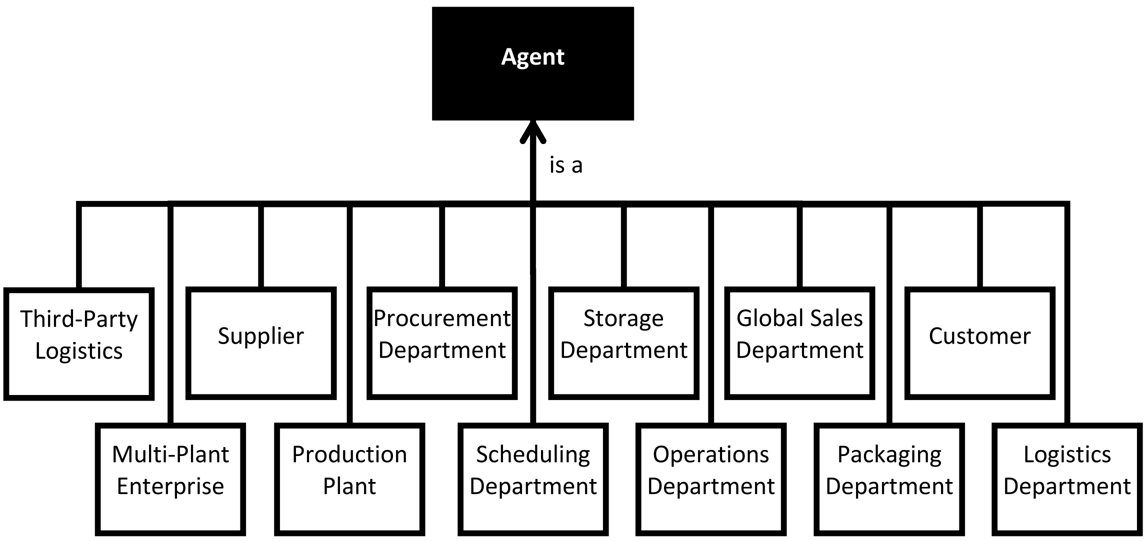

Figure 6.24. Sub-classes of Agent for case multi-plant lube oil supply chain of Chapter 7

As the description of a case is conceptualized with the classes in the framework, their behavior must be implemented in Java codes. To facilitate this process, first the case description can be shown in flowcharts or other graphical representations (like Activity Diagrams). The informal description of a real case can also be expressed in pseudo-codes before writing specific computer codes (Forsyth and Ponce, 2003). As the model structure and behavior are implemented in Java codes, we need a simulation environment to run the codes. The simulation platform that is selected is Repast. Repast is a Java-based open source simulation toolkit for agent-based modeling (North et al., 2006). It

Box 6.3- Repast Agent Simulation Toolkit

The Recursive Porous Agent Simulation Toolkit (Repast) is a free open source toolkit for agent-based simulation (North et al., 2006). Originally developed by the Social Science Research Computing at the University of Chicago and subsequently, maintained by Argonne National Laboratory, Repast provides a core collection of classes for the building and running of agent-based simulations and for the collection and display of data through tables, charts, and graphs (Repast, 2012).

Besides Repast, several other agent modeling toolkits are available such as Swarm, Ascape, NetLogo, MASON. Reviews of these agent-modeling toolkits can be found in Serenko and Detlor (2002), Gilbert and Bankes (2002) and Railsback et a. (2006). Tobias and Hofmann (2004) also had a review and comparison among different agent-based simulation tools and concluded that Repast, in general, is the most suitable simulation framework for modeling social systems.

Each Repast model usually has three main methods (Repast, 2012):

- **buildModel**: is responsible for creating the main body of simulation. More specifically, the agents and their environment are created here, together with any optional data collection objects. Clearly, this part of simulation is largely case-specific.
- **buildSchedule**: builds the Schedule of actions in the simulation. This, in fact, means what methods to call on which objects and when. Repast scheduler is a discrete time simulator where every tick was checked to see if any actions were scheduled for that tick.
- **buildDisplay**: creates those parts of the simulation that have to do with displaying the simulation to a user.

More information on using Repast for modeling can be found in Repast web site (http://repast.sourceforge.net/)

offers the necessary support code, like a scheduler, graph plotting, statistics collection, experiment setups, etc.

The codes from simulation tool (Repast) and the model which is defined by customizing framework classes form the **computer model** for a specific case. This computer model, next, can be used for experimentation and decision support.

The steps to develop the model for a specific case and how this model is used to experiment with different aspects of disruption management are further discussed for a case of lube oil supply chain in Chapter 7.

6.7. Chapter summary

In this chapter a conceptual modeling framework for disruption management in supply chains is presented. This framework consists of three main components. Firstly, an agent-based representation of a supply chain is discussed in which “Agent” (representing the decision-making units in the system) is the central concept. Agent together with other main concepts to describe the structure and operation of a supply chain are, next, formalized in an ontology. This ontology is basically the conceptual model for a supply chain as a complex sociotechnical system. Afterward, the conceptual model of supply chain disruption is discussed. Finally, we described how different disruption management practices can be defined and implemented in the model. These three components present a conceptual modeling framework for disruption management in the supply chains. This framework is very flexible in modeling different types of disruption and disruption management practices. Firstly, they can be defined in both social and technical entities within the system. Moreover, the disruption management can be by improving the structure or behavior of system elements. For instance, the structure of a supply chain can be improved by changing the characteristics of technology and physical facilities (e.g., increasing the storage capacity) or by a new contract with a backup supplier. As an alternative, to handle disruption we can define new logic for decision-making or different types of activities for different agents in the system. This flexibility in modeling is further elaborated in the next chapter for a case of lube oil supply chain.

7. LUBE OIL SC CASE: MODEL DEVELOPMENT AND USE FOR NORMAL OPERATION

In this chapter, the application of modeling framework of chapter 6 for a case of lube oil supply chain is presented. First, we discuss how a computer model for a specific case can be developed with generic objects of modeling framework. Next, the application of this model to handle different aspects related to normal and abnormal operation of supply chain is explored.

7.1. Introduction

In Chapter 6 a modeling framework for supply chain disruption management was presented. In this chapter we discuss the application of this modeling framework for a case of Lube Oil Supply Chain. First, a description of the case is presented. Next, we describe how this case definition could be translated into the computer model. The developed model, then, will be used in some experimental set-ups to support the decision-making in the normal operations management in the supply chain and managing disruption in different steps of the InForMDRiSC framework.

7.2. Case description

The model of supply chain in this chapter is developed based on the case of an international Lube Oil Company. The description of the system layout and operating procedures are described in a report by (Wong, 2007) and was the motivation to develop a multi-plant simulator (Adhitya and Srinivasan, 2010). As in the two mentioned studies, the name and profile of the company remains confidential throughout this chapter and it is called MPE hereafter. The lube oil supply chain consists of a lube additive manufacturing enterprise, its customers in the downstream and the suppliers for raw materials (i.e., base oils and additives) in the upstream (Figure 7.1). The enterprise has three production plants in US, South Asia and East Asia. Each of these plants has its own functional departments with a specific role and certain tasks to perform. The enterprise has also a central sales department which directly interacts with customers around the world. The overall goal for the whole enterprise is to fulfill customer orders by assigning them to different plants and coordinating the behavior of different departments in each plant.

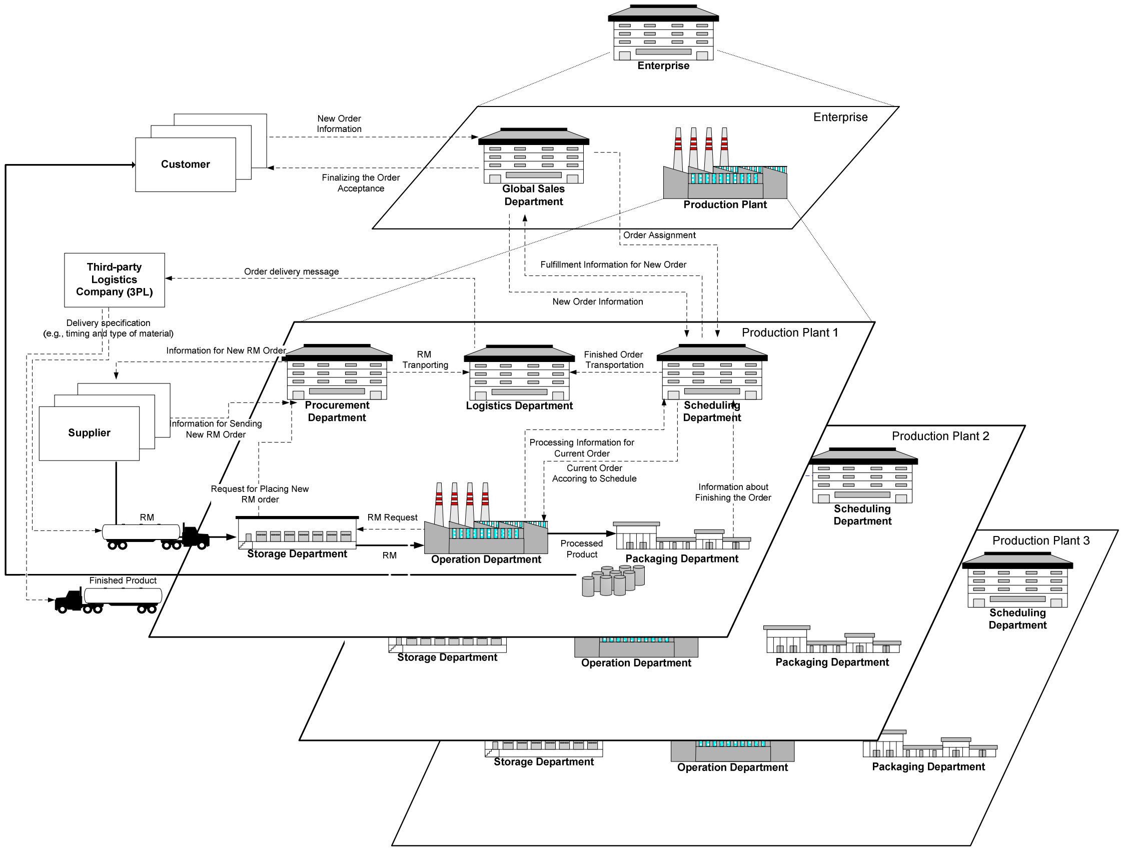

Figure 7.1. Schematic of multi-plant lube oil supply chain

Actors and their behavior in lube oil supply chain:

The actors in the lube oil supply chain can be viewed at three levels:

- **Global level:** There are four actors at the global level – customers, the enterprise, third-party Logistics Company and suppliers.
- **Enterprise level:** The manufacturing enterprise consists of the global sales department and a number of plants.
- **Plant level:** Each plant has six different functional departments – representative for scheduling, operations, storage, packaging, procurement and logistics.

In the following, the behavior of each of these actors is described in more detail.

(1) Customers: The customers in the supply chain place orders based on their material requirements and send these orders to the enterprise. Each order from customers is normally described by:

- *Product type and grade*: the product portfolio of enterprise includes three main types of Lubricant products (based on the type of base oil used) and five grades for each type. Different grades for a specific lubricant have a different ratio of additives and base oil as shown in Table 7.1.

Table 7.1. Lubricant products and grades

Product A						
Grade	**Base Oil 1**	**ZDDP**[1]	**Dispersants**	**MMA**[2]	**Anti-Oxidants**	**Metal Sulfonates**
1	0.8	0.1	-	-	-	0.1
2	0.75		0.15	-	-	0.1
3	0.8	0.05	-	-	0.15	-
4	0.7	-	0.15	0.15	-	-
5	0.7	-	-	0.2	-	0.1
Product B						
Grade	**Base Oil 2**	**ZDDP**	**Dispersants**	**MMA**	**Anti-Oxidants**	**Metal Sulfonates**
1	0.7	0.15	-	-	-	0.15
2	0.8	-	0.1	-	-	0.1
3	0.7	0.2	-	0.1	-	-
4	0.8	-	0.05	-	0.15	-
5	0.75	-	-	0.15	-	0.1
Product C						
Grade	**Base Oil 3**	**ZDDP**	**Dispersants**	**MMA**	**Anti-Oxidants**	**Metal Sulfonates**
1	0.75	0.1	-	-	-	0.15
2	0.8	-	-	0.15	-	0.05
3	0.7	-	0.2	-	0.1	-
4	0.8	0.1	-	-	0.1	-
5	0.7	-	0.15	-	-	0.15

- *Order quantity*: defines the amount of product that is needed for a customer.
- *Packaging type*: the products can be sent to customers in two different forms; Iso-Tank Containers or Drums.
- *Transportation type*: the transportation of final product to the customer location can be arranged by the production plant or the customer himself might be responsible for order pick-up from plant location. The actor who is responsible for order delivery must be determined in order specifications.[3]

[1] Zinc dialkyldithiophosphates (ZDDP) is a regular anti-wear additive to lubricants such as greases, gear oils, and motor oils (Štìpina and Veselý, 1992).
[2] Methyl Mehtacrylate(MMA) is used as an additives for improving the viscosity and rheological properties of the lubricant (Mortier, R. M., Qrszulik, 1997).
[3] In order fulfillment process, determining the actor who is in charge for order delivery is important because that actor is assumed responsible for transportation risk and insurance coverage.

- *Due date range*: is the window when the final products have to reach the customer's location, regardless of whether the products are picked up by the customer or sent by the plant. This window is described by an Earliest Due Date and a Latest Due Date.

The customers are heterogeneous in various aspects; firstly they are located in different geographical locations. This, in fact, impacts the logistics and transportation cost for order delivery. Meanwhile, although the majority of customers are global customers which send their orders to the global sales department (GSD), each production plant has also some local customers that send their purchasing orders directly to that plant. In order negotiation and order assignment, GSD also classifies customers in two classes of "Important Customers" and "Regular Customers". Important Customers place more frequent orders with the enterprise and their orders have special priority, especially during disruption occurrence in the supply chain.

As a last important feature, the customers are classified in two groups of wholesalers and industrial customers. The main distinction between these two classes is reflected in their sensitivity to price and delivery time during negotiation with GSD (more details are discussed in section 7.4.1).

(2) Manufacturing Enterprise: The Multi-Plant Enterprise (MPE) has a global sales department (GSD) that directly interacts with the customers and three production plants in different geographical locations.

Global Sales Department (GSD): Global Sales Department (GSD) is responsible for order acceptance and order negotiation with customers. After receiving a purchasing order, the Global Sales Department (GSD) also assigns the order to one of the available plants. For this purpose, GSD passes the order details to the scheduling departments of each plant and requests information on order processing (e.g., the earliest date when the plant can produce the order and deliver to the customer). The schedulers reply with the requested information and based on the replies, GSD assigns the customer order to one of the plants according to its "order assignment policy". The assignment policy is called "First Completion Date Policy". In this policy, GSD asks for the first date that the new order can be processed and sent to the customer by each of the plants. Based on the replies from each plant, assigning order to one of plants is done based on the following rules (Figure 7.2):

- The plant with the Completion Date which falls in the Due Date Range and is the closest to the Earliest Due Date will be selected.

- If all plants can only complete the order before the Earliest Due Date, the plant with the Completion Date closest to the Earliest Due Date will be selected.
- If all plants can only complete the order after the Latest Due Date, the plant with the Completion Date closest to the Latest Due Date will be selected. Negotiations with the customer to extend the Latest Due Date will be held.

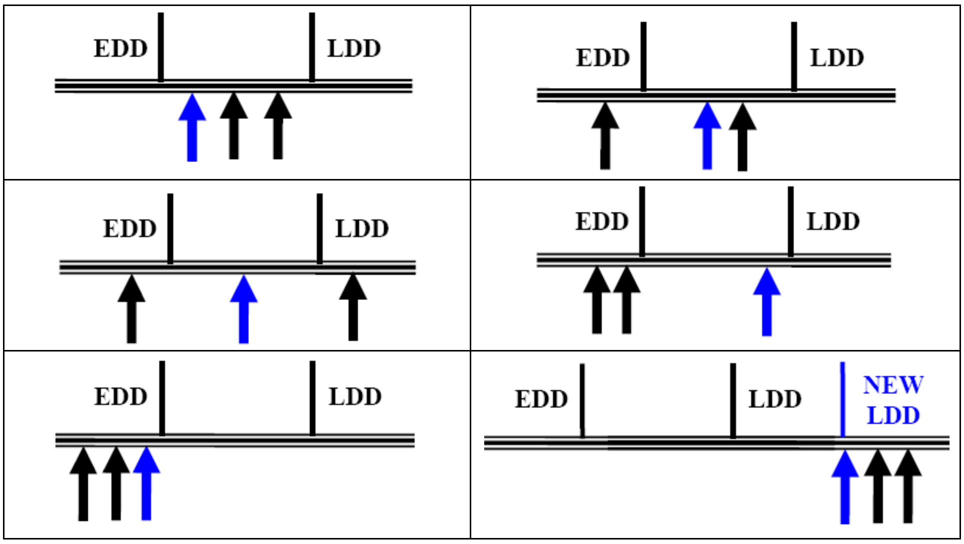

Figure 7.2. Different arrangements of completion dates for an order by different production plants in order assignment policy

Production Plant: the enterprise has three production plants. Each plant has some distinctive characteristics. This ranges from the geographical location, the production characteristics (e.g., production rate and operation costs) and the suppliers that each plant works with. Despite these differences, all plants operate on make-to-order (MTO) basis; they only begin production after receiving an "Order" that is received from customers and assigned by GSD.

Inside each production plant, many activities are done on a daily basis. These activities are divided among a number of departments which are responsible for a set of specific tasks:

- Scheduling department: This department performs two main functions:

Firstly, after receiving a new order from GSD, it sends the required information (e.g., the first possible time for fulfilling the new order) to GSD. For this purpose, the scheduler attempts to insert the new order into the current production schedule. Based on that, the scheduling department calculates the expected completion time for the

Box 7.1- Make-To-Order (MTO) vs. Make-To-Stock (MTS) Production

Generally, manufacturing environments can be divided into Make-To-Stock (MTS) and Make-To-Order (MTO) categories. MTS is the traditional production environment in which producing a product is driven by the demand forecast rather than actual customer orders (Kolisch, 2001). In other words, a company produces products and stocks them as inventory until they are sold.

In contrast, in the Make-To-Order (MTO) environment, production, final assembly and distribution of products are driven by the customers' orders; i.e. the firm produces after an order arrives, and produces only the quantity ordered (Gunasekaran and Ngai, 2005; Parry and Graves, 2008). With MTO process, therefore, a product is individually manufactured for a particular customer according to its specific requirements. Adopting the MTO production strategy creates the opportunity for a firm to offer greater product variety. In addition, the inventory holding cost will be reduced by eliminating the finished goods inventory.

new order and conveys that information to GSD for making a decision on order assignment.

As the second main function, the scheduling department determines the job schedule for the plant and informs the operations department of which job to process and when. To fulfill this task, the scheduler must communicate with the storage department to ensure the availability of raw materials before sending the order to the operations department.

The logic to determine the schedule of jobs is defined by the scheduling policy. The scheduling policy is Processing Earliest Due Date (PEDD). In this policy, the PEDD is calculated based on following formula:

PEDD = Earliest Due Date – Packaging Time – Processing Time – Expected Delivery Time

The order with earlier PEDD has the highest priority in the list of order jobs.

- Operations department: The operations department is responsible for supervising the processing of raw materials into various products through reaction and blending following a unique recipe. The recipe of production for different products and different grades is shown in Table 7.1.

To process each order, the operations department, firstly, sends a request for the release of raw materials to the storage department. Each batch of reactants is fed to the reactors and blenders (not described in detail here) and processed following pre-specified recipes to produce the products matching the specifications in the order. Following this production step, the products are sent for packaging.

- Packaging department: this department is responsible for product packaging. As mentioned before, products can be packaged in drums or iso-tanks. This depends on the packaging type specified by the customer in their order specification. Subsequently, packed products are either transferred to:

i) The storage department and wait for the customer to pick them up;

ii) The 3PL to deliver the products to the customer.

- Storage department: The storage department keeps tracks of the raw material storage of the plant. Meanwhile, it provides the raw materials for the operations department as it starts processing orders.

The other task of the storage department is to inform the scheduling department of the current inventory levels and ask the procurement agent to make a raw material order, whenever necessary.

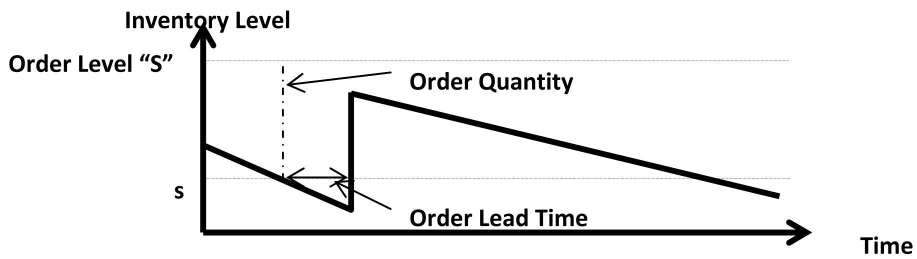

Figure 7.3. Reorder point inventory management policy

There are eight separate storage facilities for different base oils and additives in each plant. The inventory level in each of these storage tanks is continuously monitored by the storage department and , if necessary, the new orders for material are placed. The timing for raw material procurement is defined by reorder point policy. In this policy, whenever the remaining inventory is reduced to "s" (i.e., reorder point), the storage department asks the procurement department to place an order for the desired raw material to bring the inventory up to a specific target level of "S", which is the maximum capacity of storage tanks in our case (Figure 7.3).[1]

- Procurement department: The procurement department communicates with suppliers and places orders for raw materials based on the order specification that is defined by storage department. As a raw material order is received from a supplier, the procurement department has to make the payment.

The Procurement department also keeps track of pending orders which are in the process of being delivered by the Supplier. This is to avoid any potential repeat orders.

- Logistics Department: The logistics department arranges the shipping of raw material and distribution of finished product orders to customers. For this purpose, each plant has a transportation contract with a Third-party Logistics (3PL) company. Every day, the logistics department communicates with 3PL to give details on which orders must be transported to which customer and which orders of which supplier are ready to be shipped. The payment of logistics costs to 3PL and payment of lateness penalty to customers are also arranged by this department. The penalty for late delivery is defined in the contract between the enterprise and its customers.

(3) Third-party Logistics Company (3PL): 3PL provides the service of transportation for raw material from suppliers to the plant, and for the packaged lubricant products from the plant to the customer.

(4) Supplier: Suppliers provide various raw materials according to orders that are placed by the production plants. Each plant has a contract with one supplier for base oils and another contract for a second supplier to provide the additives. Each supplier has different geographical locations that can affect the delivery time. This aspect and some other characteristics of suppliers are also experimented in section 7.7.

The description of this global multi-plant specialty chemical manufacturing enterprise is formalized according to the modeling framework of Chapter 6 as described in the next section.

7.3. Computer model development

In this section, we discuss how the computer model for the specific case of the lube oil supply chain must be developed. In section 6.6, we discussed that for each concept in the

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[1] Some other possible inventory control policies are discussed and experimented in section 7.7.

conceptual model an Object in Java has been defined. To design a computer model for the lube oil supply chain case, these generic objects must be customized by defining the instances and the necessary attributes which are needed to describe this specific case.

It is noteworthy to emphasize that despite numerous actors in each system, in developing the model (as a decision support tool) only one of these actors is considered as the problem owner for whom the computer model is designed. This has two main implications in the modeling process. First, during the experiment design phase, the performance of the supply chain is studied from the perspective of this actor (i.e., the problem owner).[1] The second implication is in the level of detail for different actors in the model; for the problem owner - as the main actor - the structure and operation is defined with more detail while for other actors, the structure is usually much simpler. It is even possible that full operation details of other actors are unavailable during model development and consequently, most of assumptions in the experimentation phase are usually made about them. In our case of lube oil supply chain, the main actor and problem owner is the multi-plant enterprise (MPE). Therefore, in all experimental designs, the performance (or output as mentioned in section 5.3) is defined from the perspective of this actor. Meanwhile, the majority of efforts in the computer modeling are focused on presenting the structure and operation of MPE.

In Chapter 6, we made a distinction between static and dynamic representations of supply chains. Moreover, for static representation, the distinction between structural and operational components has been discussed. Based on this distinction, building the computer model starts by presenting the structure of lube oil supply chain. This description includes the Agents and links between Agents (Figure 7.4), Technologies and their relations with each other in the form of PhysicalConnection and the relations between Technologies and Agents in the form of Ownership (Figure 7.5).

[1] This issue will be further discussed in section 7.6.

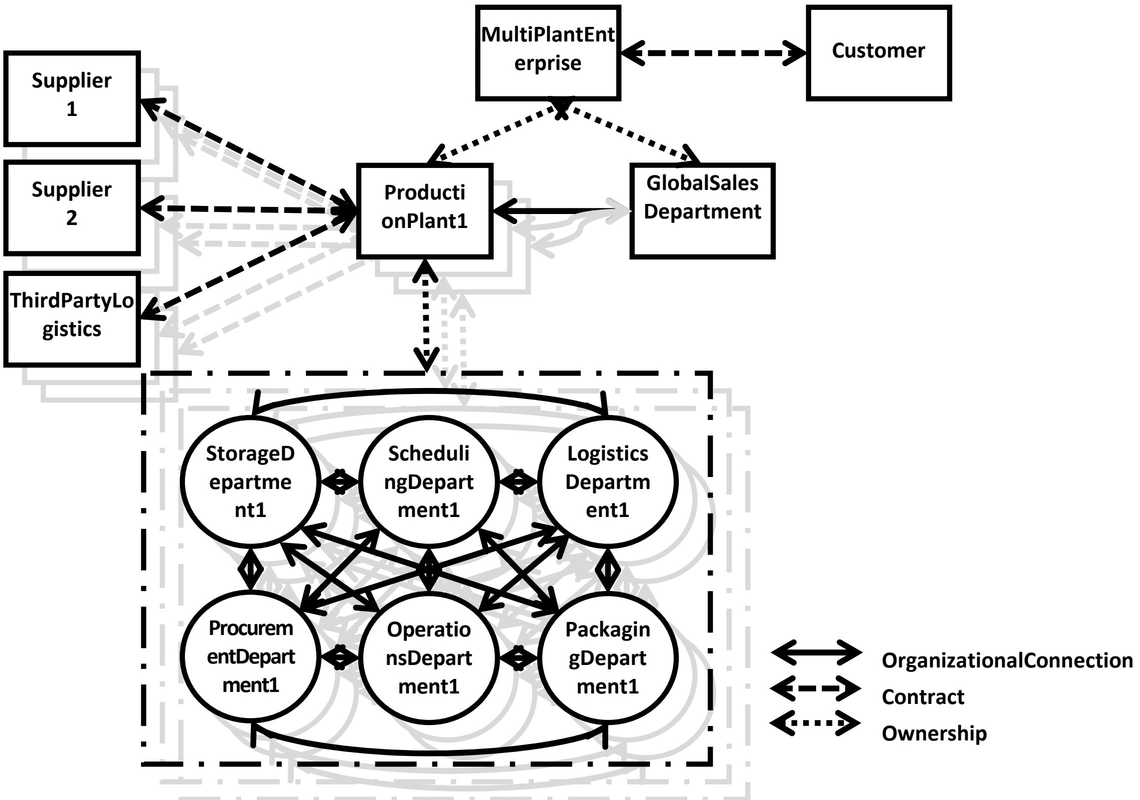


Figure 7.4. Agents and their relations in the model.

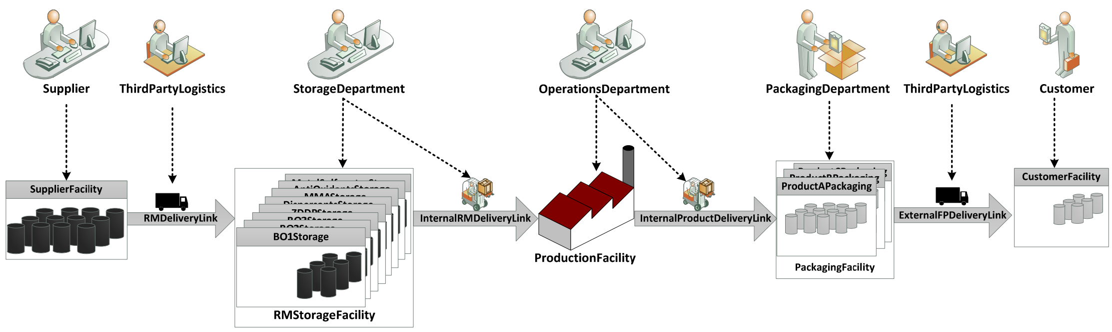


Figure 7.5. Technologies and their relation with Agents in the model

The model of the MPE supply chain has 82 instances of Agent (Table 7.2) for which the related attributes – as mentioned in Table 6.1 –must be defined. Just as examples, Table 7.3 to Table 7.5 show the attributes for MultiPlantEnterprise, ProductionPlant1 and StorageDepartment1. To experiment with the computer model, some of these attributes must be valued before simulation (this will be discussed in more detail in section 7.6). Some other attributes, i.e., operationalProperties and currentActivity, are continuously changing during the simulation runs.

Table 7.2. Instances of Agent in the computer model

Type of Agent	No. of instances
MultiPlantEnterprise	1
ProductionPlant	3
GlobalSalesDepartment	1
SchedulingDepartment	3
OperationsDepartment	3
StorageDepartment	3
ProcurementDepartment	3
LogisticsDepartment	3
PackagingDepartment	3
Customer	50
Supplier	6
ThirdPartyLogistics	3
Total	82

Table 7.3. Attributes of MultiPlantEnterprise Agent

Agent	Attributes		
	Name	value	type
MultiPlantEnterprise	label	"MultiPlantEnterprise"	String
	status	"NormalState"	String
	economicProperties	totalProfit	Property
		totalCost	Property
	operationalProperties	totalProcessedOrders	Property
		totalLateOrders	Property
	outEdges	plant1Ownership	Ownership
		plant2Ownership	Ownership
		plant3Ownership	Ownership
		owningGSD	Ownership
		prodcutPurchasingContract	Contract
	performingActivities	calculateEnterpriseProfit	Activity
		calculateEnterpriseCost	Activity
		calculateTotalLateOrders	Activity
		calculateTotalProcssedOrders	Activity
	ownedComponents	ProductionPlant1	Agent
		ProductionPlant2	Agent
		ProductionPlant3	Agent
		GlobalSalesDepartment	Agent

Table 7.4. Attributes of ProductionPlant1 Agent

Agent	Attributes		
	Name	**value**	**type**
ProductionPlant1	label	"ProductionPlant1"	String
	status	"NormalState"	String
	economicProperties	totalProfit	Property
		totalCost	Property
	physicalProperties	xLocation	Property
		yLocation	Property
	operationalProperties	totalProcessedOrders	Property
		totalLateOrders	Property
	inEdges	plant1Ownership	Ownership
		baseOilContract	Contract
		additiveContract	Contract
	outEdges	departmentOwnership	Ownership
		inTheSameEnterprise	OrganizationalConnection
	performingActivities	calculatePlantProfit	Activity
		calculatePlantCost	Activity
		calculateTotalLateOrders	Activity
		calculateTotalProcssedOrders	Activity
	ownedComponents	SchedulingDepartment1	Agent
		OperationsDepartment1	Agent
		StorageDepartment1	Agent
		ProcurementDepartment1	Agent
		LogisticsDepartment1	Agent
		PackagingDepartment1	Agent

Table 7.5. Attributes of StorageDepartment1 Agent

Agent	Attributes		
	Name	**value**	**type**
StorageDepartment1	label	"StorDepForPlant1"	String
	status	"NormalState"	String
	economicProperties	materialStorageCost	Property
	operationalProperties	currentInventoryLevelForBO	Property
		currentInventoryLevelForAdd	Property
		reorderPoint	Property
		safetyStock	Property
	inEdges	storDep1Ownership	Ownership
	outEdges	storageFacilityOwnership	Ownership
		inTheSamePlant	OrganizationalConnection
	inFlows	rMAvailabilityCheck	Flow
		askForRM	Flow
	outFlows	rMAvailabilityInfo	Flow
		rMOrderSpec	Flow
	performingActivities	checkReorderPoint	Activity
		defineRMOrderSpec	Activity
		receiveRM	Activity
		sendRMForProcessing	Activity
		sendRMAvailabilityInfo	Activity
	currentActivity	Default is “no-Activity”	Activity

Just like Agents, the Technologies in the system must be formalized by defining the instances and their relevant attributes. As examples, BO1Storage and RMDeliveryLink are defined in Table 7.6 and Table 7.7 respectively.

Table 7.6. Attributes of BO1Storage Technology

Technology	Attributes		
	Name	value	type
BO1Storage	label	"BO1StorageForPlant1"	String
	status	"NormalState"	String
	economicProperties	unitStorageCost	Property
	designProperties	storageCapaciity	Property
	operationalProperties	currentLevel	Property

Table 7.7. Attributes of RMDeliveryLink

PhysicalConnection	Attributes		
	Name	value	type
RMDeliveryLink	label	"RMDeliveryLinkForPlant1"	String
	status	"NormalState"	String
	from	SupplierFacility	Technology
	to	RMStorageFacility	Technology
	economicProperties	unitShimpentCost	Property
	designProperties	shipmentCapaciity	Property
		deliveryRate	Property
	operationalProperties	currentLevel	Property
	content	rawMaterialFlow	MaterialFlow

After defining the Agents, the Technologies and their interrelations, the structure of system is ready.[1] Next, we need to define the operational entities in the system and how the dynamic behavior is simulated.

The operation of lube oil supply chain – with the case description of Section 7.1 - is represented in 3 main processes - Figure 7.6. The figure shows the main constructs to describe the operation of lube oil supply chain. These constructs include the Activities that are done by each Agent and the interactions between supply chain entities which are shown by different types of Flows. Some of the Activities have a more detailed logic which is presented in the flowcharts. These flowcharts describe in detail when an Activity must be started, what decisions must be made for that Activity, how those decisions must be made and which aspects of system will be influenced by performing this Activity. For example, the logic behind sendOrderProcessingInfo of order acceptance process is described in flowcharts of Figure 7.7.

[1] As our focus here is on modeling the supply chain at the operational level, we assume that this structure is fixed during simulation.

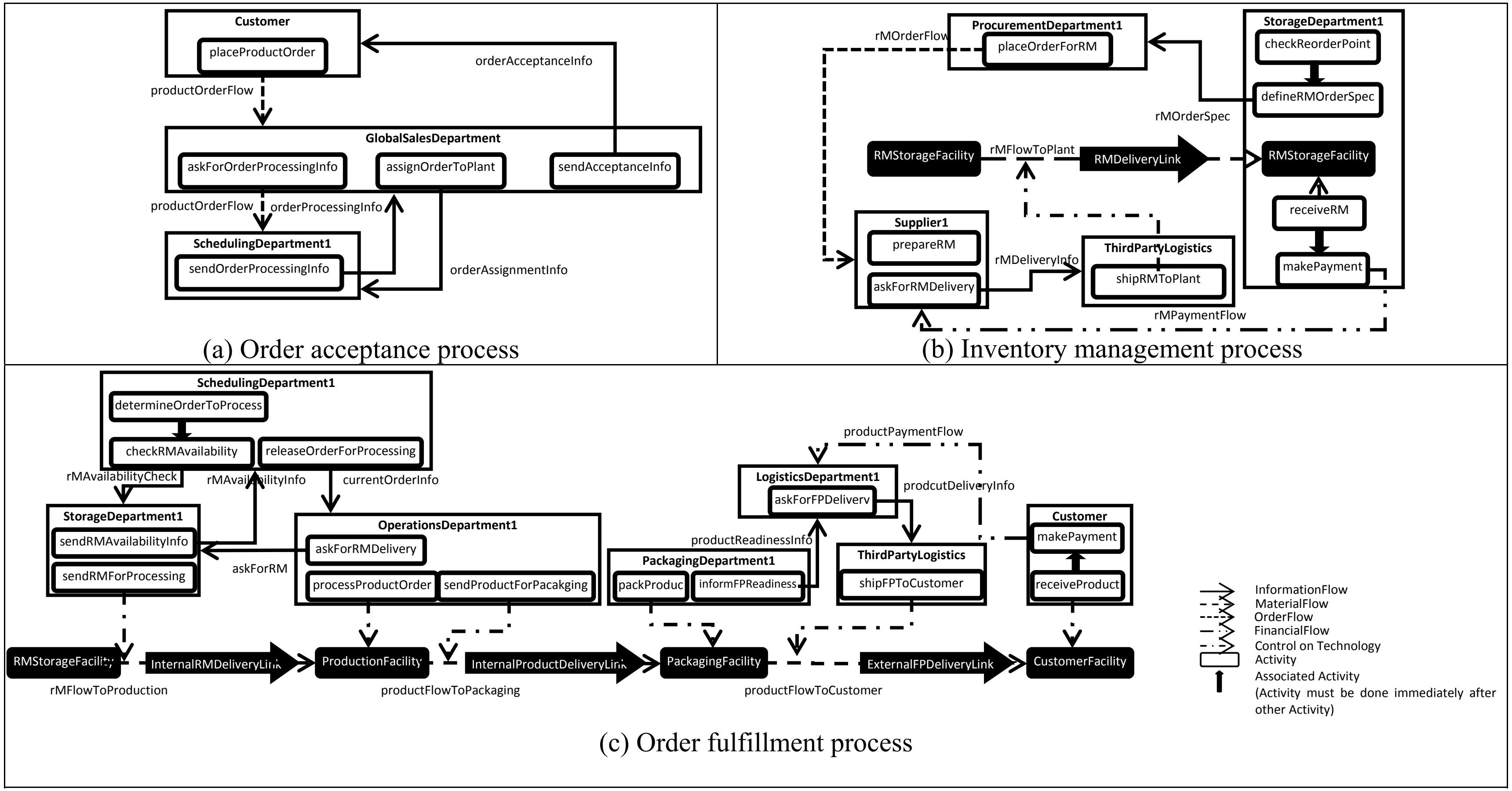


Figure 7.6. Three main processes in supply chain conceptualized in Activities and Flows

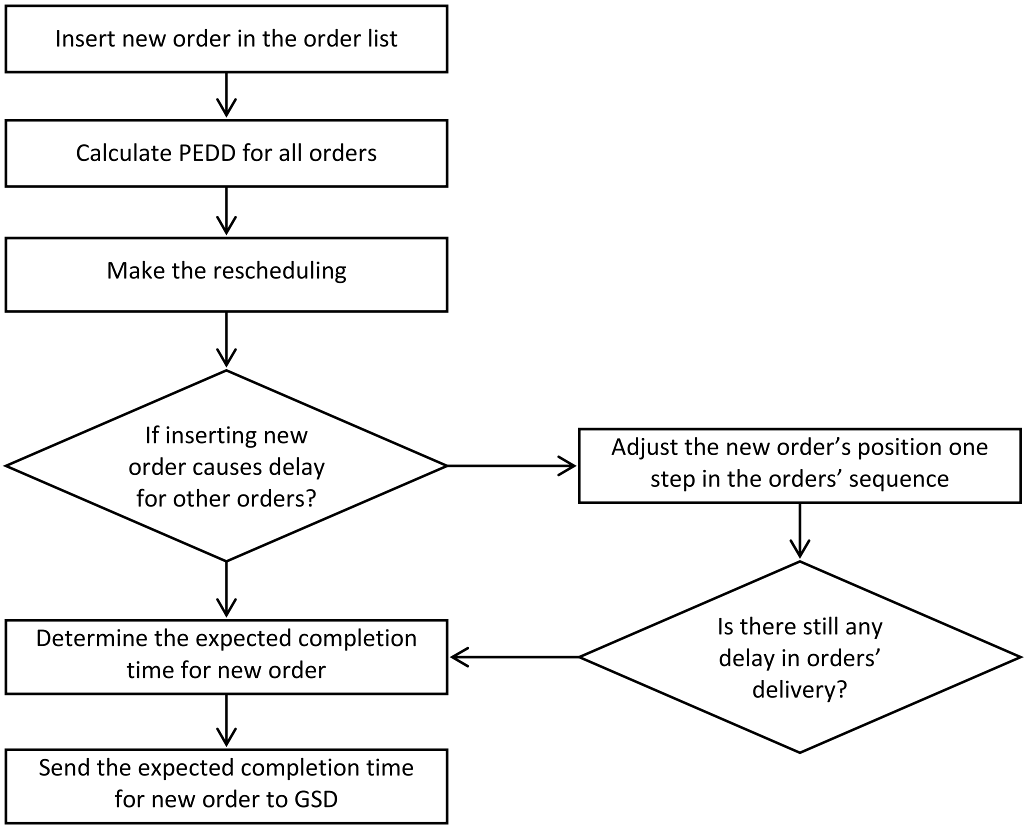


Figure 7.7. Flowchart to describe the logic behind sendOrderProcessingInfo Activity

As system structure and operation are formalized with pre-defined concepts and coded in Java Objects, the next stage is to specify the Environment. In the model of lube oil supply chain, two types of Agents have direct interactions with Environment. Firstly, a physicalConnection is defined between supplier and Environment. Through physicalConnection material flows unlimitedly from Environment to supplier as the level of raw material in the SupplierFacilities goes lower than a specific level. The other interaction with Environment is the flow of information to Customer which is formalized in demandInformationFlow and spotMarketPriceFlow. These two Flows and their application for experimentation with model are described in section 7.7.

