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STRATEGY EVALUATION AND SELECTION IN MANAGING SUPPLY RISK

Supervisor:

Prof. Roberto Pinto

PhD Candidate:

Fabiana Pirola

Matr. No. 30639

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Table of Contents

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Executive Summary

Scope and rationale of the research work

Supply chains are becoming more complex with the numerous physical and information flows that involve worldwide companies. In this way, a disruption, resulting from any of the several risks an organization is facing and occurring anywhere along the supply chain, can have a detrimental effect on a company, affecting its ability to continue operations and provide finished products and services to customers. The $400 million loss incurred by Ericsson after the fire in its sole microchip supplier in 2000 or the estimated $2 billion loss of Toyota due to gas pedal problem in 2010 (Isidore, 2010**)** are only few examples of the impact of risk resulting in supply chain disruptions and external quality failures that originate in the upstream supply chain. However, supply chains are vulnerable not only to high-impact, low-likelihood risks, as in the above examples, but also to low-impact, high-likelihood risks, arising from problems in coordinating supply and demand (Oke and Gopalakrishnan, 2009). In fact, considering day-by-day operations, delays in supplier deliveries can lead to disruption in company's production scheduling causing further delays in delivering products to customers and then their dissatisfaction or loss.

The current financial crisis that has been slowing down the global economy has drawn the attention to supply failure and has further increased the awareness among professionals that risk assessment and mitigation play a crucial role in successfully managing supply chains (O'Marah, 2009). This increasing focus on supply risk, along with the even more predominant trend to focus on core activities that creates greater dependencies on upstream supply, emphasize the importance of supply side risk management.

Integrating past academic definitions of supply risk and purchasing professionals points of view, Zsidisin (2003) defined supply risk as “the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety”.

Due to the complex and dynamic nature of a supply chain, that can be characterized by several tiers of suppliers, each of them with multiple components or members, managing inbound supply risk is becoming a very challenging task. In addition, even if in these years inbound supply chain risk management is drawing increasing attention from both practitioners and academic researchers, there is still a need for a general supply risk management methodology to classify, manage and assess this risk (Zsidisin *et al.*, 2000; Wu *et al.*, 2006; Thun and Hoening, 2009).

Several authors have proposed frameworks to support companies’ risk management considering both generic supply chain risks (AIRMIC, 2002, Ritchie and Brindley, 2007, Waters, 2007, ISO 31000:2009 and ISO/IEC Guide 73:2009) or, more specifically, supply risk (Wu *et al.*, 2006, Harland *et al.*, 2003, Matook *et al.*, 2009, Hallikas *et al.*, 2004). Even if some differences exist, all these frameworks are based on the same four phases, that are (i) *risk identification* that gives rise to awareness of risk an organization is facing, (ii) *risk assessment* to evaluate the potential impact and the occurrence probability of a risky event, (iii) *decision and implementation of risk management actions* aiming at reducing the impact or decreasing the occurrence probability of a disruption, and (iv) *risk monitoring* to ensure that risks are effectively identified and assessed and that appropriate controls and responses are in place. However, few studies focus on the third stage (i.e. risk management actions) of the risk management frameworks as a means of enhancing product quality and supplier-base performance (Matook *et al.*, 2008).

In order to fill these gaps, this research focuses on supply risk and aims at developing a methodology that supports risk management. In particular, the attention is concentrated on the third phase (decision and implementation of risk management actions) and tools supporting the evaluation and selection of the most suitable strategies to deal with supply risk are provided.

Purpose of the research work

Stemming from a typical risk management framework, this research proposes an enhanced four-step methodology to deal with supply risk, as depicted in Figure 1. While the first and the last step, namely "analysis of supply risk" and "monitoring and feedback", are essentially based on literature, the main contributions of this work concern the core phases of the entire process: "evaluation of available strategies" and "selection of the most suitable strategies". This methodology and the proposed approaches and tools are intended to address the problem of managing the risk related to strategic suppliers, namely the ones providing items with high impact on company profitability or difficult to substitute.

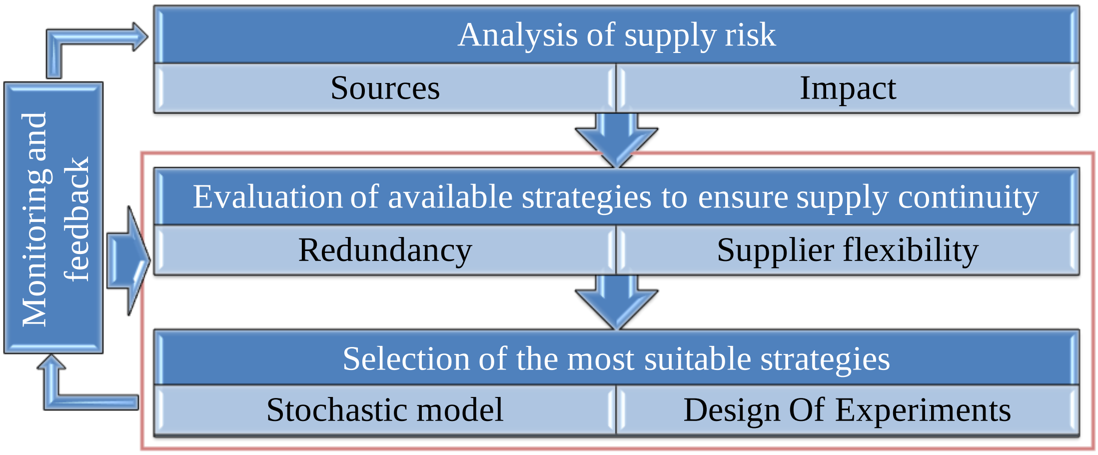

Figure 1 - The four-step methodology

An effective risk management strategy should ensure supply continuity. In other words, companies should be able to select the best strategy to increase their resilience (Sheffi and Rice 2005) - the ability to return to the original state or to move to a new and more desirable one after being disrupted (Christopher and Peck 2004). Resilience can be achieved by creating redundancy or increasing flexibility (Sheffi and Rice 2005). These concepts have been investigated in literature mainly considering the company's point of view (Sheffi and Rice, 2005; Peck, 2005; Pettit *et al.*, 2010; Christopher and Peck, 2004; Tang, 2006a); nevertheless, given the

increasing relevance of supply risk, this research moves the focus of resilience to the supply side. In this context, redundancy means keeping some resources in reserve (in terms of inventory, time and capacity) to be used to limiting the consequences of a supply disruption (Sheffi and Rice 2005). On the other hand, flexibility comprises any strategy attempting to reduce supply disruption likelihood by increasing its performance and its ability to respond in a timely and cost effective manner to changing requirements of purchased components (Tachizawa and Thomsen 2007, Tang and Tomlin 2008). In particular, this thesis takes into account actions that can be implemented in the short or medium term and that do not involve a substantial redesign of the network or of the company's internal processes and strategies.
Even though they have been named in several different ways, supply risk management strategies broadly leverage on these two concepts, briefly described in table 1 along with their main impacts on focal company and supplier performance.

	Strategy	Definition	Impact
Redundancy	Inventory buffer	To keep stocks to mitigate risk occurrence	Reduce the impact of supplier delays Increase buffer and total cost Decrease transparency and coordination level
	Time buffer	To include slack time in scheduled time or having longer delivery lead time	
	Capacity buffer	To keep extra internal capacity or have multiple or backup suppliers	
Supply Flexibility	Supplier integration	To share explicit knowledge or information with suppliers	Decrease buffer size Increase transparency Improve supplier performance Reduce transaction and acquisition costs Increase plan alignment cost
	Supplier development	To share know-how with suppliers	

Table 1 - Overview of supply flexibility and redundancy strategies

Although redundancy and supply flexibility are two different strategies, where the former aims at reducing the impact of risky events while the latter focuses on risk sources reduction, they are not mutually exclusive. On the contrary, a certain level of redundancy is always required to cope with supply risk, because even if through integration practices and/or supplier development activities, supplier reliability and stability are improved, the risk associated to that supplier will be reduced but never removed. In fact, even if the buying company achieved a really close coordination level with its supplier and the investment brought such a supplier internal processes improvement that ensures perfect on time deliveries, some external disruptions could however happen. In this case, if no buffers are taken (such as backup supplier), some economic losses will occur. Thus, supply flexibility strategies can be undertaken to decrease redundancy, but they can never exist alone without any buffer.

Despite that, flexibility and redundancy are generally investigated as two different and unrelated strategies. Furthermore, authors studying redundancy practices usually perform quantitative studies in order to identify the optimal quantity to be buffered, while researches on flexibility are more qualitative and descriptive, providing insights into the actual employment of these strategies and their perceived benefits.

These observations lead to the main research question of this work: **how to jointly evaluate the available strategies to deal with supply risk and make the right decisions that improve supply chain performance?**

To answer this question, two models have been developed:

- A **descriptive model** that supports the analysis of conjoint effects produced by the two different strategies (redundancy and supply flexibility) simultaneously adopted. This model is the central point of the second phase of the proposed methodology - evaluation of available strategies to ensure supply continuity.
- A **quantitative model** that, starting from the relationships identified in the previous step, supports supply tactical planning considering inbound disruptions and determining the most suitable strategies for ensuring supply continuity. The third step of the methodology deals with this model and the related results' analysis.

Structure of the thesis

In order to overcome the existing gaps in the supply risk management literature and to answer the main research question, this thesis is organized as follows:

- **Chapter 1** begins with the definition of risk and uncertainty. Then, after a classification of the different types of supply chain risk, it focuses on supply risk, highlighting its relevance in today's economic environment and providing a description of tools and instruments that enable its identification and its impact assessment.

- **Chapter 2** starts with a literature overview of the main supply risk management frameworks. Then, after a statistical demonstration of the actual correlation and effectiveness of the typical phases of a supply risk management framework (namely, risk identification, risk assessment, and risk management that lead to risk occurrence reduction), it introduces the four-step methodology to manage supply risk proposed in this thesis.
- **Chapter 3** focuses on the second phase of the proposed methodology (i.e., evaluation of all the available strategies) and carries out a deep literature review of redundancy and supply flexibility strategies to deal with supply risk. The main output and contribution of this chapter is the systemic model that analyzes the direct and indirect effects of these two strategies simultaneously adopted on buyer and supplier performance
- **Chapter 4** translates the core part of the systemic model presented in the previous chapter in a two-stage stochastic model to support the third phase of the four-step methodology, namely the selection of the most suitable strategies. Furthermore, it proposes an application of Design Of Experiments (DOE) in order to build a series of experiments to statistically identify factors that mainly impact on strategies selection and to draw useful insights.
- **Chapter 5** proposes a use case to show an example of practical application of the four-step methodology presented in this thesis. Particular attention is paid to the application of the DOE methodology and insights about strategy selection are also discussed.
- **Chapter 6** concludes this thesis with some remarks and further developments of this research.

1. Supply chain risk

Nowadays, supply chains are becoming more complex with the numerous physical and information flows that involve worldwide companies. To succeed in this environment and gain competitive advantage, firms need to pursue a high level of effectiveness while continuously reducing costs. For this reason, practices such as lean manufacturing, just-in-time and low-cost-country sourcing have become familiar to supply chain managers and have gained growing attention in academia. These practices allow firms to achieve better performance and lower costs through a close collaboration between customers and suppliers. However, they may lead to increasing their exposure to and/or the severity of supply chain disruptions (Craighead et al. 2007). In fact, a disruption, resulting from any of the several risks an organization is facing and occurring anywhere along the supply chain, can have a detrimental effect on a company, affecting its ability to continue operations and provide finished products and services to customers.

The impact of supply chain disruptions, while difficult to quantify, can be costly and can affect company's stock price and equity. Based on a sample of 827 disruption announcements made during 1989–2000, Hendricks and Singhal (2005) investigated the long-term stock price effects and equity risk effects of supply chain disruptions. Analyzing the stock price effects starting one year before through two years after the disruption announcement date, they found out an average abnormal stock returns of firms of nearly - 40%, along with significant increases in equity risk. Their results also showed that the majority of supply chain disruptions involved part shortages, lack of response to customer-requested changes, production problems, quality problems and so on.

In the past years, many events illustrate this phenomenon. For instance, in 1997, Toyota was forced to shut down for several days 20 auto plants in Japan because a fire destroyed its major brake valve supplier and most of Toyota plants was keeping only four-hours supply of these valves (Jüttner, 2005). In 2000, Ericsson incurred in a $400 million loss because in its sole microchip supplier caught fire. In 2004, a contamination at one of two suppliers of flu vaccine to the United States led to a severe shortage at the beginning of the flu season (Chopra and Meindl, 2006). In 2006, due to a fire hazard, Dell recalled 4 million laptop computer batteries made by Sony (Tang and Tomlin, 2008). More recently, in 2010, Toyota incurred in $2 billion loss due to gas pedal problem (Isidore, 2010).

However, supply chains are vulnerable not only to disruptions or high-impact, low-likelihood risks, as in the above examples, but also to low-impact, high-likelihood risks, arising from problems in coordinating supply and demand (Oke and Gopalakrishnan, 2009).

In fact, considering day-by-day operations, delays in supplier deliveries can lead to disruption in company's production scheduling causing further delays in delivering products to customers and then their dissatisfaction or loss. This happens because in today's business environment, it has become easier for a customer to search across stores for product availability. For example, when shopping for book on-line, if Amazon.com is out of title, a customer can easy check if another online bookshop has the title available and buy from it (Chopra and Meindl, 2006). As a result, product availability and on time deliveries represent a critical issue for modern supply chains.

Considering the greater relevance of supply chain risk, the International Organization for Standardization (ISO) developed the ISO 31000:2009 to provide principles, generic guidelines, framework and a process for managing any form of risk in a transparent, systematic and credible manner within any context.

The ISO 31000 family includes:

- ISO 31000 - Principles and Guidelines on Implementation;

- IEC 31010 - Risk Management - Risk Assessment Techniques: it provides guidance on selection and application of systematic techniques for risk assessment;
- ISO/IEC 73 - Risk Management Vocabulary: it provides a collection of terms and definitions relating to the management of risk.

Although awareness is increasing among practitioners, the concepts of supply chain vulnerability and its managerial counterpart supply chain risk management (SCRM) are still in their infancy. Many companies have recognised the need to conduct formal risk audits and to seek to manage that risk, but the definition of risk is usually fairly limited (Jüttner, 2005).

In this chapter an overview of the different risk and uncertainty definitions present in the academic literature is provided. Then, a classification of supply chain risk is introduced and a close examination of supply risk is carried out, providing its definition and listing its main sources. This chapter concludes with a deep overview of the tools for supply risk identification and impact assessment, that can be use for the first phase of the proposed 4-step methodology.

1.1 Risk and uncertainty definition

Since the beginning of the past century, risk has been investigated in several and diverse fields of literature, starting from economics (e.g. Willet, 1901; Knight, 1921; Tversky and Kahnemann, 1992) to finance (e.g. Markowitz, 1952; Smith *et al.*, 1990), engineering (e.g. Rechard, 1999; Lewis *et al.*, 1978, Helton and Oberkampf, 2004), strategic management (e.g. Bettis and Thomas, 1990; Simons, 1999), international management (e.g. Miller, 1992; Ting, 1988), operation research (e.g. Zimmermann, 2000; Jia and Dyer, 1996) and, more recently, supply chain viewpoint (e.g. Jüttner et al., 2003; Tang, 2006a). Despite that, there is no general consensus on its definition, but instead there exist several definitions and, in particular, there is not a clear distinction between risk and uncertainty. As a matter of fact, in their literature review, Samson *et al.* (2009) stated that there is no general definition for these two terms but rather many discipline and context dependent definitions. In fact, they identified different definitions and relationships between risk and uncertainty in the economic and finance, operation research and engineering fields. Some authors, especially in the world of economic and finance, consider uncertainty as risk and/or risk as uncertainty, so as synonyms. On the contrary, there are many scholars who believe that uncertainty and risk are two different concepts, but still do not agree on how they are related: someone states they are two independent concepts while some others believe they are dependent. In this last school of thought, some authors consider that risk depends on uncertainty and others that uncertainty depends on risk.

This research work considers risk and uncertainty as two distinct but related concepts, whose difference lies in the measurability and quantification of possible outcomes. Referring to Waters (2007):

- *Uncertainty* means that it is possible to list the events that might happen in the future, but there is no idea about which will actually happen or their relative likelihoods;
- *Risk* means that it is possible to list the events that might happen in the future and give each a probability.

Consequently, the key difference between the two concepts is that risk has some quantifiable measure for future events and uncertainty does not. Thus, uncertainty implies that in a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behavior or other characteristics. Zimmermann (2000) provides a quite exhaustive classification of the causes of uncertainty, that are:

- *Lack of information or knowledge*: it is probably the most frequent cause for uncertainty;
- *Abundance of information (complexity)*: it is due to the limited ability of human beings to perceive and process simultaneously large amounts of data;
- *Conflicting evidence*: it is due to the fact that some of the available information is wrong but not identifiable as wrong, or information of non-relevant features of the system is being used and so on;
- *Ambiguity*: a situation in which certain information has entirely different meanings, depending on the context;
- *Measurement*: it means that there is some uncertainty about the real measure and it is known only the measure indicated by the measurement tool;

- *Subjective belief*: all information available to the observer are subjective as a kind of belief in a certain situation.

Regarding risk, despite a lack of a generally accepted definition, it is most commonly conceived as reflecting "variation in the distribution of possible outcomes, their likelihood's, and their subjective values" (March and Shapira, 1987). Thus, the fundamental feature of risk is that unforeseen events may happen in the future and, then, risk occurs because there is uncertainty about the future.

However, when defining risk, several dimensions should be taken into account (Ritchie and Brindley, 2007; Manuj *et al.*, 2008):

- *Likelihood of occurrence of a particular event or outcome*: it is typically expressed as a probability and it can be expressed in objective terms or in subjective terms, each being capable of measurement although utilizing differing scales;
- *Consequences of the particular event or outcome occurring*: they may be expressed from a variety of perspectives including multiple perspectives simultaneously (e.g. failure of a new product launch may generate consequences for the organization's reputation, financial performance and the individual product champion); it is important to stress that consequences are not only negative and that the essence of risk taking is the potential opportunity to produce positive outcomes;
- *Causal pathway leading to the event*: it relates to the nature of the event and the sources and causes that generate it, influencing the likelihood of it occurring and the scale of the consequences or outcomes;
- *Speed*: it can be divided into the rate at which the event leading to loss happens (*speed of event*), the rate at which losses happen (*speed of losses*), and how quickly the risk event is discovered (*the time for detection of the events*). Coupled with increased lead times, lead time variability, physical distances from sources of risk, and lesser control over the supply chain, speed increases the magnitude of global supply chains problems;
- *Frequency*: it is a measure of how often a similar kind of risk event happens; in fact, some risks appear on a regularly basis in normal operations, while others are one-off risks that can cause disruptions, such as natural disasters.

1.2 Supply chain risk definition

In the previous section the debate on and a general definition of the terms uncertainty and risk have been introduced. Since supply chain is defined as "the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer" (Christopher 1992), a key feature of supply chain risk is that it extends beyond the boundaries of the single firm and, moreover, the boundary spanning flows can become a source of supply chain risks (Jüttner, 2005).

Nevertheless, several publications have addressed the question of supply chain risk definition. In general, two different approaches can be distinguished (Wagner and Bode, 2009):

- Risk as both danger and opportunity
- Risk as purely danger

In the first approach, typically used in finance, the fluctuations around the expected value (mean) of possible outcomes (both positive and negative) are used as proxy for risk. Following these considerations and the general definition of March and Shapira (1987), Jüttner *et al.* (2003) defined risk as "variation in the distribution of possible supply chain outcomes, their likelihood's, and their subjective values".

Conversely, several other scholar definitions focused only on the downside of a risk, such as Harland *et al.* (2003) who stated that supply chain risk is associated with the "change of danger, damage, loss, injury or any other undesired consequences".

The Table 1.1 below reports some definitions provided in literature of supply chain risk along with the classification based on the approach they follow.

Definition	Reference	Approach
Variation in the distribution of possible supply chain outcomes, their likelihood's, and their subjective values.	Jüttner *et al.*, 2003	Risk as both danger and opportunity
Change of danger, damage, loss, injury or any other undesired consequences	Harland *et al.*, 2003	Risk as purely danger

Definition	Reference	Approach
Disruption of “flows” between organizations, where these flows that relate to information, materials, products and money, are not independent of each other but are clearly connected.	Jüttner, 2005	Risk as purely danger
Potential variation of outcomes that influence the decrease of value added at any activity cell in a chain, where the outcome is described by the volume and quality of goods in any location and time in a supply chain flow.	Bogataj and Bogataj, 2007	Risk as purely danger
Unforeseen events that might interrupt the smooth of flow of materials.	Waters, 2007	Risk as purely danger
The expected outcome of an uncertain event, i.e. uncertain events lead to the existence of risks.	Manuj and Mentzer, 2008	Risk as both danger and opportunity

Table 1.1– Supply chain risk definitions

In their study about how executives define and react to risk, March and Shapira (1987) found out that the attention is mainly focused on critical performance targets and, then, on the negative side of potential risks. For this reason, this work focuses on the negative outcomes of a possible risk event and takes into account both the high-impact, low-probability risk, such as natural disaster, and low-impact and high-probability risk, such as supplier delay.

1.3 Supply chain risk classification

As reported in the previous section, a supply chain includes all companies and functions involved in fulfilling costumer requests. Starting from this consideration, authors have proposed several classifications of supply chain risk. This research adopts the classification based on the framework proposed by Mason-Jones and Towill (1998) and then slightly modified by Christopher and Peck (2004). These authors identified three categories of risk, which can be further divided in five (Figure 1.1):

- *Risk internal to the company*: it arises from operations within an organization and can be inherent in operations (such as accidents, equipment reliability, quality issues, human errors and so on) or can come from managers' decisions (for example, the choice of batch size, safety stock levels and so on). This category comprises:
  - Process risk
  - Control risk
- *Risk external to the company but internal to the supply chain network*: it occurs from the interaction between members of a supply chain, and it can be divided in:
  - Supply risk
  - Demand risk
- *Risk external to the network*: it arises from interaction with the environment and includes:
  - Environmental risk

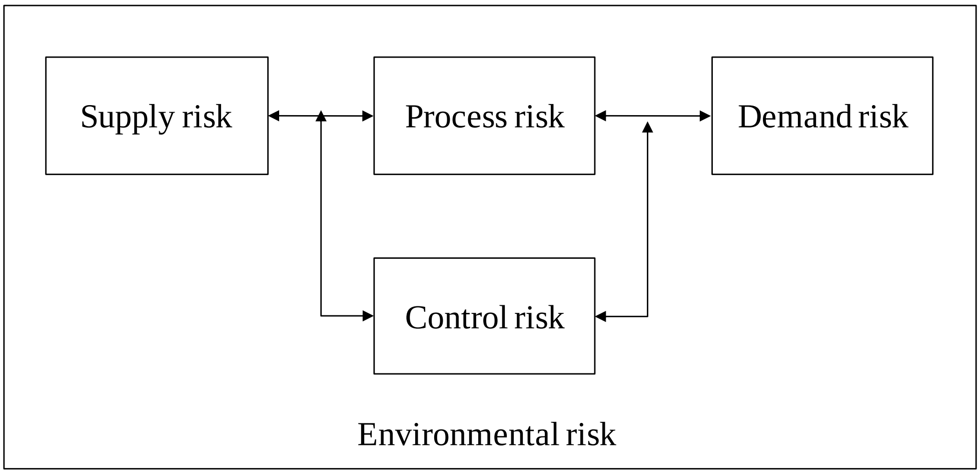

Figure 1.1 - Supply chain risk classification (Christopher and Peck, 2004)

Process risk

A process is a set of linked activities that take an input and transform it to create an output (Johansson et al., 1993). Thus, it is the sequences of value adding activities undertaken by a company to produce an output that is valuable for customers. The execution of these processes depends on internally owned or managed assets and on supporting transportation, communication and infrastructure. Process risk relates to disruptions to these processes. For example, in 2004 IBM announced that yield problems at its plant in East Fishkill, NewYork contributed to the $150 million first-quarter loss by its microelectronics division. The lower-than-expected yields reduced the plant's effective capacity and limited IBM's ability to meet customer demand (Tang and Tomlin, 2008).

Control risk

These are the assumptions, rules, systems and procedures that govern how an organization exerts control over the processes. In terms of the supply chain they may be order quantities, batch sizes, safety stock policies etc., plus the policies and procedures that govern asset and transportation management. Control risk is therefore the risks arising from the application or misapplication of these rules. For example, the effect of a sudden drop in demand is amplified in the presence of inflexible rules regarding order quantities.

Supply risk

Supply risk depends on the uncertainty associated with supplier activities and in general supplier relationships. It relates to potential or actual disturbances to the flow of product or information emanating from within the network, upstream of the focal firm (Christopher and Peck, 2004).

Since supply risk is the main focus of this thesis, better description of this kind of risk is given in the next section.

Demand risk

Demand risk depends on the uncertainty associated with the outbound logistics flows and product demand. It relates to any potential or actual disturbance to the flow of product, information, cash emanating from within the network, between the local firm and the market.

For example, to satisfy certain country-specific requirements such as power supply and language driver, Hewlett-Packard (HP) had to develop multiple versions for each model of their DeskJet printers. Each version serves a particular geographical region (Asia-Pacific, Europe, or Americas). Due to uncertain demand in each region, HP faced the problem of overstocking certain printers in one region and under-stocking certain printers in other regions. This example reflects a risk-facing companies that sell multiple products: not only is the demand volume unpredictable but so is the demand mix, i.e., the demand for each of the product variants. Demand risk therefore encompasses uncertainties in both volume and mix (Tang and Tomlin, 2008).

Environmental risk

Environmental risk sources comprise any external uncertainties arising from the supply chain such as disruption caused by political (e.g. fuel crisis), natural (e.g. foot and mouth outbreak, fire, earthquake), technological or social (e.g. terrorist attacks) uncertainties (Jüttner, 2005).

All these events may directly impact upon the focal firm or upon the upstream firm, the downstream firm or the marketplace itself. They also may affect a particular value stream (i.e., product contamination) or any node or link through which the supply chain passes (i.e., as the result of an accident, direct action, extreme weather or natural disasters). The type or timing of these events may be predictable (i.e., those arising from regulatory changes), but many will not be, though the impact of these types of events may still be assessed (Christopher and Peck, 2004).

The issue of disruptions as consequence of an environmental risk has become more popular especially as a result of the global sourcing phenomenon. Improvements of IT infrastructure that allows a worldwide connection and the willingness of the availability of cheaper and better sources of supply, have pushed western companies to get their supplies from low-cost countries, such as those in Asia, Central and South America (Ruamsook *et al.*, 2007,Wu and Olson, 2008). Although the cost benefits simply cannot be ignored, the volatile nature of various cultural, economic and political environments in conjunction with the plethora of potential logistical issues that might occur increase the disruption probability and the consequent interruption of flows within a supply chain (Deane *et al.*, 2009).

Taken together, these types of risk define the vulnerability of a supply chain, that is defined as “the exposure of a supply chain to disruption arising from the risks to operations within each organization, to interactions within the supply chain, and from the external environment” (Waters, 2007).

However, among all the introduced kinds of risk, this thesis focuses on supply risk, whose relevance and characteristics are presented in the next section.

1.4 Supply risk

The current financial crisis that has been slowing down the global economy has drawn the attention to supply failure and has further increased the awareness among professionals that risk assessment and mitigation play a crucial role in successfully managing supply chains.

A recent survey conducted by AMR Research (O'Marah, 2009) showed that, as a consequence of the world crisis, perception of risks in most companies managing a global supply chain has sensibly shifted in just few months: while in 2008 the prevailing concerns focused heavily on transportation costs (due to the increasing fuel expenses) and surging commodity prices, in 2009 default of suppliers turned out to be the first perceived supply chain risk.

Figure 1.2 shows the results of this survey, where “Supply Failure” has been rated by 38% of respondents as the main perceived risk that affects a supply chain.

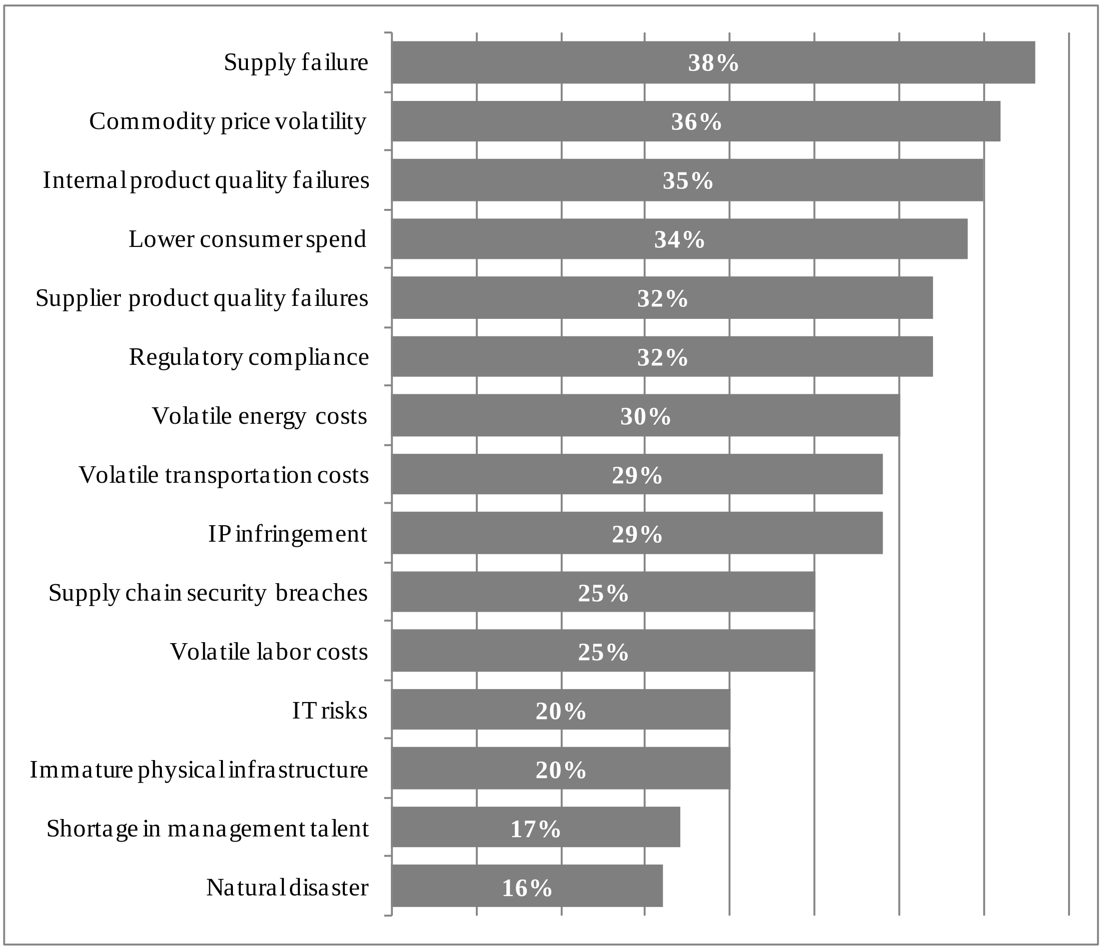

Figure 1.2 - Top Supply Chain Risks (adapted from O'Marah (2009))

Furthermore, Thun and Hoenig (2009) conducted an extensive analysis of the supply chain risk management in 67 manufacturing plants in the German automotive sector in terms of likelihood to occur and impact on the supply chain. The results showed that "supplier quality problems" is the most critical risk recognized by companies, having both a high occurrence probability and a high impact, as depicted in Figure 1.3. Analogously, supplier failure is perceived as the most severe problem with the highest impact on the supply chain, though less likely to occur.

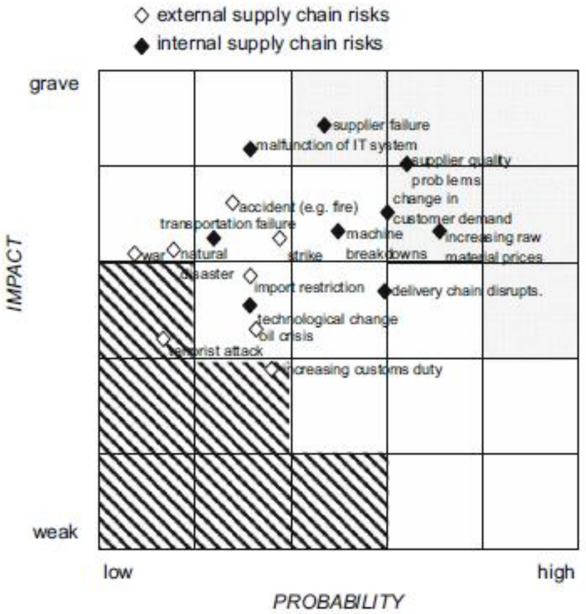

Figure 1.3 - Supply chain risks (source: Thun and Hoenig (2009))

The relevance of managing supply uncertainty has been pointed out also in a study of Boonyathan and Power (2007), which results from both product and service sectors indicate that supply uncertainty is a more significant determinant of performance than demand uncertainty in both kinds of organization. Thus, managing supplier uncertainty would appear to be a more relevant source of leverage in both sectors.

Lastly, according to Aberdeen's benchmark study on Supply Risk Management in October 2005, more than 80% of supply managers at 180 global enterprises reported that their companies experienced supply disruptions within the past 24 months. Supply glitches negatively impacted their companies' customer relations, earnings, time-to-market cycles, sales, and overall brand perception. Furthermore, it found that more than 75% of companies expect supply risks to increase over the next three years.

This increasing emphasis on supply risk emerging from the above mentioned studies, along with the even more predominant trend to focus on core activities that creates greater dependencies on upstream supply, emphasize the importance of supply risk management. Furthermore, even if in these years inbound supply chain risk management is drawing increasing attention from both practitioner and academic researchers, there is still a need for a general supply risk management methodology to classify, manage and assess this risk (Zsidisin *et al.*, 2000; Wu *et al.*, 2006; Thun and Hoening, 2009). In fact, even if the area of risk analysis is a well-researched topic, much of this research has focused on outbound flow rather than on inbound supply risk analysis.

In order to fill these gaps, this research focuses on supply risk and aims at proposing a methodology and providing a tool that supports the identification and selection of the most suitable strategies to deal with this kind of risk.

1.5 Supply risk definition

Integrating past academic definitions of supply risk and the points of view of purchasing professionals belonging to 7 organizations with established supply risk assessment or risk management process, Zsidisin (2003) proposed the following definition of supply risk:

> *"Supply risk is defined as the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety".*

Thus, supply risk is a multi-faceted and multi-dimensional concept, that it is strictly dependent on the specific context and industry. For example, aerospace firms are more likely to understand supply risk in terms of threats to customer life and safety, while other companies would give more weight to financial losses due to their inability to meet customer requests. In any case, it is imperative for supply management professionals to understand both sources as well as outcomes that incorporate supply risk because the effects of detrimental supply events can have ramifications throughout a firm's supply chains or networks.

For this reason in the next sections, the main supply risk sources and risk assessment tools are described.

1.6 Supply risk sources

Supply risk may arise from many sources. Generalizing from past studies, Ho *et al.*(2005) stated that many facts in the supply process must be considered when determining supply uncertainties, such as frequency of changing suppliers of critical materials, complexity of critical materials, complexity of procurement technology for critical materials, time specificity of materials procurement, delivery frequency of critical materials, delayed delivery of critical materials, and fluctuations in the selling price of critical materials. In other words, they recognized that the main supply risk sources are related to item characteristics, procurement process characteristics and supplier performance.

A more complete classification of characteristics that affect risk perception is provided by Zsidisin (2003). In a study about supply risk perceptions, he realized a literature review to identify supply risk sources and then conducted case studies with purchasing organizations to obtain a classification of supply risk characteristics. The results of his research suggested that supply managers perceive risk related not only to item and supplier characteristics (as reported by Ho *et al.*, 2005), but also to supply market characteristics.

The table below (Table 1.2) integrates the contributions of the two works in order to derive a more complete list of supply risk characteristics.

Class	Characteristics	Definition
Item characteristics	Impact on profitability	The unavailability of items from supplier can have detrimental effect on profit. For example, in case of shortage, item price increases with great impact on finished good cost.
	Nature of product application	The use of an item for a new product application has greater risk than using the item in existing product, because of lack of previous history to make an accurate risk assessment.