7.4. Simulation set-up

As instances from generic objects are created for the specific case of Lube Oil Supply Chain, the computer model is ready. The next steps, is defining the initial value for the attributes of each instance in the model. We call this step *simulation model set-up*. Model set-up also implies making the assumptions explicit for those aspects of the system for which the exact value is not available. The majority of these assumptions are about the downstream supply chain as the precise profile of customers and the order pattern for each individual customer is not known. In fact, as the enterprise is working on a make-to-order basis and the orders are placed by different customers around the world, the exact pattern of orders is not available to use in the simulation. Instead, based on available data, we need to define an order pattern and use that pattern as input for simulation runs. Developing this customer order pattern is done in three main steps.

(1) Defining customer list:

Firstly, we defined a customer list for the enterprise. This customer list describes the characteristics of 50 customers which place the orders with the enterprise.[1] These characteristics include:

- *customerID*: which defines the ID of the Customer.
- *Customer location*: the location of customer is defined by *xLocation* and *yLocation*. To specify the location for each Customer we assumed a world map which resides in a 10 by 10 grid. As such, any location in the model can be represented by the coordinates between (0, 0) to (10, 10). Based on this grid map, we have defined the location for customers of enterprise in the model.
- *orderFrequency*: Besides the xLocation and yLocation, for each customer an orderFrequency parameter is defined which determines the frequency that the orders are sent by this customer. Some of the customers – which are determined by their ID - are important customers which place orders more frequently (in average 4 times more than regular customers). These frequent customers are determined by importantCustomer tag and are given priority when processing the job orders in the plants.

(2) Defining the order specification

As the customer list is defined, the second step is defining the characteristics of orders. The description of each ProductOrder from Customers includes the set of attributes presented in Table 7.8.

[1] The customer list, in fact, reflects the heterogeneity in the downstream of supply chain.

Table 7.8. Attributes of ProductOrder

Concept	Attributes			
	Name	value	type	Description
ProductOrder	label	primitive	String	The tag to be identified by others
	productQuantity	primitive	Float	The amount of material that is ordered
	product Type	instances	Good	The order can be for one of 3 Products A, B or C
	productGrade	primitive	String	Each Product can have grade from 1 to 5 which defines a specific recipe for the production
	placingCustomer	instance	Agent	The Customer who places this order
	fulfillingActor	instance	Agent	The ProductionPlant which fulfills this order
	timingConditions	dateOfOrderPlacement	Property	The date of placing order by Customer
		earliestDueDate	Property	EarliestDueDate is the first possible date that order must be received by Customer; it is assumed as “dateOfOrderPlacement” + [14 ~ 21] days
		latestDueDate	Property	LatestDueDate is the last acceptable date for order delivery for a Customer; it is assumed as “earliestDueDate” + [1 ~ 14] days
	operationalConditions	packagingType	Property	Tht type of pacakaging for fininshed product which can be "Drum" or"Isotank"
		pickupType	Property	There are two options for finshed product delivery: "Customer Pick up" or "Sent by the plant"
	fulfillmentState	primitive	String	Determines the state of an Order which can be "fulfilled", "pending" or "cancelled"
	fulfillmentProperties	dateOfFulfillment	Property	The time that order is delievred at cutomer place
		ifdelayedOrder	Property	Determines if order is delayed

For each ProductOrder some of these attributes (i.e., packagingType and pickupType) are defined by a uniform random function. For example, on average, 50 percent of orders are delivered to customers by the plant and for other orders the customer itself is responsible for order pickup after finishing. Defining productQuantity, productType and dateOfOrderPlacement is, however, a more complicated task and is done based on the procedure that is described in (Wong, 2007) and Adhitya and Srinivasan (2010). The input to this procedure is the yearly demand pattern for each product. For this purpose, based on the history of demand and the expectation of the sales department, an estimated demand curve is generated for each product type for a time span of one year (Figure 7.8). This curve is increasing in slope which implies an increasing demand for the products during one year. The demand curves are next translated to discrete orders for each product in several steps (Figure 7.9). Firstly, the curves are divided into 30-day periods and the daily demandsfor a particular period is summed up to determine the cumulative monthly demand ($MD_{p,m}$; “p” is the index for each product and “m” is the index for each month). Next, each monthly demand is redistributed throughout the days in the month according to the order frequency index f_p, representing the probability of a customer order on a given day for product p, where $0 \leq f_p \leq 1$. We assume that, on each day, there can be at most one order for each product type. The higher the f_p value, the more frequent the orders for product “p” throughout the month. To check the order placement on a particular day, a uniform [0, 1] random variable, $\mu_{p,d}$, is generated for every day in the month and compared to f_p:

$$OP_{p,d} = \begin{cases} 1 & \mu_{p,d} \leq f_p \\ 0 & \mu_{p,d} > f_p \end{cases} \tag{7.1}$$

$OP_{p,d}$ is the binary parameter which determines whether an order is placed for product “p” on day “d”. The demand amount following an order occurrence is next generated as:

$$DD_{p,d} = \frac{OP_{p,d}}{\sum_{d=30(m-1)+1}^{30m} OP_{p,d}} MD_{p,m} \tag{7.2}$$

for each month “m”. For each product “p”, $DD_{p,d}$ is the portion of monthly demand ($MD_{p,d}$) that is placed on day “d”. Because this value might be unreasonably low or high, we limit the minimum and maximum order size with the following equation:

$$AD_{p,d} = \begin{cases} 0 & DD_{p,d} < D_{\min} \\ DD_{p,d} & D_{\min} \leq DD_{p,d} \leq D_{\max} \\ D_{\max} & DD_{p,d} > D_{\max} \end{cases} \tag{7.3}$$

$AD_{p,d}$ is the actual demand for product "p" on day "d" after accounting for the minimum and maximum order size limits, (i.e., D_{min} and D_{max}). If $AD_{p,d} > 0$, then a customer order will be created for which:

dateOfOrderPlacement = d

productQuantity = $AD_{p,d}$

productType = p

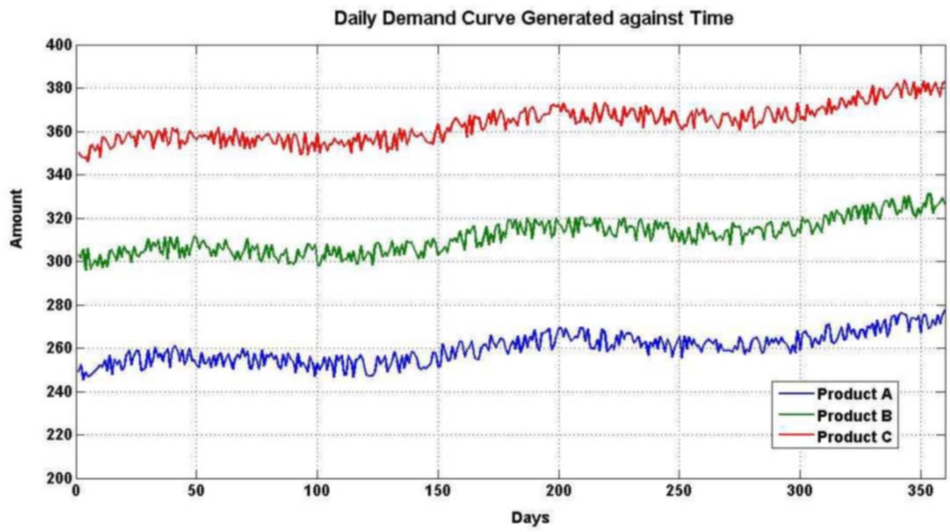


Figure 7.8. Demand curve for different products (Siang, 2008)

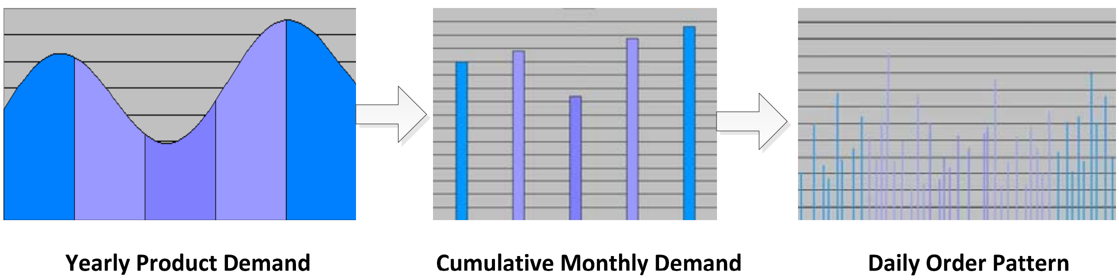


Figure 7.9. The procedure to define the order quantity

When the dateOfOrderPlacement is determined, the due date range[1] is also defined by a uniform random function in the range shown in Table 7.8.

(3) Assigning orders to customers

[1] The Due Date Range is the window when the final products have to reach the customer's location, regardless of whether the products are picked up by the customer or sent by the plant. This window is defined by earliestDueDate and latestDueDate for each Order.

The final step to define the order placement pattern is assigning one customer from customer list to each of generated orders. This is done based on the orderFrequency of Customers in the list.

With these three steps an order pattern is created before simulation starts. In this order pattern, it is specified for every day which customer places an order for which product. During simulation time, every day, each Customer agent checks if it must place an order in that specific day – based on the dateOfOrderPlacement for each order. If so, it sends the order specification with ProductOrder Flow to GSD.

Table 7.9. Nominal Values and assumptions for model start-up

Aspect of enterprise	Assumption
Plant location	Any location of customers, suppliers and plants can be represented by coordinates between (0, 0) to (10, 10) on 10×10 grid map
	The location of the three plants is (2, 4), (9, 4) and (8, 7)
Plant operation	Only one order can be processed at a particular time. Processing time per unit product (days) are 0.005, 0.002, 0.003 for product A to C. Multiple orders can be packaged and delivered at the same time. Two types of packaging are possible: "drum" for which packaging size is 100 and "iso-tank" for which packaging size is 500. Packaging time per package for is 0.1 package/day.
Products and feedstock	There are three lubricant product types (A, B and C) with five different grades for each product which is produced from 3 base oils and 5 other additives based on a particular recipe.
	The maximum capacity for base oils is 2500 units and for other raw materials are 500 units.
Customers and orders	There are 50 customers around the world; 6 of them are important customers. Customers generate orders.
	The frequency index (f_P) for products A to C is assumed 0.3, 0.4 and 0.55 respectively for the nominal case.
	On average, 50 percent of orders are sent by plant to customers and for other orders, the customer itself is responsible for order pickup after finishing
Economics of enterprise	Following assumptions about the financial aspects of enterprise are made: Product price ($/unit): [100 110 120 130 140; 200 210 220 230 240; 300 310 320 330 340] raw material price ($/unit): [Additives: 30 60 90 70 50; Base oils: 35 130 255] fixed operating cost ($/day): 2000 raw material inventory cost [$/(unit day)]: 1 delivery cost {$/[unit(unit distance)]}: 5

Finally, it must be emphasized that to avoid simulation to start empty (no order is assigned to plants), a random queue of orders must be considered for each plant in MPE. Other assumptions and initial values for parameters in the model are presented in Table 7.9. These values are used to define the initial values for attributes of each instance in the model. With these initial values, the simulation model is ready to run and experiment. For experimentation with the model in some cases, however, certain parameters will be changed as will be discussed in section 7.6.

7.5. Validation and verification

The developed computer model must be verified and validated through a set of preliminary experiments before conducting the experiments to examine the impact of different factors on the operation of supply chain.[1] The verification and validation tests [2] are, however, not limited to the initial version of model; in all steps of simulation whenever changes in the model are made, verification and validation must be done before defining the experiments and analyzing the experiment results.

- **Verification:**

Verification is the process of ensuring that the model behaves as intended: whether the concepts and relations are coded correctly in the computer model (Balci, 1994). There could be different types of test in this stage. To facilitate the verification process for a computer model it is important to check if the model:

1. *is well-written and readable*. Developing a readable model is extremely helpful in finding the source of probable errors. Also, a readable model can be used easily either by others who may join the model development later or by the client who is going to use the model. During the development of the model, we should always bear in mind to make clear, understandable documentation for each part of the code. Choosing proper names for the attributes and methods is another way to make the model easily understandable

2. *behaves properly in extreme conditions*. The Extreme-Conditions Tests can be used to check the sub-models (e.g., each agent's behavior) and the model of system as a whole. In these tests – in which selected parameters have extreme input values, such as zero or very large values – the model should behave according to our expectations.

3. *does what it is supposed to do*. For this purpose, debugging should be performed. This could be done by using a simple System.out.println() method or by more advanced debuggers in Java. In the Eclipse integrated development environment which is used for developing Java codes in this thesis, the Java program can be run

[1] The main purpose of model testing is to build confidence in the model. However, no model can be a "fully-validated model". It is generally possible only to prove the model is not wrong for the situations compared and a detailed validation/verification solely increases the confidence, but prove nothing! In the words of Quade (1980), "a particularly dangerous myth is the belief that a policy model can be fully validated—that is, proved correct. Such models, at best, can be invalidated." or North and Macal (2007): "no model using ABMS or any other computational technique will ever be fully validated. A high degree of statistical certainty is all that can be realized for any model using ABMS."

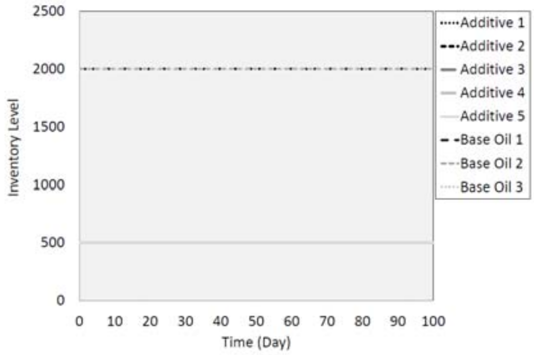
[2] A good review of verifications and validation methods is described in van Dom et al. (2012).

in the "Debug mode". In this mode, a modeler can set *breakpoints* in the Java code at which the execution of the Java code will stop. Subsequently, it allows a modeler to run the program interactively, watch the source code and examine the value for model variables during the execution of the simulation.

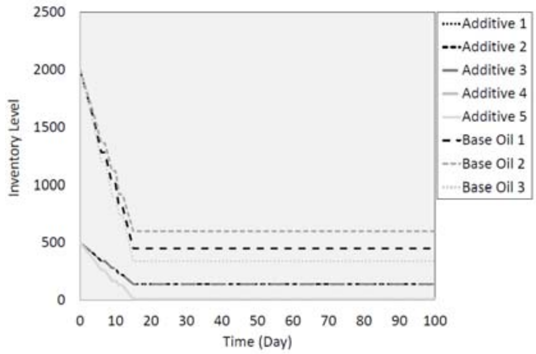
During the development of the computer model for the lube oil supply chain case, all these tests were performed. The attempt was to choose clear names, make simple documentation for each method used and provide explanation for the methods. Documentation also involves the purpose and assumptions used in the method.

Several extreme value tests are also done with the model. Some hypotheses were made, and the model has been checked whether it provides the expected results. To show the results of the model under these extreme cases, Figure 7.10 represents the inventory levels of different raw materials for the production plant 1:

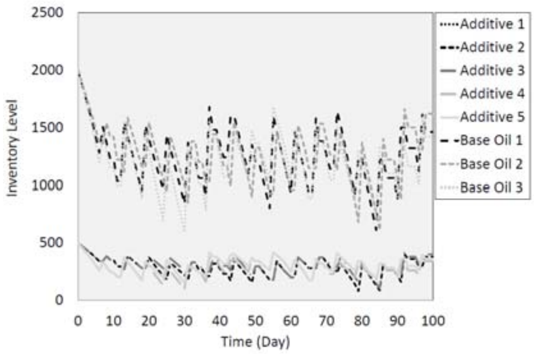
- The test related to Figure 7.10-a was conducted with the assumption of no consumer orders for the duration of the simulation. So, as we expected, the inventory level for raw materials is unaltered. The other two production plants produced similar results.
- In Figure 7.10-b, we set the reorder amount to zero. The results show that the production plant will use its initial raw material in the storage facilities, but as there is no replenishment, the raw material level will be zero for the rest of simulation time.
- Figure 7.10-c shows a case in which the reorder point is set to 0.9; i.e. when the raw material inventory level falls below 90 percent of storage capacity, a new raw material order is placed. The expected result is frequent raw material orders, and this is confirmed in the figure.
- Figure 7.10-d shows the results of a test similar to the previous case but with immediate raw material delivery (the raw material delivery time is set to zero). Again, the model behaves as expected and the stock is always near maximum capacity.



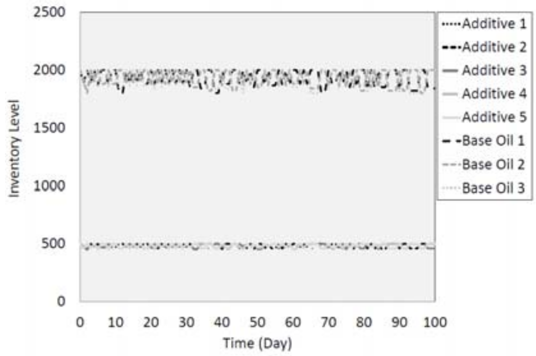
(a)



(b)



(c)



(d)

Figure 7.10. Model behavior under different extreme condition tests

Similar tests can be done by using extreme values for other parameters (e.g. order processing time, storage capacity or plant availability) to study whether those factors have the expected effect on the model outcomes.

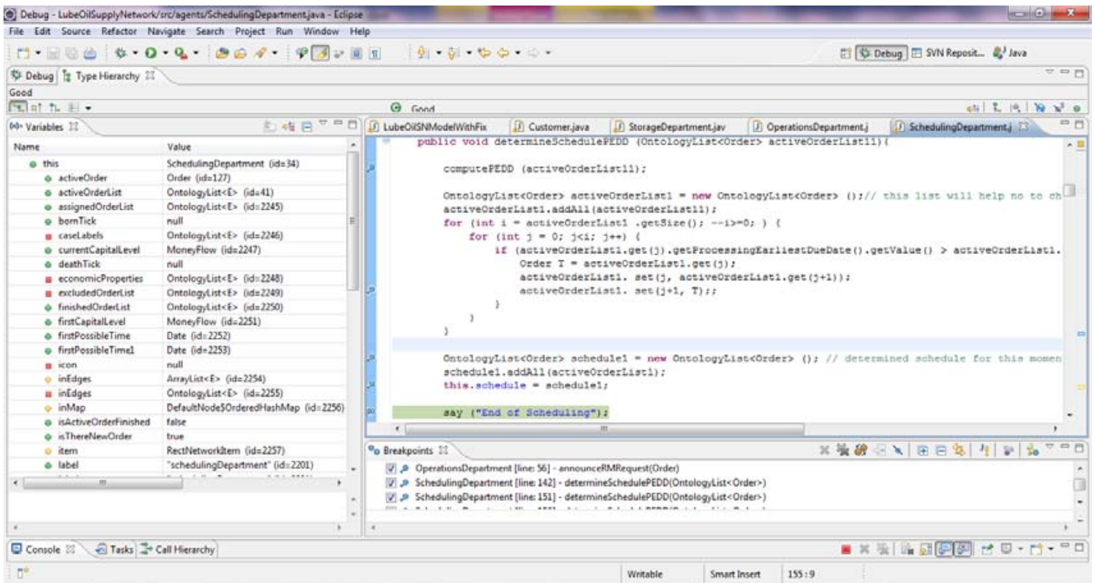


Figure 7.11. A debugging example in Eclipse

Finally, after any change has been made in the model, the formulas and methods are individually checked by debugging mode in Eclipse. Debugging allowed us to step through code, freeze output, and inspect variables. Figure 7.11 shows an example of debugging in which, the method of *determineSchedulePEDD* is checked line by line. The return value of the method is the schedule of orders for the plant.

- **Validation:**

After the model is checked in terms of consistency and we ensure that no errors have been made in representing the model in computer codes, a series of tests should be performed to validate the model. The validation in the modeling literature usually conveys two different meanings. Firstly, validation ensures that no significant difference exists between the model and the real system (Balci, 1994). Additionally, the validation of a model must show it is *fit for its purpose* and meets the objective of the modeling study (the usability of the model).

Validation of an agent-based model with the first view is a challenging process. The key caveat, in fact, is the effect of complexity and non-linear relationships in the model which can generate complex and often surprising results (Manson, 2002). Therefore, if there is an inconsistency between the model results and the reality, there is no straightforward procedure to check whether it is because of logical errors in the model development process or created by chaotic behavior of a complex system (Manson, 2002). Nonetheless, the outcome of an agent-based model must be evaluated and approved by the greatest possible number of benchmarks. For this purpose, use of multiple complementary methods is recommended by literature to provide confidence in an agent-based model's outcomes (Siebers et al., 2010). The most common, practical and readily-available validation method for agent-based models is expert validation in which the behavior of agents (micro-level) and the patterns of behavior of system (macro-level) are shared with domain experts. Such expert evaluation occurs in the model development, model testing and also model experimentation. More specifically, the following steps are followed to check the validity of models in our work:

- *Validation of conceptual model*: the conceptual model – as presented in Chapter 6 – has been developed in an iterative process. First a generic conceptual model for a supply chain was developed. Then, the negotiation among actors was conceptualized and put in the model. Finally, the disruption and disruption management practices are formalized. These steps are in fact in line with the experiments that are presented in sections 7.7 to 7.10. In each step, after the concepts have been extracted and formalized, the conceptual model has been discussed and evaluated by experts in supply chain (modeling) domain. The conceptual model was next encoded in Java to have generic modeling objects.

- *Validation of computer model for specific case*: to develop the computer model for specific case of lube oil supply chain, the instances from generic objects are created. This computer model is also shared with experts to see if current conceptual model can capture the description of lube oil case. If needed, the conceptual model was improved or additional instances from existing generic objects were defined.

- *Evaluation of simulation results*: after running the computer model, the simulation results were also evaluated and discussed with experts. In addition, the procedure discussed in last subsection - in which some hypotheses were defined and the simulation results were tested to compare with expectations- were done after each change in the computer model. The results were also discussed with experts to see their implications for decision-making in lube oil supply chain.

As the second view on validation, the major concern is to ensure that the model is *fit for its purpose*. This view is principally based on the idea that a(n agent-based) model is not necessarily created for prediction purposes but it is developed for the purpose of exploration of different possible designs for the system. According to Balci (1994), in the modeling effort, we must show the relevance of the model for the study objective that it was developed for. Hence, the main concern would be to become sure that the model is applicable for its domain and can help better understanding of the problem under study. This application relevance can be shown by different experiments performed with the model and getting insight about, e.g. the behavior of the system. A series of experiments in the following sections of this chapter shows that the developed model is *fit for its purpose*. Different settings for different parts of supply chain are designed and implemented in the model in order to evaluate the performance of the enterprise and get insight about different operational strategies in the lube oil supply chain. Meanwhile, the model application for different steps of disruption management process is illustrated with several experiments in this chapter.

As a last point, it must be emphasized that the verification and validation of a model is a continuous process, not a single test at the start of experimentation with the model. In fact, in all steps of simulation whenever the changes in the model are done the set of above-mentioned verification and validation tests must be used to find the possible errors and check if the model is useful and convincing.

7.6. Experimental set-up

Once the computer model is ready and tested, it must be used for examining the performance of alternative system configurations and/or alternative operating procedures for a system.

Through experimentation with the model we can obtain a better insight into the nature of dynamic behavior of supply chain and find solutions to the problems in a supply chain. The experimentation with model consists of three main stages (Robinson and Bhatia, 1995; Law and Kelton, 2007):

- Designing the experiments
- Performing the experiments
- Analyzing the results

In each of these three steps, several issues have to be considered as discussed in the following.

(1) Designing the experiments:

To clearly define an experiment some specific parts must be determined:

-Defining the Goal of experiment:

The main goal of simulation is to support the actors in making better-informed decisions and solving complex problems which are not possible to solve by simple calculations or solely based on the experience. Each of these decisions or problems can be considered as the goal of designing a specific experiment. In other words, the objective of experiment is answering the following questions:

- What is the specific problem in the enterprise that needs to be solved?
- What is the lack of insight that we aim to address by simulation?

For instance, in the experiment of section 7.7 the goal is making decision about the inventory aspects in the enterprise.

-Defining the input/output of experiment:

As mentioned earlier in the section 5.3, in each experiment a set of changes in the structure or parameters in the system are considered as the input of experiment. In the classical experimental design terminology, each of these changes is called a *factor*. Each factor in the experiment design can take one or more values (or levels). For example, to study the inventory management process in section 7.7, we experiment with two main factors: (1) different suppliers with different delivery lead time and (2) different raw material ordering policy by storage department. Each of these two factors can get several levels as shown in Table 7.10. For example, the ordering policy can be *reorder point policy* or *fixed interval policy*. By different combinations of factors, we can design different experiment runs to study the impact on some specific performance measures– i.e., outputs. To illustrate, all possible combinations of factor levels for inventory management case are presented in 8 experiment runs as shown in Table 7.11.

Based on the model for supply chain described in section 6.3, the input of the experiment design can be:

1- **Structural changes** in the system which include:

- Defining new entities or removing some entities
- Defining new properties for current entities

2- **Behavioral changes** in the system which might be:

- Defining new set of Activities for Agents
- Defining new logic for current Activities

For example, in the case of inventory management process, the first experimental factor – i.e., working with different suppliers with different characteristics- is a structural change in the system while the second factor – i.e., using different raw material ordering policy by storage department- is basically a behavioral change.

As input for each experiment run is defined, we must determine the *output*[1]. The output of experiment is the desired performance indicators for the system. These are, in fact, the important aspects of system performance that form the basis for decision-making for the problem owner. All experiments of this chapter are originally designed to study the influence of different alterations on the performance of the enterprise as a whole. In general, this performance can be analyzed in terms of customer service level (e.g.,

[1] In the classical experimental design terminology, the term *response* is used to describe the output of the experiment.

tardiness and number of late orders), financial aspects (e.g., profit and overall operational cost) or a combination of both. The specific performance indicators considered here are "Number of late orders" and "profit". It should be stressed that the flexibility of modeling framework guarantees an easy extension of the performance indicators in case that additional analysis is necessary. Meanwhile, the simulation can produce numerical outputs for different entities in the system. For instance, the profit or number of late orders for each production plant can be separately reported and analyzed through experimentation phase.

- *Defining the time-frame of experiment:*

The other important issue in the experiment design is deciding on how long a simulation run must be (Robinson and Bhatia, 1995; Kelton, 2000). Based on this issue, two classes of simulations are frequently discussed in the literature. Sometimes there is a natural or obvious termination point which is set by system or problem characteristics (terminating simulation); for instance, a shop closes at the end of day at 10 P.M. In such a case, there is no question about starting and ending the simulation experiments. There is however a second type of simulations which have no such a clear terminating point (non-terminating simulation). In this case, the main interest is in the long-run behavior of the system and accordingly, sometimes they are termed "infinite-horizon or steady-state simulation" (Kelton, 2000). For non-terminating simulation the basic rule is the longer the run, the better (Robinson and Bhatia, 1995).

The type of simulations which are presented in this section belongs to the first class. This is primarily because the decisions which are tested (as input of simulation experiments) here are mostly in the tactical/operational level of supply chain; therefore, the time horizon of simulation is also defined by these tactical/operational issues. More specifically, because the contracts of the enterprise with its suppliers and customers are mostly signed for one year, the simulation horizon in the majority of experiments of this chapter is also one year.

(2) Performing the experiments:

Based on the factors we identified in the previous step, we can define different runs of experiments. Each run of experiment simulates a specific setting for input and analyzes the impact on the output. The results of an experiment run, however, can be impacted because of randomness in the model. Meanwhile, the starting conditions can be different (as discussed in section 7.4). Therefore, every experiment with the model should be carried out several times and then the results of the individual trials averaged together. A single run of simulation in each experimental set-up of model is a replication. Performing multiple replications is basically a means to increase the sample size for the results collected and so improving confidence on the decision support tool. There is no generally-accepted method to define the number of replications for each experiment run. As a general rule, an experiment should be repeated with different random numbers as many times as it is convenient and practical to do so. In our case of multi-plant supply chain, we repeat each experiment run for 50 times. Considering that each replication of simulation – with the setting that are discussed in sections 7.3.1 and 7.3.2 - takes about 3 to 4 minutes on a single desktop computer (with Intel CPU of 3.16 GHz and RAM of 4 GB), the execution time for each experiment run is approximately three hours (which seems an acceptable execution time).

(3) Analyzing the results:

After conducting the experiments, the results need to be analyzed to find the answer for the deriving question that initially motivated the design of experiment. This analysis consists of two main steps. Firstly, the multiple replications for each run of experiment must be studied by statistical techniques. For this purpose, for each run of experiment the "mean value" – i.e., the average of all replications for an experiment run- and the "standard deviation" - which defines the variation of results for that experiment runs from the mean value - are calculated.

The second step is analyzing the mean values for different runs of experiments. In analyzing and comparing the result of different experiments, we would like to know about the effect of each factor on the performance of system (*main effect* of each factor) and how combinations of several factors might influence the output of simulation (Kelton, 2000).

After analyzing the results of experiment runs, it may be necessary to go back to the first step of experimentation to redesign the experiments taking into account the insight gained so far. There might be new important factors that are identified and call for further experimentation. Moreover, some new possible levels for current factors (e.g., new inventory control policy in inventory management experiment of section 7.7) might be necessary to test. There can be also new performance measures of interest which can be considered as output in designing new experiments.

7.7. Model application for normal operation of supply chain

In this section, the experiment design to support decision-making in different processes in the supply chain is discussed. The first experiment is focused on inventory management process and the important factors to improve this process are studied. The second experiment is about order acceptance process. Different aspects related to this process are discussed and experimented with simulation model.

7.7.1. Experiment set-up 1: inventory management in MPE supply chain[1]

One important process in each production plant is managing raw material inventory. This is a complicated task because the inventory-related issues may impact the cost and revenue – and subsequently, the profit – of company in many different ways. A schematic causal relation for these effects is shown in Figure 7.12. At the tactical level, an important issue is "supplier selection" and "supplier characteristics". Two important features of each supplier that impact the performance of company are supplier lead time and the price of raw material. At the operational level, the inventory management process is mainly impacted by selection of "inventory management policy". This policy determines when an order for raw material must be placed and how much of raw material must be asked for. As can be seen in Figure 7.12, all these factors can influence each other and the financial performance of company which makes the decision-making more complex.[2] Meanwhile, no general recommendation about ordering policy or supplier selection can be made for a complex supply chain like lube oil case. Instead, the experiments must be designed to see what setting can lead to more improvement in the performance of system.

[1] The experiment design and results presented here are partly based Behdani et al. (2010a) – title: "Performance analysis of a multi-plant specialty chemical manufacturing enterprise using an agent-based model" and Behdani et al. (2010c) – title: "Agent-based Modeling to Support Operations Management in a Multi-plant Enterprise".

[2] It must be emphasized that Figure 7.12 shows some of causal relations and more factors can be found in the literature or based on the experience for specific cases. Regardless of this issue, this figure gives an overall feeling how complicated decision making on inventory management is.

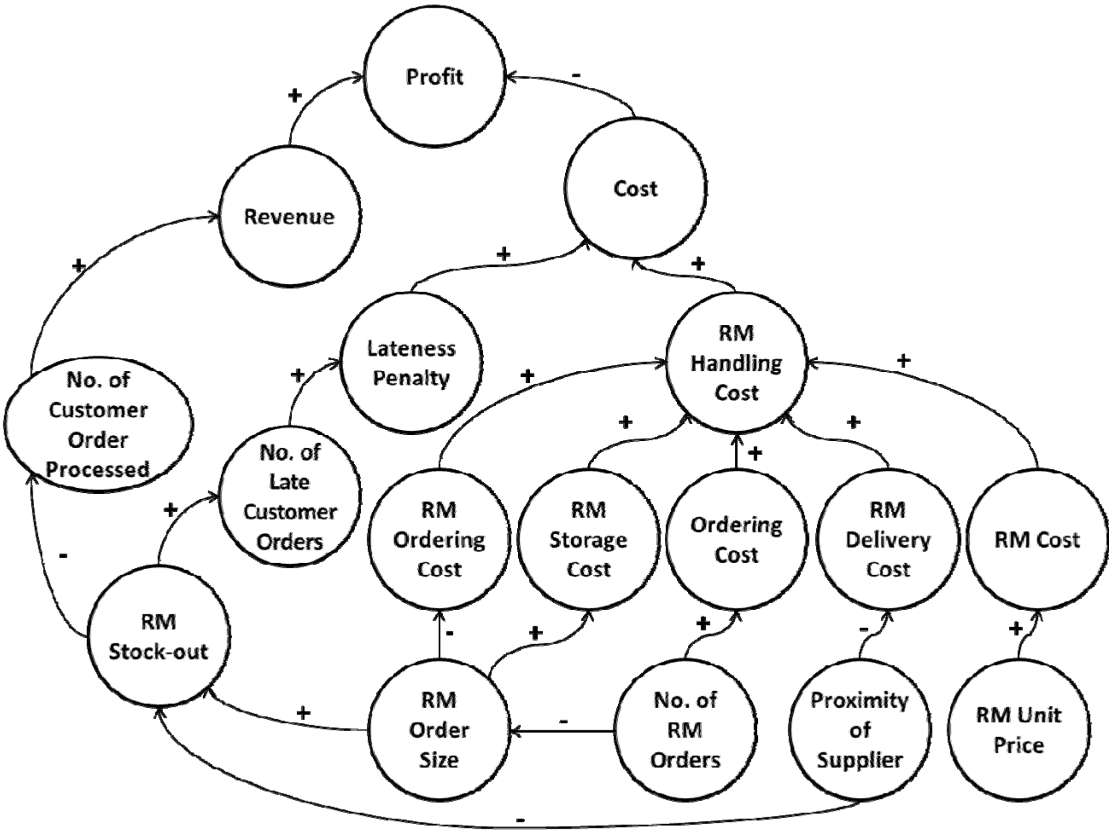


Figure 7.12. Schematic of causal relations in inventory management process

In this section, two above-mentioned factors are used for experiment design – i.e., supplier features and inventory control policy. For inventory control policy, the company can select between two policies: the reorder point policy or (s, S) policy in which as inventory level reaches a specified reorder point, "s", sufficient units are ordered to bring up the inventory to a pre-determined level "S" (Wisner et al., 2009) and fixed interval procurement policy or (R, S) in which the procurement department places orders for each raw material at every fixed interval "R" to a pre-defined top level point "S" (Tarim and Kingsman, 2006). As can be seen, each of these two policies is defined by some parameters. For reorder point policy the reorder point is the determining factor; for example, the reorder point can be on 25% or 40% of capacity of storage tanks. The top-up-to level parameter – i.e., "S" – is also set as the maximum capacity of storage tanks. For fixed interval policy the main parameters are the interval length and the top level point; for example, the new order can be placed every 10 days to increase the raw material order to 50% of storage tanks or every 20 days to increase the raw material level to 100% of storage tank.

The second experimental factor is supplier characteristics. Similarly, different levels can be defined for supplier features. In the experiment design of this section, we assume that two options for supplier lead time are available. A global supplier with delivery time of 7 days and a local supplier with delivery time of 4 days but with 25% higher unit price for raw material. These factors and levels that are used for the design of experiment are summarized in Table 7.10.[1]

Table 7.10. Experimental factors and their level for inventory management process

Experimental Factor	Levels			
Inventory management policy	(s, S) policy with s = 25%	(s, S) policy with s = 40%	(R, S) policy with R = 10 days and S = 50%	(R, S) policy with R = 20 days and S = 100%
Supplier lead time	7 days	4 days (with 25 % higher RM price)		

Based on the combination of different factors, 8 different experiment runs are defined and performed by model (Table 7.11). The objective of these experiments was to evaluate the effect on two performance measures: profit of enterprise and number of late customer orders. The simulation results for these experiments are presented in Table 7.12. The results of this table for each experiment run are the average of 50 replications for that experimental set-up. For each of replications a different demand pattern is defined according to the method we previously discussed in section 7.3.

Table 7.11. Different experiment set-ups for inventory management process

Experiment run	Inventory management policy	Supplier lead time
1	(s, S) policy, s = 25%	7 days
2	(s, S) policy, s = 40%	7 days
3	(R, S) policy, R = 10 days, S = 50%	7 days
4	(R, S) policy, R = 20 days, S = 100%	7 days
5	(s, S) policy, s = 25%	4 days
6	(s, S) policy, s = 40%	4 days
7	(R, S) policy, R = 10 days, S = 50%	4 days
8	(R, S) policy, R = 20 days, S = 100%	4 days

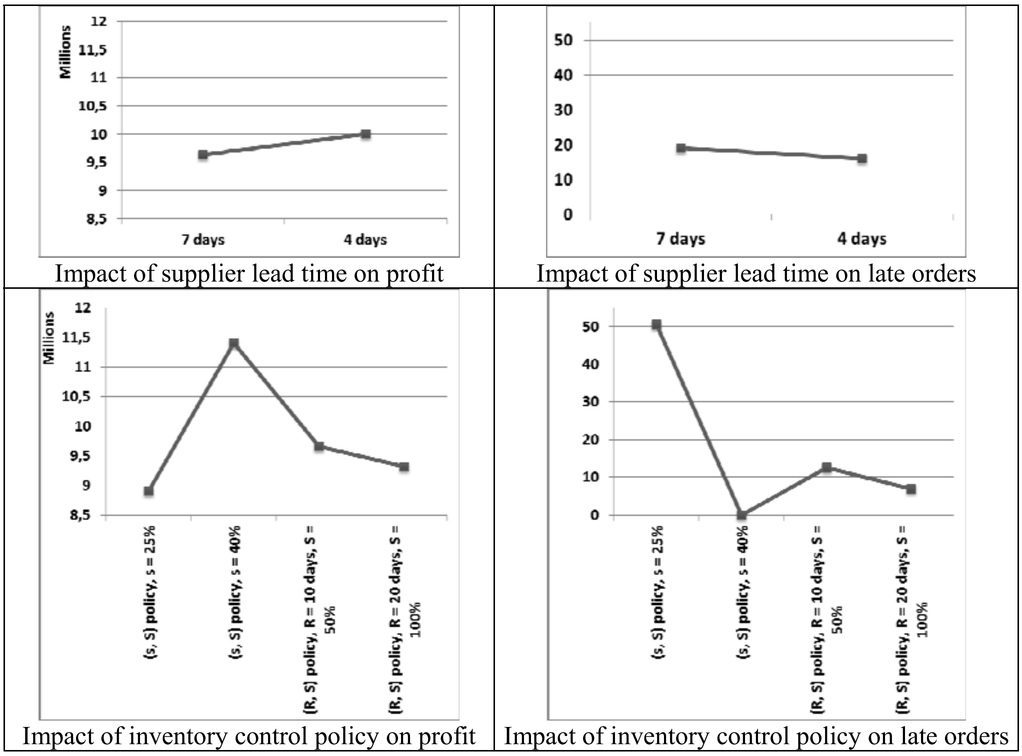
[1] Note that the simulation model user can easily define a different set of experiments be changing the level for each experimental factor (e.g., different reorder points or different supplier lead time)

Table 7.12. Results of experiments[1] for inventory management process

Experiment run	Number of Late orders	Profit of Enterprise (m$)
1	54	8.56
2	0	11.15
3	8	9.26
4	14	9.56
5	47	9.23
6	0	11.65
7	6	9.36
8	11	9.75

The results of Table 7.12 are used to evaluate the impact of different factors on the performance of enterprise. To better understand this impact, the main effect of each factor is plotted in Figure 7.13. The main effect for each factor is the average change in the output (i.e., profit and number of late orders) when that factor moves between its possible levels. For example, to evaluate the main effect for supplier delivery time the average value for first four rows in Table 7.11 (for which delivery time is set to 7 days) are compared with the average value for last four rows (for which the supplier lead time is 4 days). Analyzing the main effects of Figure 7.13 can give us several conclusions about the case. Firstly, it shows that supplier lead time, in general, cannot be considered as important factor as inventory control policy in this case – although two factors are not completely independent as shown in Figure 7.14. Therefore, setting an appropriate inventory control policy must be regarded as the main factor in improving the inventory management process. The second obvious conclusion is that (s, S) policy with s = 40% performs better than other policies both regarding the profit of enterprise and also the number of late orders. Based on these two observations, in the following we are going to focus on (s, S) policy and define more experiment runs to tune the reorder point for the inventory management process. As a last observation, it must be noted that in some cases there is a trade-off between two performance measures. For example, for (R, S) policy moving from (10, 50%) setting to (20, 100%) setting, the overall profit of enterprise decreases. This is because with (10, 50%) policy, the average raw material in the storage tanks is lower and subsequently the inventory cost will be less. On the other hand, the number of late orders with (20, 100%) policy is less as a result of higher inventory and fewer stock-out situation in the production plants.

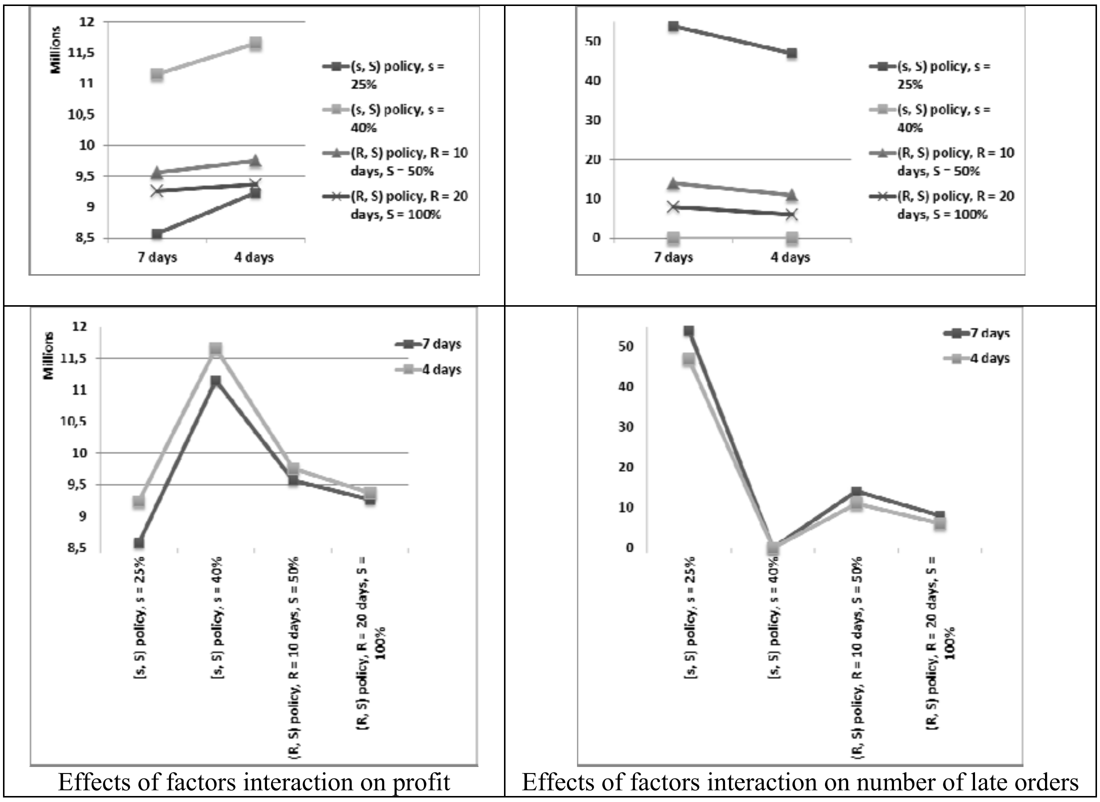
[1] In all experiments of this chapter, the results that are presented in Tables and Figures are the “mean” value for multiple replications of one experiment run unless otherwise is stated.



Impact of supplier lead time on profit | Impact of supplier lead time on late orders

Impact of inventory control policy on profit | Impact of inventory control policy on late orders

Figure 7.13. Impact of different factors on performance of enterprise



Effects of factors interaction on profit | Effects of factors interaction on number of late orders

Figure 7.14. Effects of factors interaction on performance of enterprise

As mentioned before, we continue experimentation with (s, S) policy to check different reorder points ("s") and get an insight into the appropriate level for this parameter. For this analysis we focus on the operational performance and the impact of reorder point on customer order delivery performance. Figure 7.15 shows the effect of changing the reorder point on the enterprise-level performance. As the reorder value increases, the overall performance of the enterprise improves in terms of number of late orders and also total tardiness; since without raw material, the operation department must pause the execution of an order and wait to receive the raw materials from the supplier. This causes delay in fulfilling customer orders that are assigned to that production plant. Generally speaking, with a higher reorder point the raw material availability can be a less important bottleneck for the production plant. Figure 7.15 also suggests considering a reorder point between 34 and 36 percent can be an appropriate set point for this case. This is because this range of reorder point is the first reorder value at which both total tardiness and number of late orders are zero; all customer orders are fulfilled here without any delay. Meanwhile, selecting a higher reorder point will increase the raw material holding cost and subsequently decreases the profit for enterprise.

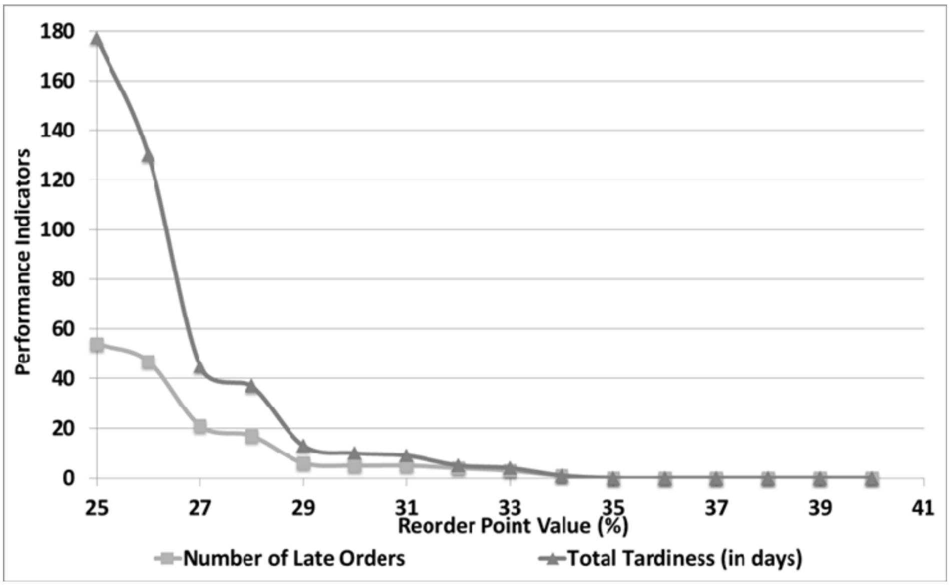


Figure 7.15. The effect of reorder value on operational performance of supply chain

Based on the case descriptions of section 7.2, a System Dynamics (SD) model is also developed for similar multi-plant enterprise (Mussa, 2009). With this SD model, we aimed to compare our agent-based model with a system dynamics representation of the same system. To compare two modeling approaches[1], we have used three following criteria:

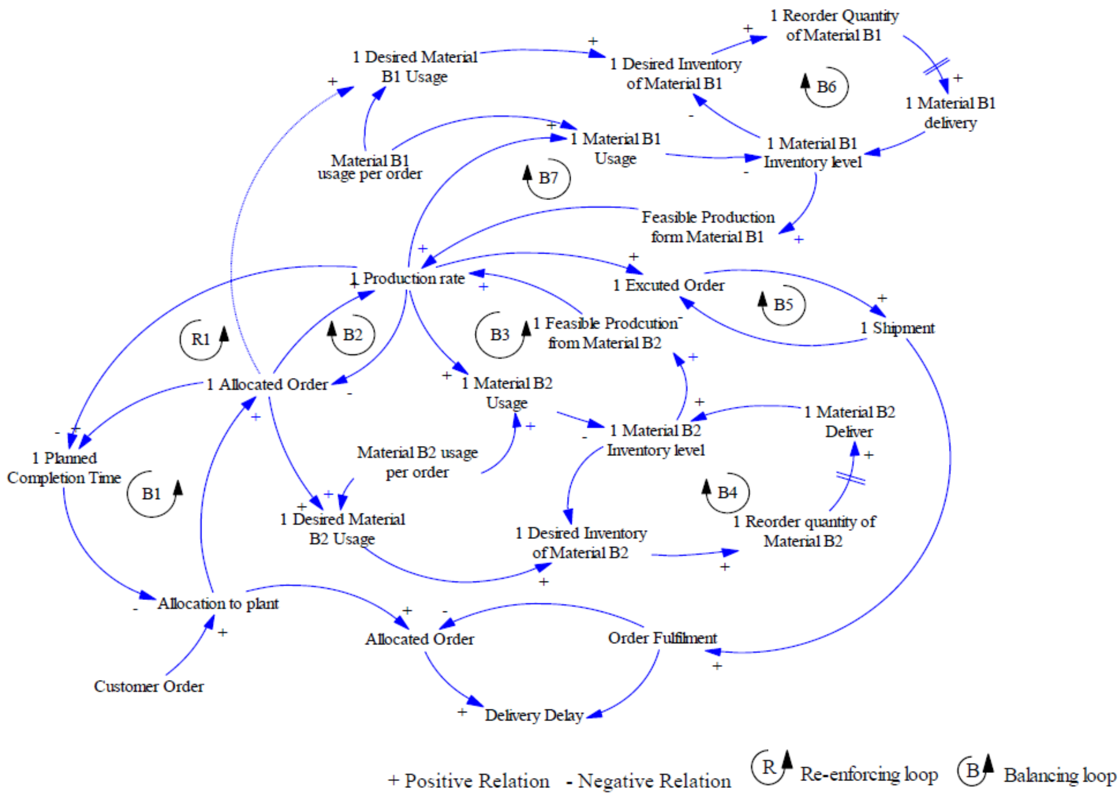


Figure 7.16. Causal relation diagram in the SD model of a production plant (Mussa, 2009)

- **Ease of model development:** the first criterion was the ease of the conceptualization of a system into a model through each of two paradigms. Some aspects can be quickly implemented in the agent-based approach and were very difficult, if not impossible, to model in System Dynamics.

  One example of such variable is the due date of an order from customer. Even though this variable plays a major role to conduct number of experiments, we

[1] In this case we have compared ABM with SD model for the same system to see which aspects are difficult to model by SD. Clearly for, the case of Experiment1, there is no fundamental benefit for ABM over discrete-event simulation (DES). In Experiment 2 in section 7.7.2 – which is more focused on the social aspects of supply chain – a DES model cannot adequately reflect the social aspects – i.e., the negotiation process – between actors. Of course, it must be emphasized here that our main goal in comparing models in this section is to show that ABM is conceptually more capable to capture the social and technical complexity of a supply chain (i.e., we can model the socio-technical characteristics of a supply chain in more details); but "if this level of complexity is needed to model for every supply chain" and "how considering more details may impact the output of a model" are secondary issues which are highly dependent on the specific supply chain we work on and specific problems we aim to tackle.

found it very difficult to include in the system dynamics model. Because of this difficulty, experimentation with some policies – like earliest due date policy for order scheduling – is very difficult, if not impossible. Likewise, SD model, because of its aggregative view, was unable to capture the attributes of individual entities in the system. In addition, the heterogeneity in the customer's characteristics and the orders' properties – e.g., the type of products or pickup type - was very difficult to model in the SD model.

- **Ease of experimenting with the model:** as far as changing the value for some of the parameters are concerned, both modeling approaches had the same levels of ease. But, the structural changes in the system is very time-taking in the system dynamics model as compared to agent based modeling. This is because in system dynamics approach, the structure has to be determined before starting the simulation (Schieritz and Grobler, 2002). Consequently, before adding any new variable to the model, its implication to the overall structure of the model and the feedback structure have to be checked. This makes the task of extending system dynamic model more time consuming. About ABM, adding a new concept – e.g., a new agent or a new type of product - into an already established model is much easier and less time-consuming. The modeler can independently define the new concepts by creating subclasses and introduce them to the existing model to experiment with new factors.

- **Ease of re-use:** the integration of earlier works into new projects makes modeling a more versatile tool in problem solving. This is an important aspect of model development. It is not only in terms of saving time and cost but also to develop models based on previously-validated components.

  In developing the system dynamics model in our study, the inventory management is adapted from a model presented by Sterman (2000). Similarly, the components developed in our model can facilitate the development of other models in the same problem area in the future. The same is true for agent-based model. It is possible to take part of the developed model and customize it for another case description. For example, one agent from a given model can be taken easily with its possible behavior and introduced to a new model. Therefore, with respect to this criterion, both modeling approaches have a good prospect of re-usability once developed for a specific problem.

7.7.2. Experiment set-up 2: negotiation-based order acceptance process[1]

As a second set of experiments with the model, the order acceptance (OA) process is analyzed in this section. We, specifically, discuss how the negotiation with customers may impact this process. In fact, instead of a pre-defined setting for order specifications – in terms of, e.g., price or time of delivery -, we assume here that the order features are determined through negotiation between customers and enterprise. Therefore, multiple actors are involved in the decision-making on order specifications (see section 6.3.1.2 for details on modeling the multi-actor decision-making).

Order acceptance has a large influence on the performance of enterprise. On the one hand, accepting every incoming order when the capacity is available may restrict the system to accept more profitable orders in the future. On the other hand, rejecting too many orders leads to low capacity utilization and also further impacts future customer relations. In addition, accepting too many orders leads to an over-loaded production environment, where lead times increase and orders are delivered late that will affect the customer satisfaction. Most of these aspects of order acceptance decision-making can be handled by having a proper negotiation with customers on order terms. However, this is a complex problem because the actors involved (customer and enterprise) have different interests and asymmetric information. Accordingly, to provide insight for the decision makers in the firms to develop proper strategies for order acceptance, developing appropriate models seems necessary. In this section, we discuss how simulation can help to experiment with different issues that influence the order acceptance process. First, the model set-up is described in 3 stages. Next, some experiments with different settings for the order acceptance process are presented and discussed.

7.7.2.1. Model set-up for negotiation-based order acceptance

To support the order acceptance process, some changes must be made in the developed model of section 7.3 and several features must be added. As mentioned in section 7.2, in the lube oil enterprise, the global sales department (GSD) has the key role in the order acceptance process and is responsible for order negotiation with customers and order assignment to the plants. To model the order acceptance, we firstly conceptualized the interaction between GSD and Customers in three main phases: *pre-negotiation*, *negotiation* and *post-negotiation*. In the pre-negotiation phase, two parties (i.e., Customer

[1] The experiment design and results presented here are partly based on Mobini (2010) – title: "An agent-based model to support negotiation-based order acceptance in a multi-plant enterprise" - , Behdani et al. (2011a) – title: "Negotiation based approach for order acceptance in a multi-plant specialty chemical manufacturing enterprise"- and Mobini et al. (2011) – title: "An agent-based model to support negotiation-based order acceptance in a multi-plant enterprise".

as buyer and GSD as seller) separately evaluate the counter-party and decide whether to enter into negotiation. Following the pre-negotiation phase, the actors who decided to enter negotiation, exchange offers one after the other to reach an agreement on the order issues, or quit negotiation either because of their constraints (e.g. time) or because of a more preferable option outside the negotiation. On the basis of the results in the negotiation phase, negotiation parties update their history about other actors in the post-negotiation phase. This history updating plays an important role in opponent-evaluation and making decision for the future trades with the counter-party. Based on this conceptualization the necessary changes in the model are done as mentioned in more details in the following.

1) Pre-negotiation phase:

In this phase, each party separately evaluates its counter-party and decides whether to enter into the order negotiation. The evaluation is performed according to the history (perception) formed on previous trading experiences.

The buyer (Customer) makes decisions based upon previous ordering experiences and the delivery performance of the enterprise. In the model, this is conceptualized with an attribute for Customer which is termed willingnessToReorder. WillingnessToReorder has a value between 0 and 1 and is updated based on the interactions with enterprise as discussed in the post-negotiation phase. At each step of simulation, a uniform [0, 1] random variable is generated and compared with willingnessToReorder for that customer. In the case that random number is higher than willingnessToReorder, the Customer places an order with enterprise.

On the other side, the decision of the seller (GSD) to initiate the negotiation depends on several factors derived from OA literature (see Box 7.2 for a review on order acceptance literature). These factors include *profit contribution of an order*, *production feasibility of an order* and *the value of the customer* placing an order. Based on these three factors, 6 different cases are considered for the pre-negotiation phase of GSD (Figure 7.17). When the order is placed by Customer, first, the GSD determines the profitability level of the received order. For this purpose, revenue and costs of the order will be calculated. Revenue is formalized as:

*Revenue= Initial price offered by Customer*Order quantity* (7.4)

The total cost of the order is the sum of raw materials, processing, packaging, inventory, and fixed costs (the details of cost estimation is presented in Table 7.9). An order is considered profitable if its revenue is equal or larger than a specific threshold that is assumed here as 20% of its incurred costs.

Box 7.2- Main directions of research in the order acceptance literature

Order Acceptance (OA) is a complex issue in a company as several internal business functions in the firm such as production planning/scheduling and sales management and also external parties – i.e., customers - are usually involved in this process. Based on this complexity, OA has been investigated from different perspectives in the literature. Some researchers have focused on the integration of *sales/marketing and production*, claiming that, in practice, the sales department often makes independent decisions on bids without consulting the production department (Cakravastia and Nakamura, 2002). In one of the first works on this topic, ten Kate (1994) showed that in tight situations with short lead-times and high utilization rate, the integrated management of sales and production performed better than cases where these functions were not closely integrated.

Another stream of research in the OA literature is *order selectivity*. In this approach, which is also referred as “revenue-based capacity management” (Defregger and Kuhn, 2007), the aim is to satisfy customer demand by allocating resources so that the firm’s revenue and profitability are optimized. Subsequently, a firm primarily serve valuable orders and reserve the capacity for future orders with higher profit margins. Missbauer (2003) used a stochastic model to derive optimal lower bounds for the profit margin of arriving orders. Only orders whose contribution margins exceeded the optimal lower bounds were accepted. In a more recent work, Arredondo and Martinez (2010) applied reinforcement learning for making OA decisions. The profit threshold was dynamically changed based on acceptance or rejection of similar orders in previous decision periods.

OA is also closely intertwined with a firm’s *customer relationship management*, with many studies focusing on managing incoming orders from different customer segments and assigning capacity to more profitable customers. The aim in customer segmentation is to keep valuable customers satisfied and therefore increase the probability of repeat purchase and long-term profitability (Korpela, et al., 2002). Meyr (2009) showed that customer segmentation on the basis of customer’s value, in terms of previous revenue brought to the firm, could improve profit substantially.

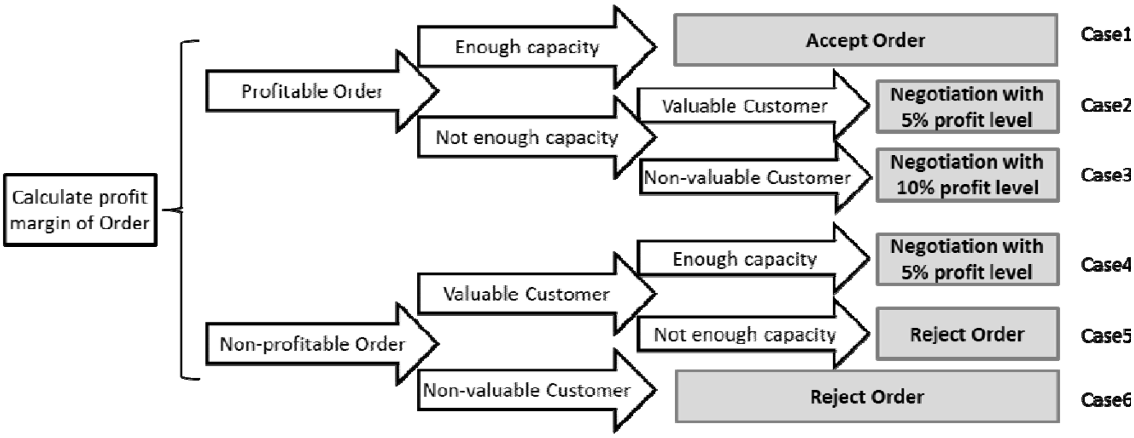


Figure 7.17. Possible cases for GSD pre-negotiation phase

After the profitability of an order is checked, 6 possible cases can be considered. These cases are summarized Figure 7.17. In three following cases the GSD is willing to enter the negotiation with Customers:

- *Profitable* order from a *valuable Customer* for which there is *not enough production capacity* (**case 2**). For valuable customers, the enterprise is willing to make concession in the price of product till 5% profit level.
- *Profitable* order from a *not-valuable Customer* for which there is *not enough production capacity* (**case 3**). For non-valuable customers, the price negotiation is limited till 10% profit level.
- *Not-profitable* order from a *valuable Customer* for which there is *enough production capacity* (**case 4**). Similar to case 2, the maximum concession on product price from GSD is limited to 5% profit level.

If an order is *profitable* and there is *enough capacity* in one of plants, the order will be accepted (**case 1**). If the order is *not profitable* and the customer is *non-valuable* (**case 6**) or customer is *valuable* but there is *no enough capacity* (**case 5**), the order will be rejected by GSD. The nested logic for entering negotiation based on these cases is implemented in GlobalSalesDepartment Agent before experimentation with model in the following.

2) Negotiation phase:

Those cases in the pre-negotiation phase in which GSD is willing to enter into negotiation are dealt with in this phase. In the negotiation phase, the involved Agents or NegotiationParties (i.e., GSD and Customer) take turns to make Offers in order to reach an agreement on a specific value for each NegotiationIssue. The specific

NegotiationIssues in this case are two characteristics of ProductOrder; *order due date* and *price for unit of product*. The NegotiationProcess in this thesis is based on the work of Jonker and Treur (2001). This procedure has been validated in several experiments with human as well as computer negotiators in different domains (Jonker et al., 2007). First a brief description of what happens in the negotiation phase is presented; then, details are provided on how Offers are evaluated and prepared in the model.

The process of negotiation includes several steps. These steps are implemented in both NegotiationParties with different type of Activities. The first counter-offer is made by the seller agent (GSD) since the buyer (Customer) has sent its Offer before in the order specification. GlobalSalesDepartment Agent sends the counter-offer to the Customer (SendOffer Activity). The Customer assesses the Offer using its utility function (EvaluateOffer Activity). If the counter-offer is acceptable in terms of utility and does not violate the Customer's constraints, then negotiation ends in agreement. If it is not acceptable, then the Customer Agent decides whether it wants to continue the negotiation with this enterprise or not. The Customer continues negotiation if:

1. its order was not accepted by an alternative seller. In fact, we assume that, at the same time that each customer places an order with MPE, it also places order with other sellers with non-negotiable price and delivery time values. This can be considered as the *outside option*[1] for the buyer. It is assumed that alternative suppliers accept the order with a probability (S_P) that is an increasing function as negotiation proceeds in order to consider the effect of time implicitly

$$S_P = round\ of\ \ negotiation \big/ Step\ Limit \qquad (7.5)$$

Whenever a Customer agent has to make a decision on continuing the negotiation process with this specific seller, it first checks the alternative sellers. This is checked in the model at each round of negotiation by a random number. If the random number is higher than S_P, the customer continues the negotiation with GSD; otherwise, it steps out of negotiation with this enterprise.

2. it does not reach its *Step Limit*. We assume that there is a limit for the number of negotiation rounds that a Customer is willing to continue the negotiation.

[1] In each negotiation setting, each party has an alternative option in case that negotiation fails. This option is called an “outside option” in the negotiation theories (Muthoo, 1999).

If these conditions are satisfied, then the Customer makes an Offer (PrepareOffer Activity); otherwise, it quits the negotiation (QuitsNegotiation Activity). When an Offer is sent by a Customer, GSD also has conditions for accepting an Offer:

1. if the value for issues fall within the acceptable range. Each NegotiationParty has an acceptable range for each NegotiationIssue and they are not willing to accept or negotiate the values beyond those ranges. For MPE, this range for price is defined based on the profitability level and the customer value as mentioned before. For due date, the lower bound is defined based on the first possible time for processing orders in the production plants.

2. the difference between the utility of the received order and the utility of last Offer by GSD is acceptable.

If the Offer is acceptable, then negotiation ends in agreement. If it is not acceptable, then GSD would ask the Customer whether it wants to negotiate on NegotiationIssues. If it has the intention to continue, the negotiation process explained in this section will start over.

According to this process, the negotiation phase is derived by choosing different Activities by NegotiationParties in different rounds of negotiation. The logic for each of these Activities – as mentioned before- is implemented in both parties (i.e., GlobalSalesDepartment and Customer Agents). EvaluateOffer and PrepareOffer Activities have a more sophisticated logic as described below (Jonker and Treur, 2001).

- **Offer evaluation and preparation procedure:**

In the negotiation procedure mentioned above, in each round each party must evaluate the Offer of it counter-party and determine the counter-offer if needed. Assessing an Offer from the counter party is done in two steps:

- **Issue Evaluation**: to evaluate each Offer, each NegotiationParty firstly evaluates the desirability of each NegotiationIssue in that Offer. The evaluation functions of each issue in the negotiation are part of parties' profile – as presented in Table 7.14. Each negotiation round (except the initial round) starts with the evaluation of issues - i.e. price and delivery time - in the previous Offer using evaluation functions for each issue.
- **Utility Determination**: The utility (U) of an Offer is the weighted sum of issue evaluation values (E_j) for different NegotiationIssues denoted by j.

$$U = \sum_j w_j E_j \qquad (7.6)$$

In the case that Agent is willing to continue the negotiation, it must prepare the counter-offer. The procedure for preparing counter-offers is somewhat in the opposite way of Offer evaluation:

- **Utility Planning**: to prepare the counter-offer, the Agent must decide about the amount of concession it wants to make for the next Offer. This concession amount will be subtracted from the utility value of the previous Offer, providing the Target Utility (TU) for the next Offer:

  $$TU = U_s - CS \qquad (7.7)$$

  Where U_s is the utility of the last Offer of the party, and CS is the concession step. The concession step is the amount of utility that a party is willing to give up at each round of negotiation. It is, in fact, a portion of difference between utility of last Offer by other party (U_O) and U_S. This portion is determined by β or negotiation speed.

- **Issue Planning**: after target utility is calculated, the target values for each NegotiationIssue in the next Offer must be defined. To find a value for an issue, first the portion of utility (UP) reduction for a discrete issue (j) (due date in our case) is determined by the following formula:

  $$UP_j = (w_j)(TU - U_s) \qquad (7.8)$$

  where w_j is the weight of that issue in the NegotiationParty's profile. Having the portion of utility, the value for issue must be determined with evaluation function in the way that is as close as possible to the portion. When the values for discrete issues are determined, the same procedure is followed for the continuous issues (price in our case) to compensate possible remaining utility. Following this approach, Offers that exactly match the target utility are prepared and sent to the counter-party.

3) Post-negotiation phase: On the basis of the interactions in the previous steps and the performance of enterprise in fulfilling the order of customer, in the post-negotiation phase, the two parties update the perception they have about one another. This perception updating, representing the adaptive decision-making behavior of agents, plays a key role in the future decisions regarding trade with the counter-party.

For the customer-side, the adaptive behavior is reflected in updating the willingnessToReorder after each trade with MPE. To model this, we consider two factors that influence willingnessToReorder:

1. The *outcome of negotiation* which can be successful or failed negotiation,

2. The *delivery performance* of enterprise as it is possible that agreement is reached on order due date but the actual delivery of the order is not on the agreed time.

These two factors influence the experience of each customer with this enterprise and are formalized in the following formula:

$$willingnessToReorder\ (new) = \begin{cases} willingnessToReorder\ (old) + d_{OA}^{+},\ if\ negotiation\ is\ successful \\ willingnessToReorder\ (old) + d_{OA}^{-},\ if\ negotiation\ is\ unsuccessful \end{cases} \quad (7.9)$$

where d_{OA}^{+} and d_{OA}^{-} are updating values for success/failure order negotiation which are assumed equal in the following experiments.

Similarly as fulfilling an order is finished in a plant and the final product is delivered to the Customer, the willingnessToReorder of Customer is updated with this formula:

$$willingnessToReorder\ (new) = \begin{cases} willingnessToReorder\ (old) + d_{DP}^{+},\ if\ order\ is\ delivered\ on\ time \\ willingnessToReorder\ (old) + d_{DP}^{-},\ if\ order\ is\ delevered\ with\ delay \end{cases} \quad (7.10)$$

where d_{DP}^{+} and d_{DP}^{-} are positive and negative impact of delivery performance of enterprise on customer. We also assume that:

$$d_{DP}^{+} = d_{DP}^{-} \times F_{DP}, \quad 0 < F_{DP} < 1 \quad (7.11)$$

F_{DP} is the relative importance of positive and negative effects of delivery performance. Consequently, this equation implies that any delay in the order delivery has more impact than on-time delivery performance.

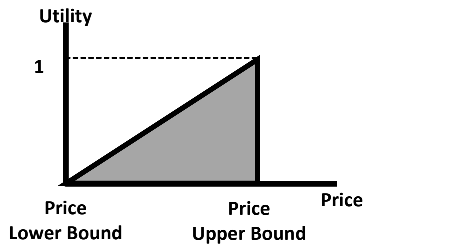
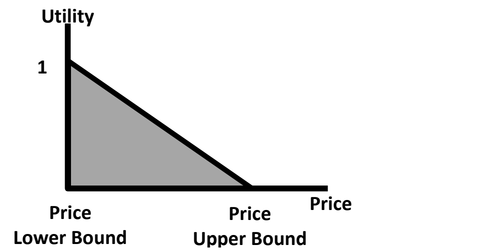
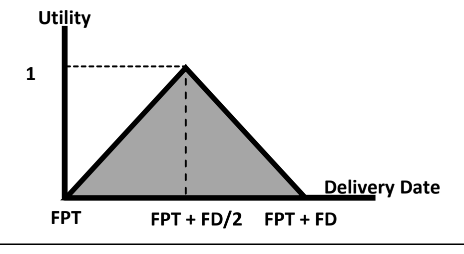
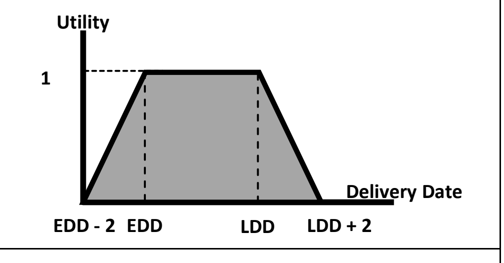
To get an overall review, Figure 7.18 shows the whole process in each three phases.

The three phases of pre-negotiation, negotiation and post-negotiation can be generic for any case of order acceptance process in a supply chain. Meanwhile, this process tries to encompass different aspects that impact the order performance of enterprise. To make some numerical experiments, two sets of experiments are described in the following. However, before running experiments, the simulation model has been evaluated based on procedure we formerly discussed in section 7.5. Some hypotheses were made, and the model was checked whether it gives the expected results. Some of tests for evaluation of model are presented in Table 7.13.

Table 7.13. Examples of tests for the evaluation of negotiation model

Hypothesis	Result
If the value of concession set as 0, there will be no successful negotiation.	The hypothesis is accepted; the agents remain on their initial offer till the step limit reaches.
By setting the step limit to 100, number of successful negotiations should increase.	The hypothesis is accepted; the effect of time is reduced. Thus, the number of successful negotiations increases. This is checked for several single session negotiations.
If the weight factor of one of the issues is set to 0, then concession should be made only on the other issues.	The hypothesis is accepted; the price weight factor is set to 0 for the buyer, and in the subsequent offers, the buyer insisted on the initial price but made concession on the delivery date.

Table 7.14. Negotiation attributes of NegotiationParties

Attribute/ Agent	Enterprise	Customer
Acceptable range for price	For valuable Customer: 1.05 (order cost/order quantity) < price < 1.2 (order cost/order quantity) For others: 1.1 (order cost/order quantity) < price < 1.2 (order cost/order quantity)	P = average price in the market[1] For Price-sensitive Customers[2] 0.95P < price < 1.05P For others: 0.9P < price < 1.1P
Evaluation function for price		
Acceptable range for delivery date	First Possible Time (FPT) < delivery date < First Possible Time + Flexibility duration(FD =14 days)	EDD = Earliest Due Date in the initial Offer LDD = Latest Due Date in the initial Offer EDD – 2 < delivery date < LDD +2
Evaluation function for delivery date		
Issue weight factors	w_P= 0.5, w_{DD}=0.5	For Price-sensitive Customers: w_P= 0.7, w_{DD}=0.3 For other: w_P= 0.5, w_{DD}=0.5
Step limit	7	7

[1] This price is read from Environment with an InformationFlow- please see section 7.3.
[2] We assumed that 50 % of Customers are Price-sensitive.

7.7.2.2. Numerical Experiment 1: different settings for order acceptance

In this experiment different views on order acceptance by enterprise are experimented. Three specific cases are defined. In the first case (No-Negotiation Case), customer orders will be accepted as long as one of production plants can produce the required products before the due date; otherwise, the order will be rejected. In the second case (Order Selectivity Case), the profit contribution of orders received from customers is checked first (case 1 in Figure 7.17); if an order meets the profitability requirement, the feasibility of the plants' production schedules will be checked. Subsequently, the profitable orders for which the requested delivery time is feasible are accepted and all others are rejected. In the third case (Negotiation Case) all cases in Figure 7.17 are considered. In fact, if an order does not meet the profitability requirement (short-term goal), it is not immediately rejected by enterprise but a negotiation session will be initiated to reach an agreement on the issue values. The enterprise expands the acceptable range of issue values and decreases the profitability lower bound for a valuable customer in order to maintain a good relationship. The assumptions for the attributes of Agents that are involved in the negotiation process are presented in Table 7.14. Based on these assumptions, the changes in the model have been made and the experiments were done. The results of simulation the profit of enterprise and average willingnessToReorder for all customers in the three settings described above are shown in Figure 7.19. In the case of No-negotiation, the total number of accepted orders by the enterprise is considerably larger than in the other two cases, as the only criterion for OA is availability of production capacity. As a result, the experience could be completely positive in Equation 7.9 and the willingnessToReorder is increasing at the start. This increase in willingnessToReorder, however, will be compromised later when customers receive their orders with delay. The delayed deliveries not only harm the reputation of the enterprise - and the future behavior of customers - but also decrease the enterprise profit because of lateness penalties paid on late orders.

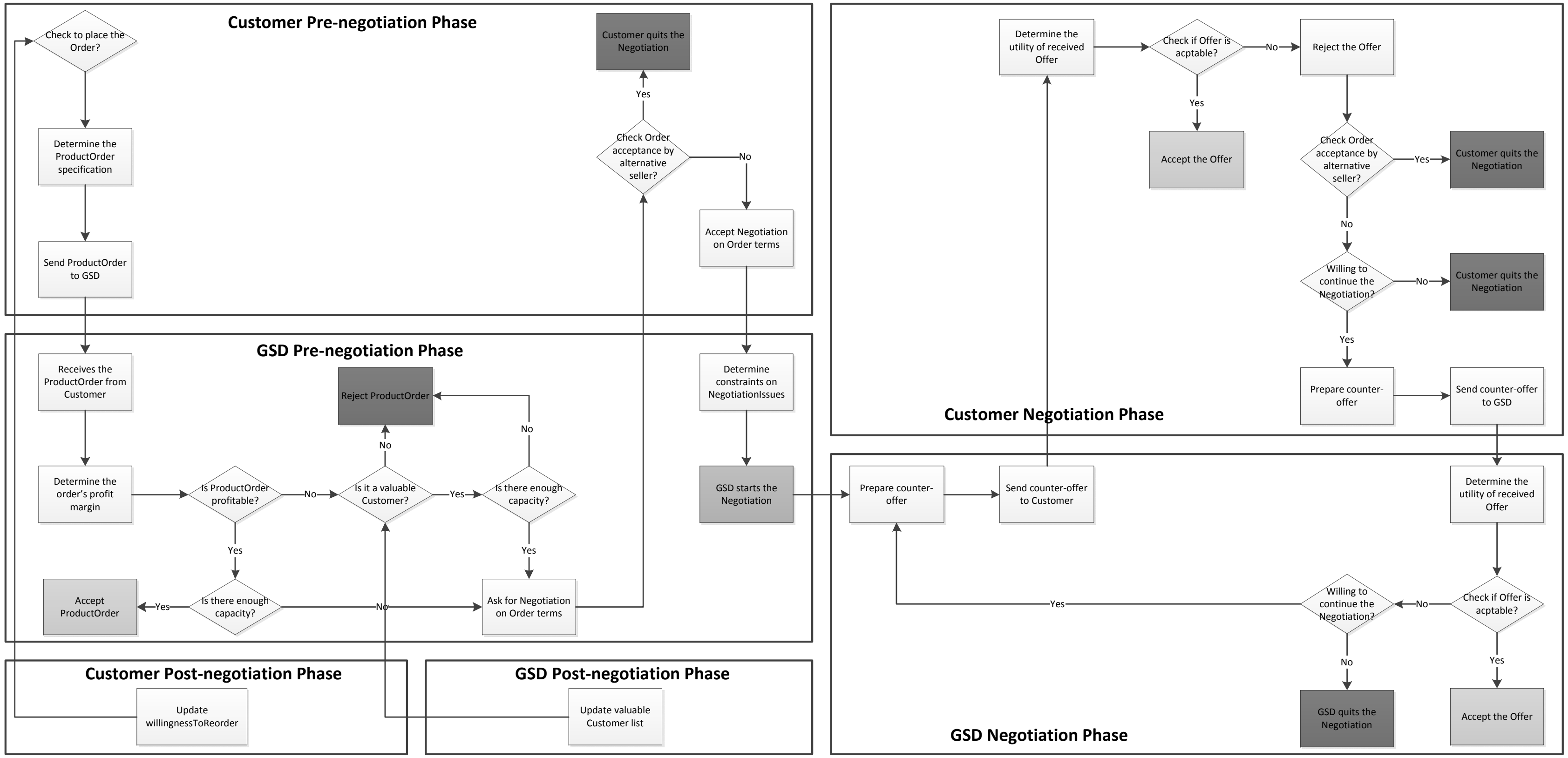
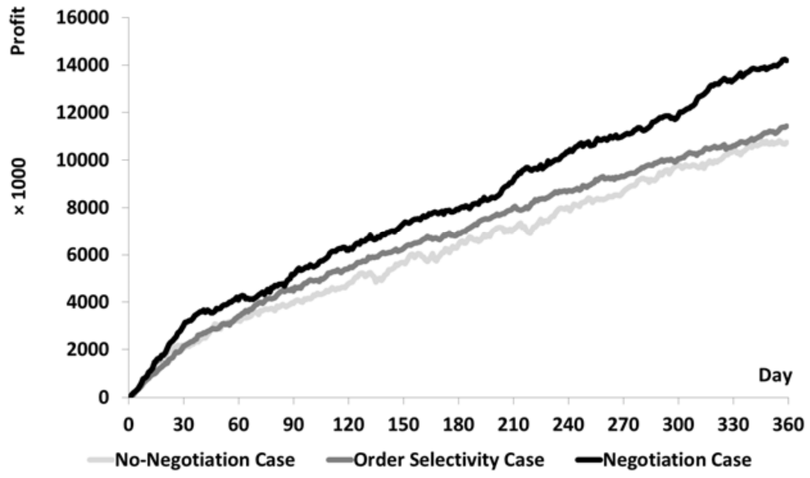
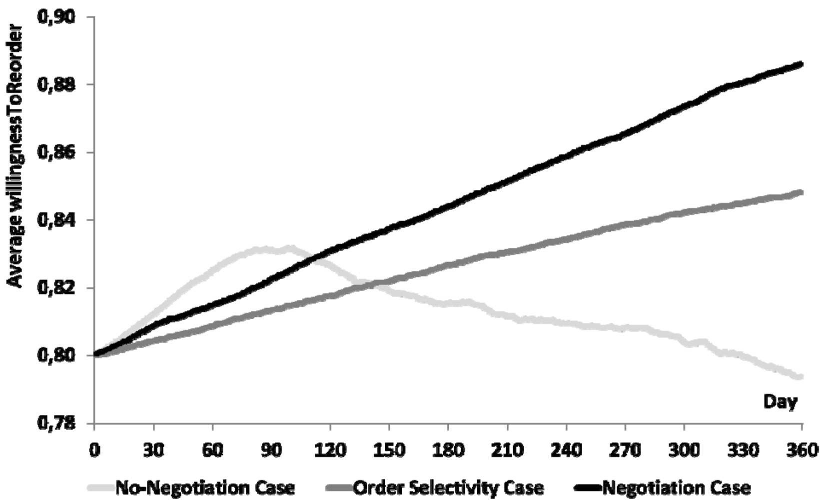


Figure 7.18. The agents' interaction diagram (three negotiation phases, decisions and activities)



The profit of enterprise



Average willingnessToReorder for all Customers

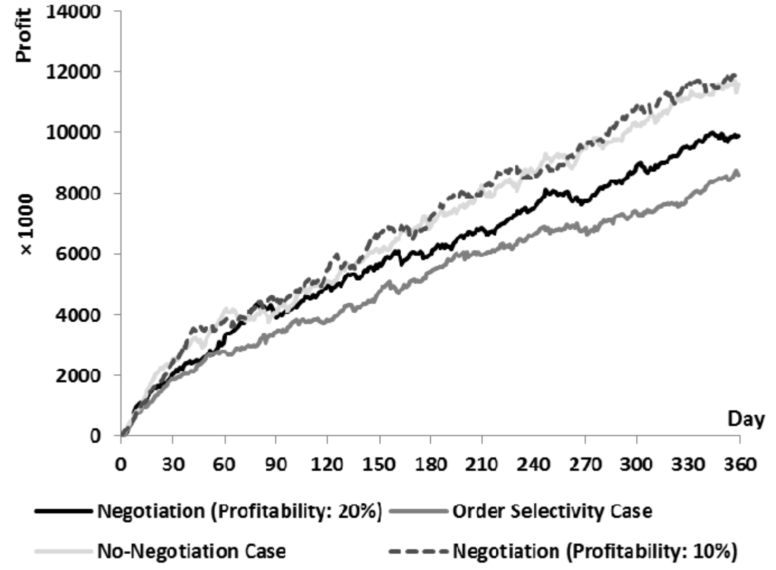
Figure 7.19. Impact of different settings for OA process on profit and customer satisfaction

Table 7.15. Comparing the simulation results for different settings for OA process

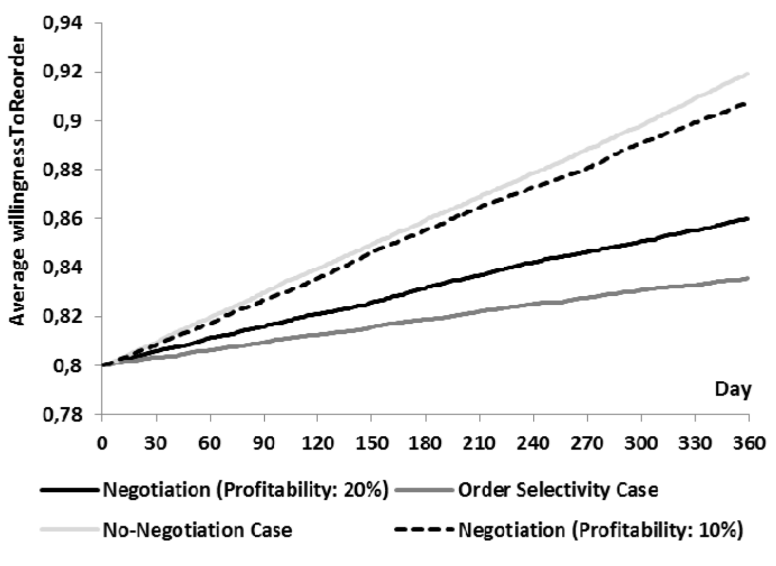
	No-Negotiation Case	Order Selectivity Case	Negotiation Case
Number of Orders assigned	534	265	373
Number of Late Orders	135	0	0
Total Profit (m$)	10.74	11.44	14.20

7.7.2.3. Numerical Experiment 2: impact of demand load

In the previous experiment, the rate of order placement by customers was assumed 1.75 orders per day. In this condition, the utilization rate of each production plant is approximately 90%, which is a high-load. To evaluate the effect of demand load, the arrival rate of orders is set to 1.25 orders per day. In this case, the utilization rate of the production plants is roughly reduced to 65%. In this lower-loaded environment, using the previous profitability bound of 20% leads to rejection of a high number of orders and weak performance in all dimensions as compared to other policies (Figure 7.20).