Class	Characteristics	Definition
	Complexity of critical material	When purchasing complex critical material, a company must assign extra manpower to handle it. A more complex material that requires more human intervention will increase the incidence of errors, and workers have to spend more time resolving them.
	Time specificity of material procurement:	If the value of an asset depends on its arriving within a particular time interval, then that asset has specificity of time. When more material procurement is associated with time specificity, the company faces greater supply uncertainty.
Market Characteristics	Global sourcing	Risk is due to currency fluctuation, supplier management, transit time and natural disasters.
	Market capacity constraints	It is the inability to produce an output quantity in a particular time. It occurs especially when there are few supply sources available.
	Market prices increases	Trends, events or development may increase prices that reduce the overall corporate profits.
	Number of qualified supplier	Even if there are many suppliers for a given item, if supplier is not certified, there is a lack of knowledge about its production processes, testing and interaction with the final product; so perceived risk increases. Having capable, qualified and certified suppliers is critical for a successful supply strategy.
Supplier Characteristics	Capacity constraints	In case of demand growth, supplier with capacity constraints cannot quickly increase production, affecting firm competitiveness.
	Inability to reduce cost	Competiveness can depend on supplier ability to reduce cost enough to meet market demands for reducing product prices to customers.
	Incompatible information system	Incompatibility can lead to supply interruption.
	Quality problems	It is the ability of suppliers to conform to specification. If supplier is unable to ensure quality on its products, organization will quickly be out of business.
	Variance of material supply lead-time	Variance of material supply lead-time usually disrupts regular production schedules. A greater variation in material supply lead-time increases the difficulty of managing material procurement.
	Unpredictable cycle time	Cycle time variability increases forecast errors and it is amplified at each level of supply chain (bullwhip effect).

Class	Characteristics	Definition
	Volume and mix requirement changes	It depends on supply flexibility, cycle time and organization capability to create accurate forecast.
	Delivery frequency of critical material	The delivery of material often carries the risk of accidents. A higher frequency of delivery of critical material and a greater importance of on-time delivery increase the likelihood that the company will face supply uncertainty.
	Delay of critical material delivery	Failure to deliver critical material at the required time may shut down production. As the proportion of critical material whose delivery is delayed increases, the company faces greater supply uncertainty.
Procurement process characteristics	Frequency of replacement of critical material supplier	When replacing suppliers of critical materials, a company must adjust its related business processes accordingly.
	Complexity of procurement technology for critical material	As the procurement technology for critical material becomes more complex, the risk of uncertainty increases because the search time is increased, the coordination requirements are increased, more data must be processed, and errors become more likely.

Table 1.2 - Supply risk characteristics (adapted from Zsidisin (2003) and Ho *et al.* (2005))

Hence, based on item characteristics, greater risk is perceived in case of high impact on profitability, its utilization in new product, high complexity and time specificity. From market point of view, risk increases when supplier are localized in natural disasters region or in market with dynamic currency rates, capacity constraints, unstable prices and few number of qualified suppliers. Considering supplier characteristics, perceptions of risk are higher in case of suppliers with limited capacity, limited capability to reduce cost, incompatible information systems, low quality level, unpredictable cycle time to meet customer requirements (in terms of both delay and variance of delay), high delivery frequency and inability to adequately respond to volume or mix requirements (inflexible suppliers). Finally, considering the internal procurement process, supply uncertainty increases in case of high complexity in procurement technologies and if the company does not adjust its business processes accordingly to new critical material suppliers.

1.7 Supply risk identification

Based on the above risk characteristics, it is important for a company to carry out an effective risk identification process and, through a deeply and organized review of the uncertainties in a supply chain, come out with a “risk register” or “risk portfolio”. This is a standardize document that records the features of the risks, in terms of description, impact, and any other useful information. Obviously, it is impossible to list every conceivable risk and, moreover, there is not a rule that establishes how many risks to focus on. This critical decision depends on the specific context and on management judgment.

In any case, risk identification process should not rely on personal knowledge and informal procedures, but need some more formal arrangements. In fact, even if people that work on operations have a detailed knowledge of what they do every day and how, this does not mean that they can be able to identify risks, which need different skills. They can fail in recognizing the most obvious risks or can be reluctant to admit any risk, as sign of failure or weakness, or can focus on risks they are responsible for (such as excess stocks, for which they are responsible for) rather than on major ones (such as terrorism, for which they are not responsible for).

The conclusion is that risk identification process should take some inputs and, applying some tools and techniques, should provide the outputs (list of risks, sources, symptoms, triggers, consequences, and so on).

In literature, several risk identification techniques are described and applied in different contexts. A broad review of these tools can be found in Waters (2007) and in ISO/IEC 31010:2009, here only briefly listed and explained, based on their objective.

Tools for analyzing past events:

- *“Root cause analysis” (or “Five why”)*: when some risk has already happened, the easiest way to identify future risk is to ask questions about causes of past event and find the likelihood that it will reoccur.
- *Cause-and-effect diagrams*: it is also called fish bone or Ishikawa diagram and it shows the relationship between risk event and their causes, as in Figure 1.4. It is useful for risk identification for its simplicity and easy to use approach (Musa *et al.*, 2010).

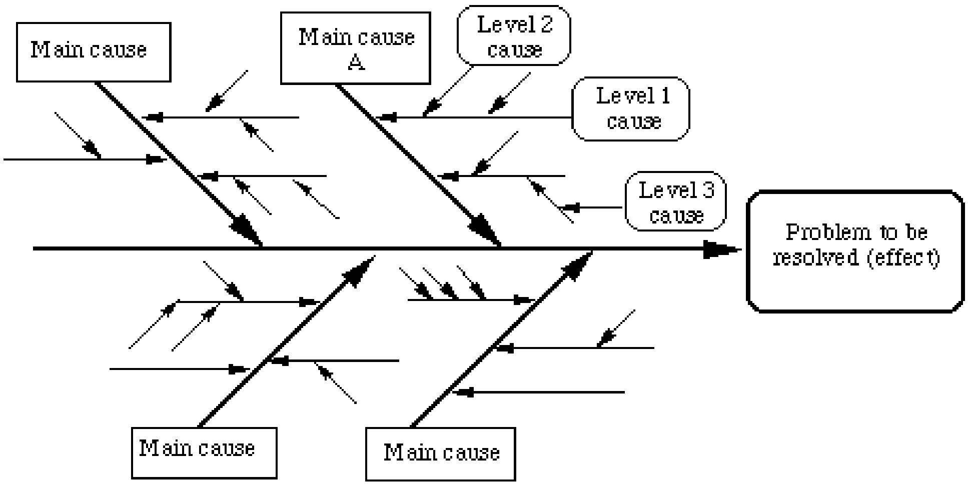

Figure 1.4 - Ishikawa diagram

- *Pareto analysis*: a frequency diagram of events occurred in the past can suggest those that are more likely to reoccur in the future. Pareto charts are based on the observation that 80% of risks come from 20% of causes (Figure 1.5).

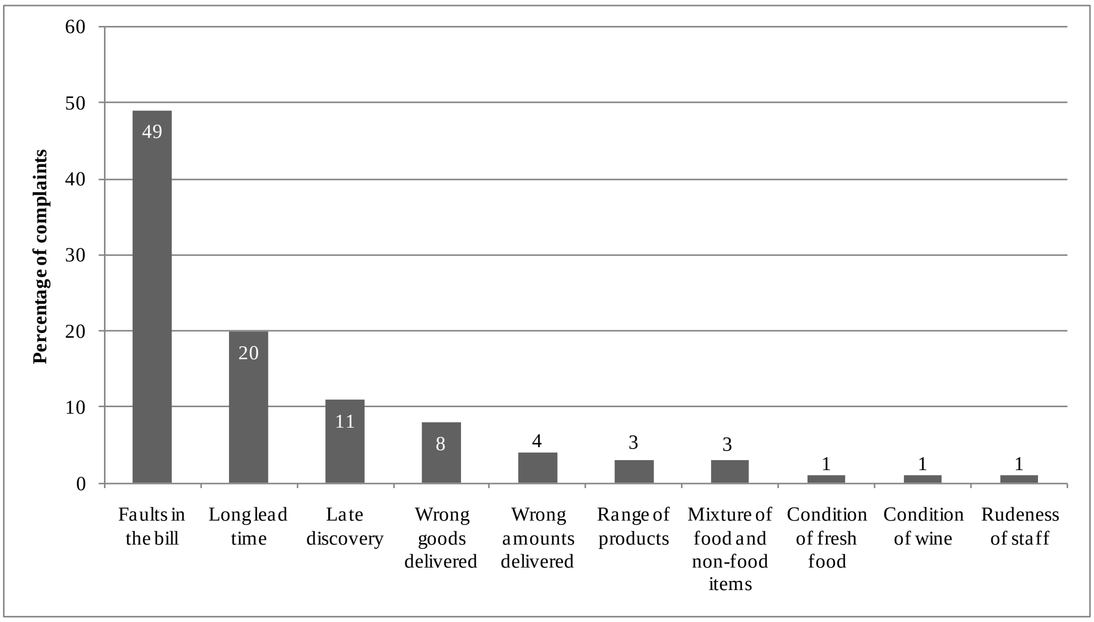

Figure 1.5 - Example of Pareto chart

- *Checklist*: when common risks can happen, an obvious way to identify them is to see what risks have been already identified by others (another supply chain, another company, standard list collected from industry forum, research institution or consultants).

Tools to collect opinions:

- *Brainstorming*: involves stimulating and encouraging free-flowing conversation amongst a group of knowledgeable people to identify potential risks, criteria for decisions and/or options for treatment. Brainstorming may be formal or informal, where the former is more structured than the latter (participants are prepared in advance and the session has a defined purpose and outcome).
- *Interviews*: if past event information are not enough, the most straightforward way of collecting new information is through interviews with knowledgeable individuals. They can be structured or semi-structured. In a structured interview, individual interviewees are asked a set of prepared questions from a prompting sheet which encourages the interviewee to view a situation from a different perspective and thus identify risks from that perspective. A semi-structured interview is similar, but allows more freedom for a conversation to explore issues that can arise. Both kind of interviews are useful when it is difficult to get people together for a brainstorming session or when free-flowing discussion in a group is not appropriate for the situation or people involved. In addition, interviews are is fast and easy to organize, but are not very reliable because they are based on few people knowledge.
- *Delphi method*: a group of about 15 experts is selected and they are required to answer a questionnaire on risk giving their personal views. These views are gathered and analyzed, with a summary sent back to respondents. Then each is asked if they would like to revise any opinions in light of the replies given by the rest of the group. All replies are anonymous, so there are no problems with face-to-face contacts, group pressure, and so on. This process of asking questions, summarizing views and asking for adjustments is repeated a number of times (usually between three and six), and by this time the group should be closer to a consensus.
- *Preliminary hazard analysis*: it is a simple, inductive method of analysis whose objective is to identify the risks and risky situations and events that can cause harm for a given activity, facility or system. It is most commonly carried out early in the development of a project when there is little

information on design details or operating procedures and can often be a precursor to further studies or to provide information for specification of the design of a system. It can also be useful when analyzing existing systems for prioritizing risks for further analysis or where circumstances prevent a more extensive technique from being used.

- *Human reliability assessment (HRA*): it deals with the impact of humans on system performance and can be used to evaluate human error influences on the system (Figure 1.6). The outputs include a list of errors that may occur and methods by which they can be reduced, error modes, error types causes and consequences and a qualitative or quantitative assessment of the risk posed by the errors.

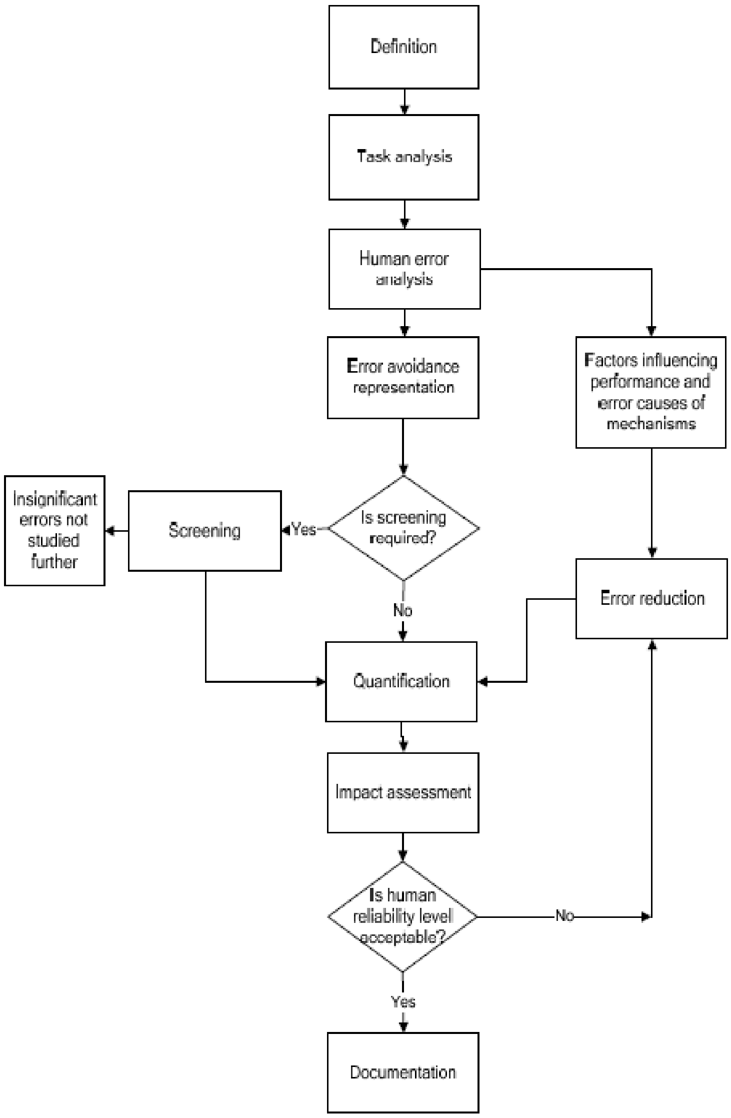

Figure 1.6 - Example of human reliability assessment

Tools to analyze operations:

- *Process charts*: through this tool, supply chain operations are broken down into a series of activities that will be deeply analyzed and the related risks identified. The format can be a list of activities, diagram, flow charts, Gantt, or process charts , and so on (Figure 1.7). As surveyed by Jüttner (2005), process mapping and brainstorming are used in 60% of firms as methods to identify risks.

Step	Description	Op	Move	Insp	Delay	Store	Time (mins)	Distance (meters)
1	Arrive	x					2	150
2	Wait for unloading				x		10	
3	Check paperwork	x					2	
4	Move to unloading bay		x				2	40
5	Wait for forklift				x		4	
6	Check delivery details	x					1	
7	Take off truck	x					2	
8	Move to receiving area		x				3	20
9	Take off wrapping	x					10	
10	Check condition			x			10	
11	Check details			x			1	
12	Update goods received	x					3	
13	Move to main storage		x				5	50
14	Wait for crane				x		4	
15	Put on to shelf	x					2	
16	Keep in store					x		

Summary				
	Number	**Time**	**Actions**	**16**
Operations	7	22	**Time**	**61**
Movements	3	10	**Distance**	**260**
Inspections	2	11		
Delays	3	18		
Storage	1			

Figure 1.7 - Example of process chart

- *Process control*: through a process control chart (Figure 1.8) it is possible to monitor the variation over time in supply chain performance. This has a target performance and two acceptance limits: if the variations stay between these two limits, the process is under control and the risk is small, otherwise, if there is a clear trend or poor results, risk is increasing.

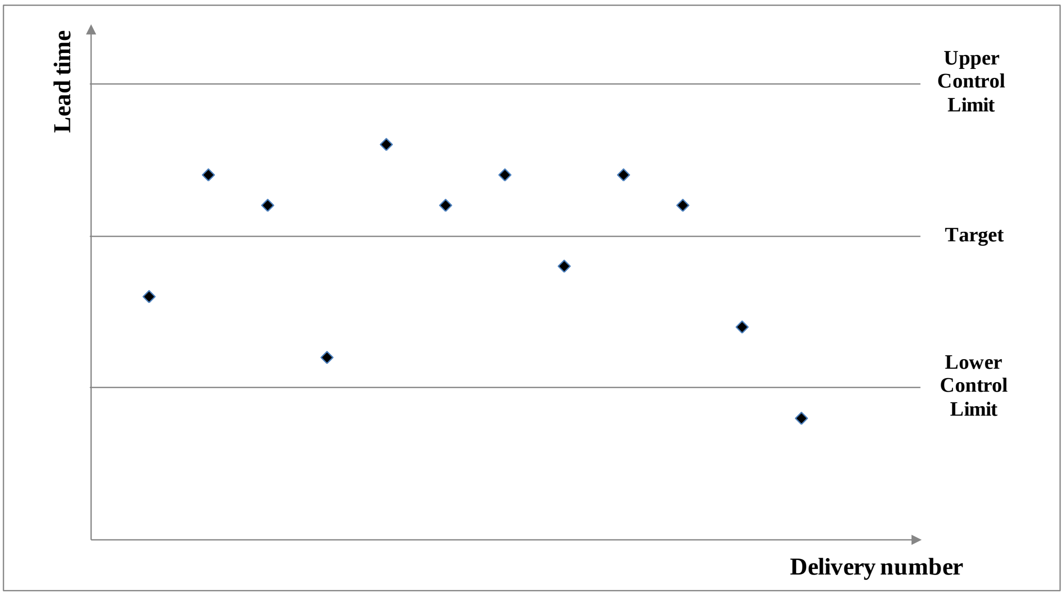

Figure 1.8 - Example of process control chart

- *Supply chain event management (SCEM)*: this term comprises different types of process control. The most common format uses structured brainstorming, where a group of experts examines the operations to find deviations from planned performance. Then they investigate these deviations and find ways of eliminating their causes or minimizing the consequences.
- *Structured "What-if" Technique (SWIFT)*: originally developed as a simpler alternative to HAZOP, it is a systematic, team-based study, utilizing a set of 'prompt' words or phrases that is used by the facilitator within a workshop to stimulate participants to identify risks. The facilitator and team use standard 'what-if' type phrases in combination with the prompts to investigate how a system, plant item, organization or procedure will be affected by deviations from normal operations and behavior. SWIFT is normally applied at more of a systems level with a lower level of detail than HAZOP.

1.8 Supply risk impact

Once having identified the main risk sources, an organization should assess possible impacts in order to be able to prioritize the different risks and identify where to focus attention and address mitigating interventions.

This risk analysis can be done following two main approaches:

- Qualitative approach: starting from the risk register, some qualitative features are added, such as consequences, likelihood, scope, responsibility, etc. This kind of approach can give good basis for discussion, but it does not give any numerical measure of the risk.
- Quantitative approach: some numerical measures of the risk are provided, especially in terms of occurrence probability and possible impacts.
- This latter approach can give more useful information for a more effective risk management, even if quantitative risk analysis can be more difficult.
- For this purpose, Waters (2007) and the ISO/IEC 31010:2009 provide an exhaustive overview of tools to categorize risks. These tools are briefly explained hereafter.
- The numerous quantitative analyses of risk are all based on two factors: (i) the *likelihood* of a risky event occurring, and (ii) the *consequences* when the event occurs.
- Thus, the first problem is to find the occurrence probability of a risk. There are three main approaches available to find these probabilities:
- Use knowledge of a situation to calculate theoretical or a priori probability: this is the most reliable method that should be employed whenever is possible.
- Use historical data to see how often an event happened in the past and give an experimental and empirical estimation of probability: this method gives good results but it is based on the assumption that nothing has changed from the past.
- Ask people for their subjective views about likelihood: this is the least reliable method because depends on people judgment, but is often the only method for complex situations.

In any case, the probability will not be a purely objective value describing risk occurrence, but it will include some people subjective perceptions of risk and then it will be just an approximation that leads the undertaking of risk management actions. This demonstrates the relevance of a careful risk analysis process.

However, regarding probability, three outcomes can be provided:

- Probability distribution of the events: instead of giving a single probability of event occurrence, probabilities of different possible outcomes or outcome distribution function are given (for example: instead of saying that a supply will be late with a probability of 0,3, it will be said the there is 0,1 probability that the supplier will deliver one day late, 0,15 that it will be two days late and so on, or, alternatively, a distribution of lead time is provided). A lot of efforts are required to derive the distribution probability, but it gives the most precise picture of the risk.
- Range of probability: it is less precise than the previous one, but it can be enough for most of the analysis.
- Category of probability: in this case punctual values for the probability are not provided, it is rated based on categorical scale, for example from 1 to 5. This is more subject to people perceptions and specific context.

In the same way, consequences of a risk event occurring can be provided as:

- Absolute measure of impact: it can be in terms of cost or time. As for probabilities, also this value are approximation because there are some losses that are not known in advance or cannot be quantified.
- Range of consequences
- Category of consequences

Based on likelihood of risk occurrence and impact evaluation, the following step is to assess the significance of risks and assign them to categories in order to derive a prioritization of risks.

Different diagrams and tools can be employed to identified the different classes of risk, some of them require a quantification of probability occurrence and impact while some others can help when these values are too difficult to predict. Some of these tools are:

- *ABC analysis*: based on the assumption that 20% of the risks causes the 80% of consequences, it is possible to identifies three classes of risk (A, B, C), where the attention needed decreases going from class A to C (Figure 1.9).

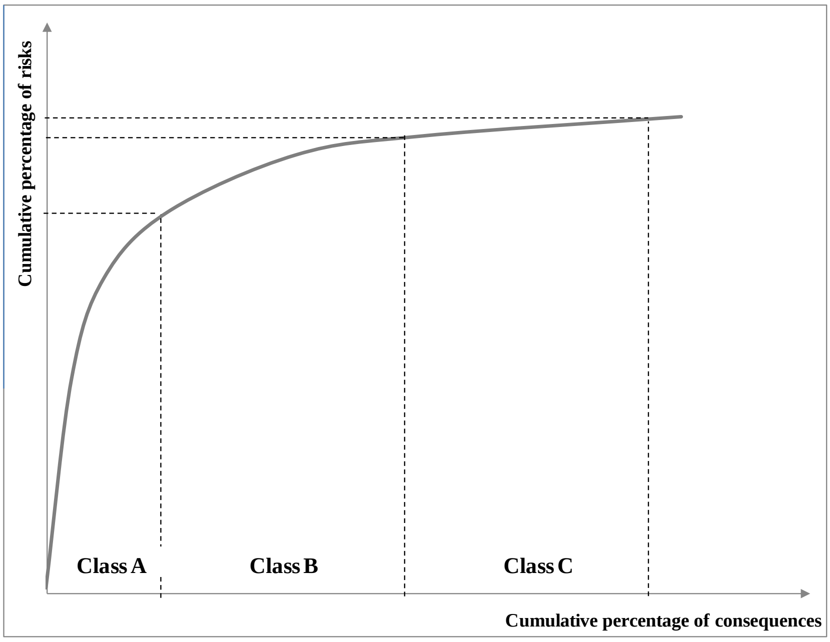

Figure 1.9 - Example of ABC analysis of risk

- *Risk map*: this is a graph that shows risks as individual point, where the vertical axis represents the occurrence probability and the horizontal axis the potential consequence. The most attention should be addressed to the risks furthest from the origin, while less attention to those nearest to the origin (Figure 1.10).

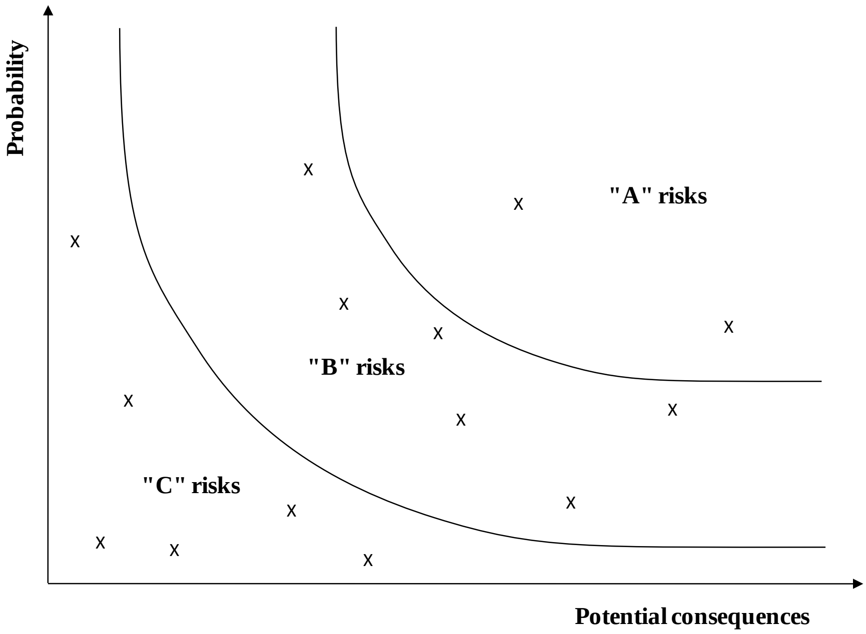

Figure 1.10 - Example of risk map

- *Probability-impact matrix*: it is very similar to the risk map, but the probability occurrence and potential impact are replaced by categories (from “Very Low” to “Very High” or from 1 to 5). Thus, the result is a table where the individual risks are put in the different cells (Figure 1.11).

		Potential consequences					
		Negligible	Minor	Moderate	Serious	Critical	Catastrophic
Probability	Very High						
	High						
	Medium						
	Low						
	Very Low						

Figure 1.11 - Probability - impact matrix

- *Cost/benefit analysis (CBA)*: it can be used for risk evaluation where total expected costs are weighed against the total expected benefits in order to choose the best or most profitable option. It can be qualitative or quantitative or involve a combination of quantitative and qualitative elements. In quantitative cost/benefit analysis, when all tangible and intangible costs and benefits have been identified, a monetary value is assigned to all costs and benefits (including intangible costs and benefits). All costs and benefits are expressed as a present value. The present value of all costs and all benefits to all stakeholders can be combined to produce a net present value (NPV). A positive NPV implies that the action is beneficial. If there is uncertainty about the level of costs or benefits, either or both terms can be weighted according to their probabilities.
- *Failure mode and effects analysis (FMEA)*: it starts by listing every activity in the supply chain and the ways in which each element can fail. For each potential failure, the occurrence probability, the severity of consequences and the likelihood that a remedial action can be taken before the failure becomes critical, are given a score from 1 to 10. Multiplying the scores together gives a “risk priority number” that represents the criticality and provides an indication of where to intervene.

- *Fault tree analysis (FTA)*: FTA is a technique for identifying and analyzing factors that can contribute to a specified undesired event (called the "top event") (Figure 1.12). Causal factors are deductively identified, organized in a logical manner and represented pictorially in a tree diagram which depicts causal factors and their logical relationship to the top event. The factors identified can be events that are associated with component hardware failures, human errors or any other pertinent events which lead to the undesired event. A fault tree may be used qualitatively to identify potential causes and pathways to a failure (the top event) or quantitatively to calculate the probability of the top event, given knowledge of the probabilities of causal events.

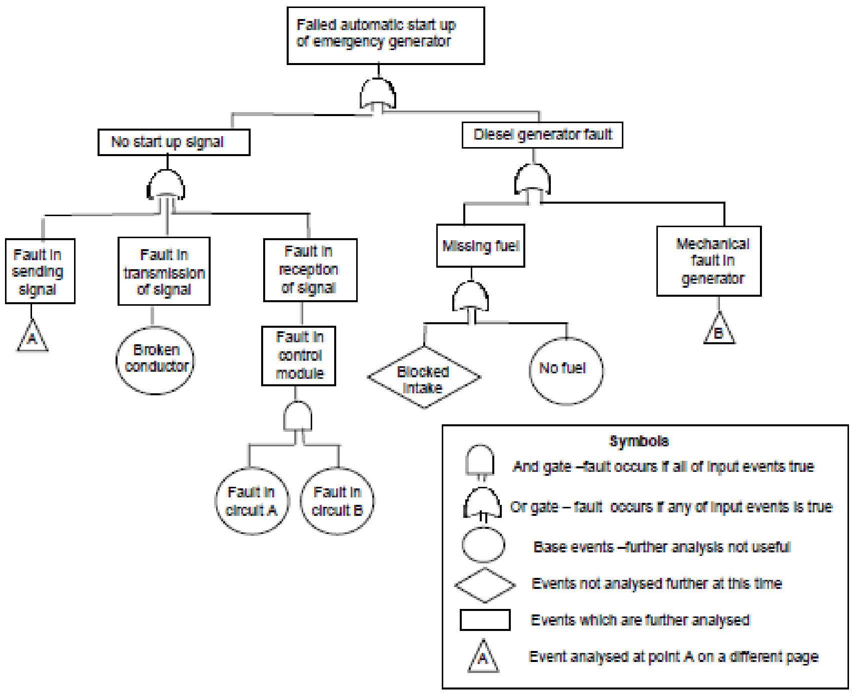

Figure 1.12 - Example of a fault event tree

- *Event tree analysis (ETA)*: It is a graphical representation of the logic model that identifies and quantifies the possible outcomes following an initiating event (Figure 1.13). It is most useful in the assessment segment where the analysis focus on particular risk event and identify various possible outcomes of the system. In context of SC, risk event is identified as the 'effect' and listed possible causes leading to it. However, the application is limited to early stage of risk identification such as in assisting brainstorming (Musa *et al.*, 2010).

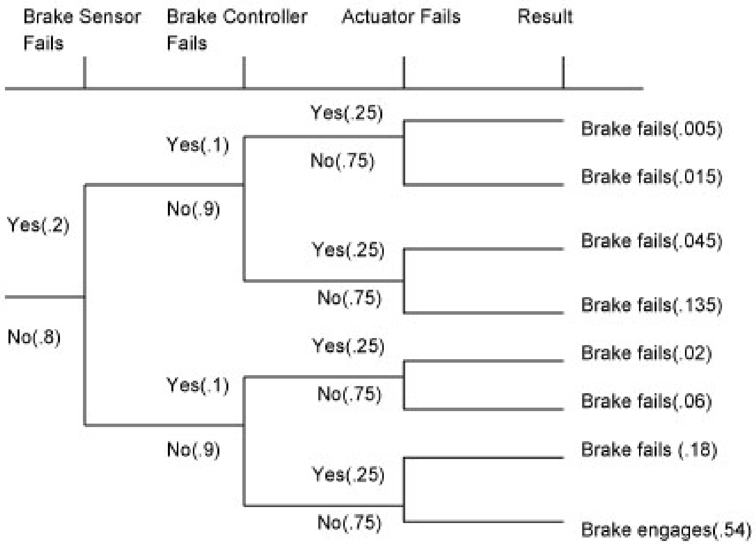

Figure 1.13 - Example of event tree

- *Cause-consequence analysis:* it is a combination of fault tree and event tree analysis (Figure 1.14). It starts from a critical event and analyzes consequences by means of a combination of YES/NO logic gates which represent conditions that may occur or failures of systems designed to mitigate the consequences of the initiating event. The causes of the conditions or failures are analyzed by means of fault trees.

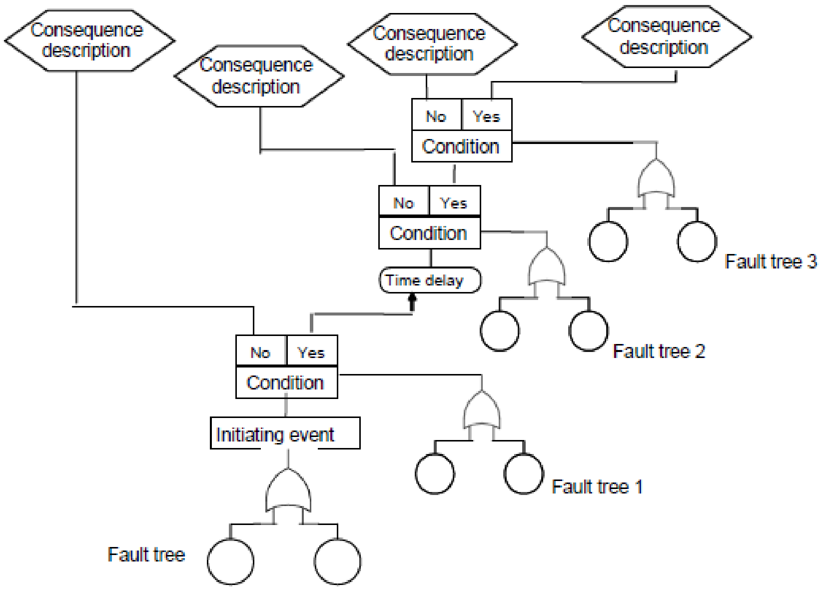

Figure 1.14 - Example of cause-consequence analysis

- *Scenario analysis*: a small group of experts constructs a likely series of decisions and a set of plausible future conditions that might follow. By analyzing these future conditions and adjusting the decisions, it is possible to determine a set of reasonable decisions that will probably give the desired results. This is a qualitative analysis where the scenarios are designed based on expertise, judgments and brainstorming and any occurrence probability will be provided.
- *Hazard and operability studies (HAZOP)*: it is a qualitative technique based on use of guide words (as in Table 1.3) which question how the design intention or operating conditions might not be achieved at each step in the design, process, procedure or system. It is generally carried out by a multi-disciplinary team during a set of meetings. The method applies to processes (existing or planned) for which design information is available. This commonly includes a process flow diagram, which is examined in small sections, such as individual items of equipment or pipes between them. For each of these a design *Intention* is specified. The HAZOP team then determines what are the possible significant *Deviations* from each intention, feasible *Causes* and likely *Consequences*. It can then be decided whether existing, designed safeguards are sufficient, or whether additional actions are necessary to reduce risk to an acceptable level.

Guide word	Definition
No or not	No part of the intended result is achieved or the intended condition is absent
More (higher)	Quantitative increase in output or in the operating condition
Less (lower)	Quantitative decrease
As well as	Quantitative increase (e.g. additional material)
Part of	Quantitative decrease (e.g. only one or two components in a mixture)
Reverse /opposite	Opposite (e.g. backflow)
Other than	No part of the intention is achieved, something completely different happens (e.g. flow or wrong material)
Compatibility	Material; environment

Guide words are applied to parameters such as:	
	Physical properties of a material or process Physical conditions such as temperature, speed A specified intention of a component of a system or design (e.g. information transfer) Operational aspects

Table 1.3 - Example of possible HAZOP guidewords

- *Business impact analysis (BIA)*: it analyses how key disruption risks could affect an organization's operations and identifies and quantifies the capabilities that would be needed to manage it. A BIA can be undertaken using questionnaires, interviews, structured workshops or combinations of all three, to obtain an understanding of the critical processes, the effects of the loss of those processes and the required recovery timeframes and supporting resources. The outputs are a priority list of critical processes and associated interdependencies, a documented financial and operational impacts from a loss of the critical processes, a supporting resources needed for the identified critical processes and an outage time frames.
- Bow tie analysis: it is a simple diagrammatic way of describing and analyzing the pathways of a risk from causes to consequences (Figure 1.15). It can be considered as a combination of the thinking of a fault tree analyzing the cause of an event (represented by the knot of a bow tie) and an event tree analyzing the consequences. However the focus of the bow tie is on the barriers between the causes and the risk, and the risk and consequences. Bow tie diagrams can be constructed starting from fault and event trees, but are more often drawn directly from a brainstorming session. It is used when the situation does not warrant the complexity of a full fault tree analysis or when the focus is more on ensuring that there is a barrier or control for each failure pathway. It is useful where there are clear independent pathways leading to failure. Bow tie analysis is often easier to understand than fault and event trees, and hence can be a useful communication tool where analysis is achieved using more complex techniques.