The profit of enterprise



Average willingnessToReorder for all Customers

Figure 7.20. Impact of different settings for OA process for a low-demand environment

In the previous experiment, considering negotiation simultaneously with order selectivity (based on profit of each order) made a considerable improvement in the performance of order acceptance process; however, in the low-demand situation, negotiation with the same threshold for profit (20%) does not have a positive impact on the profit of MPE comparing with the case of No-Negotiation in which every incoming order is accepted as long as there is enough capacity. In other words, with a high profitability threshold for order selectivity, many orders are rejected by GSD and the production facilities are left idle for a portion of simulation horizon. To adjust the lower bound of profitability, some exploratory experiments have been conducted as shown in Figure 7.21. As can be seen, decreasing the profitability threshold prevents rejecting some orders in the first place and subsequently, improves the profit of MPE. A value between 10-12% is a recommended setting for profitability check in this case because a lower margin for order's profit may result in accepting low-profit orders and negatively impact the performance of enterprise. This experiment clearly shows the capability of the developed model for fine-tuning model parameters under different situations.

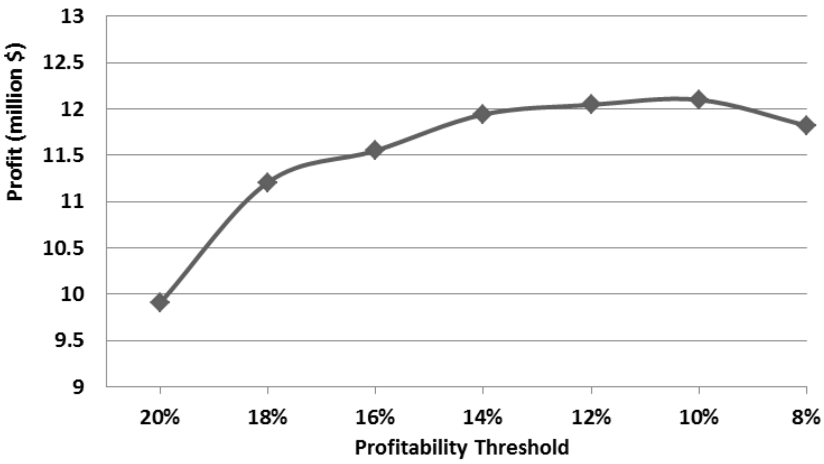


Figure 7.21. The effect of profitability threshold on the profit of enterprise

7.8. Model application for supply chain disruption management

In the previous section, we discussed how the modeling framework can be used to design experiments to manage the normal and daily operation of a lube oil supply chain. In this section and two following sections, the focus is on the application of simulation models to support disruption management. In Chapter 2 of this thesis, we made a distinction between two main perspectives on handling supply chain disruptions. In pre-disruption view, a company tries to identify the potential disruptions and makes investment in resources to reduce the risk of these disruptions. For example, to avoid the impact of late order delivery, a company may carry more inventories in its storage facilities which minimizes the adverse consequence of delay in raw material shipment. Of course, as a disruption is not a certain event, the cost of investing in advance of disruption occurrence is incurred to a company even if it does not happen at all. However, by investing in risk prevention, the likelihood and expected impact of some disruptive events can be reduced. For example, carrying more inventories may help to manage the impact of a short-time emergency shutdown of a supplier. Moreover, without investing in some resources, managing disruptions – as they happen - can be very slow. In other words, having some resources – even if they are inadequate to cover the full impact of disruption - gives a company the extra time to find additional resources. In the post-disruption view, on the other hand, a company accepts the risk of disruption and instead of investing on resources, it tries to better react once the event materializes. This can be done, e.g., by developing a contingency plan which is used just in the case of disruption occurrence. Of course, managing a disruption in the real world can happen by a combination of both pre- and post- disruption options.

As we discussed before, modeling and simulation (M&S) can be used to provide support in both these two phases. For pre-disruption, it can help to evaluate the impact of different possible disruptions and determine the possible treatments. For post-disruption, a model can help in faster detecting a disruption – by evaluating the expected impact of a triggering event on supply chain operation - and finding the appropriate solutions to handle the consequence of an actual disruption.

Application of modeling and simulation and design of experiments for disruption management might be however a challenging task. The main issue is the uncertainty about timing and magnitude of disruption. This uncertainty is especially important in pre-disruption steps as we do not know precisely when disruptions happen and how big they might be (e.g., how long a supplier disruption may last). In the best situation, we just have an estimation of likelihood of disruption occurrence. For post-disruption, this is less challenging because the approximate timing of disruption or an estimation of its magnitude is available (or will be available very soon after disruption occurrence) to use as simulation input. For example, a supplier may have an emergency shutdown which causes a delay in the raw material delivery for one week. So, the scale of disruption is reasonably known to the enterprise.[1] Because of this difference - comparing with post-disruption process - the experiment design for pre-disruption management has an

[1] Of course, the first estimation of supplier of magnitude of event might be imprecise or biased and after a while it may give an update on the time of returning to normal operation or a new expected time for order delivery. But in any case, after a disruption happens, an acceptable estimation of timing and profile of disruption is available sooner or later.

additional feature. This additional feature is defining some disruption scenarios to handle the uncertainty about the disruption timing and profile which is discussed in more detail in section 7.9.

The experiment design for pre- and post-disruption management has another difference as well. This difference is the time frame of simulation. In the post-disruption view, the simulation is used as a support for the daily operational issues and therefore the time horizon of simulation is days, weeks and at the most several months. Pre-disruption view, however, is mostly about decision in a longer period of time (e.g., one year) and it is usually focused on the tactical (and sometimes strategic) level of decision-making in the enterprise. Consequently, in the experiment design, the simulation horizon for pre-disruption view is a longer period.

Considering these two differences, section 7.9 focuses on experiment design for pre-disruption view; we describe a simulation-based risk analysis approach and its application for a specific case of supplier disruption. Next, in section 7.10, the experimentation with the model for post-disruption steps is discussed in detail.

7.9. Model application for pre-disruption process[1]

This section discusses the experiment design to support risk assessment and treatment decisions in the lube oil supply chain. As mentioned before, supply chain disruptions are generally uncertain events happening randomly during the operation of system. This creates the main challenge in the experimentation for pre-disruption view. To handle this challenge a simulation-based risk analysis approach is discussed in the following for the cases in which the probability distribution of disruption occurrence and an estimation of its duration is available. Several sources of information such as statistical time series or expert opinion might be the basis to estimate the disruption's likelihood and scale. The central idea in this risk analysis approach is the repeated simulation of different possible scenarios with the model. Firstly, based on a probabilistic description of disruption, we generate some disruption scenarios that define the day of occurrence and the duration of a potential disruption. For each scenario, the agent-based model is then used to model different possible disruption management actions and assess the impact of disruption on the supply chain performance. The steps of this approach are discussed in more details in the following.

[1] The method for risk management and the experiments of this section are the extension of work of Behdani et al. (2012) – title: "Mitigating supply disruption for a global chemical supply chain - application of agent-based modeling".

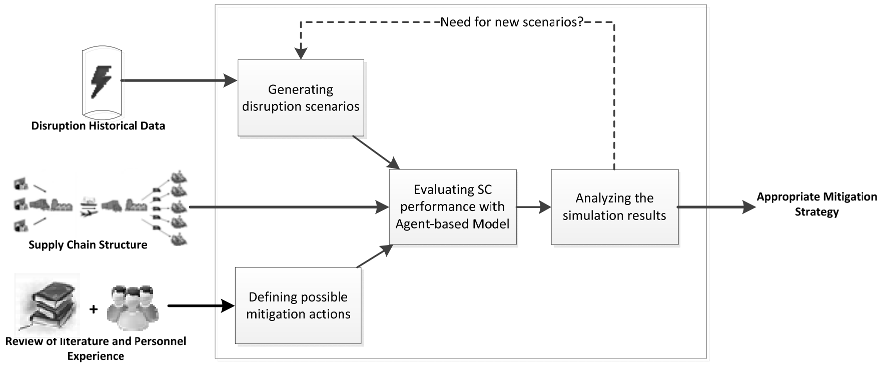


Figure 7.22. Simulation-based Risk Analysis Approach

- **Generating disruption scenarios:**

A disruption scenario is a description of a particular event and how it is expected to happen and evolve in time. For instance, one disruption scenario could be that a supplier has an emergency shutdown for a 10-day period starting at day 118 and another production stoppage at day 312 which lasts for 5 days. Therefore, each scenario defines the time of disruption occurrence and the severity of this event if it happens.

As the number of plausible scenarios can be infinite, we start with a random sample of scenarios and by analyzing the simulation results of this sample, the decision for defining more scenarios can be made.

- **Defining possible mitigation actions:**

In section 7.6, we discussed that each experiment with the model is analyzing the impact of some experimental factors (or input) on some performance measures (or output). The experimental factors for supply chain risk management are alternative risk treatment practices. To handle the risk of each potential disruption in the supply chain, many different responses can be defined and implemented. An overview of main supply chain risk mitigation strategies has been presented in Chapter 4. A good review of supply chain risk mitigation strategies can be also found in Tang (2006a) and Stecke and Kumar (2009). Expert opinion and personnel brainstorming are other possible sources for defining the risk mitigation actions (Norrman and Jansson, 2004). Based on these resources, some possible mitigation approaches must be defined for experimentation with the model.

- **Evaluating SC performance with Agent-based Model:**

Once a list of mitigation actions is generated, the necessary changes in the model need to be done. Next, the developed model can be used to estimate the impact of a particular disruption on the performance of the supply chain under different mitigation actions in each disruption scenario.

- **Analyzing the simulation results:**

With a primary set of disruption scenarios, decision makers can compare alternative risk mitigation approaches and choose the best one for each scenario. Subsequently, the mitigation approach which is dominant in the majority of scenarios must be determined. However, to be sure that the chosen strategy is a robust strategy and is generally dominant, it is necessary to generate a new sample of disruption scenarios and study the appropriate disruption management action for this new set of scenarios. If a new set of scenarios leads to a similar best disruption response, that response can be selected as the final option to implement. Otherwise, the process must continue with defining a new set of disruption scenarios. With such an iterative process, the final disruption management action can be determined.

Using this four-step experimental process, two experiments for mitigating supply chain disruptions are discussed in the following.

7.9.1. Numerical Experiment 1: mitigation of supplier risk

This experiment is aimed to find effective risk mitigation strategies to manage the risk of "Supplier Disruption". This disruption might occur in each supplier in the supply network (each production plant has a supplier for base oil and a supplier for additives) and subsequently, results in the late delivery of raw material orders to the production plants.

- Disruption scenarios:

The supply chain is subject to random supplier disruptions. These supplier disruptions are assumed to occur with probability (D_p) 0.005 (or the expected frequency of once in each 200 days). The duration of a disruption is also sampled from a triangular distribution with a minimum value of 5 days, a most likely value of 10 days, and a maximum value of 20 days. With these inputs, different scenarios for disruption occurrence are generated. One example of these disruption scenarios is presented in Figure 7.23. The procedure to generate a disruption scenario is given in Figure 7.24. First, the occurrence of disruption for each "day" in the simulation horizon (which is one year) is checked. For this purpose, for every day within the simulation horizon a uniform [0,1] random number is generated and compared with D_p. In the case that the random number is less than D_p, there is a supplier disruption in that day. In the case of disruption occurrence in a specific day, next, the duration of disruption is determined according to triangular distribution with a similar procedure. With this method, 20 starting scenarios for experimentation are defined. Each scenario describes the starting date(s) and the duration of supplier failure in one year (Figure 7.23).

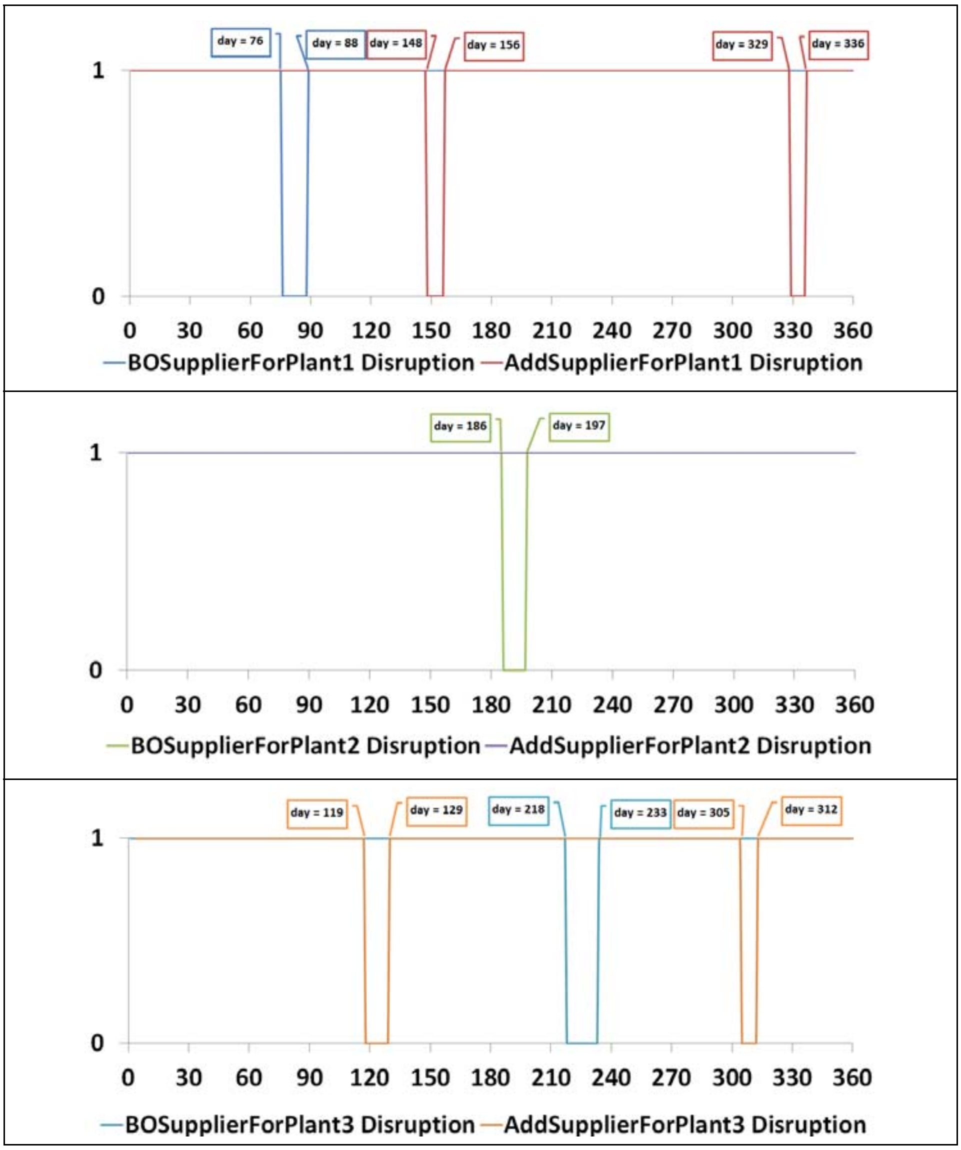


Figure 7.23. An example of disruption scenarios in supplier disruption experiment

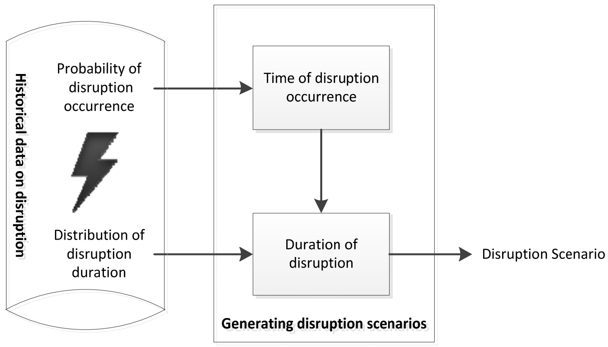


Figure 7.24. Procedure for scenario generation

- *Disruption management practices:*

Two strategies to handle supplier disruptions are modeled:

- **Inventory mitigation:** the production plants source exclusively from one supplier but carry some excess inventory to mitigate disruptions (the reorder point is considered 40% instead of 35% for other cases).
- **Sourcing mitigation:** the production plants source from two suppliers; one global low-cost supplier and a second backup supplier for the cases that there is an interruption in the raw material delivery from main supplier (the raw material price for local supplier is assumed 25% higher than main supplier).

As different disruption scenarios and the disruption management practices are defined, the necessary changes in the model must be done. This, in fact, includes two main types of changes. The first change in the model is implementing the disruption management practices. These changes include the parametric change for case of *inventory mitigation* and the structural/behavioral changes for case of *sourcing mitigation*. All these changes are done in the model in a way similar to experiment designs that are discussed before in Section 7.7. The second change in the model is defining the SupplierDisruption class. SupplierDisruption class is basically an instance of SupplyChainDisruption Object as described in section 6.4. Considering 2 suppliers per each plant, 6 classes of SupplierDisruption are defined for the simulation. The disruptedObject in these classes are one of suppliers in the supply network of enterprise.

- *Analysis of results:*

To understand the system behavior, we started running the simulation model for 20 disruption scenarios. For each scenario, two strategies are compared with each other and also with the case of no action (Table 7.16). Each simulation run yields different results; however, in general, the sourcing mitigation strategy was the dominant choice for managing supplier disruptions in most of scenarios (Figure 7.25). To evaluate the robustness of choosing this strategy, we generated 10 new disruption scenarios and ran the model for each scenario. In these new set of scenarios, the sourcing mitigation was again the best option in 6 disruption scenarios. With this analysis, it can be concluded that sourcing mitigation is the proper strategy to handle supplier disruptions in lube oil supply chain. Table 7.16 shows the mean value for enterprise profit over 20 and 30 scenarios. As can be seen with defining a mitigation strategy, the profit of enterprise can be improved up to between 5-12 percent. The mean profit for sourcing mitigation is however higher comparing with two other options in both cases. Moreover, the "mean" profit is relatively similar for 20 and 30 scenarios which reinforce the argument of selecting sourcing mitigation as the final choice.

Table 7.16. Effect of mitigation strategies on enterprise profit (standard deviation over different scenarios is mentioned in brackets)

	No disruption management	**Sourcing mitigation**	**Inventory mitigation**
Average profit for 20 scenarios (m$)	9.65 (0.77)	10.77 (0.60)	10.12 (0.69)
Average profit for 30 scenarios (m$)	9.58 (0.75)	10.73 (0.58)	10.22 (0.66)

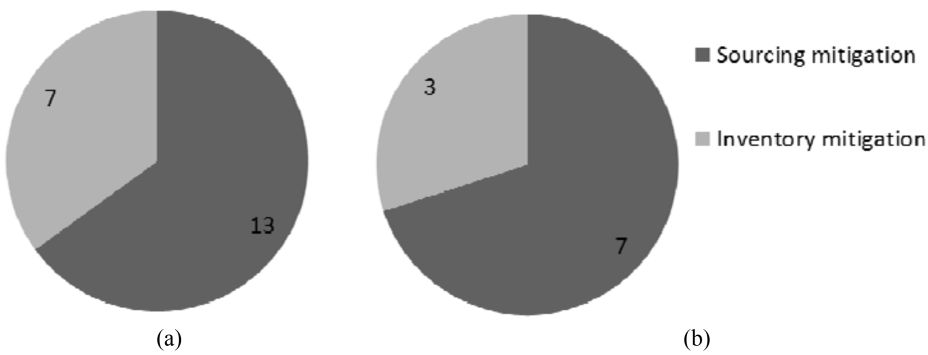


Figure 7.25. The distribution of best mitigation strategy: (a) first 20 scenarios; (b) for 10 extra scenarios

7.9.2. Numerical Experiment 2: managing multiple types of disruptions

One important feature of the modeling framework of Chapter 6 is the modularity of the computer model. This modularity allows us to experiment with multiple disruptions in the supply chain. In fact, different instances of SupplyChainDisruption object can be defined and included in the model. Each of these instances interrupts the operation of one disruptedObject according to disruption scenarios. This also implies considering multiple types of disruptive events in defining the disruption scenarios. The experimentation with multiple types of disruptions is particularly useful as resources that are invested for one risk factor can be used to handle other types of disruptions as well (Knemeyer et al., 2009). For instance, carrying extra raw material inventory may reduce the risk of supplier emergency shutdown and also transportation disruption due to a port strike.

To show the applicability of the model, we repeated the previous experiment for a case that the risk of transportation infrastructure failure is also included in the model. Interruptions in material shipment can be due to wide range of causes like union strikes, bad weather or natural disaster. For the experimentation with the model, we assume that the probability of this disruptive event is also 0.005. For duration of shipment disruption, however, a wider triangular distribution with a minimum value of 1 day, a most likely value of 7 days, and a maximum value of 30 days is considered. Based on these values, 20 starting scenarios for experimentation are defined in which the disruption occurrence in supplier is similar to previous experiment and disruptions in RMDeliveryLinks are created and included. For each disruption, an instance of SupplyChainDisruption is defined and implemented in the computer model (in total 6 instances SupplierDisruption and 6 instances of TransportationDisruption are created in this case). Two instances of disruption objects are presented in Table 7.17 and Table 7.18. as can be seen, TransportationDisruption is a disruption in an Edge at the technical level of supply chain while SupplierDisruption is a disruption at one Node in the social level of system.

Table 7.17. An example of SupplierDisruption instance

Attributes	
Name	**Value**
disruptedObject	BOSupplierForPlant1
disruptedAttribute	utilizationFactor
disruptionOccurenceTime	Based on Disruption Scenario
disruptionDuration	Based on Disruption Scenario
normalValue	1
disruptedValue	0

Table 7.18. An example of TransportationDisruption instance

Attributes	
Name	**Value**
disruptedObject	BODeliveryLinkForPlant1
disruptedAttribute	utilizationFactor
disruptionOccurenceTime	Based on Disruption Scenario
disruptionDuration	Based on Disruption Scenario
normalValue	1
disruptedValue	0

The results of experiment in this case for 20 and 30 scenarios are presented in Figure 7.26 and Table 7.19. Comparing with case of “No disruption management”, defining and implementing a mitigation strategy can improve the profit of enterprise up to 20 percent. Based on the simulation results, again, the backup sourcing strategy is a more appropriate strategy in the majority of scenarios. Meanwhile, if we compare the results of two experiments, it can be concluded that for this specific case, the sourcing strategy is even more dominant as we consider multiple types of disruption in selecting the safeguards.

Table 7.19. Effect of mitigation strategies on enterprise profit for case of multiple disruptions

	No disruption management	**Sourcing mitigation**	**Inventory mitigation**
Average profit for 20 scenarios (m$)	8.79 (0.74)	10.55 (0.58)	9.97 (0.66)
Average profit for 30 scenarios (m$)	8.76 (0.71)	10.53 (0.54)	10.01 (0.61)

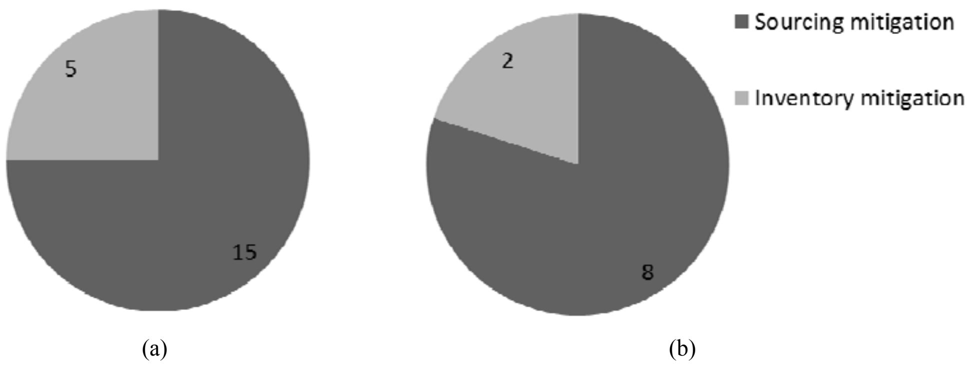


Figure 7.26. The distribution of dominant mitigation strategy: (a) first 20 scenarios; (b) for 10 extra scenarios

7.10.Model application for post-disruption process[1]

This section is focused on post-disruption experimentation and studies if and how the developed models for lube oil supply chain can be used as a support to handle disruptions as they happen. The steps to handle disruption are thoroughly discussed in Chapter 3 and Appendix B of thesis. The first step is detecting the disruption and estimating the possible consequences on the system performance. The performance of a supply chain can be evaluated by different measures. For the post-disruption process, it is recommended to evaluate the impact by more operational and detailed measures. This is especially

[1] The experiments of this section are partly discussed previously in Behdani et al. (2010a) – title: “Performance analysis of a multi-plant specialty chemical manufacturing enterprise using an agent-based model”-, Behdani et al. (2010b) – title: “Decentralized vs. centralized management of abnormal situations in a multi-plant enterprise using an agent-based approach” and Behdani et al. (2011b) – title: “Agent-based modeling for disruption management in industrial networks and supply chains”.

important because an aggregated measure like profit or operational cost might hinder the impact of disruption in the short-time. For example, a disruption may take time to impact the profit of company; however the daily operational measures (like order delivery performance which is measured in number of late customer orders) can more directly show the influence of a disruption on the supply chain operation.[1] Consequently, in the majority of experiments in this section, the delivery performance is considered as the output of simulation process.

Besides evaluating the impact of disruption on performance measures, defining an acceptable range of deviation for these performance indicators is necessary for disruption detection (Sheffi, 2005a). In fact, it must be clear which level of impact is acceptable and when a company must take action to react to a disruptive event.

As a disruption is detected in a part of supply chain, the alternative solutions must be defined, evaluated and implemented to manage the adverse effects of disruption and restore the normal operation of supply chain. This happens in the disruption reaction and recovery phase. Finally, once the company recovers from a disruption, in the disruption learning step, it may decide to redesign the supply chain with the goal of minimizing the risk of similar disruptions in future.

These three steps are the basis for the experimental set-up in this section. In fact, we want to elaborate how a computer model for lube oil supply chain can provide support in disruption detection, disruption reaction& recovery and supply chain redesign steps.

For this experimentation, the following settings are considered:

- **Disruption management settings:** To define a disruption management problem, performance indicators and their acceptable ranges for the problem owner (i.e., multi-plant enterprise) should be known. The performance indicators to define disruption in this case are “number of late orders” and “total tardiness (in days)”; the acceptable level for these indicators is “zero late orders” (and consequently, “zero tardiness”). Therefore, if any event (such as interruption in raw material shipment) causes delay in the customer orders, there is a disruption from the enterprise’s point of view.

[1] The impact of disruption on profit can be twofold. In the short-term, the number of processed orders from customers – and subsequently, the revenue of company - can be reduced. Moreover, the operational cost might increase because of several factors like lateness penalty for late order delivery or low capacity utilization for production facilities. In the mid-term, however, the impact of disruption might be amplified because of future order placement behavior of customer is influenced by poor order delivery performance.

- **Disruption set-up:** The disruptive event considered for experimentation in this section is an operational problem in BOSupplierForPlant2 which happens at day 41 of the simulation horizon. This disruption is announced by supplier 5 days later; on day 46 the supplier sends a message to ProductionPlant2 that the order for Base Oil 2 which was expected to be delivered on day 47, will be delivered with one week delay on day 54. Figure 7.27 shows the timing of events for this disruption set-up.

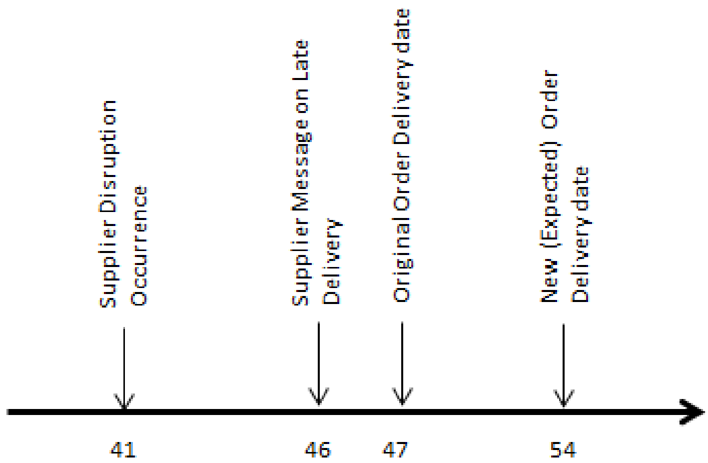


Figure 7.27. The sequence of events in disruption setting[1]

To model this abnormal situation, a SupplierDisruption instance is defined and implemented in the computer model. SupplierDisruption stops the operation of BOSupplierForPlant2 on day 41of simulation horizon and resumes its nominal operation at day 46. Subsequently, we can experiment with different possible settings to handle the event in each phases of the disruption management process as described in the following.

Table 7.20. The SupplierDisruption instance for post-disruption experimentation

Attributes	
Name	**Value**
disruptedObject	BOSupplierForPlant2
disruptedAttribute	utilizationFactor
disruptionOccurenceTime	41
disruptionDuration	5
normalValue	1
disruptedValue	0

[1] As can be seen, there is a difference between time of disruption occurrence and time of disruption announcement (and subsequently, disruption detection by MPE).

7.10.1. Numerical Experiment 1: model application for Disruption Detection

The first step is disruption detection in which an estimation of disruption impact on the performance of MPE must be made. Simulating the disruption situation can help us in this evaluation. Using simulations and without any modification in the structure and operation of supply chain, we can expect that the mentioned abnormal event in the supplier results in 7 late orders for the enterprise with 13 tardy days. Figure 7.28 and Figure 7.29 show the total number of late orders and tardy days and also the daily value of these indicators for a simulation horizon of 100 days.

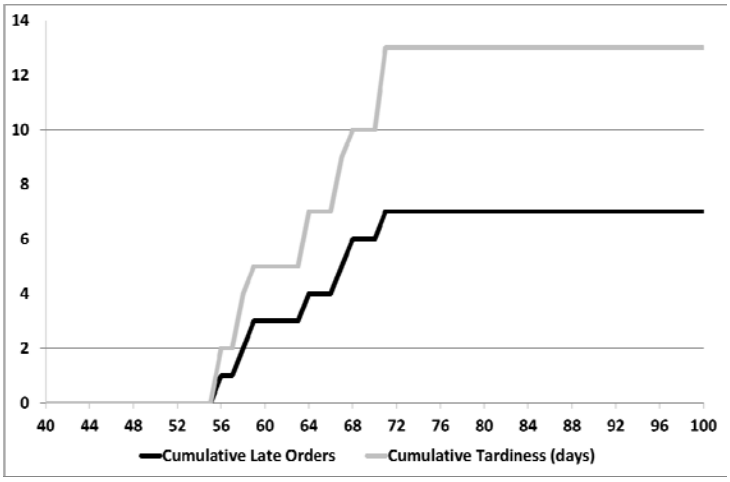


Figure 7.28. The cumulative effect of abnormal event on the performance of enterprise.

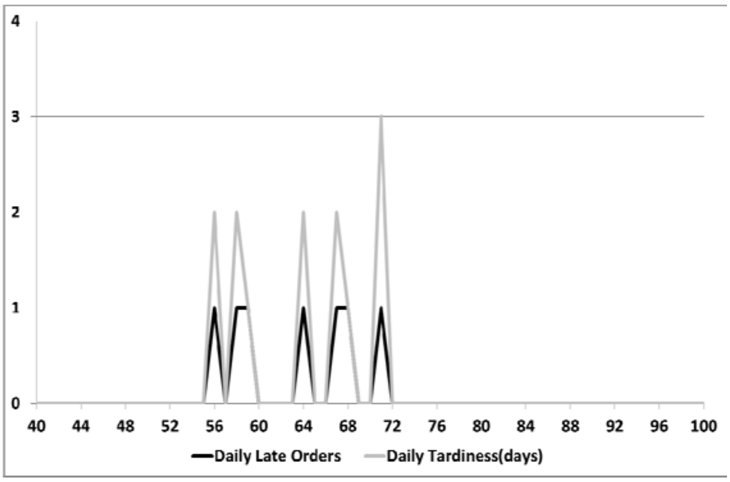


Figure 7.29. The daily effect of abnormal event on the performance of enterprise.

The first and most obvious consideration is that the performance of supply chain is out of acceptable range and the necessary actions must be taken to manage the disruption. Of course, the effect of this disruptive event is not instantaneous and the first late order will be delivered to the customer on day 56. This is primarily because the production plants still have raw material for several days after disruption. Meanwhile, the impact of disruption on supply chain performance lasts more than event duration itself as the last late order is delivered on day 71 to customers.

Simulation can also provide more details about the impact of disruption. For example, the orders that are delayed due to disruption can be determined. These orders are of two main types; the first type is the orders which are already accepted – before disruption is detected – but are not processed yet. There are also orders which are accepted after disruption is detected. This distinction is important when we define possible solutions in the reaction step.

7.10.2. Numerical experiment 2: model application for Disruption Reaction & Recovery

After a disruption has been detected and an insight of its impact is provided with the model, the next step is reacting to the event and managing the impact. For this purpose, different possible actions can be defined, tested with model and implemented in the supply chain. These actions are basically the experimental factors during experimentation with the model – see section 7.6 for details. Some of the possible reactions to supplier disruption are presented here. A reaction to disruption is generally aimed to:

1) create new resources for disruption management process.

2) re-assign the currently-available resources to better handle the disruption effects.

From a modeling perspective, each of these two classes has different modeling implications. While the second class mostly implies changes in the social-level behavior (i.e., the decision-making structure) of the system, creating new resources can be done by changes in both social and physical level as is described in some possible actions below.

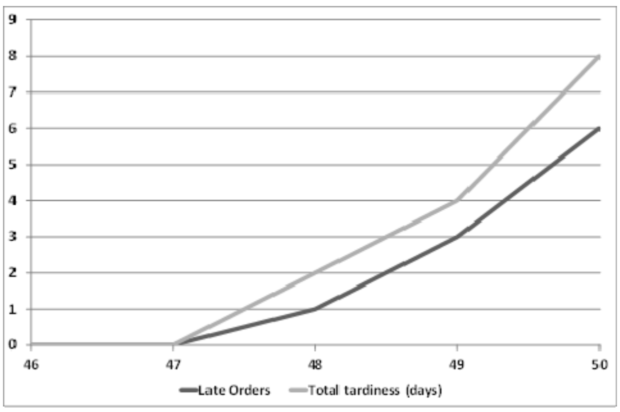


Figure 7.30. Effect of delay in placing emergency order on the performance of enterprise

From first category, one possibility is “emergency raw material procurement” from spot market. This is modeled in the system by a MaterialFlow from Environment to BO2Storgae tank in the ProductionPlant2. We also assume that raw material delivery takes 3 days. However, the process for finding and arranging this emergency procurement may take some additional days. Figure 7.30 shows the effect of delay in placing an emergency order on the performance of enterprise. Thus, placing an emergency order, immediately after the delay is announced (day 46) or at most one day after disruption detection (day 47), will avoid negative effects on the performance of enterprise. Postponing this decision, however, will influence the enterprise’ performance and cause delay in customers’ orders.[1]

An example in the second class of disruption reaction practices is order re-assignment. As we mentioned in the disruption detection, some of late orders are the orders which are accepted by enterprise before disruption detection but are not processed yet. The basic idea here is exchanging those orders among different plants in the enterprise. In other words, the available resources (i.e., the raw material in all plants) are re-allocated to customer orders based on the raw material constraint in plant 2. For this policy – which is called “order re-assignment policy”- two different settings are defined to experiment with the model:

- *Case 1: Decentralized (Plant-level) disruption management*

In this case, the affected plant (plant 2) itself tries to manage the disruption in its supply chain by negotiation with other production plants to exchange the orders. The disruption management process is done in four main steps:

1. Considering the current level of Base Oil2, plant 2 determines the schedule of orders in the plant.
2. For orders that are expected to be late, the order information is sent to other two plants.
3. Other plants reschedule their orders considering the new orders sent by plant 2. If fulfilling extra orders does not result in any delay in their previously-committed orders, they accept them; otherwise they determine their late orders and send this information to plant 2.

[1] It needs to emphasize that as the future pattern of orders is not certainly-known, each experiment with model is run several time (50 replications) with different order patterns as defined in section 7.3. Therefore, the results that are presented here are the average for those replications. For more details on number of simulation replications, please see section 7.6 of this thesis.

4. If none of production plants 1 or 3 accepts fulfilling the orders, plant 2 considers the orders received from plant 1 and 3 and reschedules its orders:

   a.Plant 2 checks if order exchange with plant 1 results in lower delay comparing with the lateness of job schedule in step1. If not, the negotiation with plant 1 is terminated. If yes, it proceeds to step 4-b.

   b.Plant 2 checks if order exchange with plant 3 results in lower delay comparing with lateness because of raw material delivery delay. If not, the negotiation with plant 3 is terminated. If yes, it proceeds to step 4-c.

   c.If the total tardiness because of fulfilling the orders of plant 1 and 3 is less than the lateness because of raw material delivery delay, the plant 2 will exchange its orders with the plant in which fulfilling its orders causes least delay.

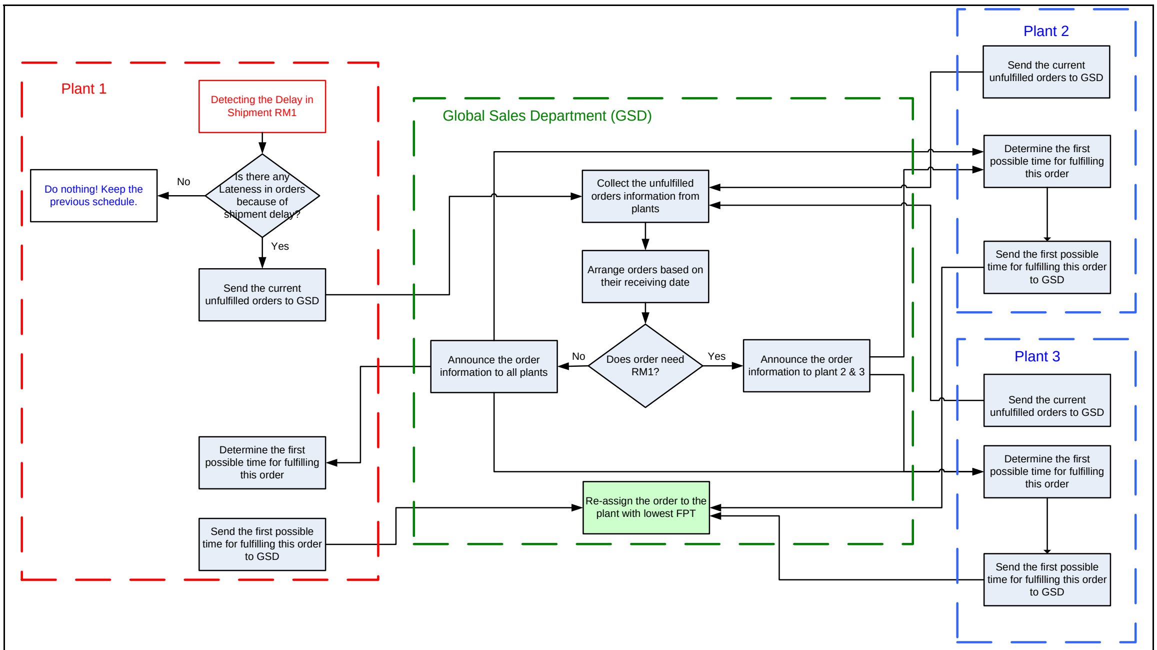
- *Case 2: Centralized (Enterprise-level) disruption management*

To handle the effects of disruption, Global Sales Department (GSD) collects the orders from all plants and re-assigns them considering the new raw material constraint for plant 2. The process has two main steps:

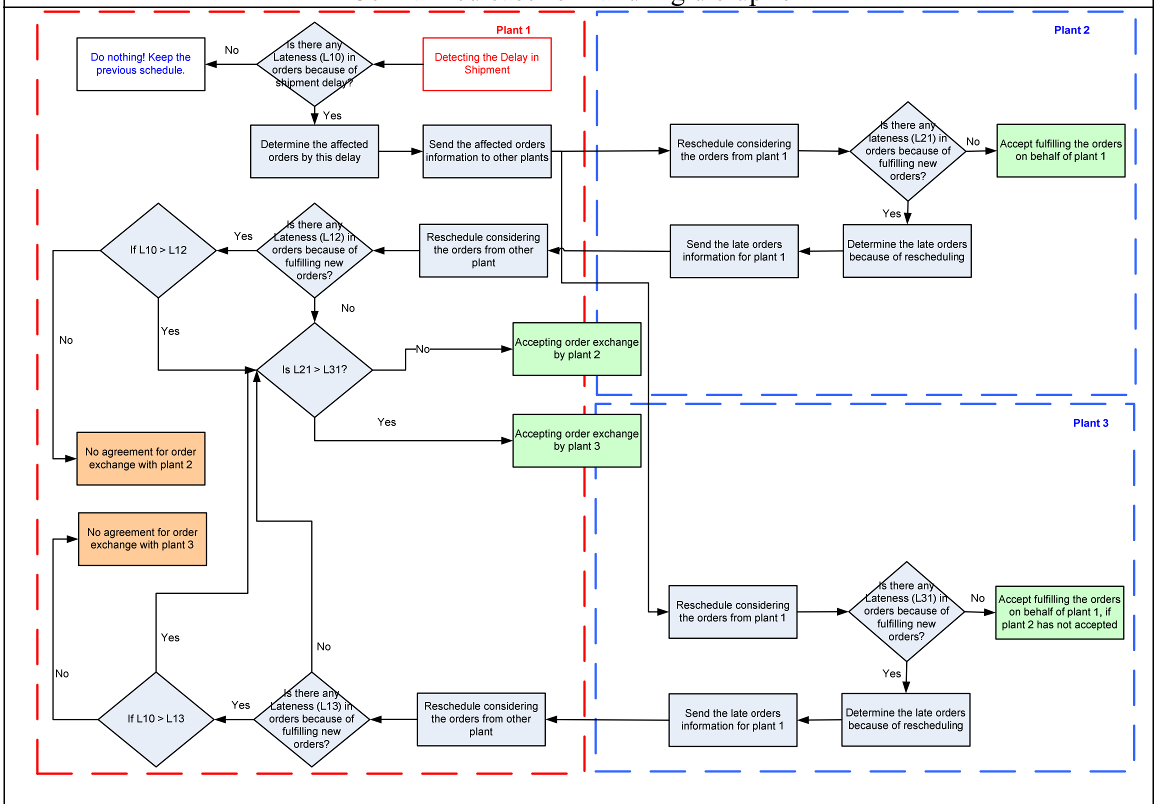
1. If the raw material disruption causes delay in the committed orders by plant 2, GSD collects the information of all unfulfilled orders from three plants.

2. GSD arranges all collected orders and sends them, one-by-one, to all plants taking into account that orders requiring unavailable raw material – i.e., Base Oil 2 - can only be sent to plant 1 or 3. After receiving the order details, each plant replies with the earliest date when it can make the product and deliver it to the customer. Based on the replies, GSD re-assigns the order to the production plant with the first possible date.

Both these two cases need changes in the behavioral aspects of system. This is conceptualized by a set of new Activities and Flows. The results of implementing these two cases are shown in Table 7.21. The decentralized policy improves the enterprise performance by reducing the number of late orders to 6 and total tardiness to 11. The centralized policy results in more significant improvement with 4 late orders and 7 total tardiness. Needless to say that for both these two settings, we assume the policy is immediately implemented after disruption detection (on day 46). Otherwise, more late orders must be expected by MPE.



Centralized case for handling disruption



Decentralized case for handling disruption

Figure 7.31. Decentralized vs. Centralized order re-assignment policy

Table 7.21. Simulation results for Decentralized and Centralized order re-assignment policy

	Order reassignment (Decentralized)	**Order reassignment (Centralized)**
Number of late orders by Plant 1	4	1
Number of late orders by Plant 2	1	2
Number of late orders by Plant 3	1	1
Number of late orders by all Plants	6	4
Total tardiness for Plant 1 (days)	8	2
Total tardiness for Plant 2 (days)	1	3
Total tardiness for Plant 3 (days)	2	2
Total tardiness for all Plants (days)	11	7

Two important aspects in this policy can be highlighted. Firstly, having a coordinator in the disruption case can improve the performance of the disruption handling process. Meanwhile, re-assigning orders causes delay in orders processed both in the affected plant (plant 2) and other plants in the enterprise. This is mainly because of increase in the load of orders in those plants. Subsequently, they are more sensitive to any imbalance in their operation (especially, the raw material availability can become a bottleneck when the utilization factor is increased in a plant).

The last response to disruption which is experimented here is “order negotiation policy”. The analysis of disruption detection step revealed that delayed orders because of disruption are either orders which are accepted before or after disruption is announced by supplier. The “order negotiation policy” tries to handle both types of orders. For the first orders, GSD starts re-negotiating with customers to extend the order due date. To handle the delay in orders which are received after disruption detection, GSD adjusts its order assignment policy in a way that for all cases of order completion date of Figure 7.2, the latest due date is considered as the committed delivery date to customers. These two actions, in fact, provide extra time for the enterprise to fulfill customer orders.

For this policy, as the acceptance of order due date extension is an uncertain factor we run the simulations with two possible parameter settings. For the optimistic case, the probability of customer’s acceptance to extend the due date is assumed 30%. For the pessimistic case, we assumed that this probability is 10%. Table 7.22 compares the results for these settings. These results are actually the average of 50 replications for each case. As can be seen, even in the pessimistic case, a reduction in the number of late orders can be achieved with this policy.

Table 7.22. Different policies to handle disruption impact

	Order Negotiation (10% acceptance)	Order Negotiation (30% acceptance)	Order Negotiation + Order reassignment (Centralized)
Number of late orders by Plant 1	5	3	1
Number of late orders by Plant 2	0	0	0
Number of late orders by Plant 3	0	0	1
Number of late orders by all Plants	5	3	2
Total tardiness for Plant 1 (days)	11	7	2
Total tardiness for Plant 2 (days)	0	0	0
Total tardiness for Plant 3 (days)	0	0	1
Total tardiness for all Plants (days)	11	7	3

Comparing the results of Table 7.21 and Table 7.22, “order negotiation policy” and “order re-assignment (centralized base)” are both appropriate policies and result in considerable improvement in order delivery performance of enterprise. However, “order negotiation policy” has a specific feature which makes it potentially more attractive; extending the due date in this policy not only reduces the number of late orders but also delays the disruption impact. In other words, the first delayed customer order happens later than in other experimented policies. This is especially important as it provides the additional time for the enterprise to look for alternative disruption management options.

Finally, the combination of the two cases of “order negotiation”[1] and “order reassignment (Centralized) policy” is experimented with the model. This combined policy can very well manage the impact of disruption in BOSuuplierForPlant2. In fact, MPE can even accept two late orders and ignore the raw material emergency procurement option. Certainly, many other alternative policies can be defined and experimented with the model. Meanwhile, different combinations and settings of above-mentioned policies are also possible to experiment. Nonetheless, the experiments mentioned here fulfill our aim to show that the presented agent-based modeling framework can support a better-informed decision-making in post-disruption process.

As a last point it is worth mentioning that both “order re-assignment policy” and “order negotiation policy” show how the normal procedures for operation of supply chain can be adapted in the case of disruptions to better handle the disruption impacts. Of course, after

[1] The simulation is with the assumption that 30% of negotiation is successful.

the system returns to the normal operation, the operational procedures must also return to pre-disruption settings.[1]

7.10.3. Numerical experiment 3: model application for Disruption Learning & Network Redesign

Once the enterprise recovers from disruption, it might decide to redesign the supply chain to minimize the likelihood of similar disruptions in future. The overall procedure to use simulation for supply chain redesign is similar to simulation-based risk analysis approach of section 7.9. First, some re-designing options should be defined by changes in the structure or operational behavior of supply chain. Next, the influence of these options should be evaluated under different disruption scenarios.

One option for network redesign which is experimented here is having dual suppliers for each production plant. This case is different from experiment of section 7.9 as the second supplier in the current case is not working as a backup supplier; but each plant has two suppliers for base oil and two suppliers for additives and the orders for each of raw materials are split between these suppliers. For the dual sourcing strategy, we considered two specific designs for the supply network:

- **Complete-dual sourcing:** in which each production plant has two suppliers for both base oils and additives. For numerical experimentation with the model, we assume that the orders are split 50-50 between two suppliers. We also assume that the price of unit of raw material is increased 10% in this case because of reduced size of orders.
- **Partial-dual sourcing:** in which plants have one main supplier for each material but there is also one second supplier for base oil and one second supplier for additives for all plants. We assume that each plant sources 80% of its needs from its main supplier and 20% of orders from second supplier. For this case, we also assume that the cost of unit of raw material from the second supplier is 20% more.

Both these two cases need defining new instances of Supplier and including them in the computer model. Changes in the logic of ProcurementDepartment Agents of each plant are also made to determine the frequency of order placement with each Supplier. Meanwhile, to define disruption scenarios, the probability of disruption occurrence and

[1] The time to return to normal procedures can be defined based on disruption detection experiment results. For example, for the case of this section in which last late order is delivered on day 71, the time to return to normal procedures is considered day 75.

the distribution of disruption in the Suppliers are assumed similar to values mentioned in section 7.9.

We also considered a third case of working with resilient suppliers. In fact, instead of dual supplier, plants source from one supplier which can return faster to its normal operation after a disruption. For this case, we assume that the likelihood of supplier disruption is still 0.005 but the duration of a disruptive event is sampled from a triangular distribution with a minimum value of 2 days, a most likely value of 5 days, and a maximum value of 10 days.

With these options to redesign the network of suppliers, the results of experimentation are presented in Table 7.23.

Table 7.23. Comparing different network redesign options

	No disruption management	Complete-dual sourcing	Partial-dual sourcing	Working with resilient suppliers	Combined pre/post disruption strategies
Average profit for 20 scenarios (m$)	9.65 (0.77)	10.48 (0.61)	10.13 (0.64)	10.01(0.70)	10.41 (0.63)
Average profit for 30 scenarios (m$)	9.58 (0.75)	10.45 (0.60)	10.09 (0.66)	9.97 (0.71)	10.44 (0.61)

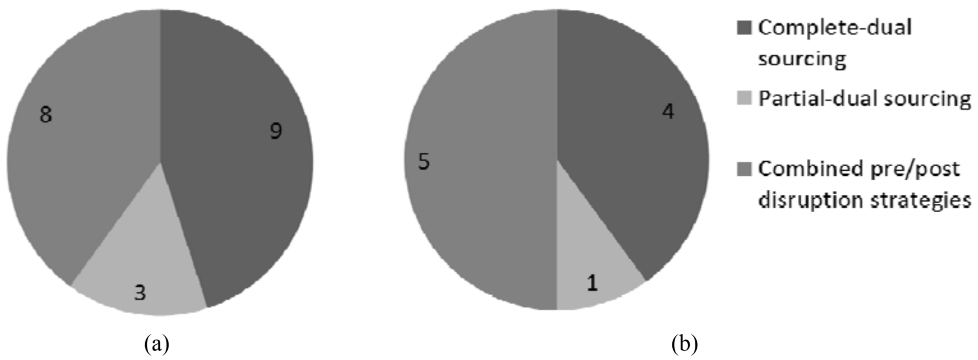


Figure 7.32. The distribution for different redesigning options: (a) first 20 scenarios; (b) for 10 extra scenarios[1]

Having dual supplier for each plant is an appropriate option in this case; however, it makes the organizational processes in the enterprise much more complex as a complex set of interactions between suppliers must be managed. The detailed analysis of this extra organizational complexity is beyond the scope of this chapter although it might impact the decision-making about possible restructuring.

[1] The case of resilient suppliers is not mentioned in this figure because for this case different set of disruption scenarios are defined based on the specific setting of supplier disruption in this case.

Having one extra supplier for base oil and additives for all plants (i.e., partial-dual sourcing case) can adequately reduce the risk of supplier failure in the production plants. This option can be, however, improved, by combining the pre- and post-disruption practices. More specifically, we consider a final experimental case - which is termed as "combined pre/post disruption strategies" in Table 7.23. This strategy includes three main changes in the system structure and operations:

- *Partial-dual sourcing* with features mentioned before.

- *Fast disruption detection*[1] option in which suppliers are obliged in their Contracts to announce their disruptions within 2 days after disruption occurrence.

- *Centralized order re-assignment* which is implemented immediately after disruption detection.

In other words, in this strategy a combination of different policies and factors to improve pre- and post-disruption management process is experimented. As can be seen this option performs as well as complete-dual sourcing option.[2] Of course, many other combinations of factors which are important in each step of disruption management process can be defined and experimented with the presented modeling framework. Moreover, for each separate step we can also zoom in and study the specific factors that influence the success of disruption management in that step. Meanwhile, more scenarios can be defined to compare possible options and validate the concluding recommendations. Nonetheless, with experiments of this section we mainly aimed to show the potential of developed modeling framework to support decision-making for handling disruptions in supply chain.

7.11.Discussion on modeling framework

In Chapters 5 to 7 of this thesis a modeling framework for managing supply chain operations - and more specifically, for handling supply chain disruptions – has been presented and discussed. The first step in developing this modeling framework was the choice of simulation paradigm. To this aim, we started describing a supply chain from a complex socio-technical perspective. Based on this system description, major characteristics of supply chains have been derived. These characteristics had two basic implications for conceptual modeling of a supply chain; firstly they provided a basis for selecting the appropriate simulation paradigm – i.e., agent-based modeling (ABM) - in

[1] In the real world, as a part of contract terms, a company can ask suppliers to announce any problem in their production facilities within a specific period of time.

[2] As can be seen, the results for these two options are very close and none of them significantly better than other option. To selct the best option between these two options, more scnerios are needed to experiment.

Chapter 5. Subsequently, the description of a supply chain as a complex socio-technical system was used as a basis in developing the conceptual model in Chapter 6. Meanwhile, the choice of ABM as simulation paradigm introduced some assumptions to the modeling and simulation and therefore, contributed to the conceptual modeling.[1] To develop the conceptual model, the existing supply chain management theories and the literature on disruption/risk management in supply chains are also used to specify the main factors which must be reflected in the model. With all these, an agent-based modeling framework has been developed and implemented in the object-oriented environment of Java (Figure 7.33). Developing this agent-based modeling framework has some specific implications for supply chain simulation:

- First, as emphasized by Axelrod, agent-based modeling (ABM) can be seen "as a bridge between disciplines" (Axelrod, 2006, p. 1565); it can be a useful means to connect different domains. This is, on the one hand, because ABM can address research questions common to many disciplines (i.e., disciplines which are working with systems that are composed of many interacting entities). On the other hand, to describe the decision rules for agents and the physical rules for technologies, we need to use different types of knowledge form different research domains. Therefore, ABM can work as a platform to connect different types of scientific disciplines. This is especially important for a domain like supply chain management (SCM) which is naturally a multi-discipline domain and is formed on the idea of integrating different domains like logistics, operations management and marketing (Shapiro, 2001). This view on ABM is also in accordance with the aim of simulation studies in Operations Research (OR) and Management Science (MS); ABM can be used to operationalize the theoretical constructs and available knowledge to help making better decisions and solving practical problems. Or as mentioned by Siebers et al. (2010): "ABS[2] might be considered as a tool to develop the relationship between the pure and applied branches of a particular discipline, in much the same way as experimental and theoretical physics have always been closely linked."
- The second important feature of the presented modeling framework is the *socio-technical perspective* in the model design. For SCM domain, this view has some important implications. Firstly, as mentioned before, it facilitates the

[1] The main assumption in ABM is that a system is modeled by defining Agents, their Environment and the interactions among Agents and between Agents and Environment.
[2] i.e., Agent-based simulation.

experimentation with different social and technical aspects in managing a supply chain. The second implication is about different views on supply chain management. It is frequently discussed in the literature that “SCM is about managing the interdependencies” (Greeff and Ghoshal, 2004) or “SCM is an integration philosophy” (Cooper et al., 1997). Despite this general consensus, there are two distinctive views about what must be integrated or which interdependencies should be managed - and subsequently, two types of definitions for SCM –in the literature. Some of the classic definitions of SCM put the emphasis on the integration of activities and business processes. We call this approach “activity-based” view. As an example of these definitions, the Association for Operations Management (APICS) defines SCM as the “design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand and measuring performance globally” (Cox et al, 1998, p.93). The second view on SCM takes an “actor-centric” perspective. In this view, the aim of SCM is aligning the firms that bring products to the market and creating incentives for collaboration across the supply chain (Lambert et al., 1998). Of course, these two views are not totally distinct as the actors in the system are responsible for performing activities and functional processes in the supply chain. These two definitions might also be more relevant for different boundary definition for a supply chain. The activity perspective is mostly about the internal supply chain; it focuses on the functional activities and on material and information flows within the enterprise. In this case, supply chain management may be viewed as the integration of previously separate operations within a company. On the other hand, the actor-centric view is mostly about the external supply chain of an enterprise which includes the enterprise, the suppliers of the company and the suppliers’ suppliers, the customers of the company and the customers’ customers.

One of the main strengths of modeling framework of this thesis is that it is compatible with both definitions of SCM and it is capable to model both perspectives. The Agents in the modeling framework represent the supply chain actors who perform the Activities or have a level of autonomy to make decisions on how and when an Activity must be done. Consequently, coordinating actors or activities in the supply chain can be modeled and experimented with this framework.

- The third feature of modeling framework is its *flexibility* to support decision-making about normal and abnormal operation of supply chain.

  Using this modeling framework, we can experiment with different aspects that impact the normal operation of a supply chain like different policies for different functional units in the system. The framework can also be used to support decision-making for disruption management in different steps of the integrated framework of Chapter 3. An additional issue about the flexibility of modeling framework is the possibility to experiment with *structural* and *operational* aspects of system. Moreover, disruption management practice might be defined by combining changes in the structure and behavior of system elements or might solely include changes in one of these two. The experimental factors can be considered in the *technical* or *social* level of the supply chain as well.

  In addition to conceptual elements, the flexibility of the modeling framework is enriched by the software implementation and the modularity of the object-oriented programming environment (i.e., Java). This modularity has two implications. Firstly, the Java objects can be seen as the building blocks from which instances for specific cases can be defined. These building blocks can be connected in different ways to carry out a number of different what-if analyses by changing supply chain configuration and input parameters (e.g., changing the policy for different parts of the supply chain or different number of suppliers or distribution centers). Modularity also allows connecting different models or re-using model components developed for a specific supply chain in *modeling other cases*. Of course, it might be necessary to customize the computer model for new specific cases.

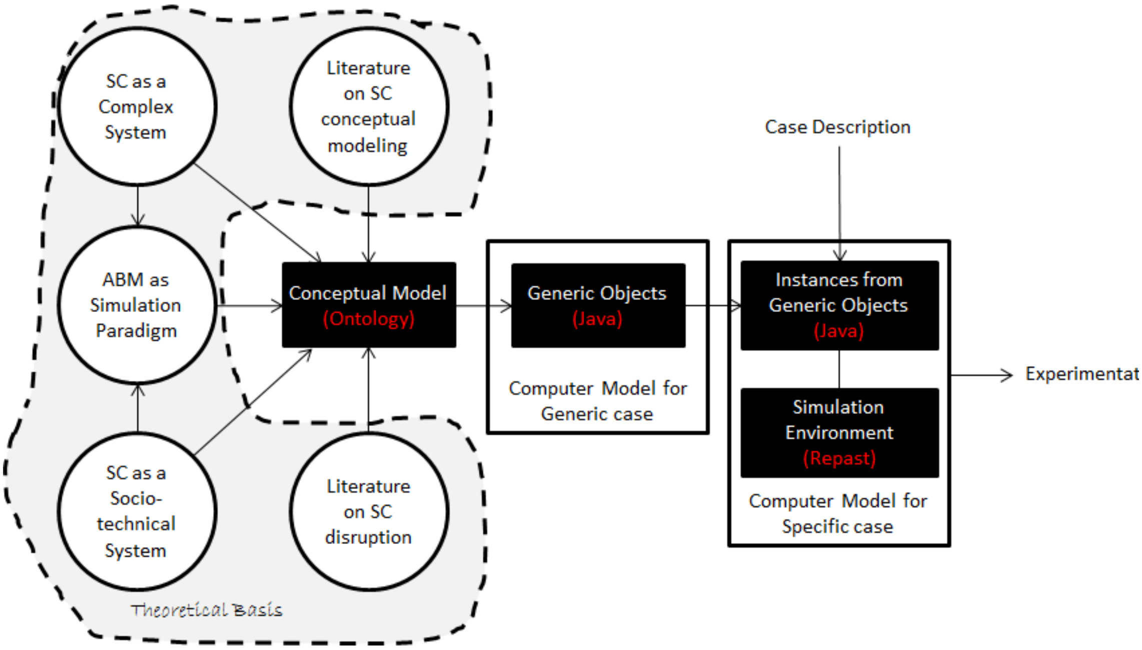


Figure 7.33. Model development process and deliverables

- The other point that must be emphasized here is that the primary goal of simulation is not making the final decision or finding the final solution for a problem; it is mainly about exploring the problem and increasing the information base from which a decision maker can decide what to do. Therefore, a simulation framework that can present more possibilities to experiment with many aspects of system is of more value for decision makers.[1] Our modeling framework provides the possibility to experiment with many settings for normal and abnormal operation of supply chain. These settings can be basically modeled by changes in the structural/operational elements of a supply chain. Meanwhile, the experiments can be designed by different factors in the social or technical level of system. With this broad range of possibilities, a model which is developed for a specific case can be used to explore many different settings to improve the supply chain (disruption) management processes.

To sum up, the modeling efforts of Chapters 5 to 7 have resulted in three main deliverables (Figure 7.33); a conceptual framework, a generic library of computer objects and a computer model which is customized for the specific case of a lube oil supply chain. On the way from the conceptual framework to the specific computer model for the lube

[1] Another possible application of this simulation framework is developing hybrid simulation-optimization models. Some important works on decision-making through simulation and optimization can be found in Mele et al. (2006a), Mele et al. (2006b) and Puigjaner et al. (2006).

oil supply chain, the generality of these deliverables is reduced. The conceptual framework is the most generic component. Instead of Java, it can be implemented in other programming and simulation environments. The Java objects that are defined for each concept are still generic enough to be customized for different specific supply chain cases. Of course, for different cases, different instances from these generic objects must be defined. Lastly, the computer model for the lube oil supply chain emulates the behavior of actors and the functional processes for this particular case. Nonetheless, this computer model can also be customized for other cases or considered as a starting point for model development. It must also be emphasized that the model development is an iterative process; the conceptual model and generic objects can be improved by defining new concepts for specific cases or by including more details based on the theoretical background about the system. Extending the current model is especially facilitated by the object-oriented nature of the software environment.

As a last point, it is worth noting that the conceptual framework can be seen as a communicative means between different actors involved in the simulation process including the modelers and problem owners. It can facilitate exchanging thoughts and sharing knowledge on system components and the important aspects that must be included in the model. In addition, the conceptual framework – by its formal structure - can support its users to better understand their supply chain and the disruption management even if they do not use it for modeling and simulation purposes.

7.12.Application of modeling framework for future cases

In Chapter 6 of this thesis, a conceptual modeling framework for supply chain (disruption) management has been presented. The concepts in the framework were also coded in Java programming language. Next, the generic Java objects were customized for the case of a lube oil supply chain by sub-classing and composing instances. Consequently, an agent-based model has been developed which was used in Chapter 7 to experiment with several issues related to normal and abnormal operation of lube oil supply chain. The modeling framework and Java objects, however, can be used to develop models for other supply chains in a similar way. The process for developing and experimenting with such a model is represented in Figure 7.34. This process consists of two main stages:

(1) Developing the computer model:

To design a computer model for a specific case, first, a clear description of the system under study must be provided. Next, this case description must be conceptualized in terms of main concepts in the modeling framework and subsequently the instances of generic Java objects must be created. In the modeling framework, we made a distinction between *static* and *dynamic* representation of a supply chain. Moreover, for static representation, the distinction between *structural* and *operational* components has been discussed. Based on this distinction, building the computer model must be done in the following sub-steps:

- **Define the static representation of a supply chain**: static representation of a supply chain is deciding which objects must be included in the simulation model. These objects are describing the *structure* or *operation* of a supply chain, the *environment* and also the interactions between the supply chain and its environment. Meanwhile, for the case of modeling for disruption management, instances of *SupplyChainDisruption* class must be defined and included in the model.

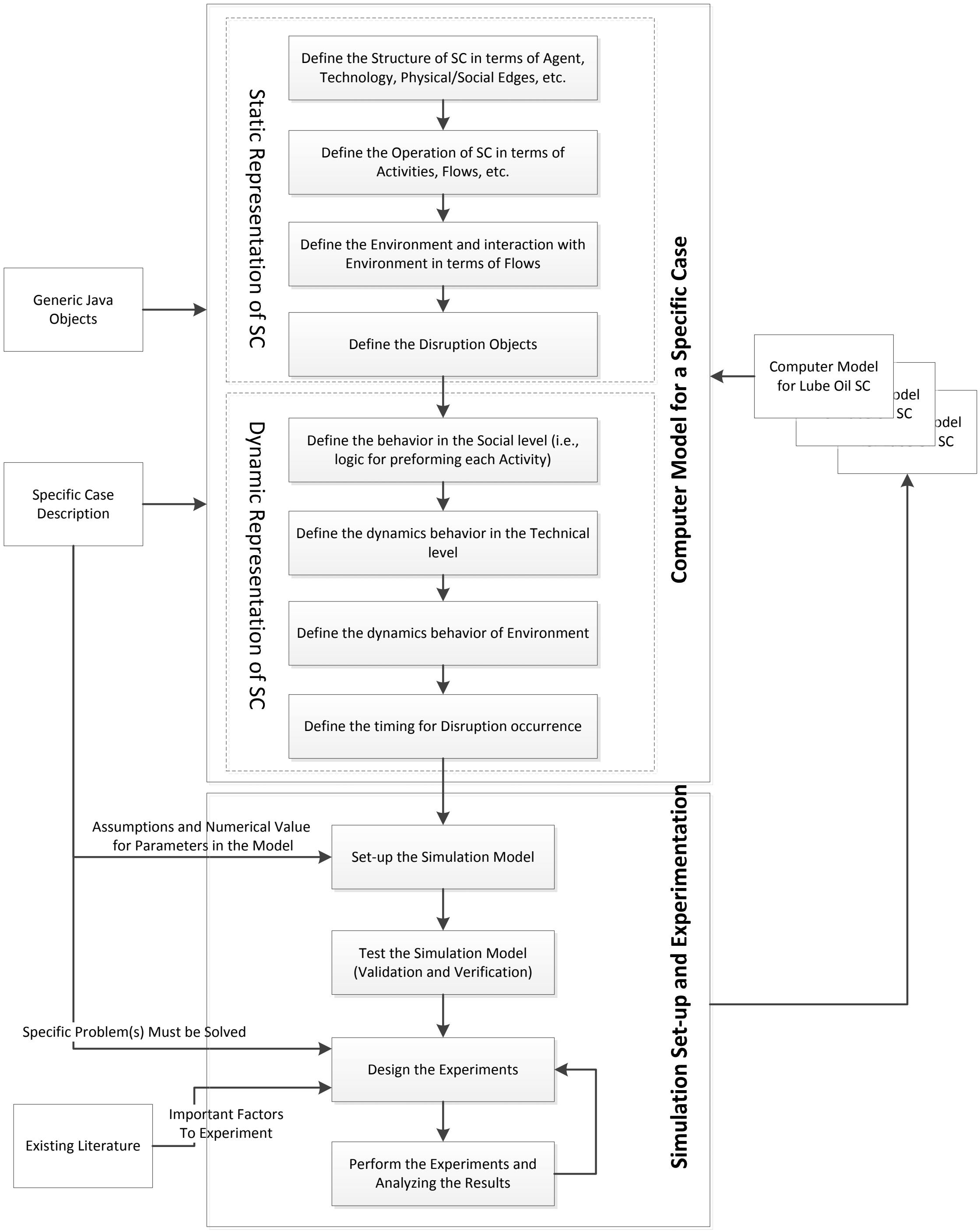


Figure 7.34. Process for developing models for other case studies

In conceptualizing the *structure* of a supply chain, two concepts are the central concepts: *Agents* which are the decision-making units in the social level of a supply chain and *Technologies* which represent the physical installations in different parts of a supply chain. Moreover, the links between Agents (in terms of Contracts and OrganizationalConnection), between Technologies (in the form of PhysicalConnection) and the relations between Technologies and Agents in the form of Ownership must be clearly defined and included in the model. As the structure of the system is defined, next, we must define the *operational* entities in the system. In our modeling framework, the operation of a supply chain is primarily defined by two main types of constructs: the *Activities* that are done by each Agent and the *Flows* which describe the interactions between supply chain entities during its operation.

- **Define the dynamic representation of a supply chain**: as the building blocks of a supply chain are defined and the necessary instances of Java objects are included in the model, the next step is to define the dynamics of system operation; what is happening at each time step when the simulation model is run.

  Four main possible sources for dynamic behavior can be considered in each model. The first and most important driver for dynamics in the system is the execution of Activities by Agents in the model. In each time step of simulation, each Agent decides about the next Activity to perform and how to perform it. By performing Activities, the state of Agents and Technologies is continuously changing throughout the simulation. Consequently, the logic of execution of Activities by each Agent must be defined in the model before running the model and experimenting with model. This logic can be shown by flowcharts before implementation in the computer model. These flowcharts describe the details on *when* an Activity must be started, *what decisions* must be made for that Activity, *how* those decisions must be made and *which aspects of system* are influenced by performing this Activity. Moreover, there are cases in which more than one Agent is involved in performing one Activity or making decision about its specification (e.g., when that Activity must be done). For these cases, the negotiation process must be conceptualized using the concepts in Table 6.2 and implemented in the computer model.

  In addition to Agent's decisions and Activities, the state of technical artifacts – and subsequently, the state of system as a whole - might be also changed by physical rules. An example is the dynamics of producing goods in a production line or the dynamic degradation of raw material quality in the storage tanks. In both cases, the physical rules need to be defined by algebraic equations and included in the model. Similarly, the Environment can be also a source of dynamics in the system. For example, the raw material price or demand pattern might change during time which must be shown by equations in the model.

And finally, for the case of model application for disruption management, the disruption objects also influence the dynamics of system operation. More specifically, when the simulation time equals disruptionOccurenceTime, the disruption model changes the disruptedAttribute of disruptedObject to disruptedValue and its Status to "disrupted". The disruptedObject returns to normalValue when the simulation time equals "disruptionOccurenceTime + disruptionDuration". If disruption has a gradual recovery profile, at each simulation time step, the disruption class must update the disruptedValue for disruptedAttribute.

These four sources cause the dynamic behavior of a supply chain and must be defined in each computer model.[1]

It must be emphasized here that the models and instances which have been created for previous cases can be customized and used in developing computer models for a new specific case. This is especially facilitated by the object-oriented implementation of the modeling framework in which the "building blocks" (e.g. Agents or Technologies) can be easily and independently connected and re-used in other models.

(2) Simulation set-up and experimentation with model:

When the static and dynamic representations are defined and implemented, the computer model for a specific case is ready. The next stage is the simulation set-up and experimentation with developed model. Firstly, the initial value for the attributes of each instance in the model must be defined. We call this step simulation model set-up. Model set-up also implies making the assumptions explicit for those aspects of the system for which the exact value is not available. The numerical values and some specific assumptions in the model are defined by the case description. With these initial values,

[1] At each time step of simulation, the changes imposed by disruption object, environment object and the physical rules in the state of system components must be done before Activity selection and performing by Agents.

the model can produce numerical value for different parameter settings. The simulation model, however, must be verified and validated through a set of preliminary experiments before conducting the experiments to examine the impact of different factors on the operation of supply chain. Of course, the verification and validation tests are not limited to the initial version of a model; in all steps of simulation, whenever the changes in the model are made, the verification and validation must be done before defining the experiments and analyzing the experiment results.

Once the computer model is ready and tested, it must be used for examining the performance of alternative system configurations and/or alternative operating procedures for a system. Through experimentation with the model several changes in the model can be done[1] to obtain a better insight into the nature of dynamic behavior of supply chain and find solutions to the problems in a supply chain. Based on the modeling framework of this thesis, these changes can be:

1- **Structural changes** in the system which include:

- Defining new entities (in the social or technical level of system) or removing some entities
- Defining new properties for current entities

2- **Operational/Behavioral changes** in the system which might be:

- Defining a new set of Activities for Agents
- Defining new logic for current Activities

If a developed model is used for disruption management, the input of a simulation experiment can be also different disruptions or different disruption management practices. Of course, these disruption management practices can be also defined by structural and behavioral changes in the model. Meanwhile, the experiment design for disruption management may need considering extra issues like defining disruption scenarios as we discussed in section 7.10.

After designing experiments, we must run the simulation model and study the impact of changes on the important performance measures[2] – which are used for decision-making or solving a specific problem. The results of an experiment run, however, can be impacted because of randomness in the model. Meanwhile, the starting conditions can be

[1] As mentioned before, these changes are called “input” in the experiment design for simulation studies.
[2] These performance measures are usually called “output” in the experiment design for simulation studies as we discussed in section 7.6.

different. Therefore, every experiment with the model should be carried out several times and then the results of the individual trials averaged together.

After conducting the experiments, the results need to be analyzed to answer the questions that motivated the design of the experiment. After analyzing the results of experiment runs, it may be necessary to go back to the first step of experimentation to redesign the experiments taking into account the insight gained so far. There might be new important factors that are identified and call for further experimentation. There can be also new performance measures of interest which can be considered as output in designing new experiments. Accordingly, the simulation modeling and experimentation must be seen as a learning process. After designing some experiments and analyzing the results, the insight can be used to make other assumptions or other changes in the simulation model and experiment with other factors.

The specific computer model that is developed and experimented based on this process can be also used or customized for other case studies in future.

7.13.Chapter summary

This chapter describes the application of modeling framework of Chapter 6 for a specific case of lube oil supply chain. We firstly discussed how the description of this specific case can be translated to the modeling components in the framework. Afterwards, it is shown how this computer model can be used to support decision makers in managing different aspects related to normal operation of their supply chains. We specifically, designed experiments to show the application of model for decision-making in inventory management process and order acceptance process in the lube oil supply chain. Next, the model’s application for handling disruptions in different steps of InForMDRiSC has been discussed in two separate parts. First, the experimentation with model to support decisions in pre-disruption process was described. Next, the model’s use for post-disruption steps was demonstrated and discussed. With different experiments performed with the model in this chapter, agent-based modeling framework of chapter 6 is proved to be a valuable simulation framework to address the main issues and important aspects in modeling for supply chain disruption management- as we discussed in chapter 5. Firstly, it can capture the complexity of supply chains in both social and technical level. In addition, it is very flexible to define a broad range of experiments with different scenarios to answer “what if” questions, which is critical to support decision-making in different steps of disruption management process. Moreover, as models are developed in a modular object-oriented environment, it is relatively simple to change the configuration:

it is easy to include new actors in the system (e.g. more suppliers with different prices and lead times in the supply chain) or to adjust the physical or social configuration (e.g. extra storage tanks for the refinery or production plants) of the system. Accordingly, a model which is developed for a specific case can be used to explore many different settings to improve the normal and abnormal operation of supply chains.

8.CONCLUSIONS AND FUTURE RESEARCH

This chapter summarizes the contributions of this thesis and discusses some possible directions for future research.

8.1. Conclusions

Today's global supply chains are delivering products and services to the market faster and cheaper than ever before. Yet, these advances have come at the price of an increased vulnerability of supply chains; new risk factors are introduced and when disruptions happen, their negative impacts can propagate much faster across the global supply network because of its high level of interconnectedness. To cope with this increased vulnerability, we argued in Chapter 1 that companies must actively work to manage the risk of disruptive events in their supply chains. This, on the one hand, needs a systematic framework to guide their efforts in managing supply chain disruptions. On the other hand, due to the complexity of supply chains, decision support tools are needed for the decision makers involved in different stages of the supply chain disruption management process. Based on these observations, two main questions have been defined for this research: *"How can disruptions be systematically handled in supply chains?"* and *"How can appropriate models be developed to support better-informed decision-making in handling supply chain disruptions?"* Answering these two research questions has resulted in a "(simulation-based) integrated framework for handling disruptions in supply chains" which consists of two part. The first part, called InForMDRiSC[1] guides the main process steps in handling disruptions. The second part contains a modeling approach to support decision makers in the relevant steps of the InForMDRiSC. These two contributions and a set of findings throughout this thesis are presented in the following subsections. After reflecting on the research method and applications in section 8.2, recommendations for future research are given in section 8.3.

8.1.1. An integrated framework for handling disruptions in supply chains

In Chapter 2 of thesis, two common perspectives on handling disruptions in supply chains were identified: preventive or *pre-disruption* perspective which focuses on pro-active

[1] Integrated Framework for Managing Disruption Risks in Supply Chains.

measures to avoid possible disruptions or to minimize the exposure to their potential impact and the re-active or *post-disruption* perspective which focuses on what must be done after a disruption has materialized in the real world.

With proper investment in risk prevention, companies face fewer disruptions or less severe disruptions in their supply chains. However, not all possible disruptions are known to the company and even for known ones, no company can afford to invest in managing all of them. Moreover, having resources and pre-defined plans in place does not guarantee success in coping with actual disruptions. How to use those resources and execute plans in real-time is also a critical issue. Furthermore, pre-defined disruption management plans, if not reviewed periodically, may be based on outdated assumptions. Indeed, when a disruption happens, the capability to gather accurate information about the event and the state of system, and to adjust the pre-defined plans to the actual information is as important as the response plan itself. These obervations call for an integrated approach in which the ex ante and ex post handling of supply chain disruptions are interlinked.

> *Conclusion 1: To systematically and comprehensively handle supply chain disruptions, both the pre- and post-disruption management process need to be addressed in coherence.*

In Chapter 2, we reviewed the literature on handling supply chain disruptions and found most contributions focusing on either the pre- or post-disruption management process. The few contributions covering both the pre- and post-disruption process in an integrated way are either too situation-specific or too general, lacking the detailed process design that is needed to make it operational for specific cases. This gap was the main motivation for the work presented in this thesis.

Building on the findings presented in the literature, an integrated framework for managing supply chain disruptions has been developed in Chapter 3. This framework, henceforth called InForMDRiSC, describes comprehensively all steps in handling supply chains disruptions - before and after their occurrence (Figure 8.1).