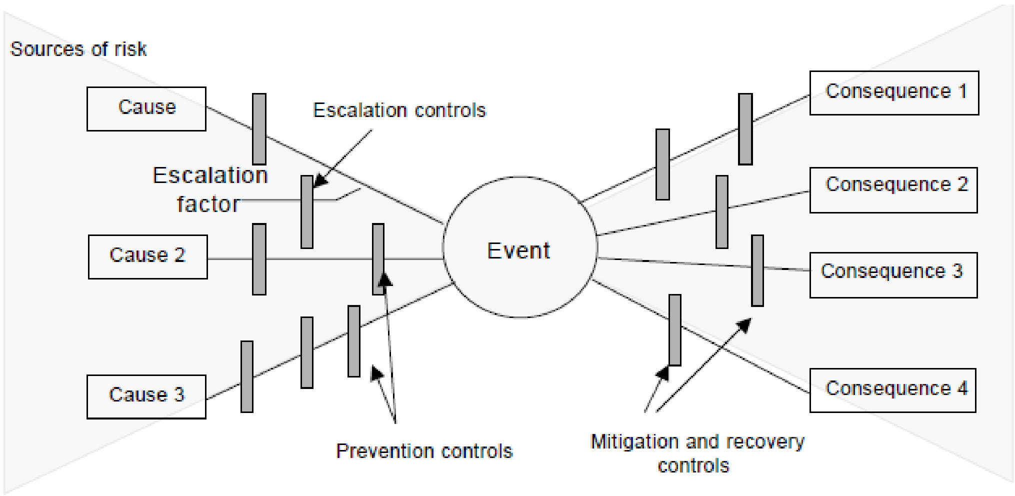

Figure 1.15 - Example bow tie diagram for unwanted consequences

- *Simulation*: using a computer, it dynamically represents real operations over a period of time.
- *Network models*: this tool allows to represent supply chain as a network of connected nodes with fixed capacity and a given flow time. Analyzing flows, paths, transportation and nodes location it is possible to identify area that are more vulnerable to risks.
- *Analytical models*: they include a variety of techniques, such as simple weighted scoring methods, multivariate analysis, complex mathematical programming, bayesian statistics, and neural network models.
- *Analytical Hierarchy Process (AHP)*: it is a multi attribute decision-making technique and depends on a hierarchy made of goal, criteria and alternatives (Figure 1.16). The elements in each level are compared as pairs: thus, the criteria are pair wise compared against the goal for importance and the alternatives are pairwise compared against each of the criteria for preference. The comparisons are processed mathematically, and *priorities* are derived for each node. Composite weights are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a vector of the overall weights of the criteria. A more comprehensive understanding of AHP can be found in Saaty (1980). This method can include

tangible and intangible factors, but it becomes impractical in cases of more than 20 requirements.

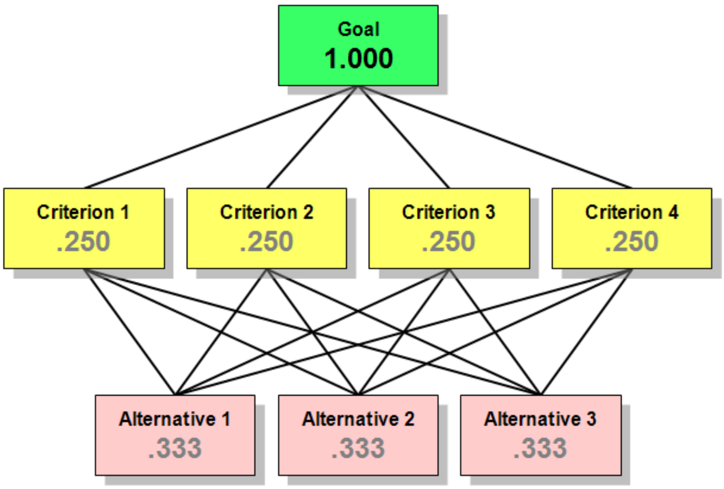

Figure 1.16 - An example of AHP hierarchy with associated priorities

1.9 Conclusion

Due to the complex and dynamic nature of a supply chain, that can be characterized by several tiers of suppliers, each of them with multiple components or members, managing inbound supply risk is becoming a very challenging task.

In order to lay the foundation for the development of an enhanced methodology to manage supply risk and assure business continuity, this chapter has reported the definition of supply risk and has described the main risk sources and the available tools and instruments to identify, assess and prioritize them.

In the next chapter, the existing supply risk frameworks are briefly reviewed and the proposed methodology is introduced.

2. Supply risk management framework

In the previous chapter an overview of supply chain risk and, in particular, supply risk has been carried out. The several above-cited examples of disruptions occurred at company level and propagated throughout a supply chain network, causing substantial losses for the firms involved, demonstrate the importance and the need of a careful risk management.

An excellent example that shows how an effective supply chain risk management can make the difference in case of disruption is the opposite impact of the fire broken out at Nokia and Ericsson supplier plant in March 2000. Nokia adjusted to the disruption quickly using several other supply plants in its networks, while Ericsson had no backup sources and was unable to react; the estimated losses in Ericsson sales were about $400 million (Chopra & Meindl, 2006).

Thus, considering the multiple risk dimensions introduced in the previous chapter and the fact that a supply chain includes the collaboration of processes and activities across different functions within the network of organizations, the following definition of supply chain risk management, adapted from Manuj *et al.* (2008) and Tang (2006a) definitions, can be provided:

> *Supply chain risk management is the identification and evaluation of risks and consequent losses in the supply chain, and implementation of appropriate strategies through a coordinated and collaborative approach among supply chain members with the objective of reducing one or more of the following – losses, probability, speed of event, speed of losses, the time for detection of the events, frequency – for supply chain outcomes that in turn can ensure profitability and continuity.*

When the members of a supply chain work on their risk management in isolation or they do not anything, the results are rarely good or even satisfactory. By acting independently or even transferring risks to other supply chain members, managers can reduce their own exposure to risks, but the overall risk does not decrease - it might even increase, making the whole supply chain more vulnerable (Waters, 2007).

Stemmers (2006) suggests that the basic requirements for integration are that managers:

- Consider risks to all three flows of material, information and finance;
- Expand their interest beyond their own organization and cover all the supply chain;
- Consider not only the broad principles of strategic risk, but also the details of operational risk;
- Expand risk management from a statutory reporting function into a planning function.

Besides collaboration, from the above definition emerges that another focal point in risk management is the concept of business continuity. The problem is that many companies leave such task to security professionals, business continuity planners or insurance professionals (Sheffi and Rice,2005). On the contrary, an organization should promote the diffusion of a broad risk management culture and address its efforts to improve company resilience, that is the ability to return to the original state or to move to a new and more desirable one after being disrupted (Christopher and Peck, 2004). In fact, resilience should be a strategic initiative that requires a well defined risk management process in a company, from its sources identification to assessment and mitigating plan definition, to avoid disruptions and ensure business continuity. Resilience can be achieved by either creating redundancy or increasing flexibility. While some redundancy is part of every resiliency strategy, it represents sheer cost with limited benefits unless it is needed due to a disruption. Flexibility, on the other hand, can create a competitive advantage in day-to-day operations. Investments in flexibility thus can be justified on the basis of normal business results without even taking into account the benefits of risk mitigation and cost avoidance.

These topics of redundancy and flexibility are better detailed in the next chapter, when the available strategies to deal with risk are listed and deeply analyzed. In the next sections, through a comparison among literature works, the main phases of a typical risk management framework are identified and, based on these, the main contributions of this thesis are presented and contextualized.

2.1 An overview of supply risk management framework

Since this thesis deals with supply risk and proposes some new contributions to improve the supply risk management process, an overview of frameworks focused on inbound risk is provided.

Kralijc (1983)

Kralijc (1983) suggests a four-stage approach to devise strategies to minimize supply vulnerability. The phases are the following:

- *Classification*: based on strategic importance (in terms of the value added by product line, the percentage of raw material in total cost, their impact on profitability, and so on) and on supply risk (depending on supply scarcity, pace of technology, entry barriers, and so on), the purchased items are classified as *strategic* (high profit impact, high supply risk), *bottleneck* (low profit impact, high supply risk), *leverage* (high profit impact, low supply risk), and *non critical* (low profit impact, low supply risk).
- *Market analysis*: based on some evaluation criteria, strengths of customer and suppliers are listed in order to evaluate the company bargaining power.
- *Strategic positioning*: the materials identified as strategic in phase 1 are positioned in the purchasing portfolio matrix (that plots supply market strength against company strength). Based on the items positioning, three

strategies are suggested: when the company plays a dominant market role and suppliers' strength is rated medium or low, an "exploit" strategy is indicated; when the company's role in the supply market is medium or low and suppliers are strong, the company must go on defensive and look for material substitute or new suppliers ("diversify"); finally, in the middle positioning, a company should pursue a balance intermediate strategy ("balance").

- *Action Plans*: in this phase the company should explore a range of supply scenarios for securing long-term supply and for exploiting short-term opportunities. The outcome of this phase is a set of systematically documented strategies for critical purchasing materials that specify the timing of and criteria for future action.

This is the first framework in the supply management literature that considers purchasing from a strategic point of view instead as a routine activity. The drawback is that the focus is on the purchasing company and it does not minimize the risk of the overall supply chain but aims only at maximizing company performance.

Harland *et al.* (2003)

Due to the more recent business trends that increase complexity of supply networks, Harland *et al.* (2003) introduce a more comprehensive model. They define a supply network risk tool divided in 6 phases (Figure 2.1):

- *Map supply network*: a diagrammatical representation of supply network with the needed data is created. This means to understand who owns what, and what are the key measures currently in place.
- *Identify risk and its current location:* the map is enriched with information concerning the type of risk (Strategic Risk, Operations Risk, Supply Risk, Customer Risk, Asset Impairment Risk, Competitive Risk, Reputation Risk, Financial Risk, Fiscal Risk, Regulatory Risk, Legal Risk) and its location. 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 realized, and what likely potential losses to whom might occur.

- *Manage risk:* the assessment information is analyzed 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 collaborative supply network risk strategies:* the chosen redesign of the network and relationships within it are effected through a reformulated collaborative supply network risk strategy
- *Implement supply network risk strategy*: the selected strategy is implemented and gives rise to a remapping of the network, i.e. back to box 1.

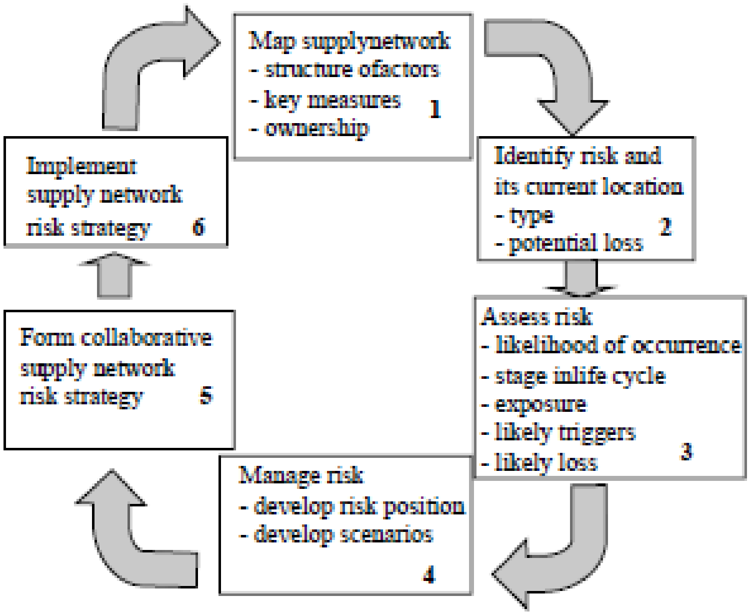

Figure 2.1 - Supply network risk tool (Harland *et al.*, 2003)

Differently from Kralijc, this model takes into account risk from supply network point of view, minimizing the overall risk instead of focusing on the buying company. Even if it is more complete and exhaustive than the previous one, its application can be more difficult because it requires an involvement of the other key network actors, with whom identify major risks and select the most suitable responses. Collaboration and overall consensus among different managers can be hard to pursue.

Hallikas *et al.* (2004)

These authors propose a method for risk management in suppliers network, defining it as long-term, purposeful arrangements among organizations that allow the operating organizations to get long-term sustainable competitive advantage.

They adapted the phases of a typical risk management process of a single company to a network environment:

- *Risk identification*: the aim of this phase is to recognize future uncertainties, taking into account the dependencies on other organizations, in order to be able to manage these scenarios proactively. In a networked environment, where business relationships are largely based on partnerships between organizations, effective information sharing is the key factor to decrease external and internal uncertainty.
- *Risk assessment*: probability and consequences are assessed separately and a risk diagram is produced as output, in order to give an overall view upon all risks. Probability must be assessed taking into account also the effect of the network, while the potential consequences should be assessed only from company viewpoint, because an event or change which is harmful to one company in a network, may have no or positive effects to another company in the same network. In addition, not only financial consequences (like costs) should be considered, but also the immaterial ones (such as trust, reputation, loss of position in a network and so on).
- *Risk management actions*: based on the results of risk identification and assessment, the optimal risk management strategies to share and balance risks at network level should be identified and implemented. Some of the risks can be reduced by collaborative development in the network, others must be managed by each company themselves. Often a strategy is transferring risk to another company that can cope with it better than the original one (for example, in case of investment, if the supplier is able to utilize an investment in several networks or customer relationships, the probability that the investment will not pay itself back may decrease).
- *Risk monitoring*: since the company and its environment are not static and the risk status can change over time, the recognized risk factors should be

monitored to identify variations in their probability or consequences or to determine new risks.

Figure 2.2 summarizes the approach proposed by the authors, highlighting the relevance and the need for a collaborative process among the network members (expressed in the figure by mutual identification, assessment, means for risk reduction and implementation boxes).

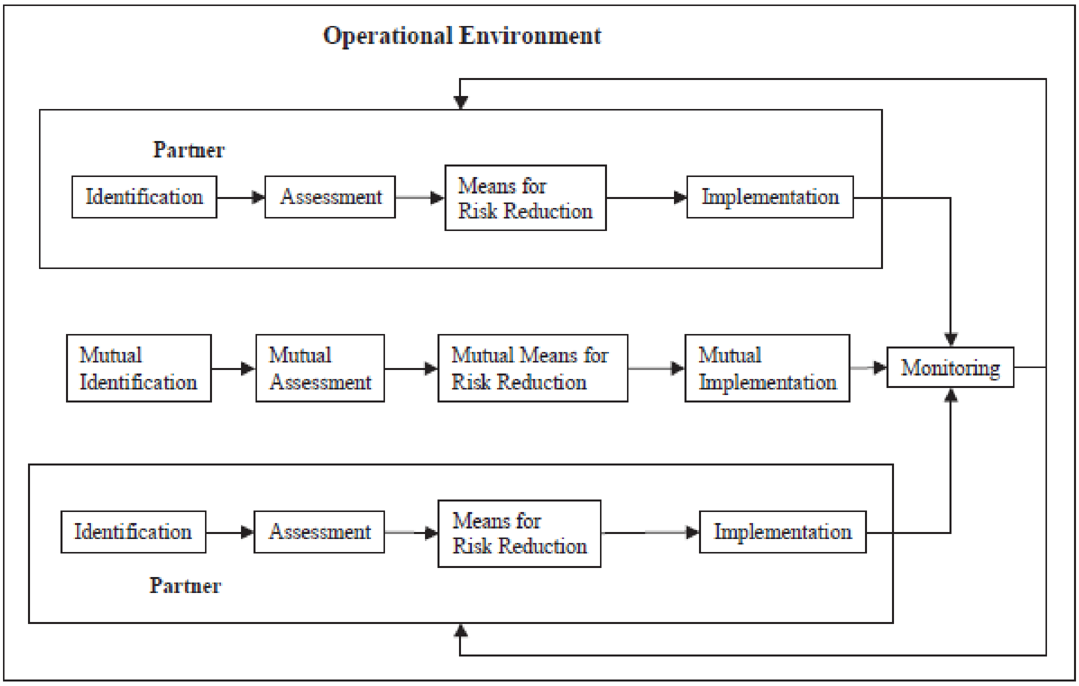

Figure 2.2 - Risk management process in network environment (Hallikas *et al.*, 2004)

As for the previous approach, the main advantage of this methods is that it considers risk from a network point of view and then, it takes into account the relationships with the strategic partners in a supply chain and proposes to look for actions that reduce the overall risk.

On the other hand, one important aspect it that the company's or the network's risk management process should be continuous and, then, companies should observe their operational environment and business processes and carry out decisions and planning procedures that have an effect on the risks. This may be difficult in practice and may be advantageous to restrict the process to certain situations.

Wu *et al.* (2006)

Wu *et al.* (2006) proposed an integrated methodology to classify, manage and assess inbound supply risks. This methodology, represented in Figure 2.3, is divided in:

- *Risk classification*: based on literature review and industry interviews, they created a hierarchical inbound risk classification, identifying six categories (‘‘Internal Controllable’’, ‘‘Internal Partially Controllable’’, ‘‘Internal Uncontrollable’’, ‘‘External Controllable’’, ‘‘External Partially Controllable’’ and ‘‘External Uncontrollable’’). From a tactical perspective, this classification enables supply managers to identify the group of factors that contributes the maximum level risk, while in a strategic perspective it enables the ability to outline long-term plans.
- *Risk identification*: for each category they identify the main risk factors, for a total of 19 supply risk factors.
- *Risk calculation*: enhanced AHP (Analytical Hierarchical Method) is applied to quantify the risk to give managers a measure of the robustness or the vulnerability of the supply chain. First, AHP is used to rank how important one category is over another category. Next, a comparison of pairs of factors within the same category is carried out. Additionally, a subjective measure of the occurrence probability is considered for each risk so that the measure includes not only its importance but also the occurrence probability. The outcomes are measures of the overall risk and of risks due to each factor for each supplier.

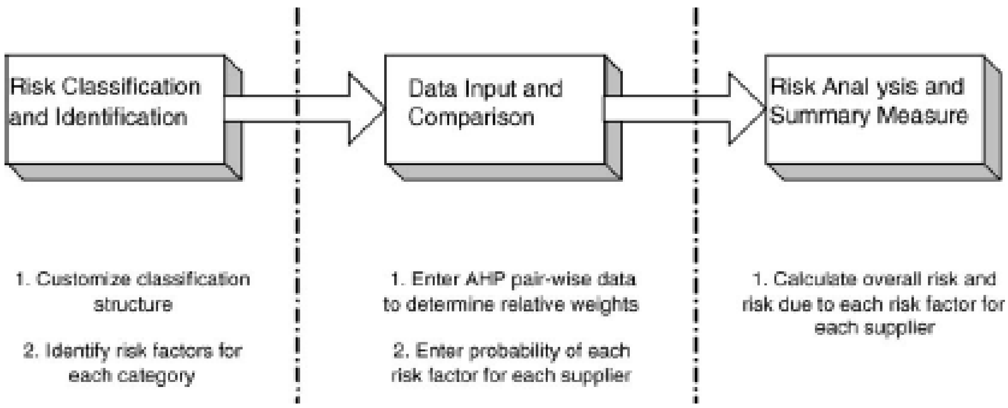

Figure 2.3 – Methodology for inbound supply risk analysis proposed by Wu et al. (2006)

The authors proposed a well defined method to analyze supply risk from supplier perspective, suggesting a supply chain independent classification and developing a prototype computer implementation system. Nevertheless they do not suggest how to deal with risk and how to intervene in order to mitigate it. In addition, even if AHP is a very powerful tool for assessment, it becomes impractical in case of more than 20 factors (Avesani *et al.*, 2005).

Matook *et al.* (2008)

Finally, based on the conceptual approach of Ritchie and Bridley (Ritche *et al.*, 2007) and the approach of the Association of Insurance and Risk Managers (AIRMIC, 2002), Matook *et al.* (2008) developed a five stages framework for supplier risk management focused on the development of suppliers into low risk performers. The proposed stages are the following (Figure 2.4):

- *Supplier risk identification*: it is concerned with the identification of risk types and risk drivers, in order to detect organizational exposure to uncertainty. In this stage, the firm needs to decide the relevant risks to consider in the analysis and to select the suppliers which will be assessed (in general, they are the suppliers of critical strategic supplies).
- *Supplier risk assessment*: the different risk categories and risk drivers identified in the previous stage are measured. For this purpose, the authors proposed a "two-sided perspective" rating mechanism, where internal firm ratings and external supplier ratings are combined to represent the supplier risk structure. They suggested as rating mechanism the categorical method, weighted point plan or AHP.
- *Reporting and decision of supplier risks*: based on ratings, suppliers are classified into high and low risk suppliers. Since risk assessment considers various risks a firm is exposed to, they suggest to use multivariate analysis procedures to select the categories to focus on. This is because in order to make any decision on risk monitoring and supplier development, a reduced number of risk categories is preferred.
- *Supplier risk management responses*: the management responses addressing the calculated supplier risk results are identified. These responses are intended to improve the risk performance of the supplier base and can include

information sharing, performance standards, joint reviews, partnership programs, and joint training seminar. However, the authors are mainly interested in supplier development activities (that, as defined by Krause (1997), includes any efforts undertaken by the firm to enhance the supplier's product quality and financial performance) and, in particular, they utilize the benchmarking approach as a tool for continuous improvements in quality and performance. This approach is particularly appropriate and useful for supplier development, because it facilitates the identification of high performers (i.e. low-risk performers) who may have achieved "best practice".

- *Supplier risk performance outcomes*: the objective is to reduce the inherent risk associated with the suppliers and to enable them to meet the manufacturing company's short-term and/or long-term supply needs.

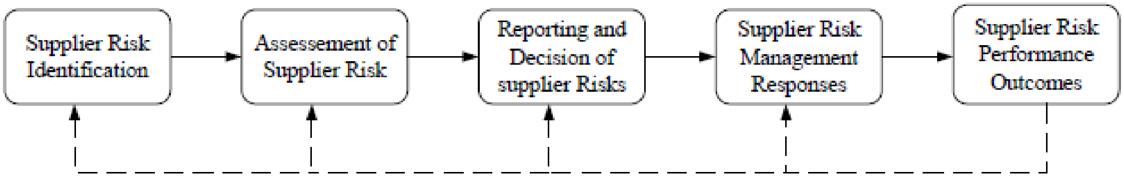

Figure 2.4 – Framework for supplier risk management proposed by Matook et al. (2008)

This framework is easy to use and understandable for practitioners, and does not require advanced knowledge in operations management. In addition, the authors developed a well explain process to be followed in order to effectively reduce supplier risk focusing on the activities that can improve supplier performance.

Summarizing, in the literature it is possible to find different frameworks to support supply risk management process. Even if some differences exist, these frameworks are based on four common phases: (i) *risk identification* that gives rise to awareness of risk an organization is facing, (ii) *risk assessment* to evaluate the potential impact and the occurrence probability of a risky event, (iii) decision and implementation of *risk management actions* aiming at reducing the impact or decreasing the occurrence probability of a disruption, and (iv) *risk monitoring* to ensure that risks are effectively identified and assessed and that appropriate controls and responses are in place. In Table 2.1 the steps constituting the supply risk management frameworks described above are classified according to these four phases and a general definitions of risk identification, assessment, management and monitoring are provided.

In the next section, a link between supply chain risk management process and information-processing theory is identified and, through a survey-based research, the actual relationships among the described phases of a typical risk management framework are statistically tested and assessed.

Element	Kralijc (1983)	Harland et al. (2003)	Hallikas et al. (2004)	Wu et al. (2006)	Matook et al. (2008)	Definition
Risk identification	Classification Market analysis	Map supply network Identify risk and its current location	Risk identification	Risk classification Risk identification	Supplier risk identification	Identification of all significant activities within the organization Definition of all the risks flowing from these activities Identification and categorization of all associated volatility related to these activities.
Risk assessment	Strategic positioning	Assess risk	Risk assessment	Risk calculation	Supplier risk assessment Reporting and decision of supplier risks	Display of the identified risks in a structured format (ex: table) Estimation of the probability of occurrence and the possible consequence (it can be quantitative, semi- quantitative or qualitative)
Risk management	Action Plans	Form collaborative supply network risk strategies Implement supply network	Risk management actions		Supplier risk management responses	Decisions about the significance of risks to the organization and whether each specific risk should be accepted or treated. Selection and implementation of measures to modify the risk
Risk monitoring		Implement supply network risk strategy	Risk monitoring		Supplier risk performance outcomes	Definition of a reporting and review structure to ensure that risks are effectively identified and assessed and that appropriate controls and responses are in place Execution of regular audits of policy and standards compliance Review of standards performance to identify opportunities for improvement.

Table 2.1 - Phases of a supply chain risk management process

2.2 A linkage between supply chain risk management and information-processing theory

In this section, the processes that are at work when firms interpret and assess information about supply chain risk in order to devise risk management measures, are described drawing on the information-processing literature. This branch of literature views firms as information-processing systems where responses to environmental events are shaped by subsequent information-processing activities (Daft and Weick, 1984; Galbraith, 1974; Hult *et al.*, 2004; Tushman and Nadler, 1978).

A basic assumption is that organizations are considered as open social systems that deal with work-related uncertainty (Daft and Weick, 1984, Tushman and Nadler, 1978). Even if there are several sources of uncertainty, both internal and external to an organization, decision makers often lack information about the supply chain or its environment and, as a result, are unable to predict the impact of possible actions on supply chain behaviors (Van der Vorst and Beulens, 2002). Consequently, a critical task that firms should pursue is to facilitate the gathering, interpreting and synthesizing of information in the context of organizational decision making (Tushman and Nadler, 1978).

In the context of the information processing theory, Daft and Weick (1984) identify three stages that constitute the overall learning process: scanning, interpretation, and learning. The first stage, *scanning*, is defined as the process of monitoring the environment and providing environmental data to managers. It entails data collection that can derive from external (managers that have direct contact with information outside the organization) or internal (people in the organization that provide data to managers) sources. Further, data can be allocated from personal (meaning direct contact with other individuals) or impersonal (whether data come from written documentation) sources. These gathered data are given meaning through *interpretation* that consists in translating events and developing a sharing understanding among managers. Once there is a common understanding, theories can be put into action in the third stage of the process, namely the *learning* phase. As a consequence of taking actions, new insights and new data to be interpreted can result, leading to a feedback loop that connects the three stages of the overall learning process. Considering this organizational information processing theory and the risk management theory, similarities can be drawn out, allowing a better understanding of the mechanisms that lead to assess supply disruption risk and to devise strategies to manage that risk.

Summarizing the finding of the previous section, a supply chain risk framework is based on four main phases: risk identification, risk assessment, risk management and risk monitoring.

Thus, the supply risk management process begins with the identification of the risk sources a company is facing. This requires a deep knowledge of the external environment and the internal strategic and operational objectives in order to be able to recognize the organization's exposure to uncertainties (AIRMIC, 2002). As in the scanning stage of the learning process in information processing theory, this phase deals with data collection that can be pursued using different techniques that facilitates awareness of supply risk. This awareness should occur at the highest management levels due to the potential detrimental effects that disruptions can have on the firm, as well as ensure that the appropriate resources are deployed to effectively and efficiently manage that risk.

Second, the identified risk factors need to be evaluated and interpreted through supply risk assessment, generally in terms of occurrence probability and impact. This evaluation can be quantitative, semi-quantitative or qualitative; for instance, both probability and impact values can be high, medium or low (AIRMIC, 2002) even if thresholds should be clearly defined and shared along all the organization. This process is akin to the interpretation phase in Information Process Theory since a greater understanding of these risk sources can be analyzed for potential further managerial action.

The third phase is related to the selection and implementation of the proper strategies to deal with risk that can be addressed to mitigate the impact or to reduce the occurrence probability of risk or disruption occurrence (Zsidisin and Ellram, 2003). Since this phase is associated with the implementation of actions following the data collection and interpretation, it corresponds to the learning stage.

Finally, the risk monitoring phase represents a feedback loop that, as in the learning process, generates new insights and new data contributing to improve knowledge about the environment and the effectiveness of the actions taken. These data represent new input for the identification and assessment phases.

Figure 2.5 graphically shows the correspondences between supply risk awareness, assessment, and management with the learning process model. These commonalities enables to describe, based on the organizational Information Processing Theory, the routines that are at work when firms interpret and assess information about supply disruptions and select the respective counteractive actions.

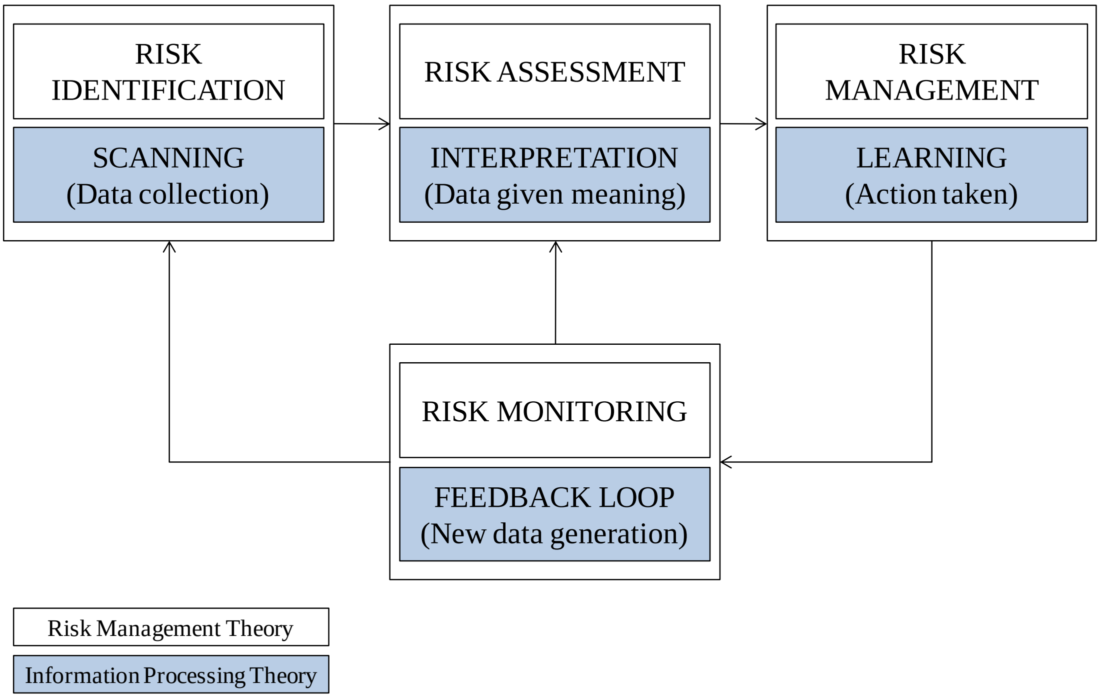

Figure 2.5 - Relationship between risk management theory and information processing theory

Highlighting these analogies between information processing theory and supply chain risk management allows to underline the importance of developing a well defined and structured risk management process within an organization.

As stated by Daft and Weick (1984), one of the widely held tenets in organization theory is that the external environment will influence organization structure and design, but that relationship can be manifested only if participants within the organization interpret the environment and respond to it. Almost all outcomes in terms of organization structure and design, whether caused by the environment, technology, or size, depend on the interpretation of problems or opportunities by key decision makers. Once interpretation occurs, the organization can formulate a response. Similarly, in the risk management it is essential gather and interpret data and information about possible risk factors, in order to devise the most effective responses and ensure business continuity.

2.3 Assessing the relationships between supply risk management process phases

Although these frameworks have been developed based on literature reviews and best practices and illustrated through case studies, quantitative evidences regarding the actual relationships between all the phases have been scarce. Consequently, this section aims at analyzing if the supply risk practices in the above-mentioned phases are correlated and if they effectively lead to a reduction in supply disruption frequency. The research hypotheses are formulated based on the above mentioned analogies between supply risk management and information processing.

Hypotheses

First, the more that top management is aware of supply risk, the greater the extent they will implement tools to assess that risk. Considering the organizational information processing theory, Tushman & Nadler (1977) state that as uncertainty increases, the amount of information needed as well as the required information processing capacity rises. In the risk management context, this can be translated with the concept that the greater uncertainty that exists in the external environment, there is a likewise greater need to implement assessment tools in order to quantify the actual risks the company is facing in order to identify the proper strategies to deal with them. These assessment tools should follow a well designed structure in order to simplify and facilitate interpretation and improve the prioritization of different risks (AIRMIC, 2002). In fact, using a formalized language is recognized as a means of increasing the capacity to process information (Galbraith, 1977). In addition, these risk assessment tools can be embedded in the supplier evaluation process, and may also focus on creating estimates of the risk dimensions of probability and impact. Based on this statement, the following research hypothesis has been formulated:

H1: Top management awareness of supply risk is positively associated with employing supply risk assessment tools.

When buyers implement risk assessment tools to a greater extent, they will improve their knowledge of the supply risk that exists, and subsequently seek to manage that risk. As stated in the information processing theory, the interpretation of data and creation of a shared understanding will result in management action taking place. In the same way, in risk management theory, once having assessed and quantified risk sources, available strategies and practices will be analyzed and the more suitable ones will be selected in order to reduce firm exposure to supply disruptions. The aim of these practices is to enhance the enterprise resilience (Sheffi & Rice, 2005) in order to return to its original state or moving to a new, more desirable one after a disruption occurrence (Christopher & Peck, 2004, Sheffi, 2005). Resilience can be achieved by either creating redundancy or increasing flexibility (Sheffi & Rice, 2005). Generally, these concepts have been investigated considering the overall company point of view (Christopher & Peck 2004, Peck 2005, Pettit et al. 2010, Sheffi & Rice 2005, Tang 2006), but, since this work deals with supply risk, the focus of the analysis is on the upstream flows. In this context, redundancy means keeping some resources in reserve (in terms of inventory, time and capacity) to be used to limiting the consequences of a supply disruption (Sheffi & Rice 2005). On the other hand, flexibility is a more proactive approach and comprises any strategy attempting to reduce the disruption likelihood by increasing the supplier ability to respond in a timely and cost effective manner to changing requirements of purchased components (Tachizawa & Thomsen 2007, Tang & Tomlin 2008). Even though they have been named in several different ways, supply risk management strategies broadly leverage on these two concepts. Analyzing the literature, while several studies evaluate the utilization level of flexibility practices to reducing disruption occurrence (Humprey et at., 2004, Krause, 1999, Modi & Mabert, 2007), redundancy has been generally investigated in a quantitative way, namely developing models identifying optimal quantities (Güllü et al., 1999, Hung & Chang, 1999, Minner, 2003, Molinder, 1997, Parlar & Perry, 1996, So & Zheng, 2003), with empirical evidences about its actual utilization rate have been scarce. Thus, regarding supply risk management, the following analysis focuses on redundancy practices and, pointing at the relationship between supply risk assessment and supply risk management practices implementation, the following hypothesis have been formulated:

H2: The utilization of risk assessment tools is positively associated with the implementation of supply risk management techniques.

If supply risk management practices are properly implemented by supply management professionals, the likelihood that disruptions will occur due to supplier problems should decrease. Regarding supply management practices, different authors have carried out survey and case studies to examine the positive impact of flexibility practices on supply risk management (Humprey et at., 2004, Krause, 1999, Krause et al., 1998, Modi & Mabert, 2007, Stevenson & Spring, 2007). In fact flexibility practices such as certification program, information sharing, supplier personnel training, or direct investment in supplier operations, have been demonstrated to be effective in increasing on-time and complete order fulfillment delivery, as well as reducing non conformities, order cycle time, and default probability because of long term relationships and process optimizations. These supplier performance improvements have the effect of reducing the probability of supplier failure as a consequence of internal problem or bad performance.
On the contrary, there is little empirical evidence on how supply risk management practices affect a company's exposure to the detrimental effect of supply disruptions. In other words, the research question that leads to formulate the last research hypothesis is "in what extent keeping extra inventories, time or capacity buffer can decrease the probability that a supply disruption undermine the focal company business continuity?". Therefore, this research hypothesis aims at evaluating if redundancy practices are actually effective in reducing the impact of supply disruptions, as stated below:

H3: The implementation of supply risk management techniques is negatively associated with supply disruption occurrence.

Given the above mentioned hypotheses, the research model depicted in Figure 2.6 have been developed. Since some commonalities between risk management theory and the information processing theory have been identified, the variables “Top management awareness” and “Supply risk assessment” and the related research hypotheses refer to the information processing, in terms of data collection and interpretation. “Supply risk management” represents the actions upon the information that should be negative correlated with the “Supply disruption occurrence”, as a result of experiencing positive outcomes.