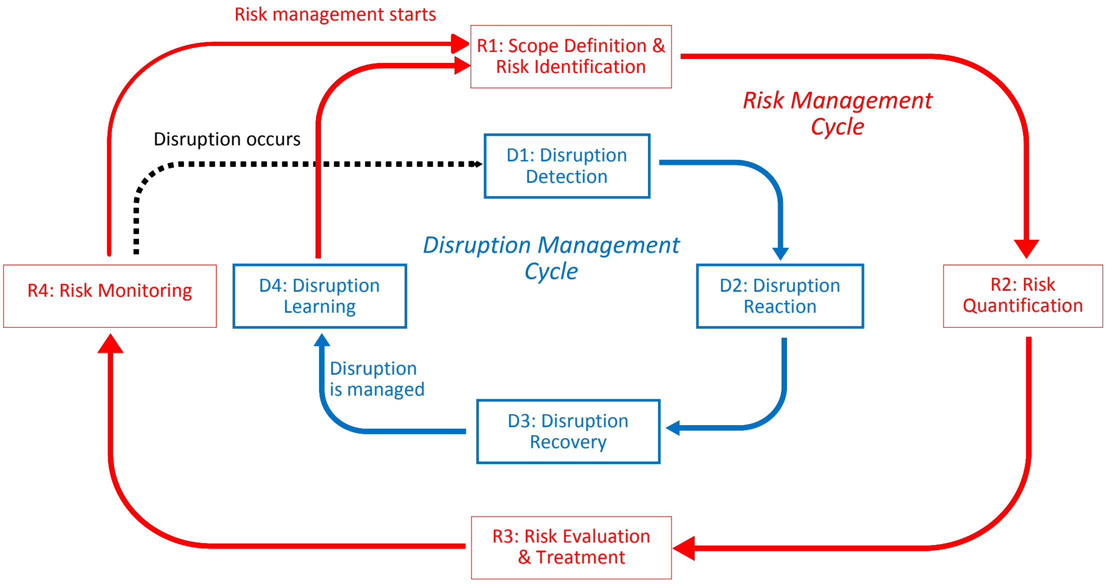


Figure 8.1. The structure of the Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)

InForMDRiSC has two main cycles. The first cycle – the *Risk Management Cycle* - is about *potential disruptions*. Firstly, the potential disruptions in the supply chain (or a subset of supply chain that is selected for study) must be identified (**R1: Scope Definition & Risk Identification**). Next, for the potential disruptions identified, the expected impact on the objectives and the performance of the system must be evaluated (**R2: Risk Quantification**). Having the risk level, the next step is to determine which potential disruptions need treatment and how they must be treated (**R3: Risk Evaluation & Treatment**). If (after treatment) the risk level seems acceptable, supply chain operations proceed. However, the level of risk must be continuously monitored (**R4: Risk Monitoring**). Due to changes in the system (e.g., changing customer needs or partner strategies) or in the business environment (e.g., new regulations or new competitors), the likelihood and expected impact of potential disruptions keep changing. Besides the risk profile, the system boundaries and structure of a supply chain may also change. For example, a new supplier might be added to the supply base, a new warehouse might be launched or a new set of products might be introduced to the market. As a result of these changes, the system definition – that is the starting point of the whole disruption management process - would change and it is therefore imperative to repeat the whole *Risk Management Cycle* by defining the new system and identifying the new *potential disruptions*.

The second cycle in the integrated process is the *Disruption Management Cycle*. Despite enough safeguards, sometime, an *actual disruption* will happen. To handle the disruption, the first step is detecting that disruption and estimating the expected impact as quickly as possible (**D1: Disruption Detection**). Once it is detected, the company must react quickly to manage the impact of the disruption and return the supply chain to normal and planned operation. The primary response should be on the basis of pre-defined response plans previously defined in the Risk Evaluation and Treatment step (**D2: Disruption Reaction**). If the pre-defined response plan is found inadequate to control the impact of disruption or if no response plan has been defined for a specific disruption, the firm(s) must quickly find alternative solutions and implement them to restore the normal supply network operation (**D3: Disruption Recovery**). After the actual disruption is fully managed and the system is restored to normal operation, the company must review the process and draw explicit lessons for handling similar disruptions in the future (**D4: Disruption Learning**). This is, in fact, the feedback loop from the *Disruption Management Cycle* to the *Risk Management Cycle*. Moreover, during managing an actual disruption, a number of changes in the configuration and structure of the supply chain might be made that necessitate repeating the *Risk Management Cycle* by a new system definition and identifying new potential disruptions.

With the step-wise presentation of the interconnected risk and disruption management cycles, InForMDRiSC describes a comprehensive integrated process for managing supply chain disruptions, which is generic in its applicability to any supply chain and detailed enough to be made operational for specific supply chains. The interactions and feedback loops between the various steps in the pre- and post-disruption cycles are further detailed in Appendix A of this thesis.

InForMDRiSC was presented to domain experts from academia and industry (including experts in supply chain management, logistics and operations management) for evaluation of its consistency and its usefulness. The experts' evaluations confirmed that an integrated approach to managing disruption risks and actual disruptions in supply chains is an important and necessary issue. InForMDRiSC is also acknowledged as a better process for handling disruptions than separate risk and disruption management processes. The majority of experts found the InForMDRiSC framework clear and useful to get a better understanding how to handle supply chain disruptions.

> *Conclusion 2: InForMDRiSC provides a comprehensive framework that integrates the risk management cycle and the disruption management cycle, which*

can be made operational for any global supply chain and which is evaluated by experts as complete, consistent and useful.

To make the framework operational, in Chapter 4 of thesis, the literature was reviewed in more depth for each step presented in the InForMDRiSC to identify the key issues and approaches reported for specific steps. In this review, the majority of contributions were found to focus on the pre-disruption process, with different levels of attention for different steps of the risk management cycle. Some steps, such as risk identification and risk treatment, have been explored extensively while risk monitoring and risk quantification have been given far less attention. Moreover, whereas some modeling and simulation tools are presented to support decision-making in the risk management cycle (pre-disruption), the application of modeling and simulation for the post-disruption management process has not been addressed adequately in the existing literature. Besides, simulation and modeling studies to support the decision makers in better handling disruptions throughout all steps of InForMDRiSC are lacking. To close this gap, a modeling and simulation framework was developed and its applicability to support InForMDRiSC as an integrated risk and disruption management process framework was illustrated in the rest of thesis.

8.1.2. A modeling framework for disruption management in supply chains

The second contribution of this thesis is a simulation framework for managing disruptions in supply chains.

To support the implementation of InForMDRiSC in global supply chain management practice, a flexible modeling and simulation environment is needed that enables decision makers to experiment with alternative risk and disruption management strategies. Further, it should be taken into account that global supply chains are characterized by both technical and social complexity. Therefore, disruptions and disruption management practices should be addressed at both the technical and the social dimension of these systems. The simulation paradigm that is best equipped to capture both the social and technical complexity of global supply chains is Agent Based Modeling (ABM). This simulation paradigm is, moreover, the only one that allows the internal system structure to change over time, which is an important feature of supply chain disruptions and disruption management strategies.

The development of supply chain simulation models from a complex socio-technical systems perspective is absent in the literature, except for the work of Van Dam (van Dam and Lukszo, 2010), which has been used as the starting point for developing the conceptual model of a supply chain in this thesis.

In each simulation study, the first step is choosing an appropriate simulation paradigm; a modeler must investigate which simulation paradigm is a better fit for the system and problem of study. This step is mostly overlooked in the simulation studies; however, it is especially important because each simulation paradigm is characterized by a set of core assumptions and some underlying concepts to describe the world. These assumptions, basically, constrain the development of a conceptual model for the system of study.

To select the appropriate paradigm, we described a supply chain from a complex socio-technical perspective. Based on this system description, major characteristics of supply chains have been derived. Next, three simulation paradigms which are usually used for simulation of complex systems and are also the most-frequently used methods in supply chain simulation literature – i.e., System Dynamics (SD), Discrete Event Simulation (DES) and Agent-based Modeling (ABM) – were critically compared and evaluated. Based on this evaluation, we concluded that ABM is the modeling approach which has the most flexibility to capture the properties of supply chains as complex socio-technical systems and also provides the greatest flexibility in experimenting with different settings in a disruption management problem. Consequently, it has been chosen for the model development in this thesis.

> *Conclusion 3: Agent-based modeling (ABM) is the appropriate simulation paradigm to capture the characteristics of global supply chains as complex socio-technical systems.*

The agent-based modeling framework for supply chain disruption management was developed in three steps, as depicted in Figure 8.2. In the "Supply Chain Modeling" step, an agent-based representation of a supply chain was made which formalizes the description of a supply chain as a socio-technical system. Thus, the *Agent* (representing the decision-making units in the system) is the central concept in the social sub-system which is responsible for control and operation of a set of *Technologies* (representing the physical components in the system). The conceptual modeling step also draws on existing supply chain management theories to specify the main factors which must be reflected in the model to describe the *structure* and *operation* of each supply chain. All these concepts were formalized in the ontology for a supply chain. This ontology is, in fact, the conceptual model for a supply chain as a complex socio-technical system. In the second step, "Disruption Modeling", a conceptual model of supply chain disruption has been formalized based on the existing literature on disruption/risk management in supply chains. In the third step, we described how different "Disruption Management" practices can be defined and implemented in the model. Together, the three resulting modeling components present a comprehensive conceptual modeling framework for disruption management in supply chains. The concepts in the modeling framework were encoded in Java programming language and a set of generic objects has been developed which can be customized for specific cases by sub-classing and composing instances (Figure 8.3).

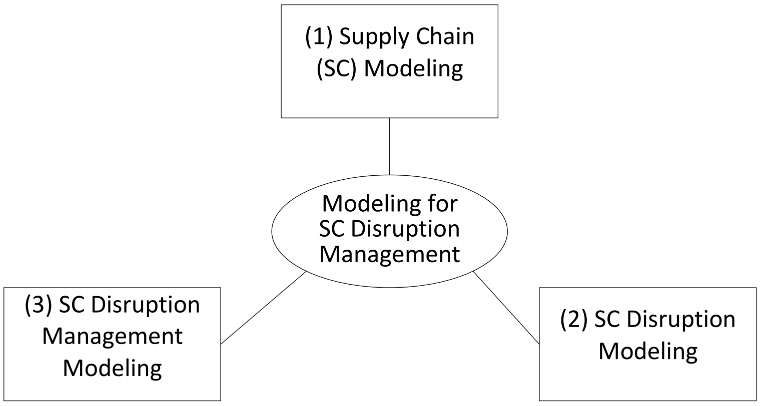


Figure 8.2. The steps in developing the supply chain disruption modeling framework

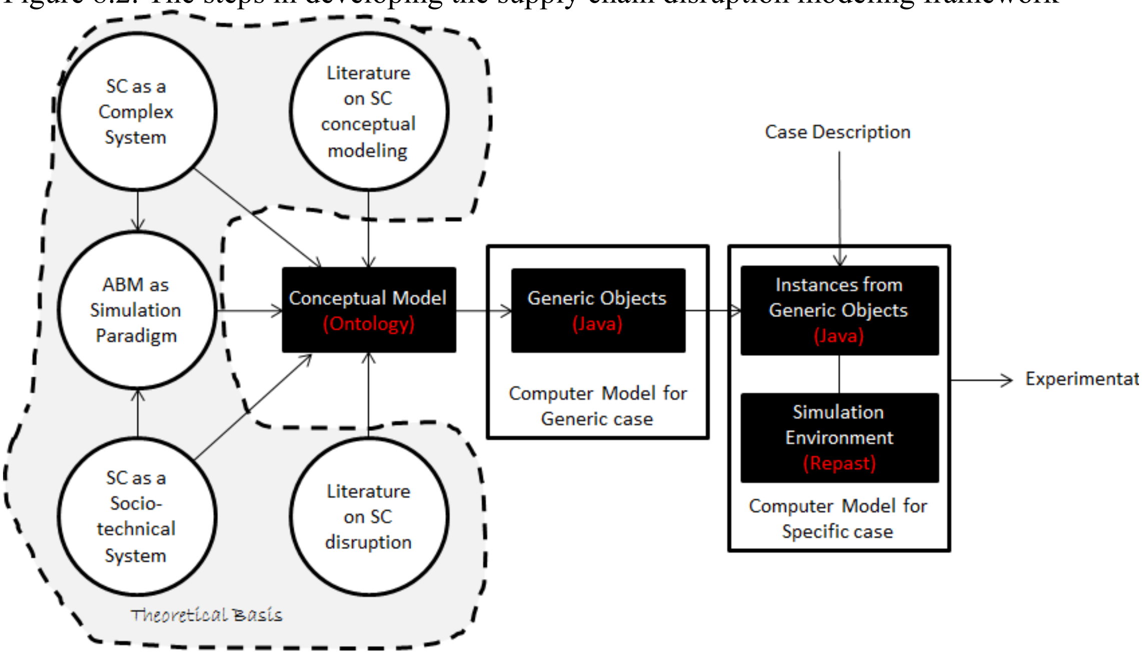


Figure 8.3. Model development process and deliverables

The modeling framework of this thesis is very flexible in modeling different types of disruption and disruption management practices. Firstly, disruptions and practices can be defined in both *social* and *technical* entities in the supply chain. Moreover, disruption management can happen by changing the structure or behavior of system elements. As examples for structural changes, the performance of a supply chain can be improved by changing the characteristics of physical facilities (e.g., increasing the storage capacity) or by a new contract with a backup supplier. As an alternative, to handle disruption we can define new logic for decision-making or different types of activities for different agents in the system.

In addition to the conceptual elements, the flexibility of the modeling framework originates from the software implementation and the modularity of the object-oriented programming environment (i.e., Java). This modularity has two implications. Firstly, the Java objects can be seen as the building blocks from which instances for specific cases can be defined. These building blocks can be connected in different ways to carry out a number of different what-if analyses by changing supply chain configuration and input parameters (e.g., changing the policy for different parts of supply chain or different number of suppliers or distribution centers). Modularity also allows for connecting of different models or re-using of model components developed for a specific supply chain in modeling other cases. Of course, it might be necessary to customize the computer model for new specific cases.

> *Conclusion 4: An agent-based modeling framework for supply chain risk and disruption management has been developed and illustrated in this thesis as a flexible platform for experimentation with alternative strategies.*

The implementation of the modeling framework is extensively discussed in Chapter 7 for the specific case of a lube oil supply chain in managing normal and abnormal operation. We first discussed how the modeling framework can be used to develop a case specific simulation model and how such a model can support the decisions to be made in different steps of InForMDRiSC. Based on the experiments, we also showed how presented simulation framework can improve the performance of a supply chain (in terms of, e.g., profit) and help a faster detection and reaction to possible disruptions in a supply chain.

Although the development of the ABM framework was inspired by the InForMDRiSC framework, both frameworks can be seen as separate contributions in their own right. On the one hand, even if we do not implement the simulation framework, InForMDRiSC can be used as a comprehensive process for handling supply chain disruptions. On the other hand, the ABM framework can also be utilized independently to build simulation models for specific supply chains and employ these to experiment with different factors which influence normal supply chain operation and can be manipulated to prevent or recover from supply chain disruptions. It is evident though that most benefit can be derived from combining both the process and the modeling framework.

Conclusion 5: The practical use of the agent based modeling framework has been demonstrated for the specific case of a lube oil supply chain. The case specific simulation model provides support for the decisions to be made in different steps of InForMDRiSC and was found to support making better-informed decisions both in normal operation and in different steps of supply chain disruption management.

8.2. Reflection

In this section we reflect on two scientific aspects of this thesis; firstly, the method which is used for developing the integrated framework and its applicability for practical cases and next, the method used for model development – i.e., agent based modeling.

8.2.1. Reflection on InForMDRiSC development and application

The integrated framework of this thesis has been developed based on existing literature on supply chain risk/disruption management. To validate the framework and evaluate its applicability and usefulness, it has been shared with domain experts from industry and academia. Their feedback is promising for the value added of InForMDRiSC versus existing practices and methods. At the same time, some experts commented on the complications to be foreseen in embedding the framework in the organization of industrial firms, since the responsibilities for the risk management and the disruption management cycle usually reside in different departments, at different management levels. The proactive risk management cycle is largely a strategic issue, whereas the reactive disruption management cycle is mostly handled at the operational level. Implementation of the integrated framework would at least require an explicit organizational embedding of the feedback loops between the two cycles. Another related issue is the inter-organizational nature of supply chain disruption management. Ideally, InForMDRiSC should be applied in a multi-actor setting, involving each of the supply chain partners or at least the most critical partners. How to approach these issues is evidently a topic for further research, which should involve actual application trials with InForMDRiSC in different global supply chains, by industrial experts themselves. Conducting pilot studies will be useful to acquire insight into how much more effort is needed for a company to switch from two single perspectives (pre- and post-disruption) to an integrated approach of supply chain disruption management. Such pilot studies will also help to verify the expected benefits of such switching and shed more light on the barriers encountered in the practical application of the InForMDRiSC framework.

8.2.2. Reflection on simulation framework development and application

As we discussed in Chapter 6, the simulation framework of this thesis has been developed based on a previously-presented framework for modeling socio-technical infrastructure systems. This framework is developed by a joint work of a group of researchers in Energy & Industry group at Delft University Technology. It is also used by different researchers to design models for different types of infrastructures including transport (van Dom, 2009), energy (van Dom, 2009; Chappin, 2011) and industrial clusters (Nikolic, 2009). We have used this socio-technical modeling framework and extended it based on the available literature and accepted theories for supply chain modeling. The application of our modeling framework is, however, dependent on the acceptance of such a socio-technical view by practitioners and scholars in the supply chain domain. At the moment, the dominant view in the supply chain modeling is on technical issues and simulation of material flow in the network. The directions for future research on the socio-technical perspective on supply chains are discussed in the following and can facilitate the acceptance of such a view. The acceptance of framework also depends on the acceptance of ABM by practitioners as an appropriate simulation paradigm. In the next sub-section, we discuss some of barriers in the acceptance of ABM. Finally, before using this framework for simulation of real-world supply chains, we must further evaluate the framework by implementing in some other case studies and making the changes, if needed.

8.2.3. Reflection on agent based modeling (ABM)

In Chapter 5, we extensively argued that ABM is the appropriate simulation paradigm to capture the complexity of a socio-technical system – such as a global supply chain. Other simulation paradigms that are frequently used for modeling socio-technical system – i.e., system dynamics (SD) and discrete-even simulation (DES) – offer less flexibility to reflect on the structure and characteristics of supply chains and to experiment with more factors influencing the operation of supply chain. It should be stressed, however, that using ABM is justified solely as long as a fairly good description of micro-level behavior of system – i.e., Agents – is available or can be discovered by observation and discussion with involved actors.

Further, the other barrier that impacts the broad application of ABM for industrial cases is difficulty in coding agent-based models. In fact, developing an agent-based model mostly needs a good knowledge of (object-oriented) programming languages (especially, Java). In spite of the fact, although several academically-developed tools for ABM (like Repast or NetLogo) are available, the commercial software tools with "drag and drop" features are still lacking. As ABM is a relatively young modeling approach, an extensive effort is needed to make it applicable in the industry in a user-friendly way.

8.3. Recommendations for future research

In this section, a number of possible directions for future research are outlined.

8.3.1. Extending the Integrated Framework (InForMDRiSC)

The integrated framework InForMDRiSC of this thesis is one among a very few efforts to combine the pre-disruption and post-disruption management process. The steps of InForMDRiSC, their inter-relations and how they support each other in the whole process of disruption management can still be further studied in future research. As a starting point, we recommend the application of the extended framework of Appendix C for some real cases. Subsequently, the sub-steps of the framework and their inter-relations can be tested and improved.

Based on this integrated framework, we also suggest developing a maturity model for supply chain disruption management with which companies can assess their performance in different steps[1] in comparison with other companies, and establish best practices. Subsequently, the strengths and gaps in the disruption management process can be identified and plans for improvement can be defined. Developing such a maturity model needs further research to see how successful companies work in each step of the framework and which factors, methods and policies are used by these companies.

8.3.2. Developing the modeling framework

The modeling framework of this thesis was built to address the key aspects of disruption management in supply chains and proved to be promising. However, there are some recommendations for further developments.

While an attempt has been made to provide as much detail as possible in the conceptual framework, the framework can be further extended considering more theoretical work or by performing other case studies. Especially, the model for disruptions in the existing

[1] For example, different levels of *maturity* can be defined for Risk Quantification in the supply chain:
Level 1- Risk Quantification based on internal personnel expertise
Level 2- Risk Quantification based on modeling and simulation
Level 3- Risk Quantification based internal expertise and quantitative modeling

framework can be further developed in future works. As one possibility for extension, it would be interesting to consider the dependencies among different disruptions in defining disruption scenarios. For example, a disruption in transportation infrastructure may have immediate impact on the raw material shipment from a supplier. Meanwhile, there might be a more long-term effect as well, because the material delivery to supplier facilities is also disrupted by this event. In other words, the occurrence of one disruption might trigger another disruptive event in the model. We can also consider a sequence of events in defining each disruption. In this case, other simulation paradigms like discrete event simulation can be also used for modeling the sequence of events in a disruption scenario.

Another topic which is recommended for future research is the application of the modeling framework in other domains. For example, the modeling framework of this thesis can be customized to study the vulnerability of critical infrastructures. Although the conceptualization in this work is mainly derived from the supply chain literature, the modeling framework seems generic enough to be customized and used to simulate different attack scenarios and evaluate their impact on critical infrastructures' operations.

8.3.3. Research on socio-technical complexity of supply chains

The supply chain concept has been studied from different perspectives in the literature. However, according to our knowledge, studying a supply chain from a complex socio-technical perspective has not been adequately addressed. We took some preliminary steps in Chapter 5 to describe the socio-technical complexity of supply chains but the detailed analysis of social and technical aspects of supply chains and how they are inter-connected call for a separate study. A socio-technical view on supply chain management can also open up many possibilities for research about the social and technical levels in supply chains and their interrelations. Just to give examples, "*how the technical capabilities of partners in a supply chain impact the level of integration or the institutional arrangements in the supply chain*" or "*how technical capabilities of suppliers may influence their level of involvement in new product design and how this might impact the supplier selection process*" can be potential topics to carry research in future.

8.3.4. Recommendations for further research on supply chain risk management

In Chapter 4 of this thesis a review of the literature on supply chain risk and disruption management has been presented. In that chapter, two main observations in the existing literature on supply chain risk/disruption management are also discussed:

- *The literature on supply chain risk/disruption is not uniform; most of the literature is focused on specific steps in the risk management cycle.* More work is needed on the disruption management cycle (i.e., disruption detection, disruption reaction and recovery and disruption learning), and in the risk management cycle, on risk monitoring and risk quantification.

- *The review of supply chain risk literature evidences a limited amount of quantitative (simulation and modeling) studies for handling supply chain disruptions*: The limited number of publication on modeling and simulation is especially visible for the disruption management cycle. Considerably more work needs to be done in this area. The agent-based modeling framework described in this thesis aims at demonstrating invaluable contribution of quantitative simulation and modeling to efficient and effective disruption management; but still, more modeling efforts are needed by supply chain risk scholars to fill this gap.

Finally, the InForMDRiSC framework may be enriched with methods and insights derived from related domains – like crisis management or humanitarian logistics. There has been intensive research in these domains which may be transferred to the supply chain risk context.

APPENDIX A: DESCRIPTION OF STEPS IN THE EXISTING FRAMEWORKS

[redacted]

Pre-disruption View		
Adhitya et al. (2009)	Risk identification	"The first step is to recognize uncertainties and possible sources of disruption to the supply chain operation, both internal and external."
	Consequence analysis	"Once the risks have been identified, their consequences have to be analyzed using an appropriate model of supply chain operations."
	Risk estimation	"Risk is usually quantified in financial terms and/or ranked according to some pre-defined criteria. Two different dimensions need to be considered: its frequency/probability and its severity/consequence, taking into account the effects of mitigating actions and safeguards, if any."
	Risk assessment	"The risk management team decides whether the risk quantified in the previous step is acceptable based on experience, industry standards, benchmarks, or business targets. If not, additional mitigation actions or safeguards are required."
	Risk mitigation	"Mitigating actions and safeguards such as emergency procedures and redundancies have to be developed, based on both the supply chain model and inputs from the risk management team or relevant supply chain personnel."
	Risk monitoring	"The supply chain structure and operation do not remain stationary but change regularly, for example due to changes in suppliers, regulations, operating policies, products, etc. The risk management team should continually monitor the supply chain for new risks. The entire analysis could be repeated when new risks arise from these changes."
Cigolini and Rossi (2010)	Risk analysis	"Within the risk analysis, risk identification can be performed by means of either forward or backward or even hybrid techniques… In particular, the most popular forward techniques in the oil industry are: (i) the hazard checklist, which consists of the plant analysis to verify if risky events identified in previous risk analyses or in similar plants can occur (Lees 1996); (ii) the Events Tree Analysis (ETA) that allows to determine the damages a potential risky event can result in, due to the safety equipment and procedures which the plant is characterised by."
	Risk assessment	"The risk assessment is performed (for each previously identified risky event) by estimating the magnitude of the corresponding damages and the damages occurrence probability (or frequency) on condition that the risky event occurs, so that the risk is measured as the product between magnitude and probability."

	Risk control	"With reference to risk control, the oil industry is characterised by prevention practices to reduce the probability of damage occurrence and by protection practices to limit the damage magnitude. Such practices, popular as loss control techniques, involve both actions (maintenance activities, safety equipments and operators training) and financial tools (insurance and not insurance transfers)."
Finch (2004)	Risk identification	"Identifying and quantifying the exposures that threaten a company's assets and profitability."
	Risk analysis	"Identifying and assessing the risks to which the company and its assets are exposed in order to select appropriate and justifiable safeguards."
	Risk reduction, transfer and acceptance	"Reducing or shifting the financial burden of loss so that, in the event of a catastrophe, a company can continue to function without severe hardship to its financial stability."
	Risk monitoring	"Continually assessing existing and potential exposure."
Harland et al. (2003)	Map supply network	"The supply network to be mapped would be defined by the problem or concern. For example, the network might be the product supply network for a particular product where it is felt there is some exposure to risk. In this stage a diagrammatical representation of the supply network enriched with appropriate data is created. Mapping this supply network is likely to involve understanding who owns what, and what are the key measures currently in place, i.e. clarity of role and responsibility within the network."
	Identify risk and its current location	"The specific risks that will be considered for the particular problem/product should be identified, through brainstorming with other actors in the supply network. At this stage only those with a significant potential loss to any actor in the network should be considered."
	Assess risk	"The chosen types of risk are assessed for the likelihood of their occurrence, exposure in the network, potential triggers of the risk, at what stage in the life cycle the risk is likely to be realised, and what likely potential losses to whom might occur."
	Manage risk	"The assessment information is analysed and alternative interventions are proposed… Depending upon the risk position, scenarios of alternative network structures and relationship strategies can be developed to realign risk, exposure to it, likely losses and location of those losses."
	Form/ implement collaborative supply network	"In [steps] 5 and 6 the chosen redesign of the network and relationships within it are effected through a reformulated collaborative supply network risk strategy. This strategy is implemented and gives rise to a remapping of the network, i.e. back to [step] 1."
Hallikas et al. (2004)	Risk identification	"Risk identification is a fundamental phase in the risk management practice. By identifying the risks, a decision-maker or a group of decision-makers become conscious about events or phenomena that cause uncertainty. The main focus of risk identification is to recognize future uncertainties to be able to manage these scenarios proactively."
	Risk assessment	"Risk assessment and prioritization are needed to be able to choose suitable management actions for the identified risk factors according to the situation at both company and network

		level. In the Finnish project the assessment is incorporated into the identification method. Here the two components of risk, the probability and the consequences of a risk event, are assessed separately on a five class scale."
	Risk management actions	"In a network environment, risks can be managed generally by developing a common network strategy, best practice modes of action and contract policies. Risk identification and assessment give a more specific indication on where to focus the actions."
	Risk monitoring	"The company and its environment are not static, and thus also the risk status changes. The recognized risk factors can be monitored to identify the potential increasing trends in their probability or consequences. In addition new significant risk factors may appear. To identify these, it is necessary to monitor the changes in the network, customer needs, technology, partner strategies and competitors and to update the risk assessment correspondingly."
Knemeyer et al. (2009)	Identifying key locations and threats	"The first step in the planning process is to identify key supply chain locations. A location is considered key if interruption of its operations results in a major disruption in the flow of goods in the supply chain."
	Estimating probabilities and loss for each key location	"At the conclusion of the first step of the proactive planning process, management will have developed a list of key locations with an associated specification of potential catastrophic events that should be considered for each key location. The next step is to estimate probabilities for each potential catastrophe for each key location."
	Evaluating alternative countermeasures for each key location	"In order to manage catastrophic risk, as opposed to mere estimation, it is useful to prepare a catastrophic risk management matrix...The catastrophic risk management matrix jointly displays the probability estimate of a catastrophic event (horizontal axis) and the estimated loss exposure for each of the firm's key locations (vertical axis)... Key locations that require the most managerial attention become visible by falling within the upper right hand quadrant of the matrix (reflecting locations with a high estimated loss and high overall probability associated with catastrophic events). Furthermore, it indicates those locations where countermeasures may be most beneficial to the supply chain network."
	Select countermeasures for each key location	"There are alternative countermeasures that managers must consider to manage the risk of catastrophic events in key locations in their supply chain. While reducing the risks or estimated loss associated with a catastrophic event impacting a key location is beneficial, not every risk should be mitigated... Countermeasures whose costs exceed the decrease in PL [Potential Loss] should therefore be excluded from further analysis."
Manuj and Mentzer (2008)	Risk identification	"Using multiple sources and classifying risks into supply, operations, demand, and security risks" "Risk identification is undertaken at both domestic and global levels and in the context of supply, operational, demand, security, macro, policy, competitive, and resource risks. The global environment includes various supply chain partners, and how the environments in these different countries interact with the focal firm home country"

	Risk assessment and evaluation	"Not all risks affect all supply chains. A supply chain can be vulnerable to certain risks, but shielded from other risks. Hence, the next step is to determine which risks identified in Step 1 are critical for the supply chain. Those risks to which a supply chain is more vulnerable should be given more attention."
	Risk management strategy selection	"After assessing and evaluating the risks, the next step is to select appropriate strategies to manage the risk."
	Implementation of Supply Chain Risk Management Strategy (s)	"Implementation of strategies for risk management requires certain structural, and/or procedural changes in harmony with the trends of globalization and increasingly customized product offerings."
	Mitigation of Supply Chain Risks	"Even after devising risk management strategies, all risks cannot be avoided. It is important to plan for situations that assume a risk that could be seriously detrimental may be realized. While risk management strategies are used to proactively address the probability of expected (though uncertain) events, risk mitigation planning provides a firm with a more mature decision-making process in facing potential unexpected losses caused by unexpected events. The key to risk mitigation is identifying the possible losses that may happen from an unexpected event. For example, if delivery issues are critical to a business, a risk mitigation plan should include identifying a back-up service provider, and developing a relationship with that provider to replace and/or pick up the capacity slack caused by the unexpected event. Another example may be for a company sourcing from overseas and using only water transportation to plan for usage of air freight in the event there are some disturbances in the low-cost surface options. A risk mitigation plan in this case may consist of identification of air freight service providers that can handle the specific product requirements on short notice."
Norrman and Jansson (2004)	Risk identification	"Initially, Ericsson identifies and analyzes its supply chain risks by mapping the supply chain upstream, looking at suppliers as well as products/services."
	Risk assessment	An in-depth analysis is carried out of the suppliers and sub-suppliers of critical products to see what the probability and impact of the risks are.”
	Risk treatment/management	"The third step in Ericsson’s process is called risk treatment, which includes both developing risk mitigation strategies and deciding on those."
	Risk monitoring	"If the risk level is very high, or high and not mitigated, risk monitoring is required. If the residual risk, after mitigation, is not reduced to an acceptable risk level it must continue to be monitored."
	Incident handling and business continuity planning	"Ericsson is putting emphasis on developing procedures and templates for incident handling and BCP to decrease the consequences of an accident. After the Albuquerque accident, the process for “incident reporting” is very important and task forces/emergency teams have been appointed. If an incident occurs, this should be reported to either the sourcing task force (if external supplier) or the SCM task force and production task force (if internal supplier)."
Oehmen et al. (2009)	Risk identification	"The first step in the risk identification was the delimitation of the scope, regarding both the causes and effects of supply chain

		risks [Supply Chain Risk Structure Model] ...Based on the complete Supply Chain Risk Structure Model, a risk matrix of risk causes (causal system) and risk effects (effect system) can be built. By means of this risk matrix, the relevant supply chain risks are given by the combinations of the risk causes and the risk effects, e.g. a sole supplier of an important component of the final product (cause) in combination with quality problems (effect)."
	Risk assessment	"The objective of the risk assessment is the detailed analysis of the identified supply chain risks. The risks are prioritised based on the dimensions 'probability of occurrence' and 'business impact'."
	Risk mitigation	"In the final phase of the SCRM methodology, strategies and measures to mitigate the 'key risks' are evaluated and implemented."
Sinha et al. (2004)	Identify risks	"There are many attributes considered in identifying risks such as technology, markets, partnerships, contracts, and culture. The focus of this activity is to understand the existing business model including the interaction between the external and internal trading partners in the supply chain. This activity identifies how these attributes affect the current supply chain network... The existing process and existing risk awareness is transformed by the activity 'identify risks' into foreseen and perceived risks ... Foreseen risks are predicted through statistical data and steps can be carried out to mitigate them. Perceived risks are identified based on intuition (Sage and White, 1980), where there are no data or statistical proof that the desirable/undesirable event may occur. These outcomes are grouped under identified and categorized risk according to their similarities."
	Assess risks	"The assessment process can be intuitive or analytical. The goal is to determine the root cause or the source of the undesirable/desirable event. Furthermore, it facilitates identifying the direct and indirect impact… The identified and categorized risks are transformed by the activity 'assess risks' into identified controllable (risks, which are within the scope of the company's control) and uncontrollable risks (risks, which are not within the scope of the company's control)"
	Plan and implement solutions	"Initially, management generates alternative strategies that mitigate risk in the supply chain. A complete description has to be provided of these strategies, how they can be implemented and what are the possible outcomes. At this stage, a comparison is conducted to evaluate the advantages and disadvantages of competitive strategies. The controllable risks are evaluated in activity 'plan and implement solutions' and the outcomes are prototype processes, methods, and strategies ... The solution developed will be implemented as a prototype and then monitored so that areas of improvement can be addressed."
	Conduct failure modes and effects analysis	"The activity 'conduct failure modes and effect analysis' ... evaluates the possible failure modes that can occur in the prototype process and develops a contingency plan against these failures, which is highlighted in an FMEA chart. An FMEA chart provides a method for identifying the potential new risks that can occur in the prototype process. The FMEA chart highlights each potential failure and classifies it

		according to its severity."
	Continuously improve	"A supply chain network can never be risk free, that is, one cannot eradicate the chance of an undesirable/desirable event occurring. As trading partner needs (internal or external) change, the redesigned process (with mitigated risk) must be improved. Therefore, embedding continuous improvements into the redesigned process is required. However, to manage risk effectively, that is monitoring and controlling it, the iterative steps of identifying, assessing, planning solutions, and conducting failure mode and effect analysis should be followed (Subramanian et al., 1999). The activity 'continuously improve' ... focuses on improving the prototype process as well as controlling the identified uncontrollable risks."
VanderBok et al. (2007)	Risk planning	"Risk Planning develops an overall plan for assessing, handling, and communicating supply chain risks for an entire program. It identifies how risk priorities are established, how risks are communicated, the training resource required, and the stakeholders responsible for each of the risk-management activities."
	Risk identification	"Risk Identification is about discovering and documenting supply chain risks."
	Risk analysis	"Risk analysis assesses each risk in terms of its likelihood of occurrence (normally over the expected life of the program), and the estimated impact should the risk occur. Impacts are measured in terms of their impact on time (delivery), cost (including all aspects), and quality or performance of the final product."
	Risk handling	"In this step, stakeholders rank-order the risks and determine what options exist to mitigate the most likely or serious risks."
	Risk monitoring	"Risk monitoring systematically tracks the risks and the risk-handling plans against cost, schedule, and performance metrics, to ensure that risks are being managed as planned. Risk-handling plans are adapted as needed, and new risks are identified and subjected to the same analysis and handling steps as above."
Wiendahl et al. (2008)	Risk identification	"The first step when identifying risks is to define the system boundary...The identification of logistic risks proceeded here are based on Ishikawa Diagrams. Thus the correlations between causes and logistic risks are systematically identified and depicted...The third step is to assign risk indicators in terms of logistic measures to the identified logistic risks which can be evaluated. The risk indicators are deduced based on the causes (influencing factors) of each logistic risk."
	Risk assessment	"After describing the relevant logistic risks, they need to be assessed and ranked to identify the potential logistic risks, which have to be handled with priority. The assessment of logistic risks implies the calculation of the probability of occurrence and the evaluation of the economic impact. This enables the ranking of logistic risks."
	Risk control	"The aim of risk control is to initiate adequate counter measures for minimizing the probability of occurrence or the impact of logistic risks."
Wu et al. (2006)	Risk classification	"The primary purpose of classifying risk is to get a collective viewpoint on a group of factors, which will help the managers

		to identify the group that contributes the maximum risk. This can enable supply managers to give the required level of importance (in the risk management process) for every group/type of factors."
	Risk identification	"This step entails the enumeration of risk factors, is performed to be later categorized into appropriate branches in the classification system."
	Risk calculation	"In general, risk factors identified in the previous step need to be evaluated to calculate the factor's impact on overall risk."
Post-disruption View		
Adhitya et al. (2007a)	Key performance indicators (kpi) monitors	"To manage disruptions in a supply chain, it is essential to measure KPIs and identify their effect on the supply chain. These KPIs are monitored by comparing their day-to-day values against their pre-specified limits and generating an alarm, when a sustained deviation is detected."
	Root cause identifier	"Causal models are used to identify the possible causes for the alarms."
	Rectification strategy proposal	"The list of corrective actions to rectify the root cause is generated using a causal model, which accounts for the linkages among the supply chain entities."
	Rectification strategy selection (optimization)	"One rectification strategy is selected based on feasibility and KPIs."
	Scheduling and coordination	"In a general case, disruption may make the existing operation schedule infeasible or sub-optimal. Optimal rectification strategy generally requires rescheduling of operations… [Meanwhile] numerous activities may be necessary to partially or completely rectify the disruption. The implementation of these rectification strategies is coordinated by [Coordinator] agent."
Blackhurst et al. (2005)	Disruption discovery	"To successfully recover (i.e. reduce or eliminate the negative impact) from a supply-chain disruption, the firm must have in place an effective means of discovering supply-chain disruptions."
	Disruption recovery	"Once the disruption is discovered, how does a firm effectively recover from a disruption?"
	Supply-chain redesign	"How the supply chain can be re-designed to become more resilient?"
Integrated view		
Berg et al. (2008)	Proactive supply chain risk management processes	"Subprocesses: identify risk, evaluate risk, manage risk and monitor residual risk and make contingency plans. Number of risk identifications and assessments made of suppliers, sub-suppliers, critical components, etc., are examples of what could be measured, as well as number of suppliers and critical components assessed. Other more quantitative indicators could be number of risk mitigation actions taken or line managers appointed to be responsible for risks in different supply chains... Still others are how suppliers and subsuppliers work with contingency plans, and how we ourselves are driving those efforts by our partners."
	Reactive supply chain risk handling	"Here again the actual processes are incorporated into the figure: incident handling, accident handling and execution of contingency plans. In the SCAA case, incident reporting was

		seen as valuable input data for improving the risk management work even further. Similarly, the focus should be on how we are working with understanding what is happening with ourselves with regard to risk sources in other parts of the supply chain, and how suppliers and sub-suppliers are doing when reaction is needed. Some indicators here could be the number of incidents handled well, number of incidents handled poorly, lead time to react and act, or how well the developed contingency plans and crisis plans are followed by the organisation when something happens."
Pyke and Tang (2010)	Readiness	"Before a potential recall, the company should implement and execute policies that improve product safety (or reduce the likelihood of having a product recall), such as TQM practices and statistical sampling inspection. It should also prepare the necessary channels in case a recall becomes necessary."
	Responsiveness	"During a recall, the company should create an action plan that is carried out during a recall and that allows a company to respond quickly to the problems at hand."
	Recovery	"After a recall, the company should take steps to restore everything (from supply to demand) back to normal. Additionally, management should review the recall procedure, so that the company can take corrective actions (product design, process control, supplier audits, etc) to prevent or reduce the likelihood of future product recalls."

APPENDIX B: THE LIST OF EXPERTS FOR FRAMEWORK EVALUATION

[redacted]

	Profession	Education
1	Country Planning & Logistics Manager at	MBA, Supply Chain & Logistics Management
2	Sr. Director, Logistics Product Management	MSIE, Operations Research
3	Export Customer Service specilaist,	Bachelor
4	SCM educator	BA, Economics
5	Director, Supply Chain	MBA, Supply Chain Management
6	Founder/President	MBA, specializing in Retail Distribution
7	Director of logistics service providing company	Diploma in Carbon Management Dip TAFE
8	Quality Assurance Technician	Bachelor, Technology (Chemical Engineering)
9	Asst. Manager Stores (Simplex Infrastructure)	Bachelor, Management Accountancy
10	Logistic manager	Post graduate, management of production
11	SCM Analyst	Business Administration
12	Supply Chain Manager	Master level
13	Vice President, Logistics, Asia Pacific Region	ACCA (Certified Accountant)
14	Supply Chain Consultant	CPIM, CSCP, SCOR-P, CMQ/OE
15	Founder and Chairman	MBA
16	SCM Manager	Business Administration & Information Technology
17	Senior Consultant	Asspciates Degree in Accounting
18	VP Logistics Solutions	P.Log - a Canadian post gradulate designation (Professional Logistician)
19	Supply Chain Manager	Master of Business Administration (M.B.A.)
20	Manager Operational Support Savoury Ingredients	Bachelor Logistics + MBA
21	Supply chain manager and Ocean transportation expert	Bsc Agriculture Engineering
22	Chairman	Fellow Chartered Institute of Logistics and Transport
23	Senior Planner	-
24	University Research Fellow	MSc/PhD SCM
25	Assistant Professor of Modeling and Simulation	Msc. Industrial Eng. , PhD. Computer Science
26	Senior level SCM professional, Pharmaceuticals	Bachelors in Business and Post Graduation in SCM
27	Logistics Manager	-
28	SC Principal	MS, Systems Engineering

	Profession	Education
29	Director, Risk Management, Supply Chain Development	EMBA, Business Administration
30	Research Associate	PhD in Technology, Policy and Management
31	Director at consultancy company and professor of marketing and supply management	PhD in Marketing
32	Professor in Safety Science	PhD in Physics and Mathematics
33	Professor in Systems & Simulation	PhD in Technology, Policy and Management

APPENDIX C: THE EXTENDED STRUCTURE OF INFORMDRISC

C.1. Introduction

In Chapter 3, the overall structure of InForMDRiSC has been presented and discussed. This overall structure includes two main cycles and several steps in each cycle as shown in Figure 3.3. In chapter 3, each of these steps was described and some important aspects were discussed for each step in Chapter 4. In this Appendix, we have tried to formalize the description of steps into some sub-steps which can be used as a starting point for further development and application of InForMDRiSC in future. The framework is also illustrated with a case in this Appendix.