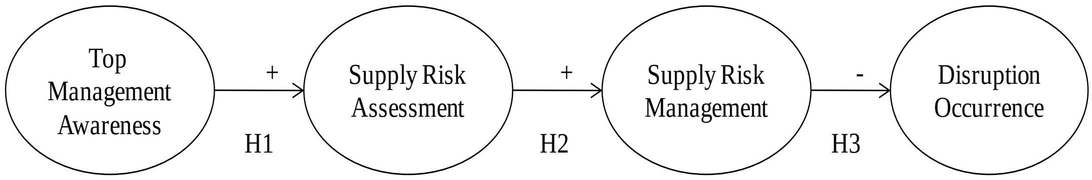

Figure 2.6 - The research model

Data Collection

The research study involved developing and administering an on-line supply risk audit instrument from a convenience sample of supply management professionals employed at five organizations. The questions in the audit instrument were developed from prior literature on the subject of supply chain risk, as well as prior researches. Dillman’s Tailored Design Method was used to guide the distribution of the survey (Dillman, 2007). The Chief Purchasing Officer (CPO – the highest supply management executive in a firm or business unit) for each organization was solicited for involvement. General descriptions of each firm can be found in Table 2.2. Please note that code names are used to ensure confidentiality. The survey was deployed on a web server at one of the Universities, and invitations to respond were sent out by the respective CPOs to their supply management (purchasing) workforce, addressed by name of respondent. Reminder emails were sent out to all companies within 2-3 weeks of the first email, except Company MHE, which had such a high initial response rate that the CPO did not initiate a reminder email.

Name (Code)	Industry	Home country	Sample	Responses	Response rate
Build	Home construction and improvement materials	U.S.	156	53	34.0%
Construction	Home construction and improvement materials	U.S.	56	34	60.7%
Equip	Paper and other capital equipment	Germany	41	33	80.5%
Aircraft	Aircraft manufacturer	U.S.	201	141	70.1%
MHE	Material handling equipment	Germany	45	35	77.8%
		Total	**499**	**296**	**59.3%**

Table 2.2 - Company demographics and response rates

Survey Instrument, Unit of Analysis, and Measures

The survey instrument and measures were developed in several stages. First, a preliminary questionnaire was drafted on the basis of prior research. Second, the survey instrument was pretested first by academic experts and then by experienced purchasing executives. During the deployment of each survey to a particular company, the survey was again pretested by the CPO prior to distribution in order to clarify use of terminology and to ensure consistency with business practices and language clarity. Third, at least one member of the research team met personally and communicated via telephone and email several times with each company's representative to review the survey prior to deployment. In the case of the German companies, a German academic member of the research team also pretested the survey for language and cultural differences prior to submission to the company, and then again participated in the review with the company for clarity and appropriateness of the questions (Schaffer and Riordan, 2003). No significant issues were uncovered during this process.

The questions used in the survey instrument asked respondents to report their answers with respect to a specific purchase they manage. Thus, the unit of analysis in this study is the risk associated with a specified purchased item, and not the firms' practices in general. This focus on the product-level allowed the research team to investigate top management awareness, supply risk assessment approaches, supply risk management practices, and impact of disruption occurrence for which the supply management professionals are knowledgeable and held responsible. Multiple-item measures were used to assess the focal constructs on 5-point scales. Descriptions of the specific measures and items used in this study are reported in the Data Analysis and Findings section.

Data Analysis and Findings

Data were analyzed following the two-step approach recommended by Anderson and Gerbin (1988). First, a measurement model that was tested using Confirmatory Factor Analysis (CFA) in order to assess convergent and discriminant validity of the scales, have been built. Then, the structural equation model depicted in Figure 2.6 was assessed and the hypothesis tested.

In structural equation modeling, there is a distinction between observed and latent variables. The observed variables are the measurable indicators and are usually represented by a rectangle or a square box, while the latent variables (constructs) are not directly measured but are inferred from the observed variables and are represented by circles or ellipses (Anderson and Gerbin, 1988). In this model the latent variables are “Top Management Awareness”, “Supply Risk Assessment”, “Supply Risk Management” and “Supply Disruption”.

The measurement model, shown in Figure 2.7, is composed of the linkages between the observed variables and the latent constructs and of curved arrows representing correlations between every pair of latent variables.

This model was run in LISREL 8 program and the resulting indicator loadings and t-values are reported in Table 2.3.

Convergent validity indicates how well the items measured are related to each other in representing a concept, so how well the observed variables are indicators of the corresponding latent variables. Convergent validity presence is argue through the discussion of the literature reported in the previous section, but it should be also statistically evaluated. Then, convergent validity can be assess from this measurement model by determining whether each indicator's estimated loading on its construct is significant (Anderson & Gerbin, 1988).

“Top Management Awareness” represents the degree to which supply managers are informed about risks related to their purchases. The respondents were asked to indicate the extent to which they agree or disagree on a list of items concerning top management awareness, using a 5-point Linkert scale (1=strongly disagree and 5=

strongly agree). According to the CFA results, the four items identified have statistically significant factor loadings and therefore represent good measurement of this variable (Table 2.3).

Similarly, "Supply Risk Assessment", "Supply Risk Management" and "Supply Disruption" have been measured using the same 5-point Linkert scale (1=strongly disagree and 5= strongly agree) and asking the respondents questions to indicate the extent to which they agree or disagree on their use of risk identification and measurement tools ("Supply Risk Assessment"), the implementation of redundancy practices ("Supply Risk Management"), and supply disruption frequency ("Supply Disruption Occurrence"). All the factors loadings are statistically significant, providing evidence of convergent validity (Table 2.3).

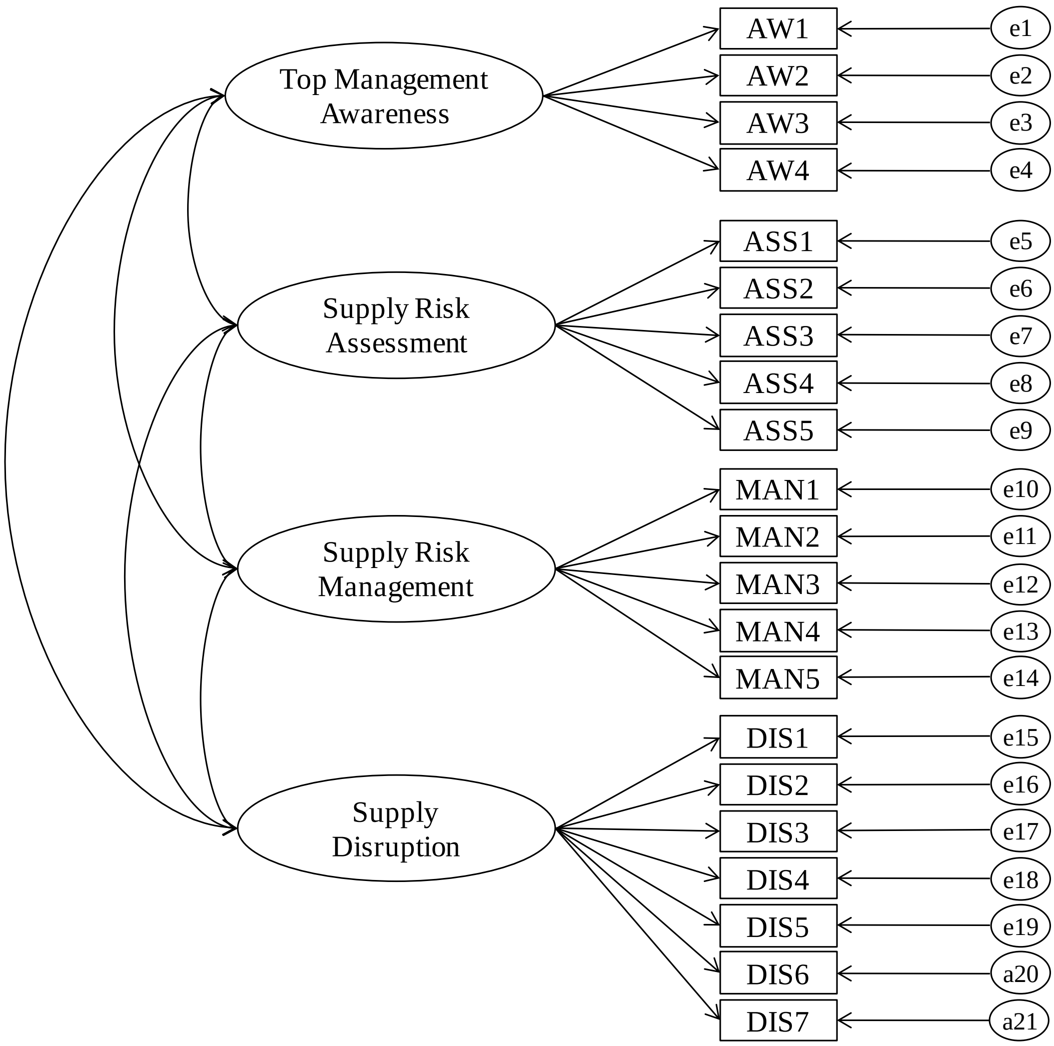

Figure 2.7 - The measurement model

	Observed variables for each latent variable	Loading	t-value
	Top Management Awareness		
AW1	We have a formal system for making supply risk visible to our top management	0,93	19,75
AW2	We have a formal system for making supply risk visible to our purchasing management	0,84	17,08
AW3	Top management regularly reviews our supply risk exposure	0,58	10,53
AW4	Top management explicitly considers supply risk when evaluating our purchasing group's performance	0,57	10,1
	Supply Risk Assessment		
ASS1	We use a formal process for rating suppliers based on the level of risk they pose	0,82	15,87
ASS2	We use a formal process for identifying and assessing supply risk	0,79	15,04
ASS3	We regularly use tools such as supply chain mapping to identify sources of supply risk	0,66	11,75
ASS4	We generate estimates of probability of potential supply disruptions	0,59	10,2
ASS5	We use supplier councils to identify and discuss potential sources of supply risk	0,51	8,48
	Supply Risk Management		
MAN1	Supply continuity / contingency plans	0,79	13,3
MAN2	Ensure that excess supplier capacity exists to deal with unplanned increases in demand	0,72	12,07
MAN3	Dual or multiple supply sources	0,53	8,48
MAN4	Require suppliers to immediately report all supply disruptions irrespective of their impact	0,45	6,99
MAN5	Require suppliers to hold inventory for you to prevent stockouts	0,42	6,52
	Disruption Occurrence		
DIS1	Operations disruption due to a late delivery	0,86	17,53
DIS2	Operations disruption due to a quality problem	0,84	16,85
DIS3	Expedited shipments to avoid a disruption due to a late delivery	0,81	15,77
DIS4	Late deliveries	0,77	14,81
DIS5	Unacceptable delivered quality	0,76	14,52
DIS6	Excess cost due to a supplier's failure to perform	0,68	12,37
DIS7	Use of an alternate source for this product because the primary sourced failed to perform	0,38	6,37

Table 2.3 - The measurement model loadings and t-values

Discriminant validity describes the degree to which the constructs that should not be correlate one each other are, in fact, not correlated. It is often evaluated by constraining the estimated correlation between the latent constructs to 1.0 and then performing a chi-square difference test on the values obtained for the constrained and unconstrained models. This test should be performed for one pair of factors at a time, rather than as a simultaneous test of all pairs of interest (Anderson & Gerbin, 1988). The increase of the chi-square in every constrained model with respect to the unconstrained one was always more than 100 with an increase of 1 degree of freedom. This means that the differences in the chi-square statistic are significant, providing support for discriminant validity.

Reliability tests were also performed for each construct using Cronbach's alpha (Cronbach, 1951), as shown in Table 2.4. Cronbach's alpha is over the value 0,7 for all factors, demonstrating a sufficiently high reliability of the four scales analyzed.

Construct	Cronbach's alpha
Top Management Awareness	0,822
Supply Risk Assessment	0,713
Supply Risk Management	0,713
Disruption Occurrence	0,89

Table 2.4 - Cronbach's alpha

Once support for convergent and discriminant validity of the scales have been provided, the proposed structural equation model was tested. Figure 2.8 presents the path coefficients along with the significance value, resulting from running the structural equation model analysis using the LISREL 8 program. All the path coefficients between the latent variables are significant with $p < 0,001$.

Regarding goodness-of-fit indices, the traditional measure is the chi-square fit index. The chi-square statistic provides a test for perfect fit in which the null hypothesis is that the model fits the population data perfectly. A statistically significant chi-square causes rejection of the null hypothesis, implying imperfect model fit and possible rejection of the model (Diamantopoulos, 2000). However, this statistic has been criticized on several grounds because it is influenced by the sample size, such that model evaluations with large samples will almost always lead to model rejection (Jaccard & Wan, 1996). As expected, a significant (p<0,001) chi-square statistic of 496.1 with 185 degrees of freedom has been obtained. For this reason, other indices were considered to evaluate the structural equation model. Among them, the RMSEA (Root Mean Square Error of Approximation) is generally regarded as one of the most informative fit indices (Diamantopoulos, 2000). The RMSEA of this model is 0,075, which indicates a reasonable fit of the model to the observed data (Diamantopoulos, 2000, Hair *et al.*, 2006).

Since the goodness-of-fit indices demonstrates that the model fits the data and the paths between “Top Management Awareness” and “Supply Risk Assessment” and between “Supply Risk Assessment” and “Supply Risk Management” are statistically significant and greater than zero, it is possible to conclude that there is a positive correlation between these variables, providing support for H1 and H2. In the same way, the path between “Supply Risk Management” and “Supply Disruption” is significantly negative, indicating that the adoption of supply risk management practices have a significant effect on reducing supply disruptions. Therefore, H3 is also supported in this model.

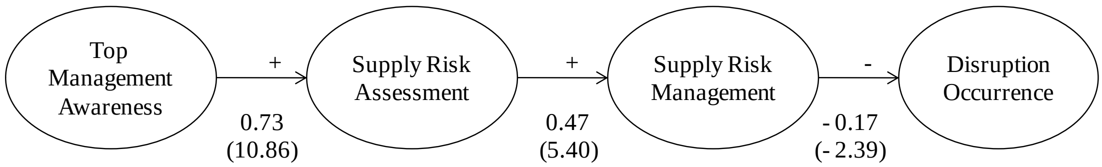

Figure 2.8 - Results of the structural equation modeling

2.4 An enhanced methodology to manage supply risk

The statistical analyses carried out in the previous section showed that the typical phases of a risk management framework are correlated one each other and, if properly implemented, lead to a reduction of disruptions due to supplier problems.

Consequently, this research proposes an enhanced four-step methodology to deal with supply risk that is substantially based on the existing frameworks but provides some original contributions on the content of the different phases. This methodology is depicted in Figure 2.9 and is composed of the following steps:

- Analysis of supply risk
- Evaluation of available strategies to ensure business continuity

- Selection of the most suitable strategies
- Monitoring and feedback

While the first and the last step, namely “analysis of supply risk” and “monitoring and feedback”, are essentially based on literature, the main contributions of this work concern the core phases of the entire process: “evaluation of available strategies” and “selection of the most suitable strategies”.

In fact, as reported by Matook *et al.* (2008), even if several frameworks have been developed to guide firms in the management of risk, few studies focus on the latter stage (i.e. risk management) as a means of enhancing product quality and supplier-base performance.

More specifically, this methodology and the proposed approaches and methods are intended to address the problem of managing the risk related to strategic suppliers, the ones providing items with high impact on company profitability or difficult to substitute.

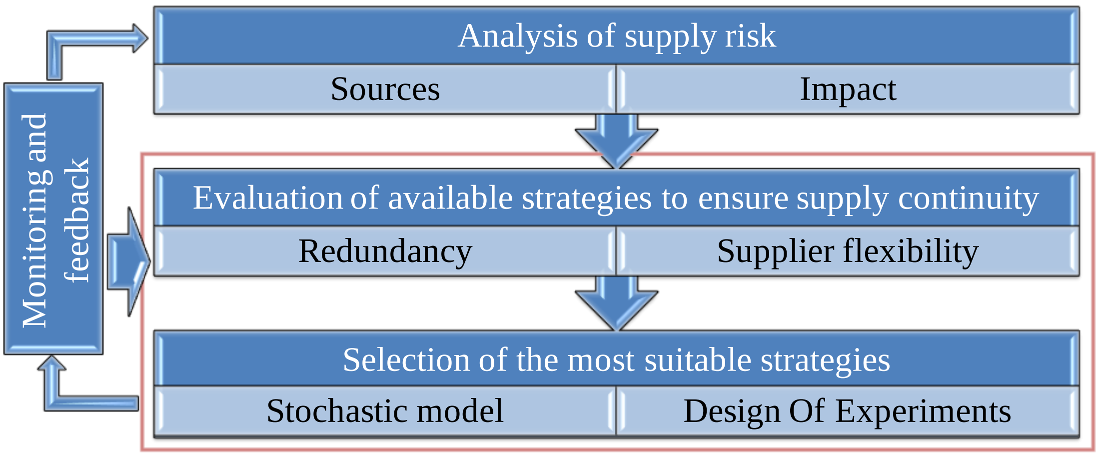

Figure 2.9 – The proposed four-step methodology

As mentioned at the beginning of this chapter, an effective risk management strategy should ensure supply continuity. In other words, companies should be able to select the best strategy to increase their resilience (Sheffi and Rice 2005) - the ability to return to the original state or to move to a new and more desirable one after being disrupted (Christopher and Peck 2004). According to Sheffi and Rice (2005), resilience is a strategic objective that can be achieved mainly by creating redundancy or increasing flexibility. These concepts have been investigated in literature mainly considering the company's point of view (Sheffi and Rice, 2005; Peck, 2005; Pettit *et al.*, 2010; Christopher and Peck, 2004; Tang, 2006a); nevertheless, given the increasing relevance of supply risk, this research moves the focus of resilience on the supply side. To this end, some possible interventions to improve the resilience of a company's supply are analyzed.

In the supply context, redundancy means keeping some resources in reserve (in terms of inventory, time and capacity) to be used to limiting the consequences of a supply disruption (Sheffi & Rice 2005). On the other hand, flexibility comprises any strategy attempting to reduce supply disruption likelihood by increasing its performance and its ability to respond in a timely and cost effective manner to changing requirements of purchased components (Tachizawa & Thomsen 2007, Tang & Tomlin 2008). In particular, this thesis takes into account actions that can be implemented in the short or medium term and that do not involve a substantial redesign of the network or of the company's internal processes and strategies.

However, although redundancy and supply flexibility are two different strategies, where the former aims at reducing the impact of risky events while the latter focuses on risk sources reduction, they are not mutually exclusive. On the contrary, a certain level of redundancy is always required to cope with supply risk, because even if through integration practices and/or supplier development activities, supplier reliability and stability are improved, the risk associated to that supplier will be reduced but never removed. In fact, even if the buying company achieved a really close coordination level with its supplier and the investment brought such a supplier internal processes improvement that ensures perfect on time deliveries, some external disruptions could however happen. In this case, if no buffers are taken (such as backup supplier), some economic losses will occur. Thus, supply flexibility strategies can be undertaken in order to decrease the buffer size, but they can never exist alone without any redundancy.

Despite that, flexibility and redundancy are generally investigated in literature as two different and unrelated practices, as will be demonstrated in the next chapter. In addition, authors studying redundancy usually performed quantitative studies in order to identify the optimal quantity to be buffered, while researches on flexibility are more qualitative and descriptive, providing insights into the actual employment of these strategies and their perceived benefits, based on surveys and case studies.

These observations lead to the main research question of this research: **how to jointly evaluate the available strategies to deal with supply risk and make the right decisions that improve supply chain performance?**

To answer this question, two models have been developed:

a. A **descriptive model** that supports the analysis of conjoint effects produced by the two different strategies (redundancy and supply flexibility) simultaneously adopted.
b. A **quantitative model** that, starting from the relationships identified in the previous step, supports supply tactical planning for inbound disruptions determining the most suitable strategies for ensuring supply continuity.

A brief overview of main contents of these four phases is reported below and, in the next chapters, step 2 and step 3 are deeply explained.

Step 1: Analysis of supply risk

The aim of this phase is to detect the organizational exposure to supply uncertainty, in terms of the main supply risk sources the organization is facing and their impact. Discussion about supply risk sources and impacts and the tools available for their identification and assessment have been carried out in the first chapter of this thesis.

As reported there, supply risk sources can be classified based on item characteristics, market characteristics, supplier characteristics and procurement process characteristics. An accurate analysis of these factors allows a company to quantify its exposure to supply risk and assess the impact of possible inbound disruptions.

Referring to the impact on focal firm, this research considers the risks that affect the incoming product availability and delivery timeliness, while purposely neglecting those ones that cause uncertainty in terms of the price to be paid for inbound supplies (such as price volatility and currency rate fluctuation). Thus, the main consequences of a supply risk occurrence can be classified as follows:

- **Delay**: supplier delivers late the entire quantity ordered;
- **Short-shipment**: supplier delivers on time only a portion of the order and the remaining quantity is delivered at a later time;

- **No shipment at all**: all the quantity ordered is lost and no more order can be placed to this supplier because it does not provide supply anymore (there can be several reasons, such as going out of business, being bought out by another firm, changing the direction of its business and customer market, or determining that the customer is no longer profitable).

This classification contemplates also quality problems and wrong part deliveries. In fact, both cases require supplier intervention in order to repair or substitute the defective/wrong products and this can result in a delay in the final delivery.

Based on sources analysis, on supplier histories and on other internal and/or external data, a company should be able to estimate the probability of the above reported risk occurrences in order to proceed with the following phases.

Step 2: Evaluation of all the available strategies

As stated above, this work analyzes redundancy and supply flexibility practices as means to decrease supply risk. In this phase, the mentioned descriptive model is developed using a *systemic approach*, that considers the system made up of the buying company and its suppliers, in its totality, its complexity, and its own dynamics. This model evidences both the positive and negative impacts that a simultaneous implementation of redundancy and supply flexibility strategies has on buyer and supplier performance.

This phase and the related model will be deeply explained in the next chapter.

Step 3: Strategies selection

The aim of the qualitative model described in the previous step is to increase awareness about the broad impact that a decision can generate. In this step, some of these qualitative relationships are interpreted in a quantitative way and have been translated in a two stage mixed-integer stochastic programming model. The aim is to support the tactical supply planning of a firm when it comes to decide the best strategy to be implemented considering supplier-oriented risk.

Finally, a method for building a set of experiments in order to be able to discern the impact of different input variables on the outcome of this stochastic model and to support more effectively managers' decision making has been proposed.

Chapter 4 and 5 will describe this phase in an exhaustive way.

Step 4: Monitoring and feedback

As stated in the previous risk management frameworks, since the company and its environment are not static and the risk status can change over time, the recognized risk sources should be monitored to identify variations in their probability or consequences or to determine new risks.

2.5 Conclusion

Starting from an overview of the supply risk management frameworks presented in literature, the proposed four-step methodology to deal with supply risk has been described in this chapter.

In the following chapters, the two phases that represent the main contribution of this work, namely the "evaluation of all the available strategies" and the "selection of the most suitable strategies", are deeply explained.

3. Evaluation of all the available strategies

In this chapter a systemic and qualitative overview of the strategies to deal with supply risk is provided. As previously mentioned, these strategies are means to increase company resiliency addressing to redundancy and supply flexibility.

The aim of redundancy is to limiting the impact of a supply risk occurrence on the buying company through keeping resources in reserve. On the other hand, supply flexibility comprises any strategy attempting to reduce the likelihood of a supply disruption. As reported by Duclos *et al.* (2003) much of the practitioner literature stresses the importance of supply chain flexibility, nevertheless little academic research has been carried out on this topic. As suggested by these authors, lot of work has been done in defining internal manufacturing flexibility (Sethi and Sethi, 1990; Gerwin, 1993; De Groote, 1994; Upton, 1994; Suarez *et al.*, 1995), but, since supply chains extend beyond the enterprise boundaries, also flexibility concept may extend beyond one firm's internal flexibility. Thus, they proposed six component of supply chain flexibility: operations system flexibility, market flexibility, logistics flexibility, supply flexibility, organizational flexibility, and information systems flexibility. Since this research focuses on the inbound side of supply chain and risk, the aim is to provide insights about the possibility for the focal firm to make investments in order to improve supply flexibility, that is the supplier ability to respond in timely and cost effective manner to changing requirements of purchased components, in terms of volume, mix and delivery date (Tachizawa and Thomsen, 2007; Tang and Tomlin, 2008).

Furthermore, building “supply resilience” is not a linear process, since dynamic complexity and feedback should be considered. In fact, in building resilience it is possible to recognize a combination of lags, delays, inertia and feedback that leads to a complex dynamic behavior, even in a deterministic system (Fowler, 2003). Rehashing Fowler’s (1998) observation with regard to the Business Process Reengineering context, the complexity, structure and dynamic interconnectivity encompassed by the supply resilience building processes imply that the unassisted human mind is probably incapable of retaining and manipulating sufficiently representative models during the decision phase. Thus, a descriptive model is needed in order to assist managers to harness the available knowledge.

To this purpose, first, the systemic approach is introduced and, then, the analysis of redundancy and supply flexibility practices is carried out. The main outcome of this phase is the development of a qualitative model, following the System Thinking methodology, that shows the casual relationships between the two investigated strategies and the buyer-supplier performance.

3.1 A systemic approach to analyze supply risk management

One of the main evidences resulting from the performed literature analysis is that the effects of supply risk management practices are normally presented in isolation, neglecting reciprocal effects they can have on each other and nonlinearities caused by feedback loops. This latter aspect could be ascribed to the tradition of linear thinking, that “has become so firmly established that it has diverted most analysts from even recognizing the importance of nonlinearities” (Forrester, 1987); the performed literature review substantially confirms Forrester’s claim.

Nonetheless, a real system is generally multiple-looped, interconnected and nonlinear, characterized by strong interactions between the composing elements.

This kind of multi-looped and nonlinear systems must be tackled with a *systemic approach*, considering it in its totality, its complexity, and its own dynamics from a holistic perspective. The system is thus viewed as a set of diverse interacting elements within an environment, recognizing that the relationships or interactions between them are more important than the elements themselves in determining the behavior of the system (Mingers and White, 2010).

In order to overcome the limits of the widespread linear thinking approach, the main contribution of this research is to enhance the understanding of the conjoint effects of supply risk management practices on a complex system made up of a firm and its suppliers, using the systemic approach.

The model has been developed using the System Thinking (ST) methodology, since (i) it focuses on the way the parts constituting a system interrelate, (ii) it analyzes how systems dynamically work over time and (iii) within the context of larger systems, it takes into account larger and larger interactions instead of isolating parts of what is being studied (Sterman, 2000).

As a general understanding of the formalism used in the following figures of this chapter, a ST approach is based on causal loop diagrams, namely variables connected by arrows denoting causal influences. In this sense, a plus (+) sign at the end of the arrow between two variables indicates that these variables change in the same direction, while the minus (-) sign indicates that they change in the opposite direction. The "R" letter next to the loop names indicates a positive loop, or a self-reinforcing feedback system, which contains the mechanisms to amplify whatever is happening in the system. The "B" letter indicates a balanced loop, or a self-correcting feedback system, which, on the contrary, opposes the change and seeks a steady state of the system.

In the next section, an in-depth review of the available theoretical and managerial literature on supply risk management will be presented and the resulting ST models will be extensively discussed.

3.2 Definition of available strategies: supply flexibility and redundancy

Redundancy

The ST loop diagram depicted in Figure 3.1 graphically synthesizes the logical relationships among the variables affecting the choice of investing in redundancy in order to reduce the impact of a risky event.

As stated in the previous chapter, this research considers timeliness of delivery as consequence of supplier risk. In fact, further simplifying the list of risk sources reported in the first chapter and synthesizing the results of Ho *et al.* (2005) in their study about supply uncertainty, inbound uncertainty is more commonly related to complexity, quality and, especially, timeliness of delivered products. Indeed, the more complex is a product the more human intervention is required; this increases the probability of errors and the time needed to resolve them, leading to delivery delays. Relating to quality, two different cases can occur: in the first one, defects are detected by the supplier before the shipment, so it can quickly repair it; in the second one, the quality problem is identified by the buying firm and a supplier intervention is required in order to repair or substitute the defective product. In both cases, delays in delivery can occur, especially when problems come out at the company's plant. Consequently, both complexity and quality can be referred to the time dimension of deliveries that disrupt company's processes and schedules. Thus, supply risk is here measured as supplier delay. This variable includes also the "not shipment at all" of the ordered products (for example due to supplier default) because, if it occurs, the required quantity will be lost and the delay will theoretically grow to infinity.

As emerge from literature, a common way to reduce uncertainty and avoid supply risk consequences is buffering the effect of the risk through inventory, time, and capacity buffers in order to ensure the continuation of the business and on-time delivery to customers (Caputo, 1996; Hung and Chang, 1999; Zsidisin et al., 2000; Stecke and Kumar, 2009). Also Lapide (2008), in a MIT research aiming at identifying and analyzing the critical success factors of future supply chains, found that one of the most useful laws for identifying risk management strategies is the "Variability Buffer Law", that states that "variability in a production system will be buffered by some combination of inventory, capacity, and time". This law also helps companies identify methods for adding buffers needed for sustaining performance and mitigating risks against future uncertainties.

All these methods belong to the class of redundancy practices (Sheffi and Rice, 2005), an outcome-based approach to reduce the detrimental effects, rather than decreasing the occurrence probability of an undesired event. To avoid operation disruptions, an organization can decide to increase buffer sizes. This is a well known remedy in the supply chain management literature, where in the past several authors have proposed quantitative models for defining the best quantity to be buffered, especially in terms of inventory (Parlar and Perry, 1996; Molinder, 1997; Güllü *et al.*, 1999; Hung and Chang, 1999; Minner, 2003; So and Zheng, 2003; Kouvelis and Li, 2008). Though being the most widespread one, holding inventory is not the only method to create redundancy. Beside this, several other kinds of buffer are available, but among them the most cited in literature and most suitable to reduce the impact of a supplier disruption are time buffer and capacity buffer (Vorst and Beulens, 2002; Zsidisin and Ellram, 2003; Kaipia, 2008; Kouvelis and Li, 2008; Stecke and Kumar, 2009).

The former consists in including slack time in scheduled time or declaring slightly longer delivery lead time to customers to allow production or assembly after the receipt of an order, especially for products with a large number of possible configurations.

The latter can be further divided in internal and external capacity buffer. The first one consists in keeping capacity (slack) in the form of production capacity or workforce, for example running two shifts with a capability to run a third one. Even if not using 100 percent of the capacity can be unappealing from the production managers' point of view, using operations below their theoretical maximum can avoid problems in case of increase in demand or supplier delay (Lapide, 2008). External capacity buffer consists in having multiple sourcing or backup suppliers; multiple suppliers' base is considered by Tang (2006b) as one of the nine robust strategies a company can establish in order to make a resilient supply chain, that can assure business continuity when either regular demand fluctuations or major disruptions occur. For instance, HP has two suppliers producing its inkjet printers, enabling the company to handle demand fluctuations and to maintain continuous supply of materials in case of a major disruption Tang (2006b). Furthermore, Kouvelis and Li (2008) developed a quantitative model to justify the use of a backup supplier as an emergency response to delivery delays of the main supplier, demonstrating that the total benefits depend on the difference between the two purchasing costs and on the backup supplier lead time. The significance of buffers in reducing losses likelihood due to risky events is expressed in the Figure 3.1 by the "Buffer 1" causal loop diagram.

As the "Buffer 2" diagram highlights, even if these redundancy methods can help companies manage uncertainties and avoid operation disruptions, they have some negative impacts on buyer-supplier relationship performance beyond the mere increase of costs. In fact, researches state that the main problem is that buffers can hide problems without correcting the real sources (Caputo, 1996). Theoretically, the greater the risk associated to the inbound logistic flows, the greater the stock out probability and, then, the greater should the buffer size be. Furthermore, as the buffer level increases, the visibility of the upstream and downstream flows and stocks decreases. Due to the lack of visibility, confidence in the supply chain declines and further buffers are taken to cope with uncertainty (Christopher and Lee, 2004). As a result, buffer level would continuously increase and, consequently, lead to limited performance and reduced competitive advantage (Giunipero *et al.*,2005), due to long purchase order lead time, poor productivity and increased production costs for the buying firm. These lasts can be related to major inventory costs, because of storage space, potential obsolescence and capital investment in stocks, or to additional capacity costs due to the employment of more workforce or lower production yields. Hence, as shown in "Buffer 3" diagram, cost increase would seriously affects the cash flow availability for further investments (Caputo, 1996).

"Buffer 1", "Buffer 2" and "Buffer 3" diagrams are all represented in Figure 3.1. For the sake of simplicity and clarity, the different methods belonging to buffer category (inventory, time and capacity) are considered as a single variable ("buffer size"). As reported in the previous section, the signs at the end of the arrows indicate the relationship between two variables. For instance, when the probability of supplier delay increases, the losses likelihood also increases, as indicated by the plus sign at the end of the arrow between "supplier delay" and "likelihood of losses due to delay" variables. On the contrary, when the total cost increases, the cash flow availability to make new investments decreases, as indicated by the minus sign at the end of the arrow pointing at "actual cash flow".

An important element of the balanced loop is the goal-gap formulation: when a loop detects a gap between the desired and actual level of a variable, it initiates corrective actions attempting to reach a new equilibrium. For example, in the loop named "Buffer3", the goal-gap formulation has been used related to the cash flow variable. A company can set a desired cash flow level that maximize its performance, but if additional costs occur the actual cash flow will decrease generating a gap between the actual and the desired level. In order to close this gap, the corrective action of reducing the buffer size would be taken by the system.

In Table 3.1, the most significant loops that compose this first part of the ST model are briefly explained and the related literature references are reported.

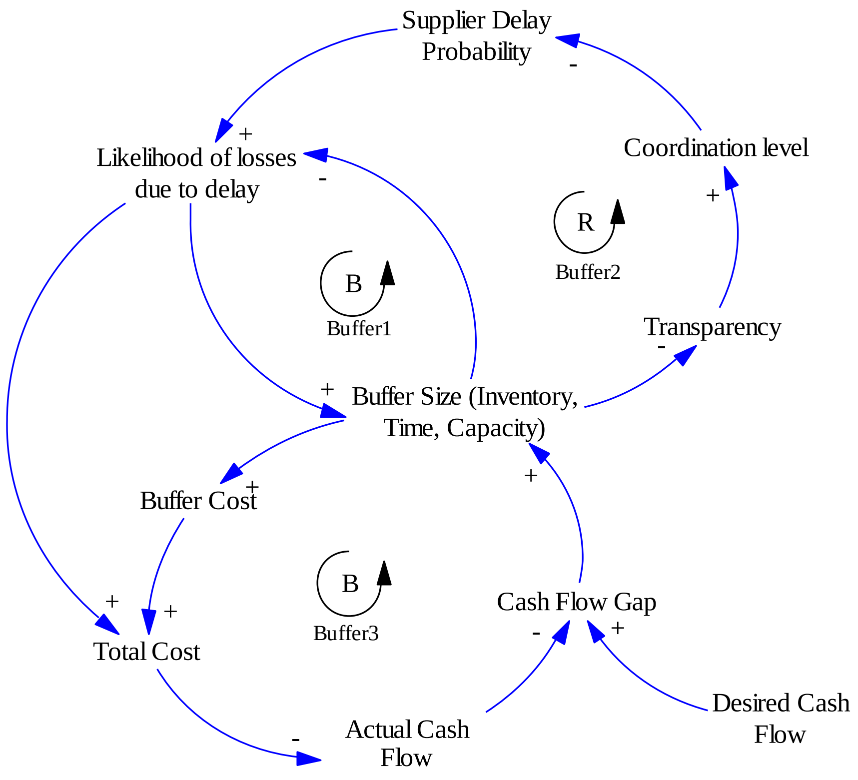

Figure 3.1 - Redundancy strategies

Loop Name	Type of loop	Description	References
Buffer1	Balanced	Delivery delays can cause losses (for example in the forms of penalty or loss of future purchases) to the company due to poor service level and delayed order satisfaction. The higher the likelihood of these losses, the greater the cautionary buffer sizes. In turn, the higher the buffer size, the lower the likelihood of a loss.	Parlar and Perry (1996) Molinder (1997) Güllü *et al.* (1999) Hung and Chang (1999) Vorst and Beulens (2002) Minner (2003) So and Zhen (2003) Sheffi and Rice (2005) Kouvelis and Li (2008) Oke and Gopalakrishnan, (2009) Stecke and Kumar (2009)
Buffer2	Reinforced	The higher the supplier delay probability, the higher will be the likelihood of losses due to delay and, then, more buffers will be built to reduce losses. However, increasing buffer size decreases transparency and coordination among actors and, then, increases supplier delay probability.	So and Zhen (2003) Christopher and Lee (2004)
Buffer3	Balanced	Raising buffer sizes increases buffer costs and, consequently, total costs; this decreases the actual cash flow and increases the gap between the actual and the desired cash flows. As a consequence, the cash flow availability to make new investments in buffers is reduced.	Caputo (1997) Molinder (1997) Zsidisin and Ellram(2003) Giunipero *et al.* (2005) Sheffi and Rice (2005)

Table 3.1 – Description of causal loop related to redundancy

Supply Flexibility

An alternative and more effective method to reduce supply risk is to deeply analyze its sources and consequently undertake strategies aiming at increasing the flexibility of supplier, focusing on the processes of a supplier rather than on its outcomes (Zsidisin and Ellram, 2003; Sheffi and Rice, 2005; Tachizawa and Thomsen, 2007).

Several researches on Operations Research area have been carried out focusing on internal manufacturing flexibility, leading to identify several facets of the same concept and, consequently, different ways to pursued it (Sethi and Sethi, 1990; Gerwin, 1993; De Groote, 1994; Upton, 1994; Suarez *et al.*, 1995). However, the focus on this type of flexibility is insufficient to deal with the current turbulent environment where firms are connected through complex chains, so flexibility should be considered from supply chain point of view. Among the different kinds of supply chain flexibility reported above, this work centers on the scarce researched topic of supply flexibility and then on having suppliers that can respond in timely and cost effective manner to changing requirements of purchased components, in terms of volume, mix and delivery date (Tachizawa and Thomsen, 2007). In particular, the pros and cons and the related feedback loops of an investment made in supply flexibility in order to counter supply risk and reduce the probability of inbound problems generating operation interruptions and undermining business continuity have been investigated. The discussion about the specific object of this investment is out of the scope of this work, since it might be the focus of a following step of the strategy implementation process and it will depend on the specific context.

From the literature review on supply flexibility and management, a distinction emerges between *supplier integration* and *supplier development* activities (Wagner and Johnson, 2004), as means to increase supplier performance and responsiveness and, consequently, supply flexibility. They are both related to knowledge transfer between buyer and supplier (Modi and Mabert, 2007; Wagner and Krause, 2009), but integration aims at sharing explicit knowledge or information, which can be easily codified, while, on the other hand, supplier development involves tacit knowledge or know-how, that resides in the individuals and can be observed through application and acquired only by practice. These two kinds of strategies encompass long-term relationship between companies. Since long-term orientation leads to the establishment of trust (Modi and Mabert, 2007; Stevenson and Spring, 2007), the first step to be made in order to undertake an effective strategy is to intensify the communication and information sharing between the buying firm and its supplier, improving the transparency and then the coordination among their operations and plans (Bensaou and Anderson, 1999; Tang, 2006a). In other words, increasing supply flexibility requires first of all the implementation of *supplier integration* strategies.

Supplier integration

The relevant role of information sharing is provided by Stevenson and Spring (2007), reporting in their literature review about supply chain flexibility some evidences on the positive correlation between information sharing and flexibility. Considering more in detail the risk management context, Faisal *et al.* (2006) and Stecke and Kumar (2009) demonstrated that information sharing, collaborative relationships and trust among supply chain partners play a key role to counter risks and anticipate problems at supplier plant. Moreover, referring to supplier performance (that, as said above, are related to supply uncertainty), Carr and Kaynak (2007) demonstrated that communication with suppliers through telephone, fax, e-mail and written or face-to-face contacts, increases the information sharing level between the two companies with a positive impact on the buyer's products quality and then on its financial performance. In addition, Modi and Mabert (2007) showed that a collaborative communication between two companies, that should be bi-directional, frequent and timely, is positively associated with the performance improvement of the supplier because it reduces inefficiencies due to information asymmetry. This improvement leads to a reduction of supply uncertainty and then to lower delays in inbound deliveries, decreasing the buffer sizes needed to cope with supplier problems and the related costs (Joshi, 2009). A further demonstration of the reduction of buffer sizes due to communication efficiency in a supply chain is given by the Wilson's research (Wilson, 2007) that applies system dynamics methodology to investigate the impact of supply disruption on a 5-echelon supply chain, analyzing the differences between a traditional supply chain, with a low integration level, and a Vendor Managed Inventory (VMI) system, with a higher integration level. The simulation showed that the impact of the disruption is less severe in the VMI structure with a lower level of retail inventories even if the unfilled orders are approximately the same. This behavior is due to the information sharing, since the retailer does not overreact to disruption by placing an excessive order to warehouse, as in the traditional structure (the traditional behavior is also demonstrated in Hung and Chang (1999)). Besides buffer related costs, supplier integration practices allow the buying firm to get also other cost advantages. In fact, from transaction cost analysis, they reduce both transaction and acquisition costs (Das *et al.*, 2006). The establishment of a long-term relationship allows pursuing lower search and contracting costs, while the higher coordination level and information sharing increase familiarity and trust between partners and, consequently, decrease the risk of opportunism by the supplier and then the monitoring and enforcement costs. Regarding the acquisition costs, integration with a few number of suppliers allows the buying firm to take advantage of scale and scope economies (Burke *et al.*, 2007; Costantino and Pellegrino, 2010).

Obviously, these strategies have also some drawbacks associated to plan alignment and company inflexibility costs, where the first one arises because the need of coordination can increase the response times and the human capital requirements, while internal inflexibility comes up because the firm is locked into a partner's technology and the supplier could not be incentivized to innovate new product or services. For these reasons, Das *et al.* (2006) state that a curvilinear relationship between supplier integration and performance exists and, consequently, a firm should find the optimal integration investment that maximizes performance in relation to the industry and market context.

Supplier development

Once a certain level of coordination and information sharing is reached, the following available step to achieve supply flexibility and reduce the associated risk is to focus on know-how transfer and actively facilitate supplier performance and capability improvement through supplier development (Narasimhan *et al.*, 2008; Stevenson and Spring, 2007). This is defined by Krause (1997) as "any effort by a buying firm to improve a supplier's performance and/or capabilities to meet the buying firm's short and/or long term supply needs". Supplier development is a phenomenon that started in the 1980s in the US automotive sector, when companies began to reduce the number of suppliers, establishing more cooperative and long term relationships with them, and to outsource non-core activities. Interviewing five big automotive companies, Hartley and Choi (1996) found out that the supplier development implementation process was similar among companies. They identified five main steps: (1) gaining commitment from supplier's top management, (2) identifying a leader in the supplier's organization, (3) forming a capable buyer-supplier development team, (4) implementing data driven changes, after a thorough understand of supplier's processes and system, and (5) demonstrating success using a "model line."

In general, supplier development activities can be characterized by different levels of commitment of the buying firm. It can decide to commit itself only if supplier improves (for instance promising incentive to suppliers) or choose an active involvement in supplier development. Table 3.2 reports the possible supplier development activities and the related company commitment.

Activities to improve performance and capabilities of suppliers	Commitment of the buying company
Certification program by a buying firm representative (no further inspections required)	Direct involvement
Raising performance expectations	Direct involvement
Training and education of supplier personnel - providing suppliers with training	Direct involvement
Exchange of personnel between the two firms	Direct involvement
Direct investment in a supplier by the buying firm - providing suppliers with equipment and technological support	Direct involvement
Recognition and awards for outstanding suppliers	Only if supplier improves
Promises of increased present and future business if supplier performance improves	Only if supplier improves

Table 3.2 - Supplier development activities (adapted from Krause et al. 1998)

Research findings further demonstrate that, through these activities, suppliers increase on-time and complete order fulfillment delivery, as well as reduce non conformities, order cycle time and default probability because of long term relationships and process improvements and optimizations (Krause, 1997; Krause *et al.*, 1998, Krause, 1999; Humphreys *et al.*, 2004; Carr and Kaynak, 2007). For instance, in the 1990s General Motor completed supplier development projects with 2000 suppliers obtaining an average improvement of supplier productivity of up to 50 percent, lead time reductions of up to 75 percent, and inventory reductions averaging 70 percent during their one-week work-shops (Hartley and Choi, 1996). In addition, from a transaction cost analysis, supplier development practices, as in the case of integration investments, allow a reduction in both transaction and acquisition costs (Dyer, 1997; Krause, 1999; Swink and Zsidisin, 2006). Regarding the former costs, Dyer (1997) in his study showed that lower transaction costs are associated to repeated exchanges, greater total volume of exchange between transactors, higher degree of information sharing and specific investments; these are typical features of relationships where supplier development activities are carried out. From the point of view of acquisition costs, integration with few suppliers allows to take advantage of scale and scope economies and then to reduce unit costs of items. Furthermore, Carr and Kaynak (2007) demonstrated that investments in supplier development are positively related to the improvement of the product quality provided by the buyer and, consequently, to its financial performance, in terms of profits, return on investments, return on assets, cost reduction, market share and customer loyalty.

Obviously, investments in supplier development represent also a risk for the buying firm because they are non transferable and benefits are unrecoverable if the relationship is prematurely dissolved, even involving high switching costs if a relationship with a new supplier needs to be established (Krause, 1999; Giunipero *et al.*, 2005; Swink and Zsidisin, 2006). Furthermore, the firm's dependence on supplier increases as a result of the large quantity of items provided by that supplier (Giunipero *et al.*, 2005); as a consequence, the negotiation power of the buying company can be reduced, causing a higher opportunistic behavior risk of the supplier (Bensaou and Anderson, 1999; Hallikas *et al.*, 2005; Lee *et al.*, 2009). The awareness of this possible risk affects the willingness to share information, lowering the level of transparency and coordination between companies.

The causal loop diagram in Figure 3.2 depicts the impacts of flexibility strategies as emerged from the literature. As done for the redundancy, both balanced and reinforced loops (then described in Table 3.3) have been identified and the goal-gap formulation has been used for the cash flow variable.

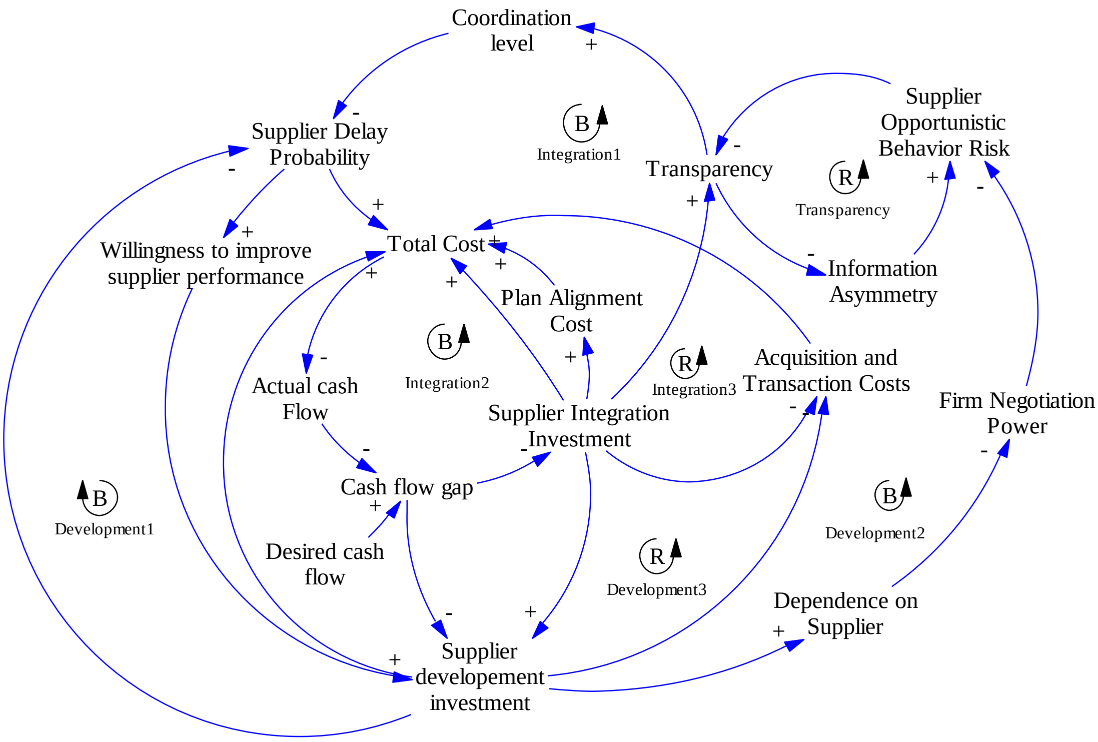

Figure 3.2 - Supply flexibility strategies

Loop Name	Type of loop	Description	References
Development1	Balanced	In case the supplier delay likelihood increases, the willingness (or sometimes the need) to improve supplier performance increases as well. This leads to carry out investments in supplier development aiming at reducing the probability of delays of suppliers.	Hartley and Choi (1996) Krause(1997) Krause *et al.* (1998) Krause (1999) Zsidisin and Ellram (2003) Humpreys *et al.* (2004) Carr and Kaynak (2007) Stevenson and Spring (2007)
Development2	Reinforced	Making investments in supplier development increases the dependence on supplier, decreasing the firm negotiation power and, then, increasing the likelihood of supplier opportunistic behavior. Consequently, the coordination level decreases as a result of lower transparency, raising the delay	Bensaou and Anderson (1999) Giunipero *et al.* (2005) Hallikas *et al.* (2005) Swink and Zsidisin (2006) Lee *et al.* (2009)

Loop Name	Type of loop	Description	References
		probability and the consequent willingness to improve supplier performance. As a result, supplier development investment will be favoured.	
Development3	Reinforced	Increasing cash flow increases the chance to make investments in supplier development and, thus, decrease transaction and acquisition costs which in turn reduce the total cost.	Dyer (1997), Krause (1999) Swink and Zsidisin (2006) Modi and Mabert (2007)
Integration1	Reinforced	Making integration investments increases the transparency and the coordination between firms, reducing the probability of delays of suppliers. Decreasing the delay probability, the total cost will decrease as well, raising the actual cash flow and increasing the availability to make new investment in supplier integration.	Bensaou and Anderson (1999) Christopher and Lee (2004) Tang (2006a) Modi and Mabert (2007) Stevenson and Spring (2007) Wilson (2007) Joshi (2009) Oke and Gopalakrishnan (2009) Stecke and Kumar (2009)
Integration2	Balanced	Increasing cash flow increases the chance to make investments in integration and, then, increase plan alignment costs due to the need of coordination that can increase the response times and the human capital requirements.	Das *et al.*(2006)
Integration3	Reinforced	Increasing cash flow increases the chance to make investments in integration and, then, decrease transaction and acquisition costs.	Das *et al.* (2006) Burke *et al.* (2007) Costantino and Pellegrino (2010)
Transparency	Reinforced	Increasing transparency through supplier development investments decreases information asymmetry between buyer and supplier and, then, its opportunistic behavior risk.	Modi and Mabert (2007)

Table 3.3 - Description of the loops related to flexibility strategies

External factors affecting supply strategy decisions

Flexibility strategies generally require more substantial and long-term investments than those strategies based on redundancy. Their real outcome is also affected by a series of external factors which could act as enablers or inhibitors. From the analysis of the relevant literature, these main factors can be divided in three main groups, namely product-related, market-related and partner-related (Leeuw and Fransoo, 2009), as summarized in Table 3.4.

Group of factor	Factor	References
Product-related	Item impact on profitability	Kraljic (1983) Cannon and Perreault (1999) Krause (1999) Handfield *et al.* (2000) Pyke and Johnson (2003) Modi and Mabert, (2006) Leeuw and Fransoo (2009)
Product-related	Customization level	Bensaou and Anderson (1999) Leeuw and Fransoo (2009)
Product-related	Security need	Giunipero *et al.* (2005)
Market-related	Technological level and technology pace	Kraljic (1983) Bensaou and Anderson (1999) Giunipero *et al.* (2005) Hallikas *et al.* (2004), Lee *et al.* (2009)
Market-related	Market uncertainty	Kraljic (1983) Cannon *et al.* (1999) Pyke and Johnson (2003) Leeuw and Fransoo (2009)
Partner related	Supplier capability and importance	Chiesa and Manzini (1998) Bensaou and Anderson (1999) Krause (1999) Humphreys *at al.* (2004) Leeuw and Fransoo (2009)
Partner related	Effective communication	Newman and Rhee, (1990) Krause and Ellram (1997) Krause (1999) Narasimhan *et al.* (2008)
Partner related	Trust in supplier	Handfield *et al.* (2000) Humphreys *at al.* (2004) Leeuw and Fransoo (2009)
Partner related	Top management support	Handfield *et al.* (2000) Watts and Hahn, 1993) Krause (1999) Humphreys *et al.* (2004)

Table 3.4 – External factors in investment decision

Product-related factors: establishing a close relationship and, eventually, investing in suppliers depends on the characteristics of the supplied item. Kraljic (1983) stated that a critical factor that should be considered in the decision making is the strategic importance of the purchasing items in terms of the value added by a product line, the percentage of raw material over the total cost, their impact on profitability and so on. More recently, also other authors demonstrated the relevance of product volume and criticality on investment decision (Krause, 1999; Cannon and Perrault, 1999; Handfield *et al.*, 2000; Pyke and Johnson, 2003; Modi and Mabert, 2006; Leeuw and Fransoo, 2009). Among them, Handfield *et al.* (2000) proposed a process map for supplier development investment and suggested to focus on suppliers that provide strategic items in order to define which ones to develop. Referencing to the Kraljic portfolio matrix, these are the items characterized by high-volume purchases and a high market risk. In addition, Bensaou and Anderson (1999) and Leeuw and Fransoo (2009) maintained that the more customized is a product, the more is the willingness of the buying firm to make transaction-specific investment. Finally, Giunipero *et al.* (2005) added also the security need of the specific item, arguing that those suppliers that provide products that have high security requirements, require a more extensive risk management.

Market-related factors: the external environment plays an important role in defining the more suitable strategy. Kraljic (1983) recommended to establish closer relationships with the suppliers in highly risky markets, where the level of supply risk depends, among others, on supply scarcity and entry barriers. Another critical factor is the technological level of the market: in general the higher is the technological level and the pace of technology the closer should be the relationships (Bensaou and Anderson, 1999; Giunipero *et al.*, 2005; Hallikas *et al.*, 2004). In this context, Lee *et al.* (2009) specified that technology change leads to specific investments in supplier only if it is “competence-enhancing”, namely if skills and knowledge required to explore it are built on the existing ones. On the contrary, if the change is “competence-destroying’’, the relationship with the related suppliers may be preferably short-term based because the buying firm desires a flexibility in changing suppliers more easily. The uncertainty of the market is also considered a driver of investment decisions and close collaboration in a supply chain under conditions of uncertainty is generally perceived as beneficial. In general terms, uncertainty arises from both the downstream and upstream side of the supply chain due to yield uncertainty, supply lead time uncertainty, short product lifecycle, lumpiness on customer demand and market growth (Cannon and Perrault, 1999; Pyke and Johnson, 2003; Leeuw and Fransoo, 2009).

Partner-related factors: this group comprises all the factors related to the perception of the buying firm toward the supplier in terms of supplier capability and importance, sharing of the same objectives and level of trust (Bensaou and Anderson, 1999; Handfield *et al.*, 2000; Humphreys *at al.*, 2004; Leeuw and Fransoo, 2009). Regarding capabilities, these consist of familiarity of a firm with technology, knowledge and competencies (Chiesa and Manzini, 1998) or technological and design capabilities. As emphasized by the literature, one of the most critical aspects to achieve stable relationships and effective investments is the communication level and the information sharing between a buyer and a supplier (Newman and Rhee, 1990; Krause and Ellram, 1997; Krause, 1999; Narasimhan *et al.*, 2008). In particular, Handfield *et al.* (2000) considered the unwillingness to share information and the lack of trust as pitfalls that can turn the supplier development into a unsuccessful project. Also the involvement of the buyer's top management is considered a success factor in the strategy definition and the achievement of results (Watts and Hahn, 1993; Krause, 1999; Handfield *et al.*, 2000; Humphreys *et al.*, 2004).

Figure 3.3 provides an overall view of the causal loop diagrams including the main factor described above, resulting from the extensive analysis carried out in this chapter. In particular, it shows the main loops related to the impact of supply flexibility and redundancy strategies – synthetically referred to as "Buffer size" – on the performance of a company and the influences of the above mentioned external factors in the decision making process. In order to simplify the overall model, some loops and variables have been grouped together; this is, for example, the case of supplier integration and supplier development investment variables, which have been grouped under the variable “Flexibility Investments”.

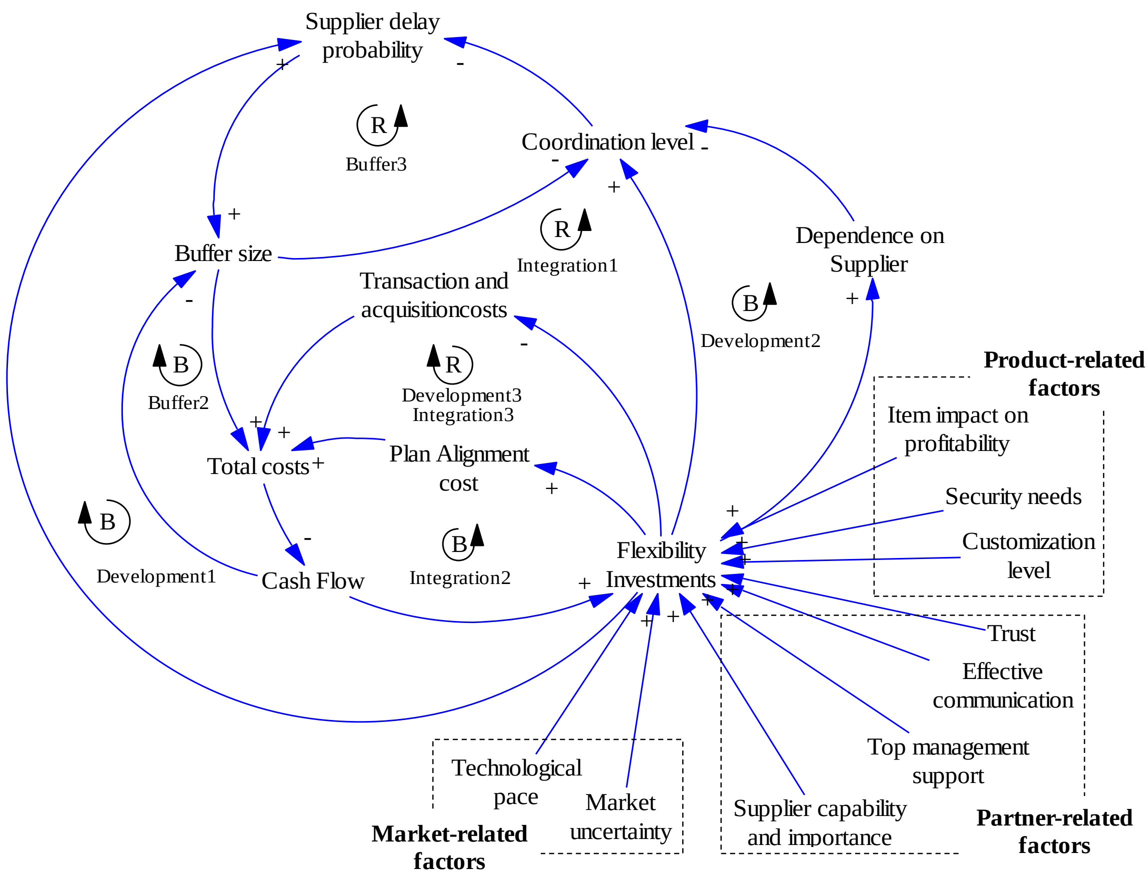

Figure 3.3 - The overall System Thinking model

3.3 Conclusion

Referring to the main objective of building a resilient supply process, the systemic approach adopted in this chapter allowed highlighting the relationships between the two main risk management strategies: redundancy and supply flexibility. The proposed systemic model takes into account financial and non-financial aspects and identify both direct and indirect relationships among variables in the system made up of the buying company and its supplier.

However, even though several studies have theoretically proved the effectiveness of supply flexibility and redundancy practices, researches should also be directed to a quantitative evaluation of the real impact of these practices, shifting from the world of the theorist into the world of the practitioner. In this sense, in the next chapter, starting from this Systems Thinking model, a two stage mixed-integer stochastic programming model is defined in order to quantitatively support supply tactical planning considering supply risk.

4. Supply risk management strategies selection

The qualitative nature of the model presented in the previous chapter can only support the interpretation of cause-effect relations, but cannot effectively support quantitative decision making processes. For this reason, a quantitative model representing the core part of the system thinking model has been developed and presented in this chapter along with a procedure to build experiments and a analyze results.

4.1 Stochastic model: problem description

Problem Description

Within a supply chain, suppliers play a key role for the success of a focal company since their selection influences costs, profit margins, component quality and timely delivery. In order to choose the right suppliers, a company has to define a *sourcing strategy*, characterized by three key decisions (Burke *et al.*, 2007):

- A criterion for establishing a *supply base*, composed by all the suppliers that meet the quality, delivery, and other objectives of the buying company. Scoring models which rank each supplier in terms of objectives are typically used to evaluate suppliers for inclusion in the base.
- A criterion for selecting suppliers (a subset of the base) who will actually receive an order from the company. Generally, not all suppliers in the supply base will receive an order; hence, from the approved supply base, a specific subset of suppliers which will actually receive an order to fulfill the demand for a specific product must be determined. Dominant industry practice appears to base this decision primarily on cost considerations.
- The quantity of goods to order from each selected supplier. Once the selected set of suppliers (a subset of the base) is determined, the firm must allocate product requirements among them. While the supplier's price quote is important, for the allocation decision other factors such as supplier yields (in terms of percentage of ‘‘good’’ units), delivery reliability, order quantity policies, and transportation costs are typically considered.

Focus of this work is on the latter two decisions about *supplier selection* (i.e. the selection of suppliers among the supply base to which place orders) and *quantity allocation* (i.e. the size of the orders). Hence, we assume that the firm has already established an adequate supply base.

As seen in the previous chapter, this thesis and the following quantitative model analyze the convenience to make investment to improve supply flexibility. The literature review suggests that these investments in supplier make sense only in case of high supply risk, high item profitability impact, and high importance of the supplier. For this reason, the considered supplied items cannot be commodities but should be some custom products. Dealing with customized products means that the characteristics of the specific item are not easy to find on the market and then the suppliers are not easy to substitute. Consequently assuming that the supply base is made of 2/3 qualified suppliers can be appropriate.

Since the supplied items are supposed to have a relevant impact on the final product, frameworks agreements between buying company and the selected supplier(s) are usually signed. The purpose of a framework agreement is to establish the terms governing contracts to be awarded during a given period, in particular with regard to price and quantity. In other words, a framework agreement is a general term for agreements with providers which set out terms and conditions under which specific purchases (call-offs) can be made throughout the term of the agreement (Office of Government Commerce, 2006). Through the framework agreement, the buying company and the supplier define a quantity X (*committed* or *contracted quantity*) that should be ordered over the entire planning horizon at a given unit cost c. Once the agreement is in place, in each time bucket of the horizon the buying company will order (call-offs) a quantity x coherent with its specific and contingent needs (thus, even null orders are allowed in some periods). The company should carefully determine contracts and quantities, and rely on spot contracts to cover potential lacks of materials from contracted suppliers.

As discussed in the previous chapter, when a company finds its suppliers lacking in performance, it can help them to improve their capabilities (Krause, 1997; Modi and Mabert, 2007). Buying firms that encounter shortcomings in supplier performance and/or capabilities have several alternatives:

- invest time and resources to increase performance and flexibility of their present suppliers (supply flexibility practices);
- keep buffers, in terms of inventory, time or capacity (this last comprises also having multiple supplier);
- manufacture the purchased item in-house.

Since supply flexibility investment can be a strategic weapon for the buying firm, this work focuses on the combination of the first and the second option, considering the possibility for the buying firm to invest in the supplier integration and/or development, in order to reduce the disruption likelihood. Clearly, an investment makes sense only for those suppliers that have a framework agreement in place. It is implicitly assumed that either the company has time to implement the investments in the suppliers or the time required to implement the investment is short.

The resulting classification of suppliers is depicted in Figure 4.1.

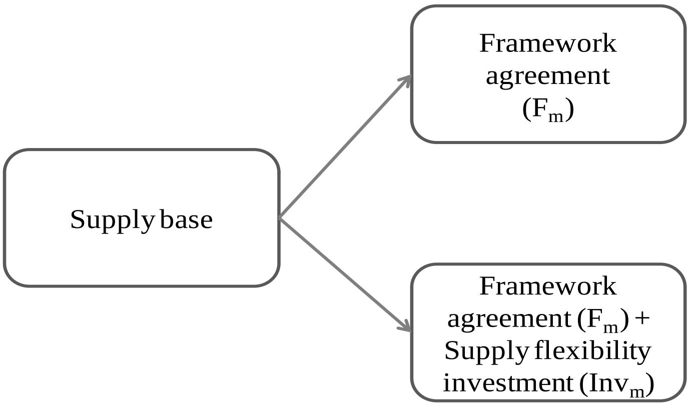

Figure 4.1 – Supplier classification

In order to define the quantity to allocate to each supplier (that is, the actual size of the orders), it is important to define how to order the call-off quantities contracted with each supplier. Considering a multi-period planning horizon, there are two possible ways to deal with this problem:

1. An extremely simplistic approach that uniformly spreads the committed quantity X_m contracted with supplier m in equal parts just dividing the contracted quantity by the number of planning periods T, that is:

$$q_{mt} = \frac{X_m}{T} \quad \forall m \in M \tag{1}$$

2. A more realistic approach that explicitly considers the stock holding and backlog cost and the possible demand distribution over the planning periods.

This work considers this second option, since it leads to a more realistic problem and also includes option 1.

Hence, in the following formulation a single-product/multi-period problem is presented.

The Core Model

A decision maker who comes to define the most suitable supply risk strategy faces the problem described above: so, given a supply base available, he/she has to decide the buffer size and whether to sign a framework agreement with one or more suppliers or invest in some supply flexibility activities. During this decision making process, advantages and disadvantages of all possible strategies should be analyzed as well as the interrelationships among the variables determining system behavior. In other words, the relationships described in the System Thinking model in Figure 3.3

should be deeply analyzed. In order to define a quantitative model supporting the decision maker, the more quantifiable relationships and loops of the general ST model are considered and an application of stochastic programming is proposed in order to identify the sourcing strategy that minimizes the total cost, given supplier delay and loss probabilities and different possible investments in suppliers. The buffers analyzed are multiple suppliers, time and inventory, purposely omitting the internal capacity buffer.

Regarding the "quantifiable" ST model the loops shown in Figure 4.2 describe the following concepts: to face with supplier delay the buying company should increase the buffer sizes (in this case inventory, time or the number of suppliers) to reduce losses (Buffer1), but raising the buffer and total costs (Buffer3). Nevertheless, to avoid excessive buffers and costs, the firm can make supply flexibility investment in order to decrease the production cost because of scale economies (Integration3 and Development3) and reduce supplier delay and loss probabilities (Development1 and Integration1). In fact if the company decides make an investment in a certain supplier the acquisition cost will be reduced because of quantity discounts and the supplier will become more reliable and its delay and default probabilities will decrease of a fixed percentage. Despite that, supply flexibility investment entails other costs, such as plan alignment cost and the pure cost of the investment (Integration2).

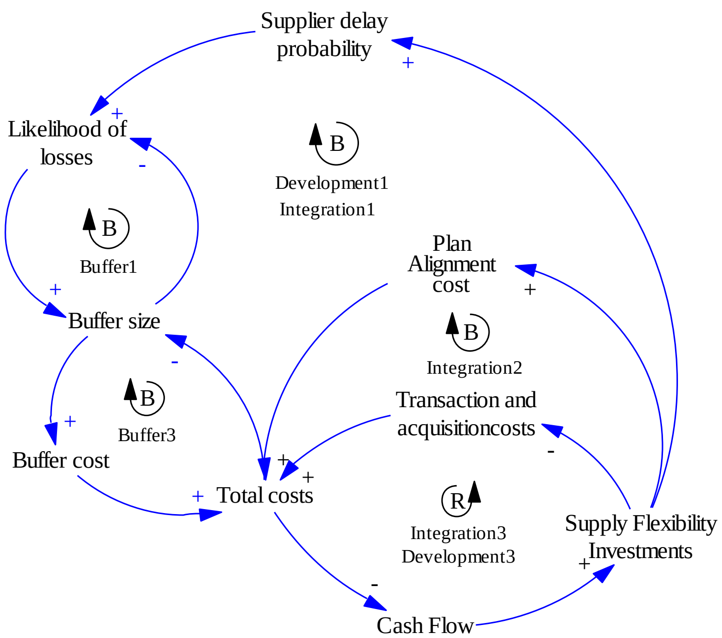

Figure 4.2 - The core ST model

Starting from this quantifiable System Thinking model, the stochastic programming formulation of the problem is introduced in the next section.

4.2 Stochastic model: problem formulation

The qualitative model presented in Figure 4.2 has been translated in a two stage mixed-integer stochastic programming model (Birge & Louveaux 1997).

In a two-stage stochastic optimization approach, the uncertain parameters are considered as random variables with an associated probability distribution and the decision variables are classified into two stages. The first-stage variables correspond to those decisions that need to be made prior to the realization of the uncertainty. The second-stage or recourse variables correspond to those decisions made after the uncertainty is unveiled. After the first-stage decisions are taken and the random events realized, the second-stage decisions are subjected to the restrictions imposed by the second-stage problem. Due to the stochastic nature of the performance associated with the second-stage decisions, the objective function, traditionally, consists of the sum of the first-stage performance measure and the expected second-stage performance.

Summarizing the problem description, this model supports the tactical planning of a buying company that has to define the long/medium term strategy (or mix of strategies) to supply customized products selecting from a small supply base made of 2/3 suppliers and considering the impact of possible risky events that could affect the inbound flow. In particular, it considers only the risks that affect the incoming product availability and delivery timeliness, while purposely neglects those ones that cause uncertainty in terms of the price to be paid for inbound supplies, such as price volatility and currency rate fluctuation.

As previously mentioned, the main consequences of a supply risk occurrence can be classified as follows:

- *Delay*: supplier delivers late the entire quantity ordered.
- *Short-shipment*: supplier delivers on time only a portion of the order and the remaining quantity is delivered at a later time.
- *No shipment at all*: all the quantity ordered is lost and no more order can be placed to this supplier because it does not provide supply anymore. There can be several reasons for this, such as natural disaster, going out of business,

being bought out by another firm, changing the direction of its business and customer market, or determining that the customer is no longer profitable.

This classification contemplates also quality problems and wrong part deliveries. In fact, both cases require supplier intervention in order to repair or substitute the defective/wrong products and this can result in a delay in the final delivery.

Thus, more specifically, considering these risk occurrences and an uncertain demand, the objective of this model is (i) to define the optimal number of suppliers to deal with among a supply base composed by M suppliers, (ii) select the best strategy (or mix of strategy) to be implemented (in terms of redundancy practices and flexibility investment) and (iii) allocate the needed quantity to the selected supplier(s) in order to negotiate a framework agreement.

This model assumes a planning horizon of one/two year(s) and a time bucket of one week. Even if for tactical planning a weekly time bucket can be considered too small, the effect of delay is better shown using the week as time bucket. For example if the lead time is 2 week, having a delay of 1 week can be relevant for the buying company; considering a monthly time bucket, if the supplier delivered a week later it would not come out as delay.

As already mentioned, the available medium/long term strategies are:

- Sign a framework agreement with supplier: this means that supplier and company define the yearly quantity that should be ordered.
- Making supplier investment to increase supplier performance: decrease delay probability and supplier loss probability
- The company decides to manufacture the purchased product in house (all or a partial quantity).

Uncertain parameters

On time and completeness of supplier delivery

In each time bucket of each scenario, the supplier should deliver the entire order placed by the firm *LT* periods before (where *LT* is the lead time) or only a portion of that order, depending on the realization of the "on time delivery uncertainty". To do so a parameter $\delta_{mkt} \in [0 ; 1]$, that represents the on-time delivery of the supplier and can assume different values with different probabilities, is defined. If this value is 1 then the supplier delivers all the ordered quantity on time, otherwise if it is less than

1 then the supplier delivers δ_{mkt} % of the order. For the sake of simplicity δ_{mkt} can be reduced to a discrete set considering only a finite number of values that this parameter can assume: for example it can be 1, 0,75, 0,5 and 0 with different probabilities (depending on the history of this supplier).