C.2. The extended structure of InForMDRiSC

As mentioned in Chapter 3, InForMDRiSC is a continuous process with two main cycles. Each of these two cycles, their steps and sub-steps are described in the following.

Risk Management Cycle

The first cycle – that is called *Risk Management Cycle*- is about *Potential Disruptions*. The main steps and sub-steps of *Risk Management Cycle* are presented in Figure C.1.

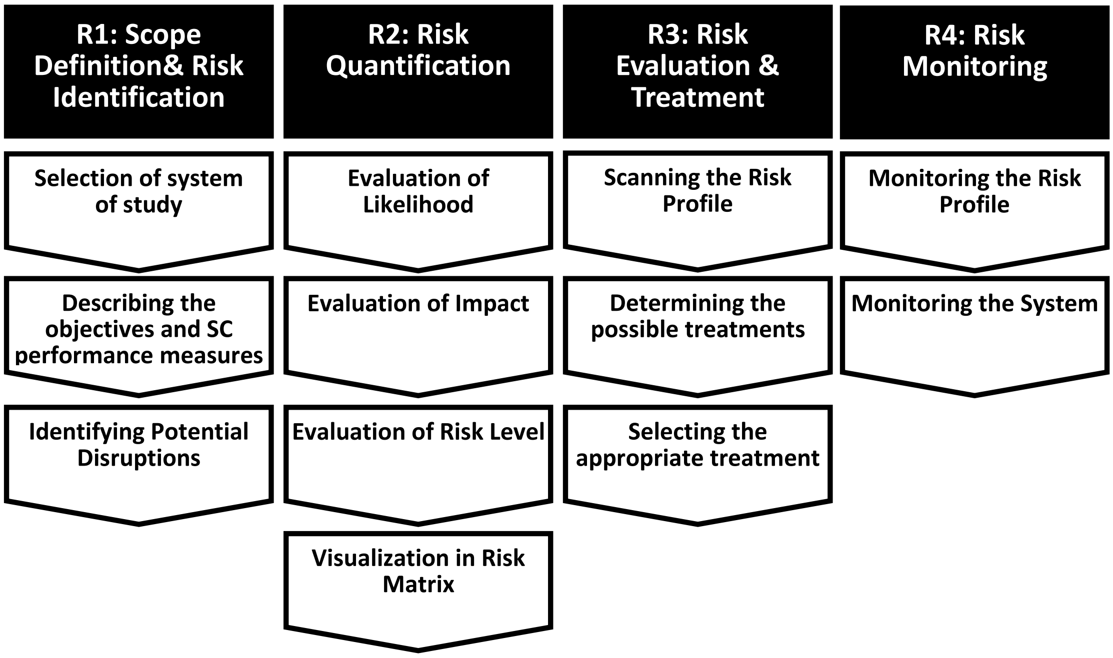


Figure C.1. The main steps and sub-steps of Risk Management Cycle

R1: Scope Definition& Risk Identification

R1-1: Selection of system of study

To start the process for handling disruptions, it is important to carefully define the system, delimit its boundaries and give a clear description of the system structure (Wiendahl et al., 2008). After decision on the system of study has been made, a map of system - which describes the system elements and their interdependencies - should be provided. Mapping the system might also incorporate a description of key risk management measures that are currently in place (Harland et al., 2003).

R1-2: Describing the objectives and supply chain performance measures

As mentioned, a supply chain disruption is characterized by its impact on the performance of supply chain and its objectives. Therefore, in addition to the system, the critical objectives and performance measures must be addressed in defining the scope of study. The list of *Possible Consequences* of disruptions will be used in the evaluation of disruption impact in the next step of the framework – i.e., "Risk Quantification".

R1-3: Identifying Potential Disruptions

When the system of study and the expected consequences are described, the possible disruptions, which might result in these adverse consequences, must be identified. An extensive list of *Potential Disruptions* can be generated by analysis of past losses, intensive literature review or insurance company checklists. Next, this extensive list might be narrowed down to key *Potential Disruptions* by interviewing with employees or meetings with experts (Canbolat et al., 2008; Yang, 2010).

Subsequently, for each *Potential Disruptions*, a *Causal Pathway*, which describes the main causes leading to the event, needs to be developed (Norrman and Jansson, 2004; Ritchie and Brindley, 2007). For example, the "Supplier Failure to Deliver On-time" might be because of "Supplier Production Constraints" which itself might be caused by "Human Resource Problems (e.g., strike in its plants)", "Permanent Closure of a Production Plant", "Temporary Production Stop in a Plant" "New Customers for Supplier". This *Causal Pathway* can serve as a basis to estimate the likelihood of a Potential Disruption or disruption ranking in the "Risk Quantification" step –especially, for the cases in which there is not enough data to make a quantified estimation of disruption likelihood. For instance, the likelihood of material discontinuity from a supplier which has single plant in a specific location is higher than a supplier with similar production capacity that is distributed between manufacturing facilities in different geographical locations. The *Causal Pathway* is also used in "Risk Monitoring step" to constantly track changes in the likelihood of disruptions over time; as an example, having a new big customer for the main supplier of company might be a sign for the increase in the likelihood of delay in raw material devilry from that supplier.

Finally, for each of *Possible Consequences* identified in previous sub-step, an *Impact Causal Pathway* should be mapped. This *Impact Causal Pathway* determines the *Potential Disruptions* that might result in a specific consequence. For instance, the "Delay in Customer Order Delivery" can be because of several disruptions including "Supplier Failure to Deliver On-time", "Transportation Disruptions", "Rush Order Acceptance" or "Internal Process Failure". This *Impact Causal Pathway* is used in "Disruption Detection Step" when the root cause of performance deviation is not observable in the first place (Adhitya et al., 2007).

So, with these three sub-steps, "System Definition& Risk Identification step" provides a company with:

- A *Risk Catalogue* which consists of a list of *Potential Disruptions* and for each of them, the expected consequences and disruption *Causal Pathway* is described.
- An *Impact Causal Pathway* which is a list of Disruptions leading to each Consequence.

R2: Risk Quantification

R2-1: Evaluation of Likelihood

One of the dimensions in the evaluation of each *Potential Disruption* is the likelihood or frequency of its occurrence. The historical data can be the main source to estimate the disruption likelihood. However, in the absence of adequate and accurate data, a company may use other approaches to estimate the probability of disruptions, e.g. expert opinion, simulation or combination of these methods (Knemeyer et al., 2009). The *Causal Pathway*, developed in Risk Identification step, can support decision makers to have an estimation of disruption likelihood, especially when they want to rank different disruptions rather than having an absolute value of the likelihood of disruptive event. For instance, the probability of delay in raw material delivery from a supplier with one factory and several important customers is higher than a supplier which has several factories around the world and the focal company is its main customer.

R2-2: Evaluation of Impact

Each disruption may influence multiple objectives of a company and consequently, have a range of *Possible Consequences*. Determining all these consequences in a complex network of actors and activities can be a challenge for most companies. Accordingly, using modeling and simulation to evaluate the impact of disruption is very much suggested (Wu et al., 2006; Wilson, 2007; Wagner and Neshat, 2010). Similar to likelihood estimation, the evaluation of impact can be based on semi-quantitative ranking methods too.

R2-3: Evaluation of Risk Level

Having the likelihood and impact of disruption, the *Risk Level* can be calculated by multiplying these two dimensions. The *Risk Level* calculated for all *Potential Disruptions* is used for making decision on whether an identified disruption needs to be treated in the next step of the framework.

R2-4: Visualization in Risk Matrix

Risk Matrix (also known as Risk Diagram (Hallikas et al., 2004) or Risk Map (Berg et al., 2008)) is a visual output of Risk Quantification step which demonstrates the relationship between impact and likelihood of all disruptions in two axes (Figure C.2). This graphical representation of *Potential Disruptions* helps decision makers to get an overall (and quick) insight of the *Risk Profile* of the company and the important disruptions which need treatment (Hallikas et al., 2004).

The output of Risk Quantification step is a *Risk Profile* for company that includes the *Risk Catalogue* and the *Risk Level* for each of *Potential Disruptions*. This *Risk Profile* – that can be presented in a *Risk Matrix*- is the basis for further analysis in the next step- i.e., Risk Evaluation and Treatment.

			Likelihood				
		Descriptor	Rare	Unlikely	Possible	Likely	Very likely
	Descriptor	Rating	1	2	3	4	5
Impact	Insignificant	1	1	2	3	4	5
	Minor	2	2	4	6	8	10
	Moderate	3	3	6	9	12	15
	Major	4	4	8	12	16	20
	Catastrophic	5	5	10	15	20	25

Figure C.2. An example of Risk Matrix and rating system

R3: Risk Evaluation & Treatment

R3-1: Scanning the Risk Profile

The first action is to go over the Risk Profile and determine whether the *Risk Level* for *Potential Disruptions* is acceptable or mitigation actions and safeguards must be provided. For this purpose, a firm may define a threshold for acceptable *Risk Level* (Harland et al., 2003). Comparing the *Risk Level* for each *Potential Disruption* in the *Risk Profile* with that acceptable level separates the disruptions into minor (acceptable) and major (unacceptable) ones.

R3-2: Determining the possible treatments

For unacceptable disruptions the possible treatment options must be identified. Using the *Causal Pathway* can be beneficial in finding alternative treatments for a disruption (Norrman and Jansson, 2004). For example, selecting a certified supplier will reduce the probability of order rejection due to unsatisfactory quality and also the late raw material delivery.

R3-3: Selecting the appropriate treatment

The possible treatments for each *Potential Disruption* must be evaluated and the appropriate treatment must be selected. This evaluation must be based on a systemic view:

- The impact of implementing risk mitigation measures on the daily operation of supply chain must be also considered and taken into account (Sheffi, 2005).
- Choosing a risk mitigation approach for a specific disruption may increase the *Risk Level* for other disruptions (Olson and Wu, 2010). This influence must be also considered in selecting risk mitigation approaches.
- A specific risk mitigation approach may address more than one *Potential Disruption* in a supply chain; so, it is recommended to consider whole *Risk Profile* – and not single disruptions- in selecting the safeguards (Knemeyer et al., 2009). In this way, the resources invested to mitigate the risk of one specific disruption might be also deployed as alternative solutions for other disruptions. The resources which can be shared between different disruptions or used to handle more than one - not necessarily as the first priority but maybe as a secondary option- are called *Movable Resources*. Having a list of *Movable Resources* is extremely beneficial for Disruption Recovery step when the first reaction to a disruptive event is not effective and decision makers start looking for new options to manage disruption.

R4: Risk Monitoring

R4-1: Monitoring the Risk Profile

The *Risk Profile* of company must be monitored constantly. Some new disruptions might be identified which were not recognized before in Risk Identification step. Moreover, for the *Potential Disruptions* that are currently documented in the *Risk Profile*, the likelihood and expected impact needs to be updated with new information gathered by company and - if necessary - the disruption treatment must be improved (Blackhurst et al., 2005). The *Causal Pathway* of *Potential Disruptions* can be used as a guide to recognize the changes need to be monitored. For example, having a contract with a big competitor of focal company can be a signal for higher likelihood of delay in raw material shipment from that supplier in future. It can be also considered an early warning sign that the intellectual property of company is increasingly at risk.

R4-2: Monitoring the System

Besides the *Risk Profile*, the system boundaries and structure may change in different ways. For example, a new supplier might be added to the supply base, a new warehouse might be launched or a new set of products might be introduced to the market. As a result of these changes in the supply chain, the system definition –that is the starting point of whole disruption management process- would change from time to time. Thus, it is imperative to repeat whole *Risk Management Cycle* by a new definition for the system and identifying the new disruptions. In addition, the *Risk Level* for currently-listed disruptions in the *Risk Profile* might need to be updated –because of interdependencies between different risk factors.

Disruption Management Cycle

The second cycle is *Disruption Management Cycle*. Despite enough safeguards, at a specific point, an *Actual Disruption* may happen. The main steps and sub-steps of *Disruption Management Cycle* are presented in Figure C.3 and discussed in the following.

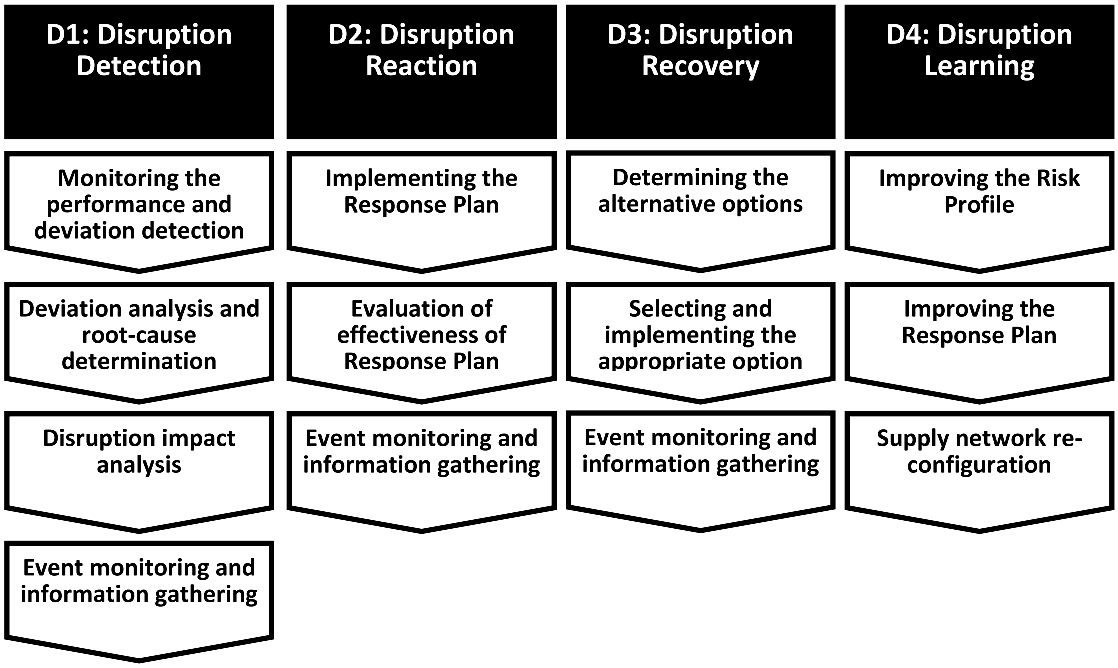


Figure C.3. The main steps and sub-steps of Disruption Management Cycle

D1: Disruption Detection

Detecting a disruption can take two forms. The first case is when an actor can directly observe (or being informed by other partners of) the occurrence of an event in a part of supply chain (type-A). For example, a supplier may send a message that there is an emergency shutdown in one of its plants which may cause delay in raw material shipment to the manufacturer. However, in some other cases, a firm can see solely the impact of disruptive events on its performance and it needs to explore the cause of deviations (type-B).

Each of these two types of Disruption Detection calls for different actions to be done and needs different types of capabilities. In following the necessary actions are discussed in more detail. The first two actions are exclusively to type-B detection:

D1-1: Monitoring the performance and deviation detection

Fast detection of disruptions in a supply chain calls for enhancing visibility and developing advanced monitoring systems which tracks performance indicators over time to identify deviations and determine if they are reaching unacceptable level (Christopher and Lee, 2004; Blackhurst et al., 2005; Adhitya et al., 2007). For this purpose, pre-defined limits for the performance indicators can be defined and based on these control limits, early warning alarms of disruption occurrence might be generated (Blackhurst et al., 2008). Moreover, a sustained trend toward unacceptable level – even if performance measures are within acceptable limits- could be flagged as a possible disruption.

D1-2: Deviation analysis and root-cause determination

As a deviation in the performance is identified, a company must find the main factors that cause that abnormality in the supply chain operation (Blackhurst et al., 2005). The cause of deviation can be one of *Potential Disruptions* identified and documented in the *Risk Profile* or a new type of disruption which has been overlooked in Risk Identification step.

For type-A detection in which the disruptive event is known or informed by other partners in the network, the necessary action is evaluating the impact of that event on the planned and normal operation of supply chain. This is further elaborated under following sub-step.

D1-3: Disruption impact analysis

After a company is informed about a disruptive event in one part of the supply chain, the first action must be the assessment of disruption impact on the operation of supply chain. This assessment might take two forms. A disruption might push the performance measures out of acceptable range (Adhitya et al., 2007; Wilson, 2007) or make the operational plans non-optimal or even infeasible (Qi et al., 2004; Yu and Qi, 2004). Each of these two conditions can be called as an *Abnormal Situation* in the supply chain and needs organization to take actions and response to the situation. Conversely, when, none of performance indicators goes out of acceptable range or there is no significant impact on the pre-defined plans, then the situation will not be an *Abnormal Situation*; no intervention is needed and company can continue with its regular operation. The important point here, however, is that the impact of disruptive event, in some cases, is not necessarily immediate; it takes time for the abnormality to show its full impact on the system performance. For example, an earthquake in a specific region may have no immediate influence on the supply base of company but because of transportation difficulties, the production in 2^{nd} or 3^{rd} tier suppliers might be halted. The delays and supply disruptions in the higher tier suppliers can cause a domino effect and impact the supply base of focal company and after a while, production in focal company might be stopped because of raw material shortage. With appropriate modeling and simulation tools, a firm can have an estimation of possible consequences of a disruptive event and determine if (and, approximately, when) that initial event may lead to unacceptable consequences in the system (Tuncel and Alpan, 2010; Behdani et al., 2010a). With significant importance of speed of response, this ability to predict a problem before it occurs can be a critical issue in handling disruptions.

For both types of disruption detection discussed here, continuous monitoring of disruptive event is an essential action. This is further discussed as following sub-step.

D1-4: Event monitoring and information gathering

A disruptive event is a dynamic phenomenon and its state can change frequently (Blackhurst et al., 2005). In addition, when disruptions occur the downstream actors may have little or inaccurate information about the disruption; firstly, because the supplier's estimation of the problem might be biased and secondly, it might not be feasible for the firms to have all related information in the early stages of disruption (Chen et al., 2010). Accordingly, a supplier which previously announced a shutdown in one of its plants may give an update on the time of returning to normal operation or a new expected time for order delivery. Considering all these aspects, it is imperative for company to continuously monitor the event, gather information from different sources and exchange information with other actors in the chain.

D2: Disruption Reaction

D2-1: Implementing the Response Plan

The first action to handle an *Actual Disruption* is implementing the *Response Plan* as quickly as possible. How prepared and trained the response actors are and how coordinated they perform in the real-time are important factors in successful implementation of the response plan. In addition, the pre-defined response plan might need adjustment based on the current situation of supply chain.

D2-2: Evaluation of effectiveness of Response Plan

After implementing the *Response Plan*, its effectiveness in returning system to the normal operation must be evaluated. If this plan cannot successfully recover system, it is necessary to continue with next step – Disruption Recovery- to find alternative solutions.

D2-3: Event monitoring and information gathering

Collecting and analyzing information about the disruptive event and the action of other actors in handling the disruptive event – for example, the actions done by supplier to return its plant to normal production after an emergency shutdown- is still an important action. With initial information on the scope of disruption, the first response might seem adequate; however, by gathering more information or by updates from other actors in the chain, it might be necessary to look for some other options to cope with the full impact of disruption.

D3: Disruption Recovery

D3-1: Determining the alternative options

To define alternative solutions, a company must have the ability to:

- Estimate the *Necessary Resources* to manage disruption (Charles et al., 2010): based on the impacted area in the supply chain and the expected duration for a disruptive event, an estimation of *Necessary Resources* can be made.
- Determine the *Available Resources* to manage disruption: a list of resources that are available and can be used in managing disruption must be created. Examples of *Available Resources* to handle the supplier emergency shutdown are the available material in storage facilities or in-transit raw material (the material which has been order but has not arrived to the factory) shipments.
- Find *Alternative Resources*: In addition to the resources which are still available for a company, it must start looking for *Alternative Resources* across its supply chain. The list of *Movable Resources* determined previously in Risk Evaluation and Treatment step is beneficial for this purpose. Search for *Alternative Resources* might also necessitate close collaboration with other partners in the network and sharing some of resources with others.

It must be emphasized that preparing resources for Disruption Recovery step can start in parallel with first response in Disruption Reaction step (Sheffi, 2005). For example, when rescheduling the orders might be a first response to raw material delay from a supplier, qualifying new suppliers and finding customers that might be willing to re-negotiate their due-dates can be followed at the same time. Matching the *Available Resources* and *Alternative Resources* with *Necessary Resources* would lead to a primary list of options to cope with disruption.

D3-2: Selecting and implementing the appropriate option

With a list of preliminary alternatives, the appropriate option must be selected and implemented. Selecting the proper option to manage disruption can be an iterative process which starts with finding and executing a first response to a disruptive event and based on the feedback of the effectiveness of that action, the system/disruption information can be updated and a new action might be implemented. This iterative process is especially important because of the critical role of time in disruption response and also the uncertainty about the event and current status of supply chain. The process must continue until system returns to its normal operation.

To better –and faster- evaluate the alternative options in this step, using modeling and simulation would be of considerable benefit (Adhitya et al., 2007; Tuncel and Alpan, 2010).

D3-3: Event monitoring and information gathering

Similar to Disruption Detection and Reaction steps, continuous monitoring of disruptive event (and information exchange with other actors in the network) is critical in this step of framework.

D4: Disruption Learning

D4-1: Improving the Risk Profile

Based on company’s experience with a real disruption, it can update its estimation of likelihood and impact of that type of disruption in the *Risk Profile*. Moreover, during handling a specific disruption, some new disruptions might be identified that were not identified before or being considered as less significant ones (Cheng and Kam, 2008).

D4-2: Improving the Response Plan

An *Actual Disruption* in supply chain gives a company the opportunity to test and verify the response plans with a real case (Norrman and Jansson, 2004). By reviewing the effectiveness of existing plans to handle an *Actual Disruption*, the gaps in the existing plans can be identified and the strengths of plans can be kept or will be used as a basis for defining some new emergency plans.

D4-3: Supply network re-configuration

Once the company recovers from disruption, it may decide to redesign the supply chain with the goal of minimizing the probability or impact of similar disruptions in future (Blackhurst et al., 2005). For example, a new warehouse might be added to the current supply network or a new contract might be signed with a local supplier. These modifications in a supply chain imply changes in the system structure and its boundaries and accordingly, it is a necessity to repeat the *Risk Management Cycle* by identifying new *Potential Disruptions*.

C.3. The illustrative case

R1: Scope Definition& Risk Identification

To illustrate the steps of framework and their interrelations, the activities done by an Asian chemical company to handle the disruption in its supply-base has been described here[1].

The structure of supply chain of company is presented in Figure C.4. The focus of disruption management study in this case, is solely on the supply base of company which consists of 11 suppliers for 7 different raw materials. Different suppliers in the supply base have different characteristics. For example, they are located in different places. However, most of suppliers are local suppliers (located less than 500 km from focal company). The only exception is supplier1 which its sole production facility is located in Europe. In the same way, the available information about each supplier and its past performance was gathered before starting the disruption management process.

[1] The examples are motivated by a case study of risk management in a pharmaceutical company. The readers can find more details of the case in Li (2011).

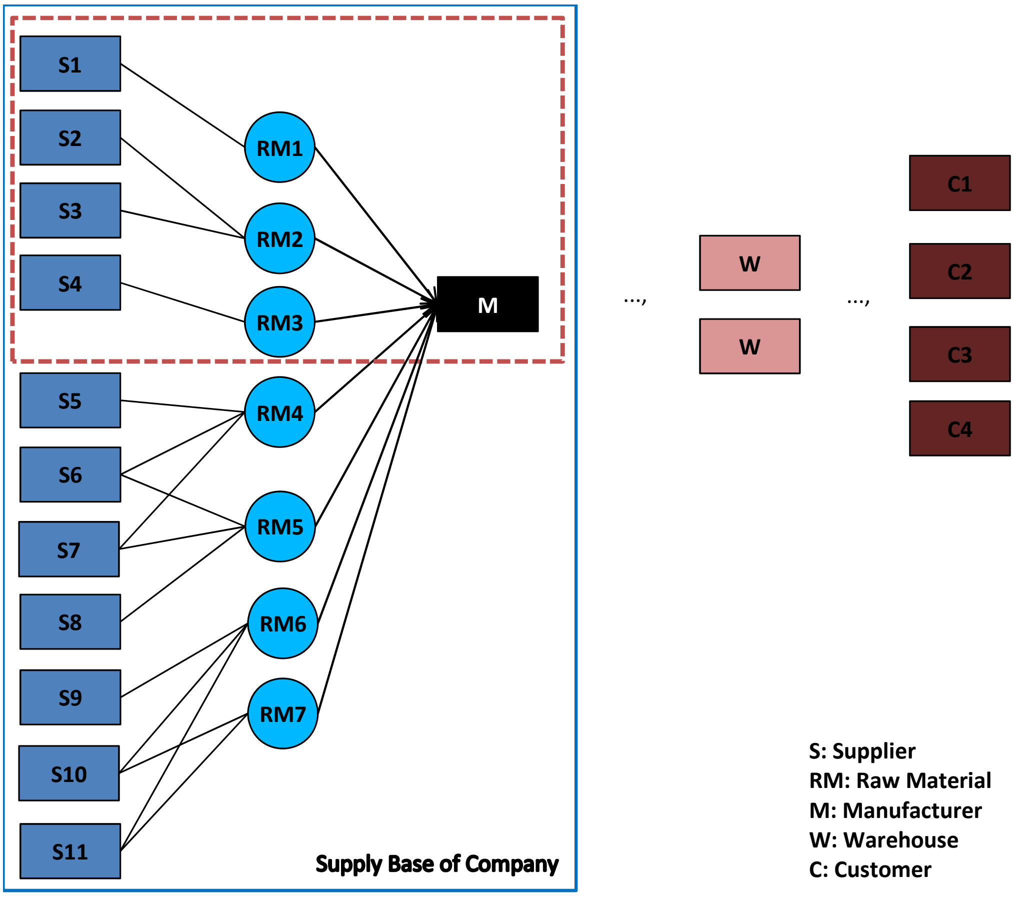


Figure C.4. Schematic of supply base of company

The first step in managing disruptions in the supply base was recognizing what factors might go wrong that will have adverse influence on the supply chain operation. With several sessions of brainstorming and the review of checklists, the disruption management team, consisting of supply chain manager and representatives from operation, storage, procurement, sales and logistics departments, has identified four important categories of *Potential Disruptions* in the supply base:

- *Supplier Failure to Deliver On-time*: a supplier does not fulfill the promised delivery dates for the raw materials.

- *Quality Problems in Raw Material*: the material shipped to the plant does not meet the quality specifications.

- *Transportation Disruption*: a significant delay or temporary stoppage of raw material delivery occurs due to, e.g., transportation incidents, natural disasters or 3PL mishandling.

- *Permanent Loss of Supplier*: the supplier goes out of business (e.g., because of bankruptcy) or stops producing a specific product (e.g., because of new safety and environmental regulations).

Table C.1. Examples of *Potential Disruptions* in the supply base

Disruption Group	Specific Disruption in Supply Chain
Supplier Failure to Deliver On-time	Dis1- Delay in shipping RM1 from supplier1
	Dis2- Delay in shipping RM2 from supplier2
	Dis3- Delay in shipping RM2 from supplier3
	Dis4- Delay in shipping RM3 from supplier4
Quality Problems in Raw Material	Dis5- Quality problem in RM1 from supplier1
	Dis6- Quality problem in RM2 from supplier2
	Dis7- Quality problem in RM2 from supplier3
	Dis8- Quality problem in RM3 from supplier4
Transportation Disruption	Dis9- Transportation disruption in RM1 delivery from supplier1
	Dis10- Transportation disruption in RM2 delivery from supplier2
	Dis11- Transportation disruption in RM2 delivery from supplier3
	Dis12- Transportation disruption in RM3 delivery from supplier4
Permanent Loss of Supplier	Dis13- Permanent loss of supplier1
	Dis14- Permanent loss of supplier2
	Dis15- Permanent loss of supplier3
	Dis16- Permanent loss of supplier4

These generic groups of possible disruptions were then specialized for the specific system of Figure C.4. As an illustration, a list of *Potential Disruptions* in the part of supply base which is restricted by dashed box is presented in Table C.1.

The possible impacts of disruptions on supply chain operation were also categorized in four main areas:

- Excess Operational Cost
- Reduced Sales
- Poor Delivery Performance
- Damaged Reputation

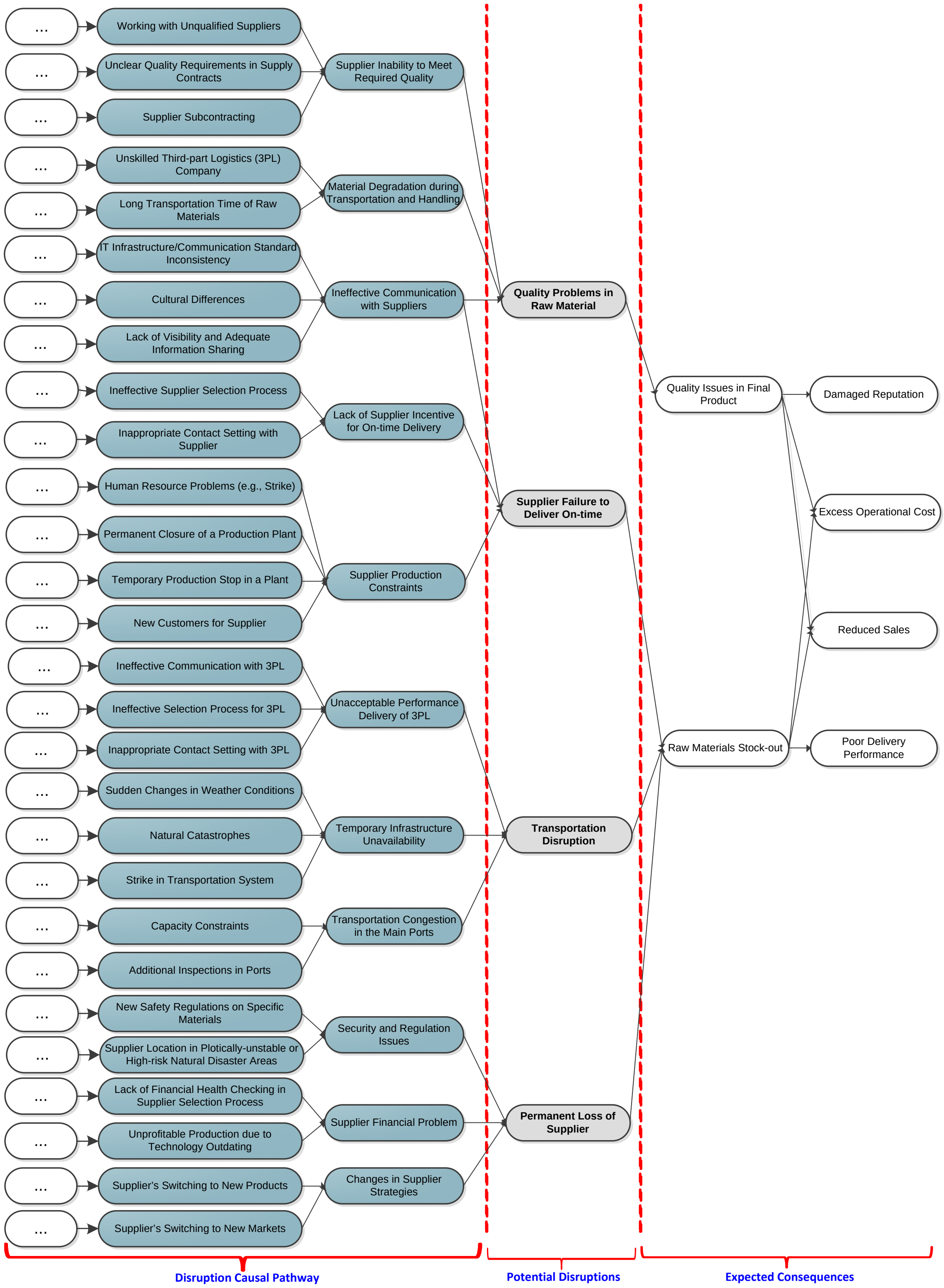


Figure C.5. A part of *Causal Pathway* for identified disruptions

The last three factors are impacting the revenue generation across supply chain and the first factor is the impact of disruption on the cost of production. Therefore, in general, the profitability of company is being impacted by *Potential Disruptions* in the supply chain[1].

For the *Potential Disruptions*, the *Causal Pathway* -which shows the development path for disruptions and possible root cause relationships - is also created. Part of the *Causal Pathway* is presented in Figure C.5. Thus, for example, the stock-out of RM2 might be because of delay in shipping RM2 from supplier2/3, transportation disruption in RM1 delivery from supplier2/3 or permanent loss of supplier2/3. Each of these *Potential Disruptions* might be caused by several other factors in the supply chain. For instance, delay in shipping RM2 from supplier2 might be because of miscommunication with supplier2 (on the delivery date), production constraint in supplier2 (because of, e.g., emergency shutdown in one of facilities) or lack of suppliers' incentive for on-time delivery. This *Causal Pathway* is frequently used in the succeeding steps of disruption management process.

R2: Risk Quantification

To evaluate the risk level for each potential disruption, a 5×5 matrix has been used (Figure C.6) in risk quantification step. The members of disruption management team were asked to rate the likelihood and the impact of disruption in the five-class scale. To support participants in their evaluation, the available historical data for the supplier's performance and also past events in the supply base were firstly discussed in a session. The *Causal Pathway* of Figure C.5 was also used as a support to have a comparison of the relative likelihood of different disruptions. Examples of arguments that have been done based on the *Causal Pathway* are as following:

- As the supplier1 has single production plant and it is also the only global supplier in the supply base, the likelihood of delay from this supplier and also the probability of transportation disruption in raw material delivery is higher than other suppliers. Moreover, the long distance of supplier may impact the quality of RM1 that is delivered to the plant.

[1] The list of impact areas considered here are the short-term and direct negative impacts of disruption. However, it must be emphasized that the impact areas are not totally independent as the "Poor Delivery Performance" might impact the "Damaged Reputation" of company and together, they might result in "Reduced Sales" in the mid- and long-term. Consequently, the "Reduced Sales" might consist of both short-term lost sales because of unavailability of products and the mid- and long-term indirect effect of damaged corporate image.

• As supplier4 is the only supplier with no quality certification (e.g., ISO 9001), the probability of quality issues in raw material delivery from this supplier is higher than others.

• Limited number of suppliers in the market can produce RM3; consequently, the permanent loss of supplier4 would have a high impact on the supply chain as finding alternative supplies might be a challenge and take a while.

	Likelihood (1-5)	Impact (1-5)	Risk Score (1-25)
Dis1- Delay in shipping RM1 from Supplier1	2	4	8
Dis2- Delay in shipping RM2 from Supplier2	1	2	2
Dis3- Delay in shipping RM2 from Supplier3	2	2	4
Dis4- Delay in shipping RM3 from Supplier4	1	3	3
Dis5- Quality problem in RM1 from Supplier1	2	3	6
Dis6- Quality problem in RM2 from Supplier2	1	4	4
Dis7- Quality problem in RM2 from Supplier3	2	4	8
Dis8- Quality problem in RM3 from Supplier4	2	4	8
Dis9- Transportation disruption in RM1 delivery from Supplier1	3	4	12
Dis10- Transportation disruption in RM2 delivery from Supplier2	1	2	2
Dis11- Transportation disruption in RM2 delivery from Supplier3	1	2	2
Dis12- Transportation disruption in RM3 delivery from Supplier4	1	3	3
Dis13- Permanent loss of supplier1	2	3	6
Dis14- Permanent loss of supplier2	2	3	6
Dis15- Permanent loss of supplier3	1	3	3
Dis16- Permanent loss of supplier4	1	4	4

			Likelihood				
		Descriptor	Rare	Unlikely	Possible	Likely	Very likely
Impact	**Descriptor**	Rating	1	2	3	4	5
	Insignificant	1	Dis2				
	Minor	2	Dis10 Dis11	Dis3			
	Moderate	3	Dis4 Dis12 Dis15	Dis5 Dis13 Dis14			
	Major	4	Dis6 Dis16	Dis1 Dis7 Dis8	Dis9		
	Catastrophic	5					

Figure C.6. Part of *Risk Catalogue* and its mapping in Risk Matrix

After the rating for likelihood and impact was assigned, by multiplying the likelihood and impact, a Risk Score for each potential disruption was calculated. The list of *Potential Disruptions* and the risk level for each disruption has formed the *Risk Catalogue* of company. Part of this *Risk Catalogue* is presented in Figure C.6. The potential disruptions are also mapped in the risk matrix.

R3: Risk Evaluation & Treatment

After the risk scores were evaluated for all identified disruptions, the disruption management team had a meeting to discuss the possible treatments for these disruptions. Considering the available resources for investing on disruption management, the team decided to firstly focus on the disruptions for which the risk score is higher than 8 (or disruptions in the orange and red area).

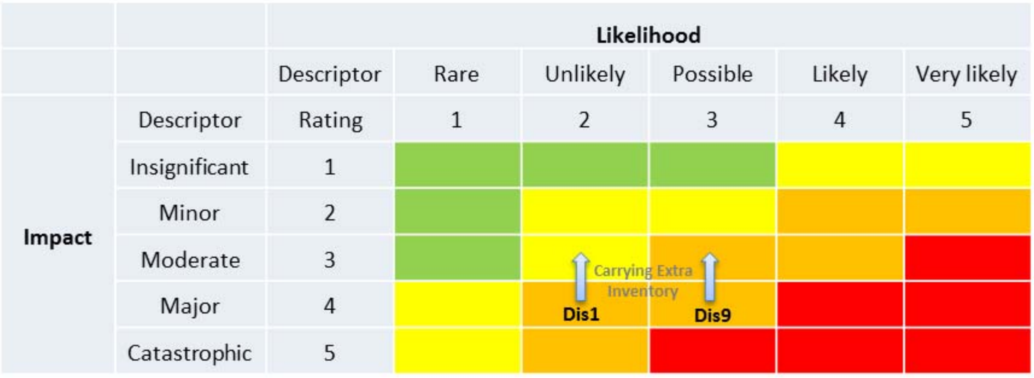


Figure C.7. The possible treatment for Dis1 and Dis9

Possible options to manage four selected disruptions (Dis1, Dis7, Dis8 and Dis9) were discussed. For example, to reduce the impact of Dis1 (Delay in RM1 from supplier1) and Dis9 (Transportation disruption in RM1 delivery from supplier1), the disruption management team came to agreement of considering an excess buffer of 20 percent for RM1[1]. This option was expected to reduce the risk score of Dis1 to 6 and the risk score of Dis9 to 9 (Figure C.7). However, the risk level of Dis9, after this treatment, was not yet in the acceptable area; accordingly, for the cases for which this extra buffer is not adequate to handle the delay, two contingencies have been discussed and agreed upon by the team members:

- *Rescheduling the production of customer orders*: delay in raw material delivery can create some constraints for production; however, if possible and none of customer orders would be delayed, the scheduling departments must change the timing of some part of production. Moreover, as part of the rescheduling procedure, a rating system has been suggested to classify the customers based on their importance for re-negotiating the order delivery date.

[1] As can be seen, one disruption management action in the mitigation of risk for more than one potential disruption. This systemic view is an important aspect in selection of possible treatments for disruptions in supply chain.

• *Emergency procurement*: a detailed emergency procurement procedure has been developed by disruption management team. Operation Department must determine the "quantity" and "expected delivery" of RM1 order, based on the existing backlog of orders, and send the raw material request to Scheduling Department. After approval by Scheduling Department, Procurement Department starts looking for alternative suppliers or buys the raw material on the spot market.

The other example of risk treatment in this chemical supply chain is changes that were suggested in supplier selection process and contract setting with suppliers. For instance, as a part of supplier selection, the candidate suppliers must be asked to send a copy of their quality system certifications. Suppliers who are not third-party certified shall present their plan for management of quality and may be subject to a Quality Management System audit by focal company. In addition, adding more clear requirements to current contract format was also being discussed by team members. Moreover, subcontracting must be explicitly banned in the contract terms[1].