If in period *t* the supplier delivers, for example, only the 50% of the quantity ordered, then in period *t+1* the supplier will deliver the quantity ordered for the period *t+1* plus the remaining quantity of the period *t* multiplied by the parameter δ_{mkt+1} (unless it fails in the meanwhile). The following example can better clarify the situation:

Period	Quantity ordered for this period	Quantity remaining from the previous period	δ_{mkt}	Quantity delivered
t	10	0	0,5	5
t+1	20	5	1	(20+5)*1=25

or alternatively:

Period	Quantity ordered for this period	Quantity remaining from the previous period	δ_{mkt}	Quantity delivered
t	10	0	0,5	5
t+1	20	5	0,5	(20+5)*0,5=12

A further assumption is that the quantities ordered by the buying company are based on traditional demand and it is not put on allocation with its supplier(s), otherwise the purchasing firm, knowing it is being put on allocation, may inflate their orders.

Loss of supplier

In each period of each scenario, each supplier has a given default probability, potentially leading the company to face a reduced supply base. If this happens, all the quantity ordered to the defaulted supplier will be lost and no more order can be placed to that supplier. To do so a binary parameter $loss_{mkt}$ is defined. This variable represents the occurrence of the loss of the supplier and can assume the value of 0 (no loss in the considered period) o 1 (loss) with a given probability.

The assumption if that there is no forewarning of these possible events, or the switching time is longer than the time notice the firm has from the supplier that is no longer providing product to your firm.

Demand uncertainty

In each period of each scenario there is the realization of the actual demand. Based on this, the quantity ordered in each period will vary. The total quantity ordered during the entire planning horizon must not be too far from the total quantity defined in the first stage (i.e. signed quantity $\pm\ \alpha\%$).

Whether in the period *t* the supplier that was supposed to deliver is late or lost, it is possible to order the missing quantity to another supplier (if there is) requiring a shorter lead time but at a higher price (between 1,5 and 2 times the normal price). In addition, it is assumed that the urgent order is delivered on time with a shorter lead time than the normal one.

Since investment in supplier aims at increasing the supply flexibility and then the ability of the supplier to react to change in demand, it is assumed that if the company makes an investment in a supplier, then the acquisition cost in case of urgent order is lower than in case of no investment.

Problem formulation

The tables below (Table 4.1 and Table 4.2) summarize the variables and the parameters of the model.

Variable	Description	Type
y_m	Supplier with a framework agreement	Binary variable
z_m	Supplier in which to invest	Binary variable
MAKE	Decision to make the product in house	Binary variable
X_m	Total quantity of the framework agreement with supplier *m* that should be ordered during the entire planning horizon	
x_{mkt}	Quantity delivered from the supplier *m* with framework agreement in the scenario *k* in the period *t*	
$xinv_{mkt}$	Quantity delivered from the supplier *m* with investment in the period *t* in the scenario *k*	

Variable	Description	Type
$xmake_{kt}$	Quantity to be produced internally in the period t in the scenario k	
ORD_{mkt}	Quantity ordered from the supplier m with framework agreement in the period t in the scenario k	
$ORDINV_{mkt}$	Quantity ordered from the supplier m with investment in the period t in the scenario k	
$TODEL_{mkt}$	Quantity that must be still delivered by the supplier m with framework agreement at the end of the period t in the scenario k	
$TODELINV_{mkt}$	Quantity that must be still delivered by the supplier m with investment at the end of the period t in the scenario k	
$x^{urg}{}_{mkt}$	Urgent quantity ordered to the supplier m with framework agreement in the period t in the scenario k	
$xinv^{urg}{}_{mkt}$	Urgent quantity ordered to the supplier m with investment in the period t in the scenario k	
I_{kt}	Inventory level in the period t in the scenario k	
w_{kt}	Inventory/backlog costs in the period t in the scenario k	

Table 4.1 - List of variables

Parameter	Description	Type
F_m	Fixed cost of a framework agreement with supplier m	
INV_m	Investment cost in supplier m	
INVMAKE	Investment cost to produce the product in house	
LT_m	lead time of the supplier m (decided by the buying company based on supplier indication/history, that comprises also the safety lead time)	
LT_{make}	Lead time for internal production	
LT_{urg}	Lead time in case of urgent order	
CAP_m	Capacity of the supplier m	
CAPINT	Internal capacity	
c_m	Acquisition cost from the supplier m with framework agreement	
$cinv_m$	Acquisition cost from the supplier m with investment	
cmake	Unitary production cost	
urg_m	Increase of acquisition cost from the	

Parameter	Description	Type
	supplier m because of urgent order	
$urginv_m$	Increase of acquisition cost from the supplier m with investment because of urgent order	
h	Holding cost	
bk	Backlog cost	
δ_{mkt}	Realization of delay of the supplier m with framework agreement in the period t in the scenario k	It can assume a finite number of values between 0 and 1 with a given probability. These values represent the delivered portion of the order and can be: 0, 0,5, 0,75, 1 (δ_{mkt}=1 means on-time delivery of the order), with probability Δ_{1m}, Δ_{2m}, Δ_{3m}, Δ_{4m} respectively, where $\Delta_{1m}+\Delta_{2m}+\Delta_{3m}+\Delta_{4m}=1$
θ_{mkt}	Realization of delay of the supplier m with investment in the period t in the scenario k	It can assume a finite number of values between 0 and 1 with a given probability. These values represent the delivered portion of the order and can be: 0, 0,5, 0,75, 1 (δ_{mkt}=1 means on-time delivery of the order), with probability Θ_{1m}, Θ_{2m}, Θ_{3m}, Θ_{4m} respectively, where $\Theta_{1m}+\Theta_{2m}+\Theta_{3m}+\Theta_{4m}=1$
$loss_{mkt}$	Realization of loss of the supplier m in the period t in the scenario k	It can assume the values 1 or 0 with probability $LOSS_m$ and (1- $LOSS_m$) respectively. If it is 1, the supplier m is lost in the period t in the scenario k
$lossinv_{mkt}$	Realization of loss of the supplier m in the period t in the scenario k	It can assume the values 1 or 0 with probability $LOSSINV_m$ and (1- $LOSSINV_m$) respectively. If it is 1, the supplier m is lost in the period t in the scenario k
d_{kt}	Actual demand of the period t in the scenario k	
B	Big number	
p_k	Probability of scenario k	
α	Possible variation of the total quantity ordered during the entire planning horizon from the quantity X_m	

Table 4.2 - List of parameters

First stage

The two-stage stochastic problem (SP) formulation of the problem discussed so far is presented hereafter. The SP model incorporates uncertainties by the inclusion of the recourse problem and probabilistic scenarios for demand and suppliers' reliability.

Before the beginning of the planning horizon and then before the uncertainties are discerned, the buying company has to define whether to sign a framework agreement with one or more suppliers, to invest in one or more suppliers in order to increase their flexibility and subsequently their reliability (decreasing delay and supplier loss probability), or to manufacture all or a partial quantity of the product in house. In the first two cases the buying company should also determine the total quantity that should be ordered during the entire planning horizon from each selected supplier.

As stated before, if the company decides to invest in a supplier, it also signs a framework agreement with that supplier. Thus, let y_m be the binary variable representing the supplier *m* with which a framework agreement is signed and z_m the variable representing a supplier that benefits from an investment. Signing an agreement with a supplier implies a fixed cost F_m, while an average investment is valued Inv_m (clearly, $Inv_m > F_m$ since it includes the framework agreement cost). In the same way, *INVMAKE* represents the investment needed to manufacture the product in house and *MAKE* is the binary variable indicating that decision.

$$Min\ z = \sum_m (INV_m \cdot z_m + F_m \cdot y_m) + INVMAKE \cdot MAKE + E[G(Z,Y,\xi)] \qquad (1)$$

$$z_m + y_m \leq 1 \qquad \forall m \qquad (2)$$

$$z_m \leq B \cdot MAKE \qquad \forall m \qquad (3)$$

$$y_m \leq B \cdot MAKE \qquad \forall m \qquad (4)$$

$$X_m \leq (z_m + y_m) \cdot B \qquad \forall m \qquad (5)$$

$$X_m \geq 0 \qquad \forall m \qquad (6)$$

$$y_m, z_m\ bin \qquad \forall m \qquad (7)$$

where *Y* and *Z* represent the decisions about "contracted" and "invested" suppliers, respectively, and ξ represents the scenarios.

The objective function (1) encompasses all the relevant costs in this stage, that are the supplier investment costs, the framework agreement costs, the in house production investment cost and the expected cost E of the second stage decisions. Constraint set (2) enforces the fact that a supplier m can either benefit from an investment, sign a framework agreement or none of them.

For each contracted/invested supplier the size of the framework agreement X_m is defined before the actual requirements are known (constraint set (5), where B is a "big number"). For the sake of clarity, it is assumed that the size of the framework agreement does not influence the unit cost c_m that only depends on the supplier, even though this assumption can be removed by considering, for example, quantity discounts related to X_m.

It is worth noticing that the cost of the committed quantity X_m does not appear in the objective function of the first stage, since it will manifest itself along the planning horizon, depending upon the realization of the demand in the second stage and the related orders.

Constraints set (6) and (7) are the non negativity and binary constraints.

Second stage

The main objective of this second stage is not to define the right quantity to be ordered each time (this would be the aim of a following operational planning), but is to define the theoretical optimal quantity to be ordered in each scenario in order to calculate the expected cost allowing to select the best strategy and the contracted quantity.

A basic assumption of the model is that the investment in a supplier m leads to a reduction of both loss and delay probabilities, while these values are higher in case of no investment. All these probabilities are used in the definition of the scenarios set Ξ used in the second stage problem, each of them has a probability p_k to occur.

Therefore, for a choice represented by a couple (Y, Z) and any scenario $\xi \in \Xi$ (where $|\Xi| = K$) the following second stage problem should be solved with the aim of defining the actual orders (call-offs) to place in each period t to each supplier (ORD_{mkt} and $x^{urg}{}_{mkt}$ to "contracted" suppliers and $ORDINV_{mkt}$ and $xinv^{urg}{}_{mkt}$ to "invested" suppliers) or the quantity internally produced ($xmake_{kt}$). This second stage represents those decisions that should be made during the planning horizon when the uncertainties (actual demand, on time and completeness of deliveries, and supplier loss) are unveiled.

$$\min \sum_{kt} p_k \cdot w_{kt} + \sum_{m,k,t} p_k \cdot (x_{mkt} \cdot c_m + xinv_{mkt} \cdot cinv_m) + \sum_{k,t} p_k \cdot xmake_{kt} \cdot cmake + \sum_{m,k,t} p_k \cdot (x_{mkt}^{urg} \cdot c_m \cdot (1 + urg_m) + xinv_{mkt}^{urg} \cdot cinv_m \cdot (1 + urginv_m)) \quad (8)$$

$$w_{kt} \geq h \cdot I_{kt} \quad \forall k,t \quad (9)$$

$$w_{kt} \geq -bk \cdot I_{kt} \quad \forall k,t \quad (10)$$

$$x_{mkt} = ORD_{mk(t-LT_m)} \cdot \delta_{mkt} \cdot (1 - loss_{mkt}) + TODEL_{mk(t-1)} \cdot \delta_{mkt} \cdot (1 - loss_{mkt}) \quad \forall m,k,t \quad (11)$$

$$xinv_{mkt} = ORDINV_{mk(t-LT_m)} \cdot \theta_{mkt} \cdot (1 - lossinv_{mkt}) + TODELINV_{mk(t-1)} \cdot \theta_{mkt} \cdot (1 - lossinv_{mkt}) \quad \forall m,k,t \quad (12)$$

$$TODEL_{mkt} = TODEL_{mk(t-1)} + ORD_{mk(t-LT_m)} - x_{mkt} \quad \forall m,k,t \quad (13)$$

$$TODELINV_{mkt} = TODELINV_{mk(t-1)} + ORDINV_{mk(t-LT_m)} - xinv_{mkt} \quad \forall m,k,t \quad (14)$$

$$ORD_{mkt} \leq CAP_{mt} \cdot y_m \cdot (1 - loss_{mk(t-1)}) \quad \forall m,k,t \quad (15)$$

$$ORDINV_{mkt} \leq CAP_m \cdot z_m \cdot (1 - loss_{mk(t-1)}) \quad \forall m,k,t \quad (16)$$

$$xmake_{kt} \leq CAPINT \cdot MAKE \quad \forall k,t \quad (17)$$

$$x_{mkt}^{urg} \leq CAP_m \cdot y_m \cdot (1 - loss_{mk(t-1)}) \cdot int(\delta_{mkt}) \quad \forall m,k,t \quad (18)$$

$$xinv_{mkt}^{urg} \leq CAP_m \cdot z_m \cdot (1 - lossinv_{mk(t-1)}) \cdot int(\theta_{mkt}) \quad \forall m,k,t \quad (19)$$

$$I_{kt} = I_{kt-1} + \sum_m (x_{mkt} + xinv_{mkt}) + xmake_{k(t-LT_{make})} + \sum_m \left(x_{mk(t-1)}^{urg} + xinv_{mk(t-1)}^{urg}\right) - d_{kt} \quad \forall k,t \quad (20)$$

$$\sum_t (ORD_{mkt} + ORDINV_{mkt}) \leq X_m \cdot (1 + \alpha) \quad \forall m,k \quad (21)$$

$$\sum_t (ORD_{mkt} + ORDINV_{mkt}) \geq X_m \cdot (1 - \alpha) \quad \forall m,k \quad (22)$$

$$x_{mkt}, xinv_{mkt}, xmake_{kt}, ORD_{mkt}, ORDINV_{mkt}, TODEL_{mkt}, TODELINV_{mkt}, x_{mkt}^{urg} \geq 0 \quad \forall m,k,t \quad (23)$$

$$xmake_{kt} \geq 0 \qquad \forall k, t \qquad (24)$$

The objective function of the second stage considers acquisition costs from contracted and invested suppliers (c_m and $cinv_m$), the cost of manufacturing the product in house (*cmake*), stock holding/backlog costs (ω_{kt}, expressed by constraint sets (9) and (10), where *h* is the unit holding cost and *bk* the backlog cost) and the increase of acquisition cost in case of urgent orders (that is, urg_m in case of contracted suppliers and $urginv_m$ in case of invested suppliers). In fact, the company can decide to place urgent orders of quantity $x^{urg}{}_{mkt}$ or $xinv^{urg}{}_{mkt}$ to a supplier in the supply base with a framework agreement in place or with investment, respectively. In this case, the acquisition cost increases of a percentage urg_m or $urginv_m$ and, since the contract is cash-based and related to short-term horizon, those orders are assumed to be delivered on time.

Considering supplier lead times, the constraint sets (11) and (12) define the quantity actually delivered from each supplier *m* in the period *t* in the scenario *k* (x_{mkt} and $xinv_{mkt}$), that can differ from the quantity ordered (ORD_{mkt} and $ORDINV_{mkt}$) because of delivery delay and supplier loss.

As already mentioned, the binary parameters $loss_{mkt}$ and $lossinv_{mkt}$ represent the loss occurrence of supplier *m* in period *t* in the scenario *k*, the former in case a framework agreement is signed and the latter in case of supply flexibility. If the supplier *m* is lost in the period *t*, the corresponding binary parameter is equal to 1 and no more orders can be placed to this supplier in following periods (to do so, the binary parameter value are forced to be equal to 1 from the time when the loss occurs until the end of the planning horizon). In the same way, delay occurrence is expressed setting the two parameters δ_{mkt} (in case of framework agreement) and θ_{mkt} (in case of investment in supplier) equal to 0, 0,5, or 0,75 if the supplier *m* delays all, 50% or 25% of the ordered quantity, respectively; contrarily, if the supplier *m* is not late and delivers all the quantity on time, these parameters are set equal to1. Similarly, constraint sets (13) and (14) define the quantity that should be still delivered from the supplier *m* in period *t* in the scenario *k*.

The quantities ordered to each supplier (ORD_{mkt} and $ORDINV_{mkt}$ with agreed lead time, and $x^{urg}{}_{mkt}$ and $xinv^{urg}{}_{mkt}$ urgently) and the quantity manufactured in house

($xmake_{kt}$) are defined in the constraints sets from (15) to (19). These quantities are subjected to internal capacity availability (*CAPINT*), supplier capacity availability (CAP_{mt}) and supplier operating business ($loss_{mkt}$ and $lossinv_{mkt}$).

The inventory levels I_{kt} in each time bucket is determined by constraint set (20). It accounts for the actual quantities delivered in each period and for the quantity produced internally to the company. The demand in each time bucket of each scenario d_{kt} is considered within this constraint set.

Constraint sets (21) and (22) assure that the total quantity ordered during the planning horizon and the total quantity of the framework agreement should not differ of a percentage greater than α%.

Finally, constraints set (24) are the usual not negativity constraints of the variables involved in the problem.

4.3 Design of Experiments (DOE)

Once defined the stochastic model, the main objective of the phase 4 of this methodology, is not to get a single solution, but rather to analyze the model results in order to identify the factors that mostly impact strategy selection.

To this purpose, this research suggests to apply Design of Experiments (DOE) techniques to build a set of experiments in order to assess the strategy selection process and to be able to discern the impact of different input variables on the stochastic model outcomes.

DOE is a powerful technique used in the field of engineering and science for exploring new processes, gaining increased knowledge of existing processes and optimize them. Typical application examples are the production of wafers in the electronics industry, the manufacturing of engines in the car industry, and the synthesis of compounds in the pharmaceutical industry. Another main type of DOE application is the optimization of analytical instruments (Ericksson *et al.*, 2000).

In general, Design of Experiments refers to the process of planning, designing and analyzing the experiment so that valid conclusions can be drawn effectively and efficiently. In order to draw statistically sound conclusions it is necessary to integrate simple and powerful statistical methods into the experimental design methodology.

To analyze experiments, the DOE methodology suggests the following procedure (Antony, 2003):

1. *Cause and effects analysis*: catalog of all possible variables that affect the process and all possible responses.
2. *Document the process.*
3. *Write a detailed problem statement*: description of responses to be studied and their goals or constraints, an estimate of the smallest practically significant change in the response that the experimenter is expected to detect for the purpose of sample-size calculation, presentation of any relevant theory or physical model for the problem that can provide additional insights, description of relevant historical data or other experiments studying the same problem, list of possible experimental variables, list of expected possible interactions, citation of evidence that the process is in control, estimates of personnel time and material required, assumptions.
4. *Preliminary experimentation* (10-15% of total resources allocated): small set of runs to investigate one variable or procedure at a time. The purpose is to gain experience with new experimental variables, confirm that there are not unidentified variables, confirm that the classification of each variables as fixed, experimental or uncontrolled is appropriate, identify safe upper and lower bounds for experimental variables, investigate the need for an intermediate level of a quantitative variable to detect or quantify curvature in response, confirm that the procedures are accurate, confirm that the operators and equipment function correctly, estimate the standard deviation of the response so that a sample-size calculation can be done.
5. *Design the experiment*: the goal is to extract an appropriate model from an experimental set.
6. *Sample size, randomization, and blocking*: in order to eliminate noise factors and unwanted sources of variability, it is important that the input factors and the experiments order are random (randomization) and that the observations are collected under the same experimental conditions (blocking).
7. *Run the experiment.*
8. *Analyze the data.*
9. *Interpret the results.*

10. *Run a confirmation experiment*: the purpose is to confirm the validity of the model. It may be small, perhaps consisting of just a single crucial condition, but it should address the most important claims or conclusions. If conclusions are robust, then the confirmation experiment will successfully reproduce the desired results.
11. *Report the experiment.*

In this thesis the process under evaluation is supply strategy selection, that is performed through the application of a stochastic model. Therefore, since the output of this process depends on a mathematical model, where external noise factors do not exist, a slightly different application of the described DOE methodology is proposed. In fact, since this research is not dealing with manufacturing or similar experiments, some recommended actions and steps are not required and then skipped. For example, preliminary experimentation, randomization and blocking can be avoided without compromise the analysis.

Matching the research features and the DOE procedure, the main steps followed to design and conduct experiments are reported below.

Cause and effects analysis

As a result of the literature review and the considerations reported in the previous chapters, the input factors analyzed are:

- the cost of an investment to improve supply flexibility;
- the reduction of supply disruption probability due to this investment;
- the holding cost;
- the backlog cost;
- the lead time of each supplier.

The dependent/outcome variables are:

- the number of suppliers with which sign a framework agreement;
- the number of supplier in which to invest;
- the total cost;
- the inventory cost.

Document the process

The analyzed process is the selection of strategies to deal with supply risk. The main possible occurrences of this kind of risk are: delivery delay, short-shipment and not shipment at all (loss of supplier). Each of these has a given probability to occur.

The available strategies are limiting the impact of a risk occurrence on the buying company, through the adoption of redundancy practices (especially in terms of inventory or time buffer), or undertaking actions to reduce the occurrence probability (in terms of increasing supply flexibility, through framework agreements or supplier development investments).

Design the experiment

The main reason why DOE techniques have been chosen is because they enable decision makers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. In this way, it will be possible to evaluate which are the factors an organization should focus on in order to reduce the cost arising from problems in the supply side.

The most efficient and easy way to identify variable interactions is use the *factorial design* of the experiments**,** where factors are the independent variables that are supposed to have direct or interactive impact on the dependent /outcome variable. To systematically vary experimental factors, a discrete set of levels is assigned to each factor. Factorial designs can be full or fractional.

Full factorial designs are expressed using the notation l^k, where l is the number of levels of each factor investigated and k is the number of factors investigated. This design measures response variable using every combination of the factor levels. It allows to study the effect of a single factor and the effects of interactions between factors on the response variable. A full factorial design for k factors with $l_1, ..., l_k$ levels requires $l_1 \times ... \times l_k$ experimental runs (l^k runs) - one for each combination. Generally, many experiments can be conducted with two-level factors, using two-level designs (expressed using the notation 2^k). In this kind of design, the factor levels are commonly coded as +1 for the higher level, and −1 for the lower level (for a three-level factor, the intermediate value would be coded as 0).

While advantageous for separating individual effects, full factorial designs can make large demands on data collection especially in case of experiments with many factors. For example, a two-level full factorial design with 10 factors requires 2^{10} = 1024 runs. Often, however, individual factors or their interactions have no distinguishable effects on a response. This is especially true in case of higher order interactions. As a result, a well-designed experiment can use fewer runs for estimating model parameters.

To this purpose, *fractional factorial designs* use a fraction of the runs required by full factorial designs. They are expressed using the notation l^{k-p}, where p describes the size of the fraction of the full factorial used. Formally, p is the number of generators, assignments as to which effects or interactions are confounded, i.e., cannot be estimated independently of each other (see below). A design with p such generators is a $1/(l^p)$ fraction of the full factorial design and requires l^{k-p} runs. For example, a 2^{5-2} design is 1/4 of a two level, five factor factorial design. Rather than the 32 runs that would be required for the full 2^5 factorial experiment, this experiment requires only 8 runs (2^3).

As a consequence, a subset of experimental factor combinations is selected based on an evaluation (or assumption) of which factors and interactions have the most significant effects. Once this selection is made, the experimental design must separate these effects. In particular, significant effects should not be confounded, that is, the measurement of one should not depend on the measurement of another.

The term confounding refers to combine influences of two or more factor effects and their interaction effects. In other words, one cannot estimate factor and interaction effects independently. Effects which are confounded are called aliases. For example, consider a 2-level design with two factors (say, factor A and factor B). Two experiments are performed when both factors are at their low level and high level, respectively. The effect of the factor A is the difference between the two experiment outcomes. In the same way, also the effect of the factor B is the difference between the two outcomes. Then, it is not possible to tell if the calculated effect is due to factor A or B, so the effects are confounded.

Design resolution is a summary characteristic of aliasing or confounding patterns. The degree to which the main effects are aliased with the interaction effects (two-factor or higher) is represented by the resolution of the corresponding design and it is a key tool for determining what fractional factorial design will be the best choice.

A design is of resolution R if no x-factor effect is aliased with another effect containing less than the (R-x)-factors. In other words, design resolution identifies the order of confounding of the main effects and their interactions. Obviously, it is preferred that the main effects are not confounded with other main effects.

For designed experiments, the most important fractional designs are those of resolution III, IV, and V:

- *Resolution III designs*: these are designs in which no main effects are confounded with any other main effect, but main effect are confounded with two-factor interactions and two-factor interactions may be confounded with each other.
- *Resolution IV designs*: these are designs in which no main effects are confounded with any other main effect or with any two-factor interactions, but two-factor interaction effects may be confounded with each other.
- *Resolution V designs*: these are designs in which main effects are not confounded with other main effect, two-factor interactions or three-factor interactions; but two-factor interactions are confounded with three-factor interactions.

Resolutions below III are not useful and resolutions above V are wasteful in that they can estimate very high-order interactions which rarely occur in practice.

This concept of confounding effect and resolution will become more clear in the next chapter, where a numerical example is shown.

Run the experiment

Once having defined the higher and lower levels of each input factor, the statistical software Minitab will be used for creating and analyzing fractional factorial designs and the experiments will be carried out.

Analyze the data and interpret the results

With the support of the statistical tool Minitab, the analysis of the results will be carried out. The objective is to understand there are some main or interaction effects that are statistically significant, in order to devise managerial insights.

4.4 Conclusion

In this chapter an optimization model and a method to design the experiments and analyze the results have been proposed in order to quantitatively support risk management strategy selection.

To better clarify how the proposed four-step methodology works and how should be implemented, a use case is reported in the next chapter. In addition a numerical example is provided to allow understanding how DOE methodology should be carried out and the analysis performed.

5. A use case

In order to better understand how the four-step methodology presented in this thesis works, an example of application is provided.

It is assumed that, as a consequence of several problems in the supply of a critical item, a manufacturing company decides to carry out some deeper analysis in order to identify possible actions to avoid additional trouble related to the inbound side. Thus, in the next sections, the four steps of the proposed methodology are illustrated leading the company to the definition of the strategies that minimize supply risk.

5.1 Step 1: Analysis of supply risk

Focusing on the specific critical component and following the list reported in chapter 1 of this thesis, the company analyzes the main supply risk sources. For each risk source, a qualitative score and a source weight have been provided. These scores are based on a scale from 1 to 5, where 1 means low weight importance or low risk while 5 stays for high weight importance or high risk. Table 5.1 shows the scores assigned to item, market and procurement process characteristics. For each class of factors a total score has also been calculated using the weighted mean.

Class	Risk Sources	Weight	Score
Item characteristics	Impact on profitability	5	5
	Nature of product application	1	1
	Complexity of critical material	4	5
	Time specificity of material procurement	5	4
	Total score		**4,4**
Market Characteristics	Global sourcing	3	3
	Market capacity constraints	5	5
	Market prices increases	5	1
	Number of qualified supplier	5	5
	Total score		**3,6**
Procurement process characteristics	Frequency of replacement of critical material supplier	5	1
	Complexity of procurement technology for critical material	1	1
	Total score		**1**

Table 5.1 - Supply risk sources

As emerges from the above table, item characteristics are the more relevant risk sources. In fact, the analyzed item is a critical component for the company and then represents a high source of risk for the company because a late or lost delivery can have detrimental effects.

Regarding market characteristics, the main problem is due to the unavailability of qualified suppliers in the supply market. So far, the company has identified three suppliers, which has already done business with in the past.

On the contrary, procurement process characteristics have not been considered as a relevant source of risk.

Given the criticality associated to the item and the few number of available suppliers, a thorough evaluation of the supply base is required. So, each supplier has been assessed considering its risk. Consequently, scores and weights have been provided as shown in Table 5.2.

Risk Sources	Weight	Score Supplier 1	Score Supplier 2	Score Supplier 3
Capacity constraints	5	1	1	1
Inability to reduce cost	4	2	3	3
Incompatible information system	1	1	1	2
Quality problems	5	3	4	5
Variance of material supply lead-time	1	1	1	1
Unpredictable cycle time	5	3	3	4
Volume and mix requirement changes	5	4	5	5
Delivery frequency of critical material	1	1	1	2
Delay of critical material delivery	5	4	4	5
Total score		**3,1**	**3,6**	**4,4**

Table 5.2 - Supplier Evaluation

At this stage, the acquisition cost has not been taken into account yet, but it will become important in the following strategy selection phase.

As shown in Table 5.2, all the three suppliers have a quite high risk score, meaning that some actions should be undertaken in order to improve the situation and avoid company disruptions.

Based on previous experiences with these suppliers, on available public data and on company knowledge, the main supply risk impacts can be estimated in terms of incomplete delivery probability and supplier loss probability (for example due to default), as suggested in this methodology and depicted in Table 5.3. In this table $\Delta(0)$ is the probability of delivering late all the ordered quantity, while $\Delta(0,5)$ $\Delta(0,75)$ $\Delta(0,1)$ are the probability to deliver on time 50%, 75% and 100% of the quantity, respectively.

Supplier	Δ(0)	Δ(0,5)	Δ(0,75)	Δ(1)	LOSS
sup1	0,03	0,12	0,15	0,7	0,001
sup2	0,05	0,15	0,2	0,6	0,002
sup3	0,1	0,2	0,3	0,4	0,005

Table 5.3 - Supplier delay and loss probability

5.2 Step 2: Evaluation of all the available strategies

As reported in chapter 3, interventions can be done in terms of:

- Redundancy: this strategy can be interpreted as keeping extra inventory or time buffer. In this case time buffer means ordering the product in advance, as considering a longer supplier time.
- Supply flexibility: this strategy consists in making investment in supplier operations in order to reduce the above probability, through performance improvement. In this case, investment can be, for example, increasing information sharing between buyer and supplier, provide training to supplier or exchange personnel. Obviously, these investments will require low implementation time since the following model deals with tactical planning with an horizon of one/two years. More substantial investments can be taken into account modifying the planning horizon of the mathematical model. Probability reduction depends on the amount of the investment and will be considered as a varying input factor.

Once having defined the available strategies, a qualitative assessment of the consequences should be carried out. For this purpose, the System Thinking model reported in chapter 3 can be useful: it can help the buying firm management to better understand causal loops and wide spectrum consequences triggered by some decisions and sometimes underestimated during the decision making process. Usually management is more focused on cost-related aspects and evaluates investments only from financial point of view, through an expected cash flow assessment. On the contrary, this model takes into account also not cost-related features and allows managers to highlight interdependencies among variables also from a more qualitative viewpoint. However, this model does not represent the ultimate tool for making decisions, but should be considered as a synthetic and powerful representation of the different trade-offs emerging during the decision making phase, with strong foundation in supply chain management literature and based on several best practices and case studies. For instance, when considering the possibility to make a supply flexibility investment, the casual loop diagram shows, on the one hand, the direct positive and negative consequences (such as supplier delay, buffer size, total cost reduction, cost increases and supplier opportunistic behavior) and, on the other hand, their indirect effects (i.e. supplier opportunistic behavior rebounds on cash flow and on availability to make further investments in flexibility and in buffer as well). In the same way also redundancy practices can disclose similar trade-offs and ripples that, if not carefully taken into account and appropriately weighted, could negatively affect investments success.

5.3 Step 3: Strategies selection

Once having identified and listed the possible interventions, the next phase of the proposed methodology is to apply the stochastic model and follow the Design of Experiment procedure in order to provide useful insights about strategies selection process. These insights and suggestions come out from the analyses of the impact of some defined input factors on the selected outcome variables.

As reported in the previous chapter, the input factors analyzed, in total seven, are:

- the cost of an investment to improve supply flexibility;
- the reduction of supply disruption probability due to this investment;
- the holding cost;
- the backlog cost;
- the lead time of each supplier (in this case, three supplier).

And the dependent/outcome variables are:

- the number of suppliers with which sign a framework agreement;
- the number of supplier in which to invest;
- the total cost;
- the inventory cost.

The chosen design is the two-level fractional factorial designs with seven input factors.

At this point the company has to quantify the parameters to be used in the stochastic model and, in particular, has to identify two reasonable levels for each input factor. These values will be crucial to devise the strategy (or strategies) to be undertaken.

Thus, in the following Table 5.4, the input data are reported where the variables have the same name of those in the previous chapter used in the stochastic model formulation. The numbers in bold are the input factors that will assume two different levels.

As explained in the next section where the factor combinations are selected, the experiments are run and the results are analyzed and interpreted.

h	bk	p(k)	α	D	Sigma demand
30	**50**	0,01	0,2	100	30

Supplier	LT_m	LT^{urg}	CAP_m
sup1	**2**	1	100000
sup2	**4**	1	100000
sup3	**4**	1	100000

Make	INVMAKE	LT_{make}	CAPINT	cmake
Make	1000000	2	100000	180

Framework Agreement

Supplier	F_m	c_m	urg_m	Δ(0)	Δ(0,5)	Δ(0,75)	Δ(1)	LOSS
sup1	1500	150	0,75	0,03	0,12	0,15	0,7	0,001
sup2	2000	130	0,75	0,05	0,15	0,2	0,6	0,002
sup3	2500	120	0,75	0,1	0,2	0,3	0,4	0,005

Investment

Supplier	j	INV_m	$cinv_m$	$urginv_m$	Prob. Reduction
sup1	**50**	75000	130	0,5	**0,8**
sup2	**50**	100000	120	0,5	**0,8**
sup3	**50**	125000	115	0,5	**0,8**

Supplier	Θ(0)	Θ(0,5)	Θ(0,75)	Θ(1)	LOSSINV
sup1	0,024	0,096	0,12	0,76	0,00025
sup2	0,04	0,12	0,16	0,68	0,0005
sup3	0,08	0,16	0,24	0,52	0,00125

Table 5.4 - Input data

Fractional factorial experiment (7 factors - resolution IV)

As mentioned, the 2-level factors are:

- investment (j)
- probability reduction
- holding cost
- backlog cost
- lead time of each supplier: higher lead time comprises safety lead time

The levels of these factors are the following:

Factor	Name	High level (+1)	Low level (-1)
h	**A**	50	30
bk	**B**	70	50
LT sup1	**C**	4	2
LT sup2	**D**	4	2
LT sup3	**E**	4	2
j	**F**	50	10
Probability Reduction	**G**	0,8	0,5

Table 5.5 - Factor levels

A full two-level factorial experiment with 7 factors would require 2^7=128 runs with different combinations of factors. Because of this high number of runs, a fractional factorial experiment has been selected and, more specifically, a design of resolution IV has been considered (representing 2^{7-2} design). This kind of design requires 2^5=32 runs.

Resolution IV confounds main effects with three factor interactions, and two-factors interactions with other two-factor interactions. Since three-factor interactions and higher-order interactions should be rare, it can be expected to safely recover the main effects; however, the confounding between two-factor interactions can be a problem. In this case, the design of the experiments has been defined using Minitab:

	h	bk	LT sup1	LT sup2	LT sup3	j	Probab. Reduction
RunOrder	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	-1	-1	-1	-1	1	1	-1
2	-1	1	-1	-1	1	-1	1
3	-1	1	-1	1	1	1	-1
4	1	-1	-1	1	-1	1	1
5	-1	1	1	-1	-1	1	-1
6	1	-1	1	1	-1	-1	1
7	-1	1	1	-1	1	1	1
8	-1	1	1	1	1	-1	-1
9	-1	-1	-1	1	-1	-1	-1
10	1	1	1	-1	1	-1	-1
11	1	-1	-1	-1	1	-1	1
12	1	-1	1	-1	1	1	1
13	-1	-1	1	1	-1	1	-1
14	-1	1	-1	1	-1	1	1
15	-1	-1	1	-1	1	-1	-1
16	1	-1	1	1	1	-1	-1
17	1	1	1	1	1	1	1
18	1	-1	-1	1	1	1	-1
19	1	1	1	1	-1	1	-1
20	-1	1	-1	-1	-1	-1	-1
21	-1	-1	1	-1	-1	-1	1
22	-1	-1	-1	1	1	-1	1
23	1	1	-1	1	1	-1	1
24	1	-1	1	-1	-1	1	-1
25	1	1	-1	-1	-1	1	1
26	1	1	-1	1	-1	-1	-1
27	1	1	-1	-1	1	1	-1
28	1	-1	-1	-1	-1	-1	-1
29	1	1	1	-1	-1	-1	1
30	-1	-1	1	1	1	1	1
31	-1	-1	-1	-1	-1	1	1
32	-1	1	1	1	-1	-1	1

Table 5.6 - Design of the experiments

A fractional factorial experiment is generated from a full factorial experiment by choosing an alias structure. The alias structure determines which effects are confounded with each other.

In this case, for example, the seven factor 2^{7-2} can be generated by using a full five factor factorial experiment involving five factors (say A, B, C, D and E) and then choosing to confound the two remaining factors F and G with interactions generated by F = A*B*C*D and G = A*B*D*E. These two expressions are called the generators of the design. So for example, when the experiment is run and the experimenter estimates the effects for factor F, what is really being estimated is a combination of the main effect of F and the four-factor interactions involving A, B, C, and D.

An important characteristic of a fractional design is the defining relation, which gives the set of interaction columns equal in the design matrix to a column of plus signs, denoted by I. For the above example, since F=ABCD and G=ABDE, then ABCDF and ABDEG are both columns of plus signs and consequently so is CEFG. In this case the defining relation of the fractional design is I= ABCDF = ABDEG = CEFG. The defining relation allows the alias pattern of the design to be determined.

This means that the confounding relations are:

```
A = BCDF = BDEG = ACEFG
B = ACDF = ADEG = BCEFG
C = EFG = ABDF = ABCDEG
D = ABCF = ABEG = CDEFG
E = CFG = ABDG = ABCDEF
F = CEG = ABCD = ABDEFG
G = CEF = ABDE = ABCDFG
AB = CDF = DEG = ABCEFG
AC = BDF = AEFG = BCDEG
AD = BCF = BEG = ACDEFG
AE = BDG = ACFG = BCDEF
AF = BCD = ACEG = BDEFG
AG = BDE = ACEF = BCDFG
BC = ADF = BEFG = ACDEG
BD = ACF = AEG = BCDEFG
BE = ADG = BCFG = ACDEF
BF = ACD = BCEG = ADEFG
BG = ADE = BCEF = ACDFG
CD = ABF = DEFG = ABCEG
CE = FG = ABCDG = ABDEF
CF = EG = ABD = ABCDEFG
CG = EF = ABCDE = ABDFG
DE = ABG = CDFG = ABCEF
DF = ABC = CDEG = ABEFG
DG = ABE = CDEF = ABCFG
ACE = AFG = BCDG = BDEF
ACG = AEF = BCDE = BDFG
BCE = BFG = ACDG = ADEF
BCG = BEF = ACDE = ADFG
```

```
CDE = DFG = ABCG = ABEF
CDG = DEF = ABCE = ABFG
```

The problem in this case is that CE is confounded with FG, CF with EG and CG with EF, then the effect of these interactions cannot be distinguished one each other. Running the experiments, the response data are the following:

Run Order	Total cost	Inventory	Sum of z_i	Sum of y_i	FA sup 1	FA sup 2	FA sup 3	Inv sup 1	Inv sup 2	Inv sup 3
1	659,432	6	0	2	0	1	1	0	0	0
2	654,935	5	0	2	0	1	1	0	0	0
3	712,956	27	0	2	0	1	1	0	0	0
4	654,896	0	0	2	0	1	1	0	0	0
5	657,988	8	0	2	0	1	1	0	0	0
6	659,022	5	1	1	0	1	0	0	0	1
7	651,445	3	0	2	0	1	1	0	0	0
8	697,797	33	1	0	0	0	0	0	0	1
9	636,945	2	1	1	0	1	0	0	0	1
10	646,451	3	1	1	0	1	0	0	0	1
11	655,616	1	0	2	0	1	1	0	0	0
12	705,104	20	0	2	0	1	1	0	0	0
13	703,223	36	0	2	0	1	1	0	0	0
14	658,657	7	0	2	0	1	1	0	0	0
15	665,178	13	1	0	0	0	0	0	0	1
16	680,794	8	1	1	0	1	0	0	0	1
17	694,116	6	0	2	0	1	1	0	0	0
18	667,398	3	0	3	1	1	1	0	0	0
19	661,366	2	0	2	0	1	1	0	0	0
20	639,113	4	1	1	0	1	0	0	0	1
21	677,603	28	1	0	0	0	0	0	0	1
22	692,655	26	1	0	0	0	0	0	0	1
23	662,437	3	1	1	1	0	0	0	0	1
24	654,200	1	0	2	0	1	1	0	0	0
25	644,429	2	1	1	0	1	0	0	0	1
26	644,016	3	1	1	0	1	0	0	0	1
27	682,298	11	0	2	0	1	1	0	0	0
28	644,151	1	1	1	0	1	0	0	0	1
29	686,004	18	1	0	0	0	0	0	0	1
30	691,090	12	0	2	0	1	1	0	0	0
31	647,520	2	0	2	0	1	1	0	0	0
32	667,130	12	0	2	0	1	1	0	0	0

Table 5.7 – Response data

Effects on Total cost

The response data were entered into a Minitab worksheet along with the experimental designs. To get a preliminary view of the data, main effects and interactions plot were created.

Main effects:

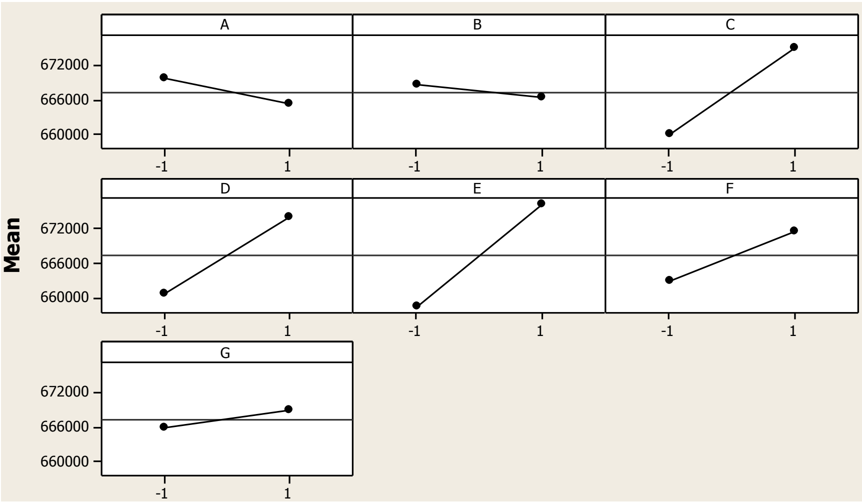

Figure 5.1 Main effect plot for total cost

Analyzing the line slopes, the main effect plot suggests that variables C, D, E and F have much stronger effect on the response data than A, B, G.

Interaction effects:

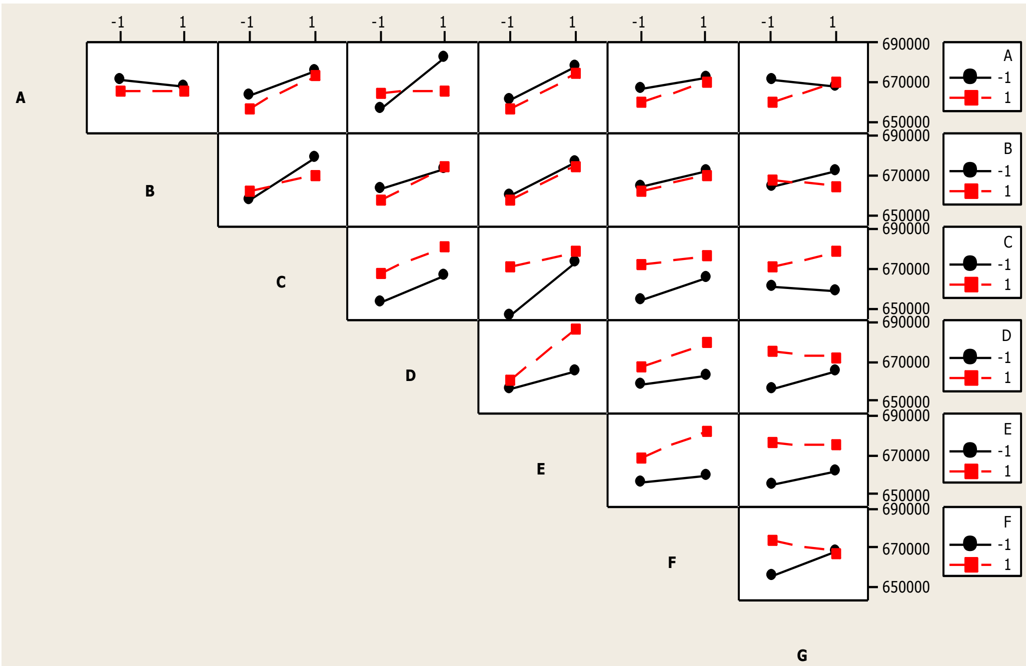

Figure 5.2 – Interaction plot for total cost

In the interaction plots, if the line segments are parallel the interaction is not significant, while if they are divergent the interaction is significant.

From the plots, the significant interactions seem to be: AD, AG, BC,BG, CE, DE,DG,FG.

Regarding FG and CE, they have confounding relations, so it is not possible to conclude if the interaction effect is due to FG or CE.

It is possible to define the predictive model for the data considering the 7 main effects and the 21 two-factor interactions. Minitab recognizes 3 confounding interactions (CE=FG, CF=EG, CG=EF) and retains in the model 17 two-factor interactions.

Data below show that no one of the two-factor interactions is significant (p > 0,05).

Estimated Effects and Coefficients for Total cost (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		667374	3678	181,43	0,000
A	-4460	-2230	3678	-0,61	0,567
B	-2106	-1053	3678	-0,29	0,784
C	15066	7533	3678	2,05	0,086
D	13314	6657	3678	1,81	0,120
E	17715	8857	3678	2,41	0,053
F	8517	4259	3678	1,16	0,291
G	3084	1542	3678	0,42	0,690
A*B	2098	1049	3678	0,29	0,785
A*C	1411	705	3678	0,19	0,854
A*D	-12590	-6295	3678	-1,71	0,138
A*E	551	276	3678	0,07	0,943
A*F	2148	1074	3678	0,29	0,780
A*G	7034	3517	3678	0,96	0,376
B*C	-7134	-3567	3678	-0,97	0,370
B*D	3662	1831	3678	0,50	0,636
B*E	252	126	3678	0,03	0,974
B*F	-345	-173	3678	-0,05	0,964
B*G	-5939	-2969	3678	-0,81	0,450
C*D	506	253	3678	0,07	0,947
C*E	-9535	-4768	3678	-1,30	0,243
C*F	-3698	-1849	3678	-0,50	0,633
C*G	4980	2490	3678	0,68	0,524
D*E	9033	4517	3678	1,23	0,265
D*F	4346	2173	3678	0,59	0,576
D*G	-6146	-3073	3678	-0,84	0,435

Rerunning the model considering only the main effects, three main effects (C, D and E) result significant in the predictive model with p<0,05, as graphically shown also in Figure 5.3:

Term	Effect	Coef	SE Coef	T	P
Constant		667374	3082	216,56	0,000
A	-4460	-2230	3082	-0,72	0,476
B	-2106	-1053	3082	-0,34	0,736
C	15066	7533	3082	2,44	0,022*
D	13314	6657	3082	2,16	0,041*
E	17715	8857	3082	2,87	0,008*

F	8517	4259	3082	1,38	0,180
G	3084	1542	3082	0,50	0,621

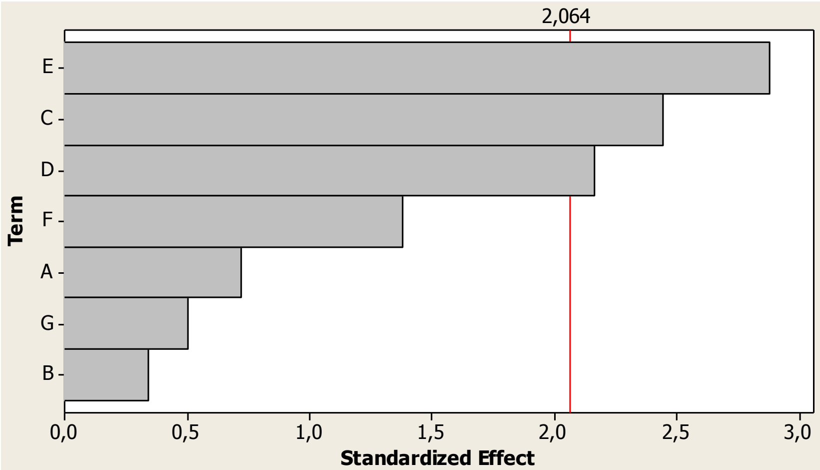

Figure 5.3 - Pareto chart of the standardize effects

Conclusions:

Lead times of the three suppliers (factors C, D and E) have the main impact on total cost.

Effect on Inventory

Main effects:

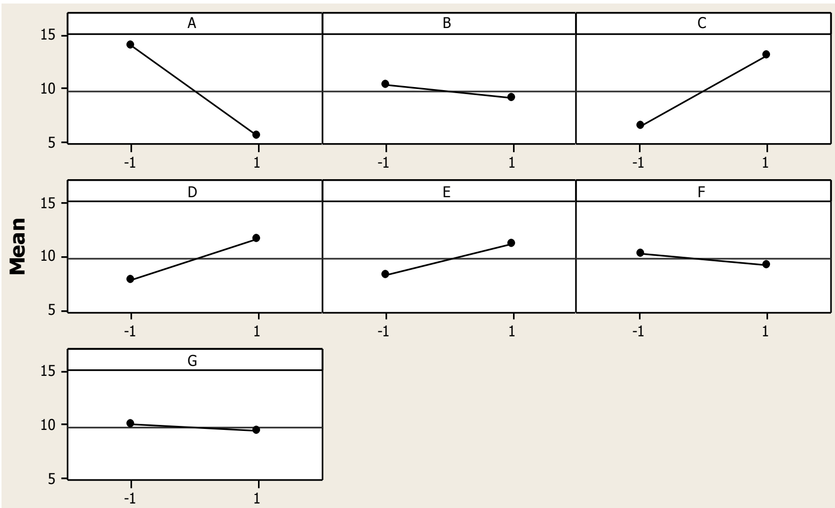

Figure 5.4 - Main Effects plot for inventory

The main effect plot suggests that variable A, C, D and E have much stronger effect on the response data than B,F, G.

Interactions effects:

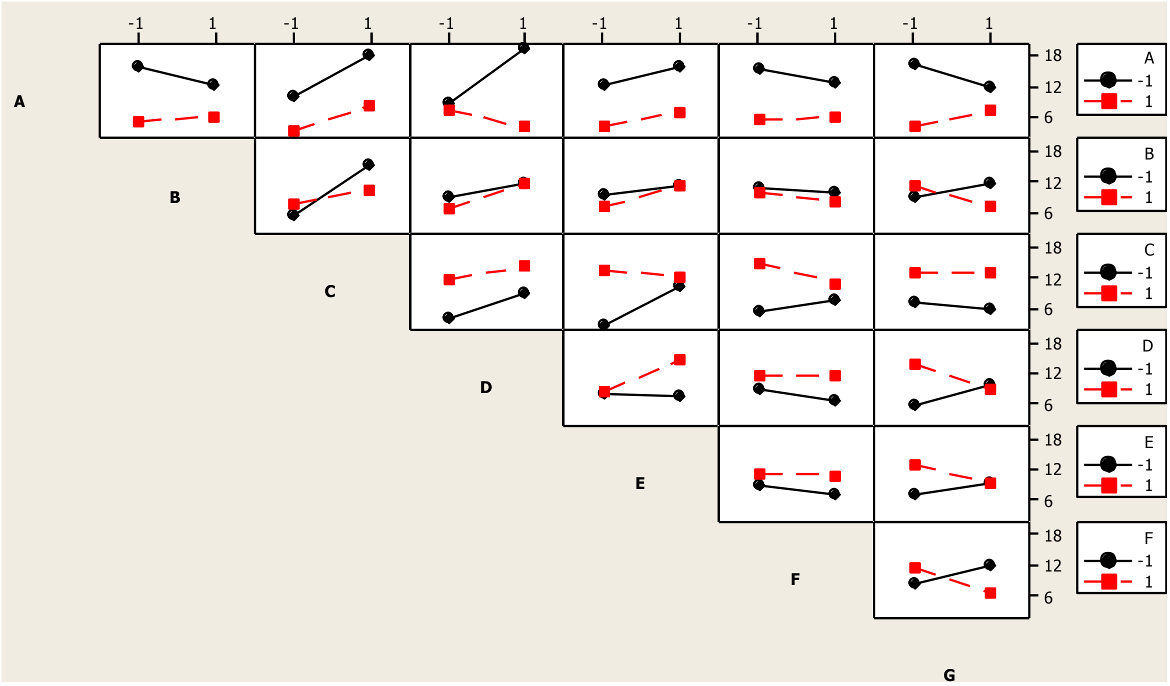

Figure 5.5 - Interaction plot for inventory

From the plots, the significant interactions seem to be: AD, AG, BC,BG, CE, CF, DE,DG, EG, FG.

Regarding FG and CE, CF and EG they have confounding relations, so it is not possible to conclude if the interaction effect is due to FG or CE or to CF or EG, respectively.

The predictive model for the data considering the 7 main effects and the 21 two-factor interactions has been defined. Minitab recognizes 3 confounding interactions (CE=FG, CF=EG, CG=EF) and retains in the model 17 two-factor interactions.

Data below show that no one of the two-factor interactions is significant:

Term	Effect	Coef	SE Coef	T	P
Constant		9,789	2,001	4,89	0,003
A	-8,484	-4,242	2,001	-2,12	0,078
B	-1,209	-0,604	2,001	-0,30	0,773
C	6,589	3,294	2,001	1,65	0,151
D	3,788	1,894	2,001	0,95	0,380
E	3,007	1,504	2,001	0,75	0,481
F	-1,165	-0,582	2,001	-0,29	0,781
G	-0,639	-0,319	2,001	-0,16	0,878
A*B	2,224	1,112	2,001	0,56	0,598
A*C	-1,724	-0,862	2,001	-0,43	0,682
A*D	-7,128	-3,564	2,001	-1,78	0,125
A*E	-0,313	-0,156	2,001	-0,08	0,940
A*F	1,525	0,763	2,001	0,38	0,716
A*G	3,599	1,799	2,001	0,90	0,403
B*C	-3,759	-1,879	2,001	-0,94	0,384

B*D	1,202	0,601	2,001	0,30	0,774
B*E	1,365	0,682	2,001	0,34	0,745
B*F	-0,565	-0,283	2,001	-0,14	0,892
B*G	-3,654	-1,827	2,001	-0,91	0,396
C*D	-1,150	-0,575	2,001	-0,29	0,783
C*E	-4,530	-2,265	2,001	-1,13	0,301
C*F	-3,108	-1,554	2,001	-0,78	0,467
C*G	0,716	0,358	2,001	0,18	0,864
D*E	3,404	1,702	2,001	0,85	0,428
D*F	1,304	0,652	2,001	0,33	0,756
D*G	-4,615	-2,307	2,001	-1,15	0,293

Rerunning the model considering only the main effects, the effect of A results significant (p> 0,05), as shown also in Figure 5.6:

Term	Effect	Coef	SE Coef	T	P
Constant		9,789	1,670	5,86	0,000
A	-8,484	-4,242	1,670	-2,54	0,018*
B	-1,209	-0,604	1,670	-0,36	0,721
C	6,589	3,294	1,670	1,97	0,060
D	3,788	1,894	1,670	1,13	0,268
E	3,007	1,504	1,670	0,90	0,377
F	-1,165	-0,582	1,670	-0,35	0,730
G	-0,639	-0,319	1,670	-0,19	0,850

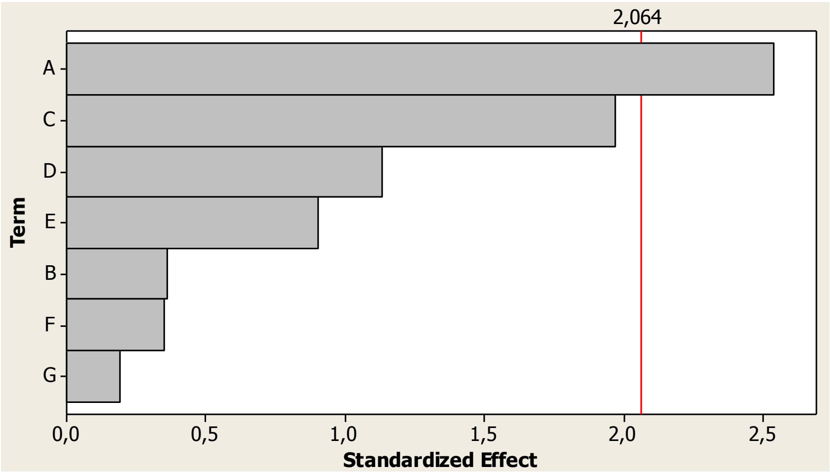

Figure 5.6 - Pareto chart of the standardized effects

Conclusions:

Holding cost (factor A) has the main impact on inventory.

Effect on the Sum of y (number of supplier with framework agreement)

The value of this variable goes from 0 to 3, because the supply base is made up of three suppliers.

Main effects:

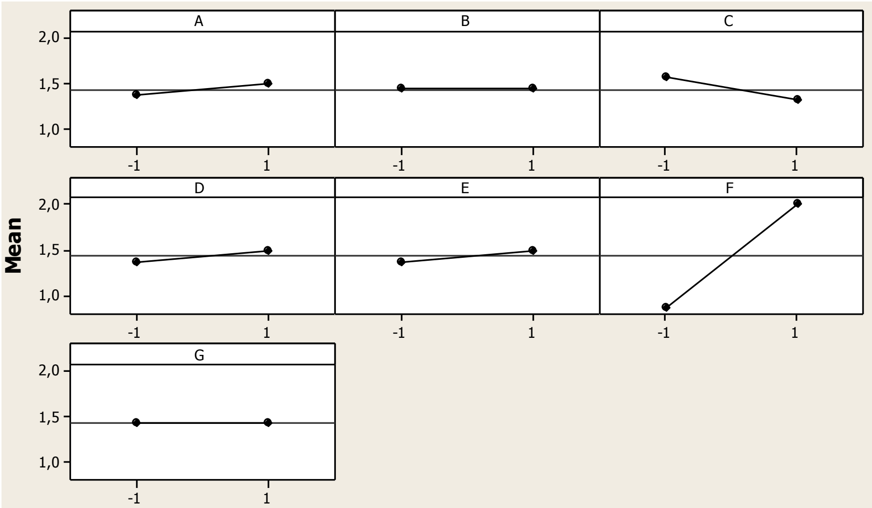

Figure 5.7 - Main effects plot for Sum of y

The main effect plot suggests that variable C and F have much stronger effect on the response data than A, B,D, E, G.

Interaction effects:

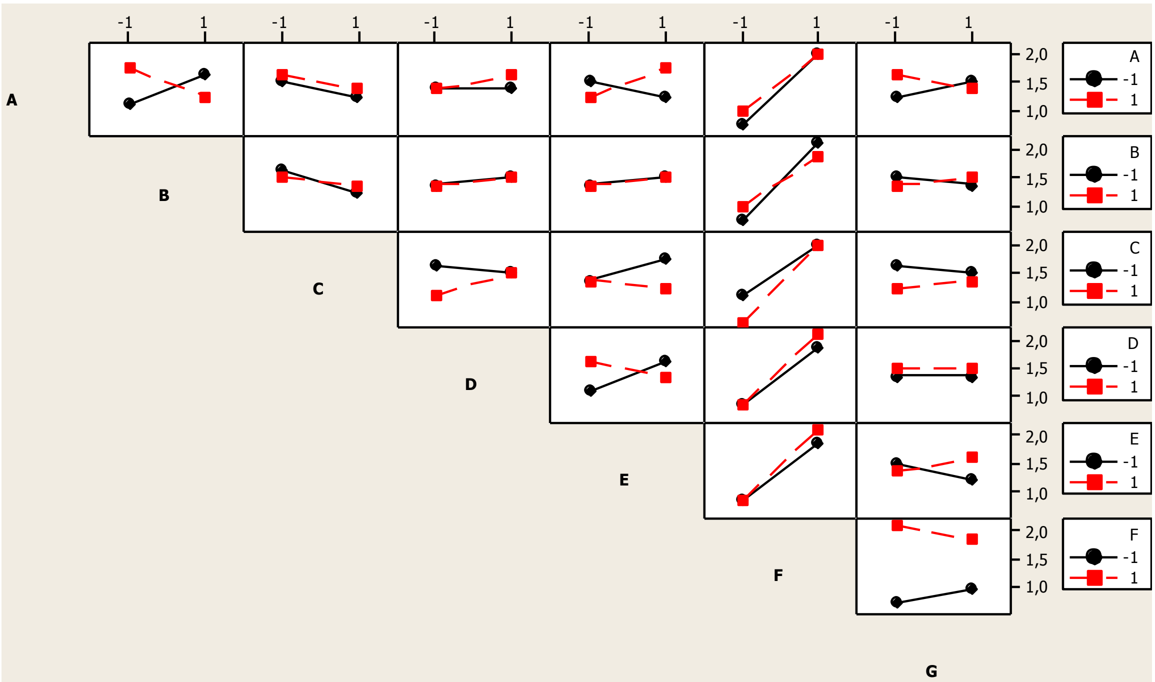

Figure 5.8 - Interaction effects for Sum y

From the plots, the significant interactions seem to be: AB, AE, AG, CD,CE, DE,EG,FG.

Regarding FG and CE, they have confounding relations, so it is not possible to conclude if the interaction effect is due to FG or CE.

The predictive model for the data considering the 7 main effects and the 21 two-factor interactions has been defined. Minitab recognizes 3 confounding interactions (CE=FG, CF=EG, CG=EF) and retains in the model 17 two-factor interactions.

Data below show that main effect F and interaction AB are significant with p<0,5 and interactions AE and DE are significant with p<0,1:

Term	Effect	Coef	SE Coef	T	P
Constant		1,4375	0,08463	16,99	0,000
A	0,1250	0,0625	0,08463	0,74	0,488
B	0,0000	0,0000	0,08463	0,00	1,000
C	-0,2500	-0,1250	0,08463	-1,48	0,190
D	0,1250	0,0625	0,08463	0,74	0,488
E	0,1250	0,0625	0,08463	0,74	0,488
F	1,1250	0,5625	0,08463	6,65	0,001*
G	-0,0000	-0,0000	0,08463	-0,00	1,000
A*B	-0,5000	-0,2500	0,08463	-2,95	0,025*
A*C	-0,0000	-0,0000	0,08463	-0,00	1,000
A*D	0,1250	0,0625	0,08463	0,74	0,488
A*E	0,3750	0,1875	0,08463	2,22	0,069**
A*F	-0,1250	-0,0625	0,08463	-0,74	0,488
A*G	-0,2500	-0,1250	0,08463	-1,48	0,190
B*C	0,1250	0,0625	0,08463	0,74	0,488
B*D	-0,0000	-0,0000	0,08463	-0,00	1,000
B*E	0,0000	0,0000	0,08463	0,00	1,000
B*F	-0,2500	-0,1250	0,08463	-1,48	0,190
B*G	0,1250	0,0625	0,08463	0,74	0,488
C*D	0,2500	0,1250	0,08463	1,48	0,190
C*E	-0,2500	-0,1250	0,08463	-1,48	0,190
C*F	0,2500	0,1250	0,08463	1,48	0,190
C*G	0,1250	0,0625	0,08463	0,74	0,488
D*E	-0,3750	-0,1875	0,08463	-2,22	0,069**
D*F	0,1250	0,0625	0,08463	0,74	0,488
D*G	-0,0000	-0,0000	0,08463	-0,00	1,000

Rerunning the model with the main effects and interactions AB, AE and DE, main effect F and interaction effects AB, AE and DE result significant whit p<0,05, as shown also in Figure 5.9.

Term	Effect	Coef	SE Coef	T	P
Constant		1,4375	0,08296	17,33	0,000
A	0,1250	0,0625	0,08296	0,75	0,460
B	-0,0000	-0,0000	0,08296	-0,00	1,000
C	-0,2500	-0,1250	0,08296	-1,51	0,147
D	0,1250	0,0625	0,08296	0,75	0,460
E	0,1250	0,0625	0,08296	0,75	0,460
F	1,1250	0,5625	0,08296	6,78	0,000*
G	-0,0000	-0,0000	0,08296	-0,00	1,000
A*B	-0,5000	-0,2500	0,08296	-3,01	0,007*
A*E	0,3750	0,1875	0,08296	2,26	0,035*
D*E	-0,3750	-0,1875	0,08296	-2,26	0,035*

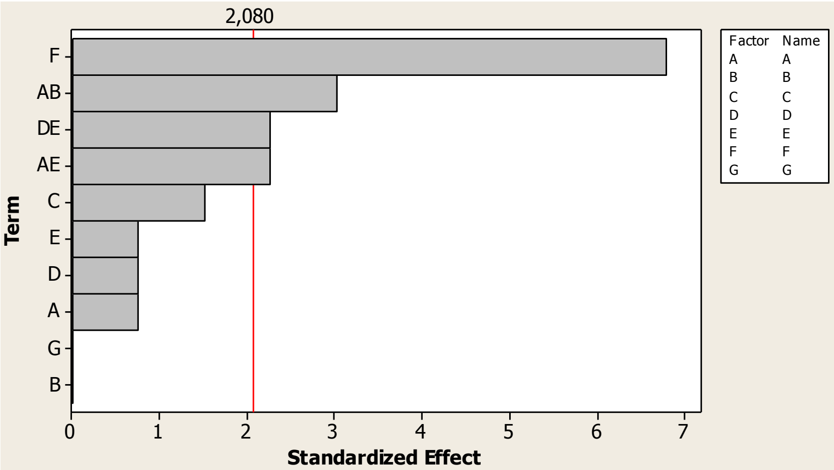

Figure 5.9 - Pareto chart of the standardized effects

Conclusions:

Investment cost (factor F) and the conjoint effect of holding (factor A) and backlog cost (factor B), holding cost (factor A) and lead time of supplier 3 (factor E), and lead time supplier2 (factor D) and 3 (factor E) have the main impacts on the number of supplier with which sign a framework agreement.

Effect on the Sum of z (number of supplier with investment)

As for the sum of y, this variable can go from 0 to 3, but in all the experiments it assumes the value of 0 or 1. In case it is 1 the selected supplier is the 3, namely that one with the lowest cost but the highest failure probability.

Main effects:

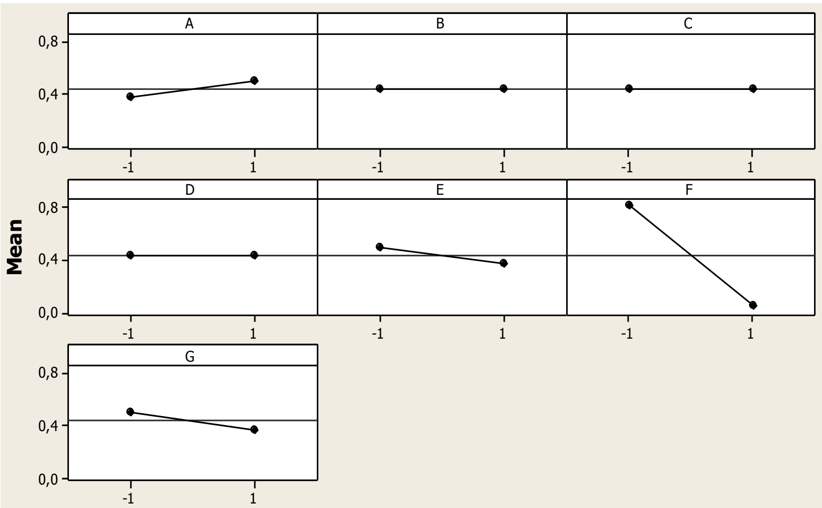

Figure 5.10 - Main effects plot for sum of z

The main effect plot suggests that variable A, E, F and G have much stronger effect on the response data than B,C, D.

Interactions effects:

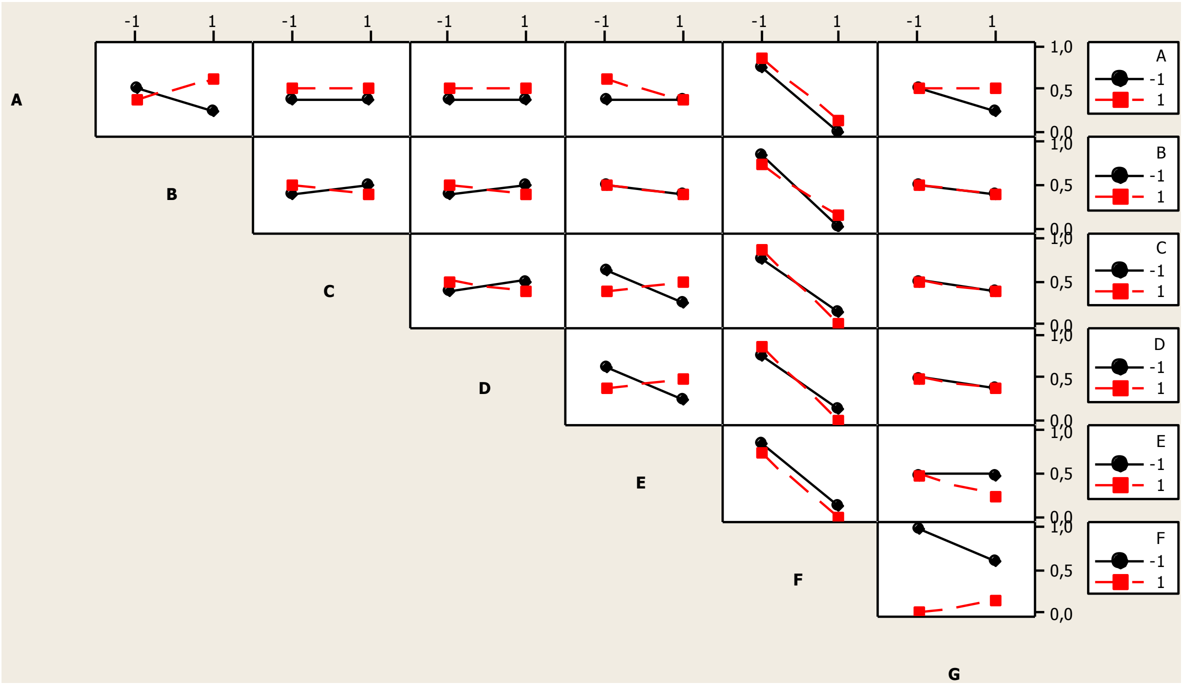

Figure 5.11 – Interaction plot for sum of z

From the plots, the significant interactions seem to be: AB,AG, CE, DE, EG, FG. Regarding FG and CE, they have confounding relations, so it is not possible to conclude if the interaction effect is due to FG or CE.

The predictive model for the data considering the 7 main effects and the 21 two-factor interactions has been defined. Minitab recognizes 3 confounding interactions (CE=FG, CF=EG, CG=EF) and retains in the model 17 two-factor interactions.

Data below show that the significant coefficients are F, AB, CE, DE. The CE effect is confounded with FG.

Term	Effect	Coef	SE Coef	T	P
Constant		0,4375	0,05103	8,57	0,000
A	0,1250	0,0625	0,05103	1,22	0,267
B	0,0000	0,0000	0,05103	0,00	1,000
C	0,0000	0,0000	0,05103	0,00	1,000
D	0,0000	0,0000	0,05103	0,00	1,000
E	-0,1250	-0,0625	0,05103	-1,22	0,267
F	-0,7500	-0,3750	0,05103	-7,35	0,000*
G	-0,1250	-0,0625	0,05103	-1,22	0,267
A*B	0,2500	0,1250	0,05103	2,45	0,050*
A*C	0,0000	0,0000	0,05103	0,00	1,000
A*D	-0,0000	-0,0000	0,05103	-0,00	1,000
A*E	-0,1250	-0,0625	0,05103	-1,22	0,267
A*F	0,0000	0,0000	0,05103	0,00	1,000

A*G	0,1250	0,0625	0,05103	1,22	0,267
B*C	-0,1250	-0,0625	0,05103	-1,22	0,267
B*D	-0,1250	-0,0625	0,05103	-1,22	0,267
B*E	-0,0000	-0,0000	0,05103	-0,00	1,000
B*F	0,1250	0,0625	0,05103	1,22	0,267
B*G	0,0000	0,0000	0,05103	0,00	1,000
C*D	-0,1250	-0,0625	0,05103	-1,22	0,267
C*E	0,2500	0,1250	0,05103	2,45	0,050*
C*F	-0,1250	-0,0625	0,05103	-1,22	0,267
C*G	-0,0000	-0,0000	0,05103	-0,00	1,000
D*E	0,2500	0,1250	0,05103	2,45	0,050*
D*F	-0,1250	-0,0625	0,05103	-1,22	0,267
D*G	-0,0000	-0,0000	0,05103	-0,00	1,000

Rerunning the model with the main effects and interactions AB, CE and DE, main effect F and interaction effects AB, DE and CE result significant whit $p<0,05$, as shown also in Figure 5.12.