With these changes in the contracts, it is expected that the quality issues with suppliers will be reduced in future.

As can be seen, the *Causal Pathway* of Figure C.5 gives lots of support in finding appropriate mitigation approaches for supply chain disruptions.

R4: Risk Monitoring

Several changes in the supply chain might introduce new *Potential Disruptions* or change the risk level for currently-identified disruptions. A list of the changes - which must be regularly monitored in the supply base - was being discussed by disruption management team in a session. To give some examples:

• *Changes in the supply chain of suppliers*: e.g., having new contracts with new customers or switching to new suppliers.

• *Changes in the daily operation of suppliers*: e.g., operational problems in supplier's facility and plant closure[2] or dispute about a labor strike in the supplier's region.

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[1] The raw material order might be subcontracted to other companies by supplier – either because it might run out of capacity or because it wants to widen the profit margin. With subcontracting the chance of a quality issues will be higher as the subcontractor might be an uncertified company.

[2] To better monitor supply chain operation, the suppliers have been obliged in the contracts to inform the manufacturer of any shutdown in their plants - even if it does not result in the late raw material delivery- within 48 hours.

- *Changes in the transportation system*: e.g., the news for a potential strike in the port of delivery or airline industry.
- *Changes in the regulations*: e.g., any international or national dispute to ban some materials that is somehow used in the production process of company or its suppliers.

In addition, the Supplier Scorecard in two areas of "On-Time Delivery" and "Received material Quality" has been designed to track the Suppliers' overall performance. These scorecards are also considered as criteria in awarding new contracts in future or extending the current contracts with the suppliers. The supplier scorecard is reported to each supplier on a quarterly basis to create motivation for performance improvement.

The supply chain disruption management team has also agreed to have similar meetings for supply chain risk management whenever:

- A new product line is established in the plant.
- A new supplier is added to supply base.
- A new 3PL or transportation rout has been considered for raw material delivery.

D1: Disruption Detection

Disruption management team has identified three important aspects when a supply chain disruption happens:

- *Visibility and information sharing across departments*: When a disruptive event is announced in the supply base – regardless of the perception of each actor of the severity of disruption – its occurrence must be urgently disseminated to other departments in the plant. For example, if storage department is informed by a supplier of a delay in raw material delivery, it must immediately pass the information to other departments. This information might impact the decisions made by each of department - e.g., order acceptance pattern by sales department- and accordingly, it would influence the severity of event.
- *Team formation*: when a disruption happens, the disruption response team must be quickly formed. The response team is a cross-functional team and consists of supply chain manager and representatives from operation, storage, procurement, sales and logistics departments. To better manage the response activities, supply chain manager is assigned as the coordinator of disruption response.
- *Analysis of disruption impact*: at the first stage, the response team must have an overview of the impact of disruption on the plant operation. Will plant production be

influenced by this disruption? Is it necessary to have a response to disruption? What are the possible areas might be impacted by disruption? …

To give an example of reaction to an *Actual Disruption* in the supply chain, the firm's response to a disruptive event is discussed here.

The disruption was a late raw material delivery: supplier1 sent a message that because of a trouble in the production facilities, it had to shut down the whole plant and accordingly, the raw material orders would be shipped with one week delay.

Receiving the message, the response team was formed and, as the first essential step, an evaluation of the impact of this delay on the performance of the plant was made. The evaluation showed that, with the current inventory and the current schedule of orders, a 10-day delay in raw material shipment can be tolerated by the plant without any significant effect on the downstream of the supply chain.

Although the effect of this delay was minor and insignificant, the supply chain manager continued the contact with supplier1 to check the status of their plant. Finally, 5 days after the first announcement, supplier1 came with a second message about the full scope of the disruption. The company now realized that it would take 4-6 weeks for the supplier to restore its normal and full operation.

D2&3: Disruption Reaction & Recovery

To better react to a disruption in supply chain, disruption management team has documented a process with three main steps:

- *Implementing the response plan*: the predefined disruption response must be the first reaction to the event as it helps a faster response. Moreover, it would reduce the confusion of response process because the aspects of this plan have been extensively discussed before in risk treatment step.
- *Option finding:* the response team must set brainstorming sessions to find alternative options for handling disruptions.
- *Option analysis*: the possible options for managing a disruption must be analyzed based on the "cost of implementation" and "time of implementation".

Continuing the case of disruption in raw material delivery from supplier1, the first reaction was rescheduling the production of customer orders. This option helped the plant to process more orders with the available raw material in the storage.

The company also started implementing the emergency procurement plan. However, because of complicated process and the amount of needed material, it took 5 days for the plant to find an alternative source and make an agreement. The emergency raw material was agreed to be delivered in one week and the plant could continue operation. However, the maximum delay that could be tolerated was 10 days; so, additional actions were necessary.

In the mean-time and before receiving the emergency order, the sales department had to contact some of the customers and start negotiation for extending their orders' due date. Moreover, to return and keep the system in the normal zone of operation, the operations department made some changes in the recipe of some of the products.

With all these efforts, the company could manage the disruption and return its system to the normal operation; it could meet the production target and prevent the disruption from affecting most of customers. The recovery step ended when supplier1 could have a full return to its nominal production.

D4: Disruption Learning

Disruption management team has defined a formal procedure for sharing the experience of different actors and documenting the possible lessons from disruption management process. This procedure consists of several brainstorming meetings in which response team members discuss the necessary changes in the current processes and how the supply chain operation and strategies must be modified to mitigate similar disruptions in future. Examples of aspects must be discussed in these meetings are:

- Is it necessary to change the disruption response plans?
- Is it necessary to change supply-based strategies (e.g., contract settings or supplier selection criteria) or supply chain structure (e.g., changing some suppliers or adding new suppliers to the supply base)?
- Could actors – which were involved in the management process - work effectively together?
- Is it necessary to update the previously-estimated likelihood and impact of disruption with the experience company had in managing an actual disruption?

For example, ***for the case of disruption in supplier1***, once the company could recover from the disruption, the disruption management team set a session to discuss the lessons that could be learned from the event. All team members agreed that the response plan (emergency procurement) was slow and they discussed the necessary changes to improve the plan. Particularly, to make the process faster, they removed the scheduling department's approval from the plan. Moreover, to reduce the probability and impact of similar disruptions in the future, they decided to redesign the supply chain and consider a reserve local supplier for RM1.

APPENDIX D: SUPPLY CHAIN DISRUPTION/RISK LITERATURE

Reference	Elements of Framework Covered by Literature[1]							Research Method used in the Research Literature						
									Qualitative			Quantitative		
	Disruption Detection	Disruption Reaction & Recovery	Disruption Learning	Risk Identification	Risk Quantification	Risk Evaluation & Treatment	Risk monitoring	Theoretical/conceptual works	Surveys and Interviews	Case study	Empirical (Statistical analysis of empirical data)	Analytical modeling (and optinization)	Simulation modeling	review
Adhitya et al. (2007a)	+++	+++								*		*		
Adhitya et al. (2007b)		+++								*		*		
Adhitya et al. (2009)				+++		+		*		*				
Appelqvist and Gubi (2005)						+							*	
Babich (2006)						++						*		
Bakshi and Kleindorfer (2009)						++						*		
Berg et al. (2008)		+		+	+	+	+	*	*	*				
Bichou (2004)				++				*						
Blackhurst et al. (2005)	+++	+++	+++	++		++			*	*				
Blackhurst et al. (2008)	+++			+	+++					*				
Blos et al. (2009)				+++	++				*					
Bogataj and Bogataj (2007)				++	++							*		
Braunscheidel and Suresh (2009)		++				++			*					
Burke et al. (2007)						++						*		
Canbolat et al. (2008)				+++	++	+++			*	*				

Reference	Elements of Framework Covered by Literature[1]							Research Method used in the Research Literature						
									Qualitative			Quantitative		
	Disruption Detection	Disruption Reaction & Recovery	Disruption Learning	Risk Identification	Risk Quantification	Risk Evaluation & Treatment	Risk monitoring	Theoretical/conceptual works	Surveys and Interviews	Case study	Empirical (Statistical analysis of empirical data)	Analytical modeling (and optinization)	Simulation modeling	review
Cavinato (2004)				+++				*						
Charles et al. (2010)	+	+				+		*	*					
Chao et al. (2009)						++						*		
Chen et al. (2010)		++										*		
Cheng and Kam (2008)				+++	+			*						
Choi and Krause (2006)						++		*						
Chopra and Sodhi (2004)				+++		+++		*						
Chopra et al. (2007)						++						*		
Christopher and Lee (2004)	++					++		*						
Christopher and Peck (2004)	++	++		+++		+++								
Cigolini and Rossi (2010)				+		+				*				
Colicchia et al. (2010)				++	+	++				*				
Cucchiella and Gastaldi (2006)				++		++		*						
Dani and Deep (2010)		+++		++							*			
Deane et al. (2009)					+	++								
Ellegaard (2008)						++			*					
Enyinda and Tolliver (2009)				+		++		*						
Enyinda et al. (2010)						++			*					
Faisal et al. (2006)						+++	+		*			*		
Faisal et al. (2007)				+++	++	++			*			*		
Finch (2004)				+++							*			
Gaonkar and Viswanadham (2007)				+++		++		*				*		
Gaudenzi and Borghesi (2006)				+++					*	*				
Glickman and White (2006)	+			+		++		*						
Goh et al. (2007)						+						*		
Hale and Moberg (2005)		++				+++		*						
Hallikas et al. (2004)				++		+		*		*				

Reference	Elements of Framework Covered by Literature[1]							Research Method used in the Research Literature						
									Qualitative			Quantitative		
	Disruption Detection	Disruption Reaction & Recovery	Disruption Learning	Risk Identification	Risk Quantification	Risk Evaluation & Treatment	Risk monitoring	Theoretical/conceptual works	Surveys and Interviews	Case study	Empirical (Statistical analysis of empirical data)	Analytical modeling (and optinization)	Simulation modeling	review
Harland et al. (2003)				+++				*		*				
Hendricks et al. (2009)						+++					*			
Huang et al. (2006)		+				+						*		
Huang et al. (2009)				+		++						*		
Iakovou et al. (2010)						++						*		
Ji (2009)						+++		*		*		*		
Jüttner (2005)				+++		++			*					
Kavčič and Tavčar (2008)				++					*					
Khan and Burnes (2007)				+++		+++								*
Kim et al. (2010)						++						*		
Kleindorfer and Saad (2005)				+++	++	++		*			*			
Knemeyer et al. (2009)					++	++		*						
Kull and Closs (2008)					+++				*					
Kull and Talluri (2008)				+	++	+++			*	*		*		
Kumar et al. (2010)				++		++			*			*		
Levary (2007)				++	++	+			*	*				
Levary (2008)				+	+	+			*	*				
Li et al. (2006)	+					+				*		*		
Manuj and Mentzer (2008)				+++		+++			*					
Matook et al. (2009)				+	+++				*	*				
Micheli et al. (2008)				++		++			*	*				
Mohtadi and Murshid (2009)					++						*			
Mudrageda and Murphy (2007)						++						*		
Munoz and Clements (2008)					++	+							*	
Norrman and Jansson (2004)						+++				*				
Oehmen et al. (2009)				++	+			*		*				
Oke and Gopalakrishnan (2009)				+++		+++			*	*				

Reference	Elements of Framework Covered by Literature[1]							Research Method used in the Research Literature						
									Qualitative			Quantitative		
	Disruption Detection	Disruption Reaction & Recovery	Disruption Learning	Risk Identification	Risk Quantification	Risk Evaluation & Treatment	Risk monitoring	Theoretical/conceptual works	Surveys and Interviews	Case study	Empirical (Statistical analysis of empirical data)	Analytical modeling (and optinization)	Simulation modeling	review
Olson and Wu (2010)				+++										*
Olson (2010)						+		*						
Parmar et al. (2010)						++						*		
Papadakis (2006)			+								*			
Peck (2005)				+++		++		*	*					
Pujawan and Geraldin (2009)				++	+	++		*		*				
Pyke and Tang (2010)	++	++	++	++				*		*				
Ratick et al. (2008)						++						*		
Ravindran et al. (2010)				+		++				*		*		
Ritchie and Brindley (2007)				++		+		*		*				
Ross et al. (2008)						++						*		
Roth et al. (2008)				++				*		*				
Sanchez-Rodrigues et al. (2010)				++	++	+			*					
Schoenherr et al. (2008)				+++	++	++	+		*					
Sheffi (2005)				++		++		*						
Sheffi and Rice (2005)	++					+++		*						
Sinha et al. (2004)				++	++					*				
Sodhi (2005)				+		++						*		
Sodhi and Lee (2007)				+++		+				*				
Stecke and Kumar (2009)				+++	+	+++		*			*			
Sutton (2006)				+				*						
Tan and Enderwick (2006)				++		++				*				
Tang (2006b)						+++		*						
Tang (2006a)				+++		+++								*
Tang and Tomlin (2008)				++		+++		*				*		
Tang and Musa (2011)				+++		+++								*
Thun and Hoenig (2011)				++	++	++			*					

Reference	Elements of Framework Covered by Literature[1]							Research Method used in the Research Literature						
									Qualitative			Quantitative		
	Disruption Detection	Disruption Reaction & Recovery	Disruption Learning	Risk Identification	Risk Quantification	Risk Evaluation & Treatment	Risk monitoring	Theoretical/conceptual works	Surveys and Interviews	Case study	Empirical (Statistical analysis of empirical data)	Analytical modeling (and optinization)	Simulation modeling	review
Tomlin (2006)						+++						*		
Tomlin (2009)						+++						*		
Trkman and McCormack (2009)				+++	+			*	*	*				
Tsai et al. (2008)				++				*	*					
Tuncel and Alpan (2010)				+++	+++	++				*			*	
VanderBok et al. (2007)						++		*						
Wang and Ip (2009)				++	++					*		*		
Wang, et al. (2010)						++						*		
Wagner and Bode (2006)				+++		++			*					
Wagner and Bode (2008)				+++					*					
Wei et al.(2010)					++	+							*	
Wiendahl et al. (2008)				++	+	+		*						
Wilson (2007)					++	++							*	
Wu et al. (2006)				+++	+++				*	*				
Wu et al. (2007)					++								*	
Wu and Olson (2008)						+++						*		
Xiao et al. (2005)						+						*		
Xiao and Yu (2006)						+						*		
Xu and Nozick (2009)						++				*		*		
Yang et al. (2009)					++	++						*		
Yang (2010)						++			*					
Yang and Yang (2010)					++			*						
Zsidisin et al. (2004)						+++				*				

1- The relevance of each paper for each step of framework is shown with "+" sign:
+++) this step is a main goal for this paper, some issues related to this step is discussed in this paper or a specific method is presented;
++) this step is relatively discussed in this paper;

+) this step is not the main objective of this paper but it is mentioned or issues are presented without a detailed discussion.

APPENDIX E: APPLICATION OF ABM IN SUPPLY CHAIN SIMULATION LITERATURE

Paper	Problem/Aim	ST view	Generalizable
Albino et al. (2007)	Studying the cooperation among supply chain (SC) firms in the industrial district (ID) context	-	+
Allwood and Lee(2005)	Presenting the business model for agent to study the network dynamics in a supply network	+/-	+
Barbuceanu et al. (1997)	An agent-based modeling approach to design and simulate global, distributed supply chains.	+/-	+
Behdani et al. (2010a)	Presenting a model for multi-plant enterprise to study the performance of the system under different behavioral rules, business policies, and environmental events	+	+
Bruzzone et al. (2005)	Presenting an ABM methodology to experiment with different aspects of the supply chain	-	+
Chatfield et al. (2006)	Presenting a supply chain simulation framework called SISCO (Simulator for Integrated Supply Chain Operations)	-	+
Chan and Chan (2006)	To evaluate the effects of demand uncertainty in a distributed supply chain and propose a coordination mechanism to minimize the negative impacts of demand uncertainty	-	+
Chan and Chan (2010)	Study the impact of flexibility and adaptability in delivery quantity and due date on the performance of a multi-product MTO supply chain	-	-
Datta and Christopher (2011)	Modeling to investigate the effectiveness of information sharing and coordination mechanisms in reducing uncertainty	-	-
Elofson and Robinson (2007)	Analyzing the impact of customer knowledge and demand information on supply-chain performance	-	-
Ferreira and Borenstein (2011)	Presenting a normative agent-based simulation modeling framework for planning of supply chains	+/-	+
Forget et al. (2009)	Presenting an agent based model to analyze the performance the lumber supply chain	+/-	-
Franke et al. (2005)	Analyzing the joint impact of reputation and price-based ranking of suppliers on the material flow in the supply chain	-	+
Garcia-Flores and Wang (2002)	Presenting such a multi-agent based model to simulate the dynamic behavior and support the management of chemical supply chains over the Internet	+/-	+
Giannoccaro and Pontrandolfo (2009)	Studying how revenue sharing contracts may form and analyzing the scenarios which favor the use of the RS contract	-	-
Giannoccaro (2011)	Modeling to identify the SC forms of governance appropriate to the SC integration problems	-	-
Gjerdrum et al. (2001)	Application of ABM to simulate and control a simple demand-driven supply chain network system with the manufacturing	-	+

Paper	Problem/Aim	ST view	Generalizable
	component being optimized through mathematical programming.		
Golinska and Kawa (2011)	Modeling to support management of reverse flow of materials in automotive industry	-	-
Hua et al. (2011)	Analyzing how bankruptcy occurs and propagates in supply chain networks	-	-
Hofstede et al. (2009)	Modeling the cultural aspects in the behavior of agents	-	+
Ilie-Zudor and Monostori (2009)	To introduce an agent-based model for partners' selection in inter-organizational supply-chains.	-	+
Jiang et al. (2010)	Analyzing the pricing strategy problems in a supply chain system	-	-
Julka et al. (2002)	Presenting an agent-based framework to simulate supply chains	+/-	+
Kaihara (2003)	Modeling supply chain as a discrete resource allocation problem under dynamic environment to demonstrate the applicability of the virtual market concept	-	+
Mele et al. (2007)	Analyzing the design and retrofit options for a production/distribution network	-	+
Moyaux et al. (2010)	Modeling supply chains operation as a network of auctions	-	+/-
Labarthe et al. (2007)	Proposing a methodological framework for the simulation of complex customer-centric supply chains	+/-	+
Lau et al. (2004)	Analyzing the impact of different levels of sharing information on inventory replenishment of enterprises in three-stage distribution supply chains	-	+
Li et al. (2010)	Modeling the evolution of supply networks	-	-
Lin and Shaw (1998)	Analyzing the reengineering of order fulfillment process in supply chain networks	-	+
Lin et al. (1999)	Developing a model to gain a better understanding of enterprise interactions via simulation.	-	+
Lin et al. (2002)	Analyzing the buyer–seller relationship in electronic commerce with an Extranet as the platform for sharing information	-	
Lin et al. (2005)	Analyzing the effect of trust mechanisms on supply-chain performance	-	+
Long et al. (2011)	Presenting a simulation framework with generic agents for modeling entities in supply chain	-	+
Swaminathan et al. (1998)	Describe a supply chain modeling framework based on multi-agent paradigm	+/-	+
Tykhonov et al. (2008)	Developing a multi-agent simulation model of the Trust And Tracing game	-	+
Valluri et al. (2009)	Investigating the performance of Reinforcement Learning (RL) in a distributed supply chain	-	-
van Dam et al. (2009)	Presenting and comparing the equation-based model and agent-based model for an oil refinery supply chain	+	+
Wang et al. (2008)	Analyzing the impact of the radio frequency identification (RFID) system on the inventory replenishment of the TFT-LCD supply chain in Taiwan	-	-
Wang et al. (2009)	Analyzing the design of a RFID-enabled inventory replenishment system for a global supply chain of a TTFT-LCD manufacturer	-	-
Yanez et al. (2009)	Analyzing the performance of various demand-driven production strategies of a timber production system.	-	-
Ye and Farley (2006)	Analyzing the impact of information sharing and control on the performance of supply network	+/-	-
Zhang and Bhattacharyya (2010)	Studying the impact of participating in e-marketplaces on participants' supply chain operations	+/-	-

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SUMMARY

Handling Disruptions in Supply Chains:

An Integrated Framework and an Agent-based Model

The management of supply chains has been transformed by new business trends in the last two decades. Globalization, outsourcing and just-in-time delivery are examples of these trends. On the one side, these trends in supply chain management have brought substantial benefit in cost reductions and improved competiveness. On the other side, supply chains have become more vulnerable to potential disruptions. Companies are not just facing more risk factors in a long globalized supply network, but the consequences of potential disruptions are also increasingly severe, as the impact of an initiating event propagates faster through the network due to lower buffer stocks and fragmentation of control in the value chain.

To cope with this increased vulnerability, companies need to actively manage (the risk of) disruptive events in their supply chains. This calls for systematic frameworks to guide their efforts. Besides, due to the complexity of today's global supply chains, decision-making tools are needed to provide support in different stages of the supply chain disruption management process. This study is conducted to address these issues.

- **An integrated framework for managing disruptions in supply chains**

In the supply chain management literature, handling supply chain disruptions is discussed from two different perspectives. One is the pre-disruption or preventive perspective which focuses on pro-active measures to avoid possible disruptions or to minimize the exposure to their potential impact. The other perspective is the post-disruption or re-active perspective which is concerned with what must be done after a disruption has materialized in the real world. To systematically manage supply chain disruptions, both perspectives are important and must be considered together in a comprehensive process. Nevertheless, the literature provides only a few contributions that actually emphasize the need for such a comprehensive integrated framework including both the pre- and post-disruption perspective. Whereas these present compelling evidence of their benefit for specific cases, a generic framework that incorporates both perspectives and details the pre- and post-disruption process steps and their inter-relations was found to be lacking in the literature. It is this gap that the work presented in this thesis has sought to fill.

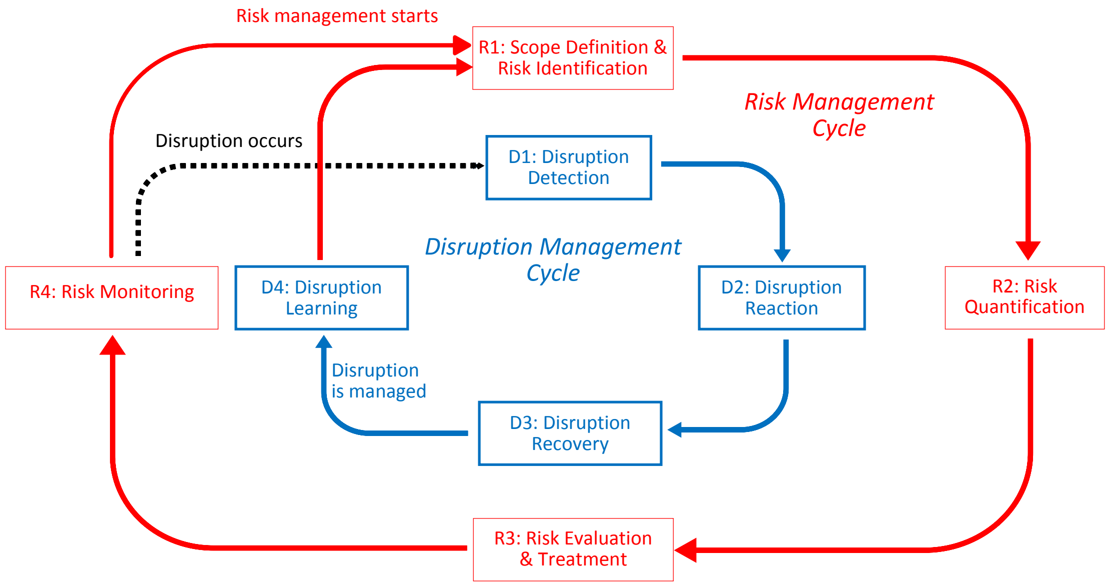


Figure 1. The structure of the Integrated Framework for Managing Disruption Risks in Supply Chains (InForMDRiSC)

The framework developed in this dissertation – called InForMDRiSC (Integrated Framework for Managing Disruption Risks in Supply Chains) – describes the process of handling disruptions in two interconnected cycles (see Figure 1): the Risk Management Cycle which is about the pre-disruption process steps and the Disruption Management Cycle which defines the process to be followed in handling actual supply chain disruptions. InForMDRiSC builds on the available frameworks in the literature and was evaluated by domain experts in industry and academia. To make the framework operational, each step including applicable supporting tools has been described in detail based on the existing literature on supply chain risk/disruption management. In the analysis of the literature, the majority of contributions were found to focus on the pre-disruption process, with different levels of attention for different steps of the risk management cycle. Some steps, such as risk identification and risk treatment, have been explored extensively while risk monitoring and risk quantification have been given far less attention. This implies that, in making the integrated framework operational, some steps could be detailed on the basis of literature available, whereas other steps need to be filled in, building on practices and tools developed in related fields. Moreover, whereas some modeling and simulation tools are presented to support decision-making in the risk management cycle (pre-disruption), the application of modeling and simulation for the post-disruption management process has not been addressed adequately in the existing literature. Tools with the ability to support all process steps in the proposed integrated framework are lacking. To close this gap, a new modeling and simulation framework was developed and its applicability to support InForMDRiSC as an integrated risk and disruption management process framework was put to the test.

- **An agent-based modeling framework for managing disruptions in supply chains**

Making decisions in different steps of InForMDRiSC needs flexible simulation frameworks enabling decision makers to explore a range of what-if scenarios and experiment with different disruption management strategies. To develop a simulation framework, we started by choosing an appropriate simulation paradigm. To this aim, a supply chain was characterized as a complex socio-technical system. Agent-based Modeling (ABM) was selected as the preferred simulation approach which is best equipped to capture both the technical and social complexity (and their interrelations) of global supply chains, and provides flexibility in experimenting with different disruption management strategies. To develop an agent-based modeling framework for supply chain disruption management, a conceptual model has been developed in three steps (Figure 2). Firstly, an agent-based representation of a generic supply chain was introduced. The Agent (representing the decision-making units in the system) was considered as the central concept in the social sub-system, responsible for the control and operation of a set of Technologies (representing the physical components in the system). The existing supply chain management theories were utilized to specify the main factors describing the structure and operation of each supply chain. In the second step, a conceptual model of supply chain disruption was formalized. Finally, we described how different disruption management practices can be defined and implemented in the model. With these three steps a conceptual model for disruption management in supply chains has been presented. The concepts in the conceptual framework were encoded in Java. The set of generic objects developed can be customized for specific cases by sub-classing and composing instances. The implementation of this modeling framework is demonstrated and discussed in this thesis for the specific case of a lube oil supply chain. Next, we showed how the simulation model developed can be used to support decision-making in different steps of InForMDRiSC.

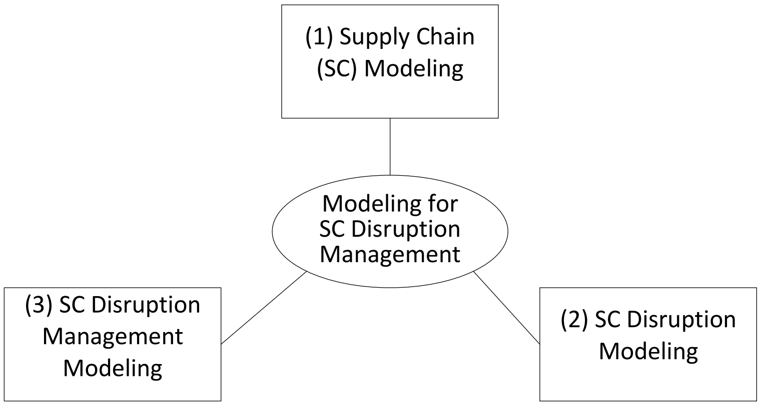


Figure 2. The steps in developing the supply chain disruption modeling framework

- **Concluding remarks**

The overall purpose of this thesis has been to provide support for handling supply chain disruptions, ex ante and ex post. To this aim, an integrated process and a simulation framework have been presented and discussed. These two contributions are, in fact, complementary means for supply chain disruption management forming a “simulation-based integrated framework for handling disruptions in supply chains”. Each of these two can also be used separately and independently. On the one hand, even if we do not implement the simulation framework, InForMDRiSC can be used as a comprehensive process for pro-active and re-active disruption management. On the other hand, the ABM framework can also be utilized independently to build simulation models for specific supply chains and employ these to experiment with different factors which influence normal supply chain operation and can be manipulated to prevent or recover from supply chain disruptions. To further facilitate the application of InForMDRiSC and the accompanying ABM framework in industrial cases, the thesis finally presents some directions for future research, which include the issue of how to embed InForMDRiSC in the organization of an industrial firm and its partners in the supply chain.

SAMENVATTING

Omgaan met Verstoringen in Leveringsketens:

Een Geïntegreerd Raamwerk en een Agent-based Model

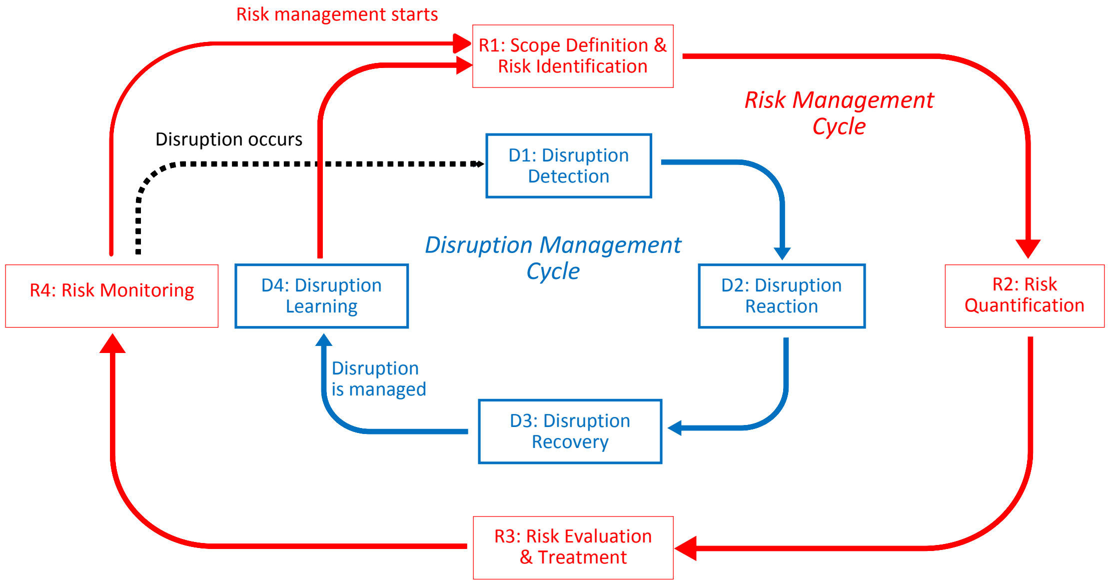
Het beheer van leveringsketens is de afgelopen twee decennia getransformeerd door nieuwe business trends: Globalisering, outsourcing en just-in-time levering zijn voorbeelden van deze trends. Aan de ene kant hebben deze veranderingen in het beheer van leveringsketens substantiële voordelen gebracht in kostenreducties en verbeterd concurrentievermogen. Aan de andere kant zijn leveringsketens kwetsbaarder geworden voor mogelijke verstoringen. Bedrijven worden niet alleen geconfronteerd met meer risicofactoren in een uitgebreid mondiaal leveringsnetwerk, maar de gevolgen van mogelijke verstoring zijn ook steeds ernstiger, omdat (de impact van) een beginnende verstoring zich sneller door het netwerk verspreidt als gevolg van kleinere buffervoorraden en fragmentatie van het beheer van de waardeketen.

Om met deze toegenomen kwetsbaarheid om te gaan moeten bedrijven (het risico op) verstorende gebeurtenissen in hun leveringsketens actief beheren. Dit vraagt om een systematische aanpak. Bovendien zijn, door de complexiteit van de mondiale leveringsketens van vandaag de dag, instrumenten nodig om besluitvormingsondersteuning te bieden in verschillende fasen van het proces van het aanpakken van verstoringen in leveringsketens. Dit onderzoek is uitgevoerd om een antwoord op deze uitdagingen te vinden.

- Een geïntegreerd raamwerk voor het aanpakken van verstoringen in leveringsketens

In de literatuur over supply chain management wordt het omgaan met verstoringen in leveringsketens vanuit twee verschillende perspectieven besproken. Eén is het preventieve perspectief, dat zich concentreert op proactieve maatregelen om mogelijke verstoringen te voorkomen of om (de blootstelling aan) de mogelijke impact van deze verstoringen te minimaliseren. Het andere perspectief is het reactieve perspectief, hetwelk datgene betreft wat gedaan moet worden nadat een verstoring werkelijkheid is geworden. Om verstoringen in leveringsketens systematisch aan te pakken zijn beide perspectieven belangrijk: ze moeten beide beslag krijgen in één samenhangend proces. In de literatuur over het management van leveringsketens vinden we slechts enkele bijdragen die de noodzaak van een dergelijk allesomvattend geïntegreerd raamwerk, inclusief zowel het pre- als post-verstoringsmanagementperspectief, benadrukken. Alhoewel deze overtuigend bewijs leveren van hun nut voor specifieke gevallen, is een generiek raamwerk dat beide perspectieven bevat, en dat de stappen van de pre- en post-verstoringsprocessen en hun interrelaties nauwkeurig beschrijft, niet gevonden in de literatuur. Het werk dat in dit proefschrift wordt gepresenteerd beoogt deze lacune te vullen.

Het raamwerk dat in deze dissertatie is ontwikkeld – genaamd InForMDRiSC: Integrated Framework for Managing Disruption Risks in Supply Chains, ofwel Geïntegreerd Raamwerk voor het Aanpakken van Verstoringsrisico's in Leveringsketens – beschrijft het proces van het gestructureerd omgaan met verstoringen in twee onderling verbonden cycli (zie Figuur 1): de Risicomanagement-Cyclus, die de processtappen voor preventie van verstoringen beschrijft, en de Verstoringsmanagement-Cyclus, die het proces definieert voor het omgaan met daadwerkelijke verstoringen in leveringsketens. InForMDRiSC bouwt voort op de beschikbare raamwerken in de literatuur en is beoordeeld door domeinexperts uit de industrie en de academische wereld. Om het raamwerk te operationaliseren is elke stap, inclusief toepasbare ondersteunende analyse-instrumenten, in detail beschreven op basis van de bestaande literatuur over risico/verstoringsmanagement van leveringsketens. In de analyse van de literatuur werd vastgesteld dat de meerderheid van de bijdrages zich op het pre-verstoringsproces concentreert, met verschillende niveaus van aandacht voor verschillende stappen van de risicomanagement-cyclus. Sommige stappen, zoals risico-identificatie en risicobehandeling, zijn uitgebreid onderzocht, terwijl risicomonitoring en risicokwantificering veel minder aandacht hebben gekregen. Dit impliceert dat, om het geïntegreerde raamwerk operationeel te maken, sommige stappen in detail beschreven kunnen worden op basis van de beschikbare literatuur, terwijl andere stappen nog grotendeels ingevuld moeten worden, voortbouwend op toepassingen en instrumenten die in verwante gebieden zijn ontwikkeld. Bovendien blijkt uit de literatuurstudie dat modelleer- en simulatietools wel worden gepresenteerd voor de ondersteuning van besluitvorming in de risicomanagement-cyclus (pre-verstoring), maar dat de toepassing van modellering en simulatie voor het post-verstoringsmanagementproces nog in de kinderschoenen staat. Tools met het vermogen om alle processtappen in het voorgestelde geïntegreerde raamwerk te ondersteunen, ontbreken. Om dit hiaat te vullen is een nieuw modelleer- en simulatieraamwerk ontwikkeld en getest voor de praktische ondersteuning van InForMDRiSC als geïntegreerd raamwerk voor risico- en verstoringsmanagementprocessen in leveringsketens.

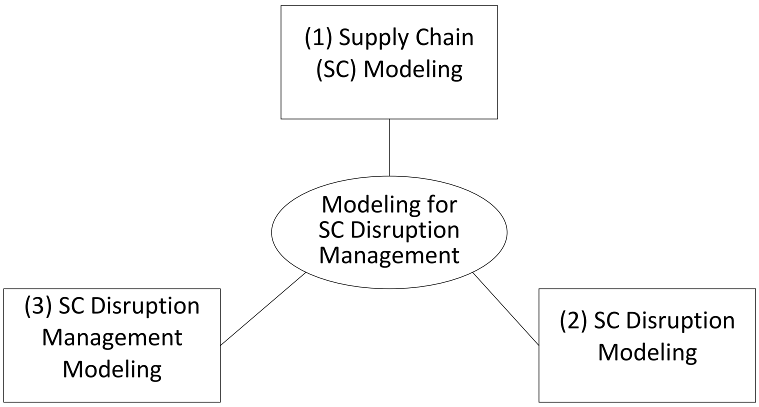


Figuur 1. De structuur van het Geïntegreerde Raamwerk voor het Aanpakken van Verstoringsrisico's in Leveringsketens (InForMDRiSC)

- Een agent-gebaseerd modelleringsraamwerk voor het aanpakken van verstoringen in leveringsketens

Het nemen van besluiten in verschillende stappen van InForMDRiSC vergt flexibele simulatieraamwerken, die het besluitvormers mogelijk maakt om een reeks "wat-als?" scenario's te verkennen, en te experimenteren met verschillende verstoringsmanagementstrategieën. Om een dergelijk simulatieraamwerk te ontwikkelen hebben we eerst een geschikt simulatieparadigma gekozen. Uitgaande van de karakterisering van een leveringsketen als een complex socio-technisch systeem, is Agent-based Modelling (ABM) geselecteerd als de meest geschikte simulatieaanpak, die het best is toegerust om zowel de technische als de sociale complexiteit (en hun interrelaties) van mondiale leveringsketens te "vangen", en de flexibiliteit geeft om met verschillende verstoringsmanagementstrategieën te kunnen experimenteren. Om een agent-based modeling raamwerk voor het beheer van leveringsketenverstoringen te ontwikkelen is een conceptueel model ontwikkeld in drie stappen (Figuur 2). Allereerst is een agent-gebaseerde representatie van een generieke leveringsketen geïntroduceerd. De Agent (welke de besluitvormingseenheden in het systeem vertegenwoordigt) is het centrale concept in het sociale subsysteem, verantwoordelijk voor de beheersing en uitvoering van een set van Technologieën (die de componenten in het fysieke subsysteem vertegenwoordigen). De bestaande supply chain management-theorieën zijn gebruikt om de hoofdfactoren die de structuur en uitvoering van elke leveringsketen beschrijven, te specificeren. In de tweede stap is een conceptueel model van leveringsketenverstoring geformaliseerd. Ten slotte is beschreven hoe verschillende toepassingen van verstoringsmanagement kunnen worden gedefinieerd en geïmplementeerd in het model. Met deze drie stappen is een conceptueel model voor verstoringsmanagement in leveringsketens gepresenteerd. De concepten in het conceptuele model zijn gecodeerd in Java. De set van ontwikkelde generieke objecten kunnen worden aangepast voor specifieke gevallen door instanties te sub-classificeren en samen te stellen.

De implementatie van dit modelleerraamwerk wordt gedemonstreerd en besproken in dit proefschrift voor de specifieke casus van een complexe leveringsketen voor smeerolie. Daarna wordt gedemonstreerd hoe het ontwikkelde simulatiemodel kan worden gebruikt om besluitvorming in verschillende stappen van InForMDRiSC te ondersteunen.



Figuur 2. De stappen in de ontwikkeling van het modelleerraamwerk voor leveringsketenverstoringen.

- Afsluitende opmerkingen

Het algemene doel van dit proefschrift is om ondersteuning te bieden voor het omgaan met verstoringen in leveringsketens, ex ante en ex post. Om dit te bereiken zijn een geïntegreerd proces en een simulatieraamwerk ontwikkeld. Deze twee bijdragen zijn, in feite, complementaire middelen voor het omgaan met verstoringen en verstoringsrisico's in leveringsketens. Het resultaat kan worden samengevat als een "simulatie-gebaseerd, geïntegreerd raamwerk voor het omgaan met verstoringen in leveringsketens". Elk van beide "instrumenten" kan ook apart en onafhankelijk worden gebruikt. Aan de ene kant, zelfs als we het simulatieraamwerk niet implementeren, kan InForMDRiSC worden gebruikt als een allesomvattend proces voor proactief en reactief verstoringsmanagement.

Aan de andere kant kan het ABM raamwerk ook onafhankelijk worden gebruikt om simulatiemodellen te bouwen voor specifieke leveringsketens en deze te gebruiken om te experimenteren met verschillende factoren die het normaal functioneren van leveringsketens beïnvloeden en kunnen worden gemanipuleerd om verstoringen te voorkomen of hiervan te herstellen. Om de toepassing van InForMDRiSC en het bijbehorende ABM raamwerk in industriële casus verder te faciliteren, geeft dit proefschrift tot slot enkele aanbevelingen voor toekomstig onderzoek, onder meer naar de verankering van InForMDRiSC in de organisatie van een industrieel bedrijf en van zijn partners in de leveringsketen.

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