Term	Effect	Coef	SE Coef	T	P
Constant		0,4375	0,04725	9,26	0,000
A	0,1250	0,0625	0,04725	1,32	0,200
B	0,0000	0,0000	0,04725	0,00	1,000
C	-0,0000	-0,0000	0,04725	-0,00	1,000
D	0,0000	0,0000	0,04725	0,00	1,000
E	-0,1250	-0,0625	0,04725	-1,32	0,200
F	-0,7500	-0,3750	0,04725	-7,94	0,000*
G	-0,1250	-0,0625	0,04725	-1,32	0,200
A*B	0,2500	0,1250	0,04725	2,65	0,015*
D*E	0,2500	0,1250	0,04725	2,65	0,015*
C*E	0,2500	0,1250	0,04725	2,65	0,015*

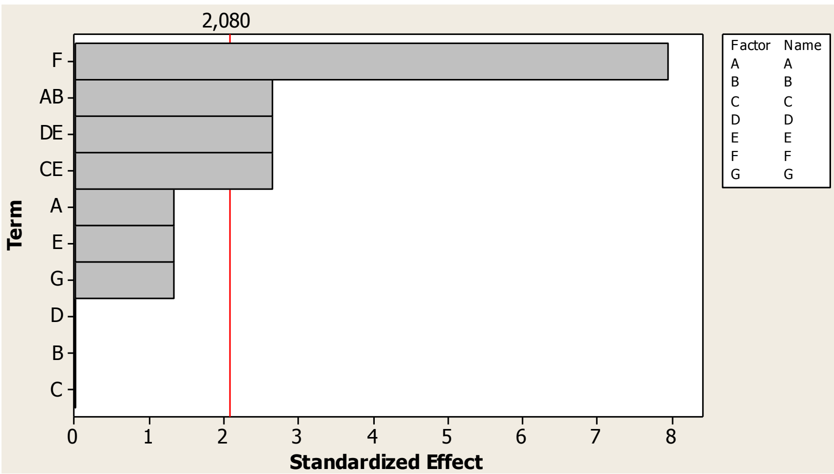

Figure 5.12 - Pareto chart of standardized effects

Conclusions:

Investment cost (factor F), conjoint effects of holding (factor A) and backlog cost (factor A), lead times of supplier 2 (factor D) and 3 (factor E), lead times supplier 1 (factor C) and 3(factor E) have the main impacts on the number of supplier in which invest. Due to the confounding problem, it is not possible to distinguish if the effect is due to the conjoint effect of supplier 1 and 3 or the conjoint effect of investment (factor F) and probability reduction (factor G).

Summarizing the results:

Response	Main effects	Interaction effects
Total cost	LT_1 (C) → positive LT_2 (D) → positive LT_3 (E) → positive	
Inventory	Holding cost (A) → negative	
Sum of y	Investment cost (F) → positive	holding*backlog cost (AB) → negative holding cost*investment cost (AE)→ positive LT_2*LT_3 (DE) → negative
Sum of z	Investment cost (F) → negative	holding*backlog cost (AB) → positive LT_2*LT_3 (DE) → positive LT_1*LT_3 (CE) or investment*probability reduction (FG) → positive

Table 5.8 - Results of fractional factorial design with 7 factors

Fractional factorial experiment (6 factors - resolution VI)

To better analyze the variables that impact the sum of z and to overcome the problem caused by confounding relations, a two-level fractional factorial experiment with 6 factors has been run.

Since in the results supplier 1 is seldom selected, its lead time has been fixed to the low level (2 weeks) and then the varying factors become: holding cost, backlog cost, LT_2, LT_3, investment cost and probability reduction. This kind of design requires 32 runs (2^{6-1}).

This is a design of resolution VI, so because of the rarity of higher-order interactions, this design does not represent any serious difficulties in analysis. Main effects will be confounded with five-order interactions and two-factor interactions will be confounded with four-factor interactions and both types of terms are very safe from confounding issues.

As in the previous case, the level of the factors are the following:

Factor	Name	High level +1	Low level -1
h	**A**	50	30
bk	**B**	70	50
LT sup2	**C**	4	2
LT sup3	**D**	4	2
j	**E**	50	10
Prob. Reduction	**F**	0,8	0,5

Table 5.9 - Factor levels

The following design has been defined using MINITAB:

	h	bk	LT sup2	LT sup3	j	Prob. Reduction
RunOrder	**A**	**B**	**C**	**D**	**E**	**F**
1	-1	-1	-1	-1	1	1
2	1	1	1	-1	-1	1
3	-1	1	-1	-1	-1	1
4	-1	1	-1	1	1	1
5	1	-1	-1	1	1	1
6	-1	-1	1	-1	-1	1
7	-1	1	-1	1	-1	-1
8	-1	-1	-1	-1	-1	-1
9	1	1	1	1	1	1
10	1	1	-1	1	1	-1
11	-1	1	1	1	-1	1
12	1	-1	1	-1	1	1
13	1	-1	1	-1	-1	-1
14	1	-1	-1	-1	1	-1
15	1	-1	1	1	-1	1
16	1	1	1	-1	1	-1
17	-1	-1	-1	1	1	-1
18	1	1	-1	-1	1	1
19	-1	1	1	1	1	-1

	h	bk	LT sup2	LT sup3	j	Prob. Reduction
RunOrder	**A**	**B**	**C**	**D**	**E**	**F**
20	1	-1	1	1	1	-1
21	1	-1	-1	1	-1	-1
22	-1	1	-1	-1	1	-1
23	1	1	1	1	-1	-1
24	-1	-1	-1	1	-1	1
25	1	1	-1	-1	-1	-1
26	-1	-1	1	1	-1	-1
27	-1	1	1	-1	1	1
28	1	-1	-1	-1	-1	1
29	-1	1	1	-1	-1	-1
30	1	1	-1	1	-1	1
31	-1	-1	1	-1	1	-1
32	-1	-1	1	1	1	1

Table 5.10 - Design of the experiments

In this case, the design generator is:

F = ABCDE

Then, the confounding relations are the following:

```
A = BCDEF
B = ACDEF
C = ABDEF
D = ABCEF
E = ABCDF
F = ABCDE
AB = CDEF
AC = BDEF
AD = BCEF
AE = BCDF
AF = BCDE
BC = ADEF
BD = ACEF
BE = ACDF
BF = ACDE
CD = ABEF
CE = ABDF
CF = ABDE
DE = ABCF
DF = ABCE
EF = ABCD
ABC = DEF
ABD = CEF
ABE = CDF
ABF = CDE
ACD = BEF
ACE = BDF
ACF = BDE
ADE = BCF
```

```
ADF = BCE
AEF = BCD
```

The response variables are:

Run Order	Total cost	Inventory	Sum of z_i	Sum of y_i	FA sup 1	FA sup 2	FA sup 3	Inv sup 1	Inv sup 2	Inv sup 3
1	647,481	3	0	2	0	1	1	0	0	0
2	645,752	2	1	1	0	1	0	0	0	1
3	664,049	14	0	2	0	1	1	0	0	0
4	696,710	30	0	2	0	1	1	0	0	0
5	656,528	0	0	3	1	1	1	0	0	0
6	699,219	43	1	0	0	0	0	0	0	1
7	642,578	4	1	1	0	1	0	0	0	1
8	688,600	37	1	0	0	0	0	0	0	1
9	694,196	12	0	3	1	1	1	0	0	0
10	658,671	2	0	2	0	1	1	0	0	0
11	712,293	38	1	0	0	0	0	0	0	1
12	662,093	4	0	2	0	1	1	0	0	0
13	656,018	6	1	1	0	1	0	0	0	1
14	698,433	18	0	2	0	1	1	0	0	0
15	709,980	18	1	0	0	0	0	0	0	1
16	685,847	13	0	2	0	1	1	0	0	0
17	670,351	14	0	2	0	1	1	0	0	0
18	687,867	13	0	2	0	1	1	0	0	0
19	689,241	14	0	2	0	1	1	0	0	0
20	663,212	0	0	3	1	1	1	0	0	0
21	644,906	2	1	1	0	1	0	0	0	1
22	686,638	27	0	2	0	1	1	0	0	0
23	698,242	19	1	0	0	0	0	0	0	1
24	697,053	32	1	0	0	0	0	0	0	1
25	647,173	3	1	1	0	1	0	0	0	1
26	651,400	6	1	1	1	0	0	0	0	1
27	661,126	10	0	2	0	1	1	0	0	0
28	673,335	10	1	1	0	1	0	0	0	1
29	639,816	4	1	1	0	1	0	0	0	1
30	639,816	4	1	1	0	1	0	0	0	1
31	683,322	25	0	2	0	1	1	0	0	0
32	721,910	33	0	2	0	1	1	0	0	0

Table 5.11 - Response data

Effect on the Sum of z (number of supplier with investment)

As in the previous analysis, this variable can go from 0 to 3, but in all the experiments it assumes the value of 0 or 1. In case it is 1 the selected supplier is the 3, namely that one with the lowest cost but the highest failure probability.

Main effects:

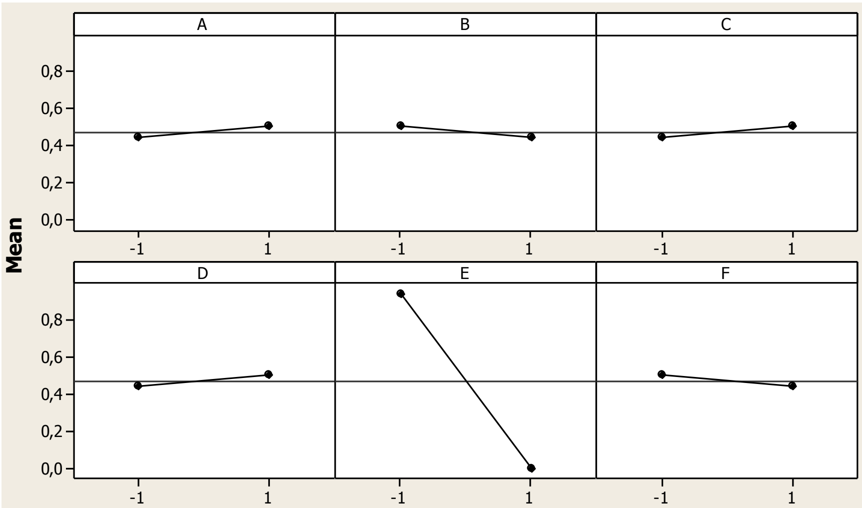

Figure 5.13 - Main effects plot for the sum of z

Analyzing the line slopes, the main effect plot suggests that variable E have much stronger effect on the response data than the others.

Interaction effects:

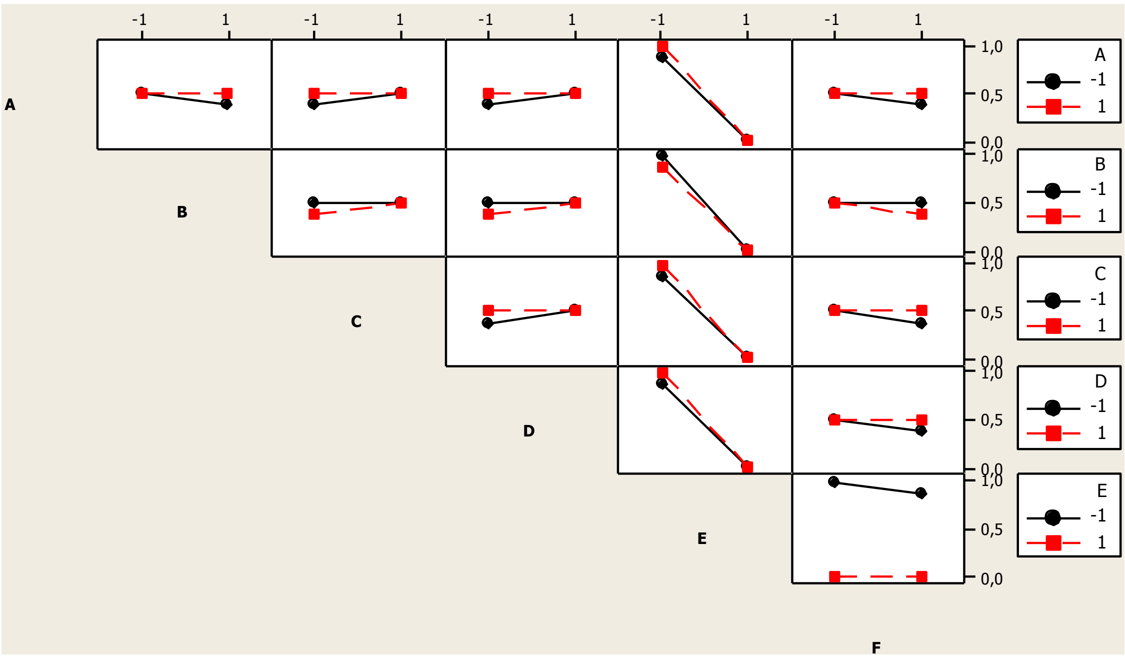

Figure 5.14 - Interaction plot for the sum of z

From the plots, the significant interactions are: AB, AC, AD, AF, BC, BD, BF, CD, CF, DF.

The predictive model for the data considering the 6 main effects and the 15 two-factor interactions has been defined.

Data below show that the significant coefficients are related only to F, as shown also in Figure 5.15.

Term	Effect	Coef	SE Coef	T	P
Constant		0,4688	0,03125	15,00	0,000
A	0,0625	0,0313	0,03125	1,00	0,341
B	-0,0625	-0,0313	0,03125	-1,00	0,341
C	0,0625	0,0313	0,03125	1,00	0,341
D	0,0625	0,0312	0,03125	1,00	0,341
E	-0,9375	-0,4687	0,03125	-15,00	0,000*
F	-0,0625	-0,0312	0,03125	-1,00	0,341
A*B	0,0625	0,0313	0,03125	1,00	0,341
A*C	-0,0625	-0,0313	0,03125	-1,00	0,341
A*D	-0,0625	-0,0312	0,03125	-1,00	0,341
A*E	-0,0625	-0,0313	0,03125	-1,00	0,341
A*F	0,0625	0,0312	0,03125	1,00	0,341
B*C	0,0625	0,0313	0,03125	1,00	0,341
B*D	0,0625	0,0313	0,03125	1,00	0,341
B*E	0,0625	0,0313	0,03125	1,00	0,341
B*F	-0,0625	-0,0312	0,03125	-1,00	0,341
C*D	-0,0625	-0,0313	0,03125	-1,00	0,341
C*E	-0,0625	-0,0312	0,03125	-1,00	0,341
C*F	0,0625	0,0313	0,03125	1,00	0,341
D*E	-0,0625	-0,0312	0,03125	-1,00	0,341
D*F	0,0625	0,0312	0,03125	1,00	0,341
E*F	0,0625	0,0312	0,03125	1,00	0,341

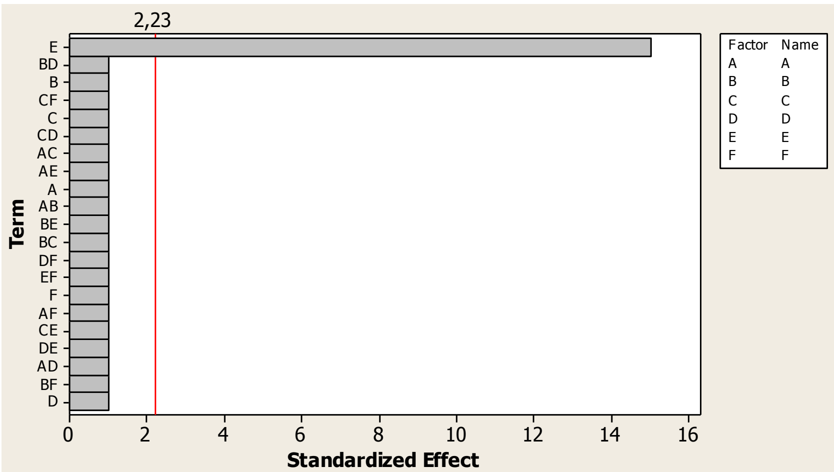

Figure 5.15 - Pareto chart of the standardized effects

Conclusions:

Investment cost (factor E) has the main impact on the number of supplier in which to invest.

Summarizing and joining the results of the two set of experiments:

Response	Main effects	Interaction effects
Total cost	LT_1 → positive LT_2 → positive LT_3 → positive	
Inventory	Holding cost → negative	
Sum of y	Investment cost → positive	holding*backlog cost → negative holding cost*investment cost → positive LT_2*LT_3 → negative
Sum of z	Investment cost → negative	

Table 5.12 - DOE results

The result of this model suggests to select supplier 2 and 3 and, based on the investment cost, to make an investment in supplier 3 in order to improve its performance and reduce its delay probability. These are the lower cost suppliers, even if with higher delay probability. The quantity assigned to each supplier will depend on the specific case.

In order to decrease the total cost, results indicate that the company should focus on supplier lead times reduction and, then, using time buffer is not a recommended strategy from cost point of view.

On the contrary, keeping inventories seems to be a better redundancy practices than time buffer because does not have direct impact on total cost. This practice is more effective also from risk point of view because it allows to pool the risk. In fact, using time buffer, and then considering a longer supplier lead time, the company tries to counter the risk of each single supplier. On the contrary, keeping inventories is a means to pool the risk of all the selected suppliers and create redundancy at a joint level.

Finally, the decision about investments is mainly determined by the investment cost while the delay probability reduction seems to be not relevant in this case (even if at least a 20% of probability reduction should be ensured through the investment).

5.4 Step 4: Monitoring and feedback

A continuous monitoring of the selected suppliers along with the supply risk should be constantly monitored in order to keep controlled supplier behaviors and the outcome of possible investment. This control should also ensure company a timely intervention in case of need or changing internal/external conditions.

5.5 Conclusion

In this chapter a use case that describes the application of the proposed four-step methodology has been shown. Special attention has also been paid to the quantitative selection of strategies to deal with supply risk. In particular, the design of experiment procedure has been deeply explained and the result analysis has been carried out. This analysis allowed to derive useful insights about the strategies to be implemented because it permits to identify the factors that have a greater impact on some outcome variables, such as total cost.

In the final chapter of this thesis, general conclusions are drawn out and further research development are proposed.

6. Conclusions and further developments

The today's business trends often push companies to establish more and more composite and convoluted supply chains, implicitly involving more risk sources and raising the possibility to amplify the effect of disruptions, undermining the business continuity and the ability to get finished goods and services to customers. In this complex environment, this paper underlines the need for a methodology to better identify, classify and manage the risk related to supplier and support the evaluation and selection of actions to improve supply resilience. To this end, this thesis proposed the following four-step methodology for supply risk management:

- Analysis of supply risk
- Evaluation of available strategies to ensure business continuity
- Selection of the most suitable strategies
- Monitoring and feedback

The first main contribution of this framework is the analysis of the available strategies to counter supply risk and ensure business continuity following a systemic approach, in order to capture the nonlinear and looped relationships between the components involved in the decision about risk management actions. As stated by Forrester (1987) "when one works in the realm of nonlinear systems, few universal answers emerge". Therefore, the presented model should be considered as a synthetic and powerful representation of the trade-offs emerging during the decision making phase rather than a consolidated working tool. Nevertheless, its strong foundation in supply chain management literature, best practices and case studies enables the identification of sound relationships between significant variables.

Referring to the main objective of building a resilient supply process, the systemic lenses allowed highlighting the relationships between the two identified main risk management strategies: redundancy and supply flexibility, where the first aims at limiting the impact of supply risk on the buying company while the latter attempts to reduce the likelihood of a supply disruption.

When management comes to evaluate possible investments in these two strategies, usually the focus is more on cost-related aspects; in fact, the assessment is generally carried out from a financial point of view using an expected cash flow perspective. Besides cost-related features, the proposed systemic model takes into account also non-financial aspects such as, for example, transparency level and willingness to improve. Furthermore, it enables managers to highlight both direct and indirect relationships among variables. For instance, when considering the possibility to make a supply flexibility investment, the casual loop diagram shows, on the one hand, the direct positive and negative consequences (such as supplier delay, buffer size, total cost reduction, cost increases and supplier opportunistic behavior) and, on the other hand, their indirect effects (i.e. supplier opportunistic behavior rebounds on cash flow and on the availability to make further investments in flexibility and in buffer as well). In the same way also redundancy practices can disclose similar trade-offs and ripples that, if not carefully taken into account and appropriately weighted, could negatively affect investments success.

Even though several studies have theoretically proved the effectiveness of supply flexibility and redundancy practices, researches should also be directed to a quantitative evaluation of the real impact of these practices, shifting from the world of the theorist into the world of the practitioner.

To this purpose, the second main contribution of this thesis is the definition of a two stage stochastic model that translates some of the qualitative relationships of the systemic model in a quantitative way. Thus, this model is intended to support supply tactical planning and, more specifically, the selection of the long/medium term strategy (or mix of strategies) to deal with supply risk, in terms of redundancy and supply flexibility. However, the main objective of this phase is not to get a single solution, but rather to analyze the model results in order to identify the factors that mostly impact strategy selection and draw sound conclusions and insights about it. To this end, Design of Experiments (DOE) techniques have been suggested in order to build a set of experiments to assess the strategy selection process and to be able to discern the impact of different input variables on the stochastic model outcomes.

Finally, the last chapter of this thesis, reports a use case that practically shows how this methodology should be applied in a real situation, from the identification of the main supply risk sources and impacts to the evaluation and selection of the available strategies in terms of redundancy and supply flexibility to improve supply resilience. In particular, in this use case, the definition of experiments and the statistical analysis of the results suggested by the Design of Experiments methodology are deeply explained and the results interpreted and discussed.

Further researches on this topic can be carried out to test the proposed methodology on companies belonging to different industries.

Additionally, the optimization model can be replaced or integrated with a computer-based simulation model, in order to better catch the dynamic nature of the variables and decisions involved. In particular, the proposed Systems Thinking model could lay the foundation for the development of a System Dynamics-based decision support tool, that can be helpful to quantitatively evaluate different policies and scenarios. Indeed, in this context, it would have an important managerial implication since it would provide the management of a company with a sort of cockpit, where the single decisional levers could be modified and their envisioned impact on the overall system simulated in order to identify the best strategy to adopt for minimizing supply risk and maximizing resilience.

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Annex: Published papers

The results of this research project have been presented in several international PhD workshops and scientific conferences. More in detail:

2009	APMS, Conference and Doctoral workshop, 19 - 23 September 2009, Bordeaux, France
	MITIP, 11th International Conference, 15 - 16 October 2009, Bergamo, Italy
2010	Sixteenth International Working Seminar on Production Economics, 1-5 marzo, Innsbruck, Austria
	ISCRiM 2010 Seminar, 6-7 settembre 2010, Loughborough University (UK)
	APMS Conference, 11 - 13 October 2010, Cernobbio, Como, Italy

Progress in this research has been promoted also by some international exchanges and visiting research periods. In particular:

August – December 2008	MIT-Zaragoza International Logistics Program - Master of Engineering in Logistics & Supply Chain Management, Zaragoza, Spain
March – July 2010	Bowling Green State University, College of Business Administration, Bowling Green (Ohio)

The papers published during the PhD program are the following:

- Pirola F., Pinto R., The Impact of Behavior-Based Strategies on Supply Uncertainty, In: Proc. of APMS 2009, International Conference on Advances in Production Management Systems, Bordeaux, France, 19-23 September 2009
- Pirola F., Pinto R., Moriggia V., Iaquinta G., Purchasing Strategy Under Supply Risk in a Single-Period Problem, In: Proc. of 11th International Conference MITIP, Bergamo, Italy, 15-16 October 2009
- Pirola F., Zsidisin G.A., Wagner S., An Investigation of the Relationships Between Supply Risk Awareness, Assessment, Management, and Supply Disruption Occurrence, In: Proc. of APMS 2010, International Conference on Advances in Production Management Systems, Cernobbio, Como, Italy, 11-13 October, 2010, ISBN: 978-88649-30-077
- Pirola F, Pinto R., Zsidisin, Supply Risk Management: Moving Towards A Quantitative Approach, In: Proc. of ISCRiM 2010 Seminar, pp. 39-45, Loughborough (UK), 6-7 September 2010
- Pirola F, Pinto R., Cavalieri S., Investing in suppliers to reduce risk. A conceptual model and an attempt of quantitative assessment, In: Proc. of Sixteenth International Working Seminar on Production Economics, pp. 383-394, Innsbruck, Austria, 1-5 March 2010
- Finke, G.R., Pinto, R., Pirola, F., Arntzen, B., Supply chain risk: commonalities and differences between Italy and Switzerland/Germany, In: Proc. of ISCRiM 2010 Seminar, pp. 63-67, Loughborough (UK), 6-7 September 2010

The papers are attached hereafter.

The Impact of Behavior-Based Strategies on Supply Uncertainty

Pirola Fabiana, Pinto Roberto

CELS – Research Center on Logistics and After-Sales Service
University of Bergamo
Viale Marconi, 5 - 24044 Dalmine, Italy
{fabiana.pirola, roberto.pinto}@unibg.it

Abstract.

Today's economical environment encompasses a high level of uncertainty, which affects decision makers capability in predicting future events, their occurrence probability and possible decision outcomes. A common way to guard against uncertainty is holding inventory in order to ensuring business continuity and on-time delivery to customer, buffering the effect of the risk. This method belongs to the buffer-oriented techniques that represent only a shield against uncertainty and contribute to raise the overall costs. A more effective way to reduce supply uncertainty is to deeply analyze its sources and try to reduce its occurrence probability adopting behavior-based strategies. A Systems Thinking model, aiming at explaining the logical relationships among different strategies and at analyzing their impact on supply uncertainty and total costs, is presented.

Keywords

Supply uncertainty, behavior-based strategy, buffer-based method

1. Introduction

Effectively manage a supply chain has become a complex and challenging task because of today's economical environment, characterized by rapid technological changes, shorter product lifecycles, demanding customers and global competitors. This context encompasses a high level of uncertainty, which affects decision makers capability in predicting future events, their occurrence probability and possible decision outcomes. Davis [5] recognizes three sources of uncertainty in the supply chain: demand, manufacturing process and supply. Demand uncertainty depends on customer orders variability, manufacturing uncertainty is due to internal problems arising during the manufacturing process, while the latter is associated with supplier failure in delivering products as required by customer. This leads to a variability in delivery lead time and then to uncertainty about supply availability. Consequently, disruption in firm production scheduling, increased inventory costs and reduced service level can occur. In their study Boonyathan et al. [1] showed that supply uncertainty is a more significant determinant of organizations performance than demand uncertainty. Therefore, managing supplier uncertainty becomes a relevant factor in developing supply chain strategies. This paper focuses on supply side of the risk and on strategies followed to deal with this risk. Common methods employed to manage supply uncertainty are buffer-oriented methods [26] that include holding stocks to reduce the stock-out probability in case of delays in supplier deliveries. Since buffers increase total cost, according to Zsidisin et al. [26], a more effective method to reduce supply uncertainty is to deeply analyze its sources and consequently undertake behavior-based strategies in order to eliminate or reduce this risk, focusing on supplier process rather than on its outcomes.

Hence, the main research questions are (i) which are the main sources of supply uncertainty, (ii) which are the main behavior-based strategies an organization could undertake to attempt to reduce or eliminate it and (iii) which are the relationships among these strategies, the uncertainty level and the overall costs.

In order to pursue these objectives, the following section provides a literature overview about supply uncertainty, its main sources, buffer-based methods and behavior-based strategies. In section 3, Systems Thinking methodology is introduced and, based on this methodology, in section 4 a model analyzing the relationship among buffer-based methods, behavior-based strategies and supply uncertainty is proposed. The last section concludes the paper with some remarks and indications for further researches.

2. Literature Overview

Due to recent increased interest in decision making under uncertainty and risk, Samson et al. [19] stated that there is no general definition for these terms but rather many discipline and context dependent definitions. For the purpose of this paper, we consider risk and uncertainty as two different but related concepts. In particular, according to Willet [19], we define risk as the "objective uncertainty regarding the occurrence of an undesirable event", while the subjective uncertainty "resulting from the imperfection of man's knowledge" is uncertainty. Consequently, considering risk as the occurrence probability of an undesirable event, uncertainty is the greatest when this probability is ½ because the decision maker completely does not know which will be the outcome (the undesired event has the same probability of occurring or not). The uncertainty level decreases when the probability increases or decreases and it is null when the probability is 0 or 1. This paper focuses on supply uncertainty, that, accordingly with the above definitions, is related to supply risk. Referring to Zsidisin [27], supply risk is defined as "the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety". In a study about uncertainty in supply chain, Ho et al. [8] stated that supply uncertainty sources are related to complexity, quality and, especially, timeliness of delivered products. In fact, the more complex is a product the more human intervention is required; this increases the errors probability and the time needed to resolve them and can lead to delivery delays. Relating to quality, two different cases can occur: in the first one, defects are detected by the supplier before the shipment so it can quickly repair it; in the second one, the quality problem is identified by the buying firm and a supplier intervention is required in order to repair or substitute the defective product. In both cases, delays in delivery can occur, especially when problems come out at the company's plant. Consequently, both complexity and quality can be referred to the time dimension of deliveries that disrupt company's processes and schedules.

A common way to guard against uncertainty is holding inventory to ensuring the continuation of the business and on-time delivery to customer ([2], [5], [10], [26]), buffering the effect of the risk. This method belongs to buffer-oriented techniques, as defined by Zsidisin [26], where buffers represent an outcome-based approach to dealing with risk that attempts to reduce its detrimental effects, rather than decrease its occurrence probability. Apart from representing only a shield against uncertainty and do not attempting to eliminate it, the main drawback of this kind of methods is that they contribute to raise overall costs due to storage space, potential obsolescence and capital investment in inventory. A more effective way to reduce supply uncertainty is to deeply analyze its sources and try to reduce the occurrence probability adopting behavior-based strategies [26]. From a literature review, this kind of strategies can be divided in supplier development and supplier integration [23].

Supplier development is defined by Krause [14] as "any effort by a buying firm to improve a supplier's performance and/or capabilities to meet the buying firm's short and/or long term supply needs" and it can be characterized by different levels of buying firm commitment. Krause identified six main activities: (i) formal supplier evaluation, (ii) visits to the supplier's site by buying firm representatives, (iii) certification programs, (iv) bringing supplier representatives on-site at the buying firm to further enhance interaction, (v) supplier award programs, and (vi) training of supplier's personnel by buying firm representatives. Modi et al. [17] added also capital and equipment investments made from procuring firms in supplier operations and partial supplier acquisition from buying firm. Investing in supplier development, the buying firm may reduce transaction costs [14] and, depending on the investment level, may obtain different rewards [13], such as more responsive suppliers and more certainty and continuity in buyer-seller relationship. Obviously, these investments are non transferable and benefits are unrecoverable if the relationship is prematurely dissolved. So, increasing the investment level increases benefits but increases also the firm dependence on suppliers and then the associated risk.

The second strategy available is supplier integration that leads to increase communication and information sharing between buying firm and its supplier and encompasses ([4] , [23]): (i) joint problem solving, (ii) direct communication between buyer and supplier production schedulers and (iii) integration of information technology. Wilson [25], applying system dynamics methodology to investigate the effect of supply disruption on a 5-echelon supply chain, showed that the impact is less severe in a supply chain with vendor managed inventory system than in a traditional supply chain, characterized by lower integration level. This behavior is due to information sharing because the retailer does not overreact to disruption by placing an excessive order to warehouse, as in the traditional structure (the traditional behavior is also demonstrated in [21]). Moreover, supplier integration practices reduce both transaction and production costs [4]. In fact, increasing the coordination level through goal and information sharing, increases familiarity and trust between the two companies and decreases supplier opportunistic behavior, leading to a reduction in transaction costs; from production cost standpoint, integration with a few number of suppliers allows to take advantage of economies of scale and scope. The main drawbacks of supplier integration are the coordination and inflexibility costs, where the first one arises because the need of coordination can increase response times and human capital requirements, while inflexibility comes up because firm is locked into a partner's technology and the supplier is not incentivized to innovate with new product or services [4].

In conclusion, referring to supply uncertainty and risk field, usually qualitative and descriptive studies ([1], [11], [26]) are carried out, especially through surveys and case studies, in order to give some insights into the actual employment of different strategies to deal with risk and their perceived benefits. An effective comparison among these strategies is still missing as well as a model that considers systems complexity to address organizations in strategy selection, based on market and firm characteristics and their evolution along the time. Thus, the aim of this paper is to define factors that favor and hinder these possible investments and identify the impact of these strategies in term of risk, uncertainty and overall costs. In order to analyze these relationships, a model is proposed and discussed in the next sections.

3. Methodology

The proposed model is realized using Systems Thinking methodology, that focuses on the way that a system's parts interrelate and how systems work over time and within the context of larger systems. The approach of Systems Thinking is different from the traditional form of analysis. While traditional analysis focuses on separating the parts of what is being studied, Systems Thinking, in contrast, focuses on how the thing being studied interacts with other constituents of the system. This means that instead of isolating smaller and smaller parts of the system, Systems Thinking works by expanding its view to taking into account larger and larger interactions. This broad view can help a decision maker to quickly identify the real causes of issues in organizations and allow to solve the most difficult types of problems. As referred by Senge [20], Systems Thinking discipline aims at seeing interrelationships among system parts rather than linear causal-effect chains and seeing processes of change rather than snapshots. In fact, Systems Thinking methodology is based on causal loops diagram [22]: they can be self-reinforcing (R) or self-correcting (B) and they consist of variables connected by arrows denoting causal influences, describing what would happen if there were a change. In the next section, a model attempting to describe how behavior-based strategies and buffer-based methods impact on supply uncertainty will be proposed, using Systems Thinking methodology.

4. The Proposed Model

The supply process involves the coupling made up by a company and its supplier which can be seen as the smallest supply chain entity. For this reason, this model will be developed from a firm point of view, considering the relationship with its main suppliers. Modi et al. [17] showed that knowledge transfer activities, and then supplier development and integration activities, are undertaken by the procuring firm especially with suppliers that satisfy a high percent of buyer requirements. Consequently, behavior based strategies make sense in case of relevant suppliers. A useful way to identify these suppliers may be the Kraljic matrix [12], where items are classified based on strategic importance and on supply risk. Therefore, behavior-based strategies can be addressed to suppliers providing strategic and bottleneck items, namely the ones with high supply risk.

The model represented in Figure 1 attempts to show the relationships among supplier performance, supply uncertainty, supplier development investments, integration investments, stock holding for a selected supplier. As shown in the literature review section, uncertainty sources depend on product complexity, quality and timeliness. Given that both complexity and quality can be referred to time dimension of deliveries, in this paper supply risk is represented by supplier delivery delay that gives rise to uncertainty because firm does not know exactly when product will be available in the factory plant. Delivery delays depend on supplier internal and external disruption probability. For each available strategy two or more casual loops has been identified, both balancing (B) and reinforcing (R) ones:

- *Buffer-based methods* ([1], [2], [3], [8], [18], [21], [26]): on the one hand, delays in supplier deliveries increase the quantity stocked by the company, the inventory and total costs, and decrease the cash flow needed to make further capital investment in inventory (Stock2); on the other hand, increase in inventory level decreases the transparency and coordination in the relationship and then even more stocks are taken to buffer uncertainty (Stock1).
- *Integration investments* ([4], [6], [9], [11], [16], [17], [23], [24], [25]]): cash flow gives the chance to make integration investments; through this kind of investments, a firm can increase transparency and coordination level with its supplier and, hence, decrease delivery delays, buffer size and costs, raising the cash flow needed to make new investment (Integration1); on the contrary, these investments increase the inflexibility costs, raising total costs and decreasing cash flow availability (Integration2). Referring to transparency loop (Transparency), increasing transparency decreases the information asymmetry between buying firm and supplier and, consequently, decreases the supplier opportunistic behavior risk and raises the willingness to achieve a more transparent relationship.
- *Supplier development investments* ([7], [9], [13], [14], [15], [17], [23]): cash flow availability increases the chance to make supplier development investments to reduce both delay probability and transaction cost and achieve a cash flow increase

(Development1 and Development2); on the other hand, supplier development investments raise the company dependence on supplier and the supplier opportunistic behavior risk, reducing transparency and increasing delay probability, stock requirement, costs and decreasing cash flow availability (Development3). Additionally, integration degree between the two firms is positively correlated to an effective supplier performance increase.

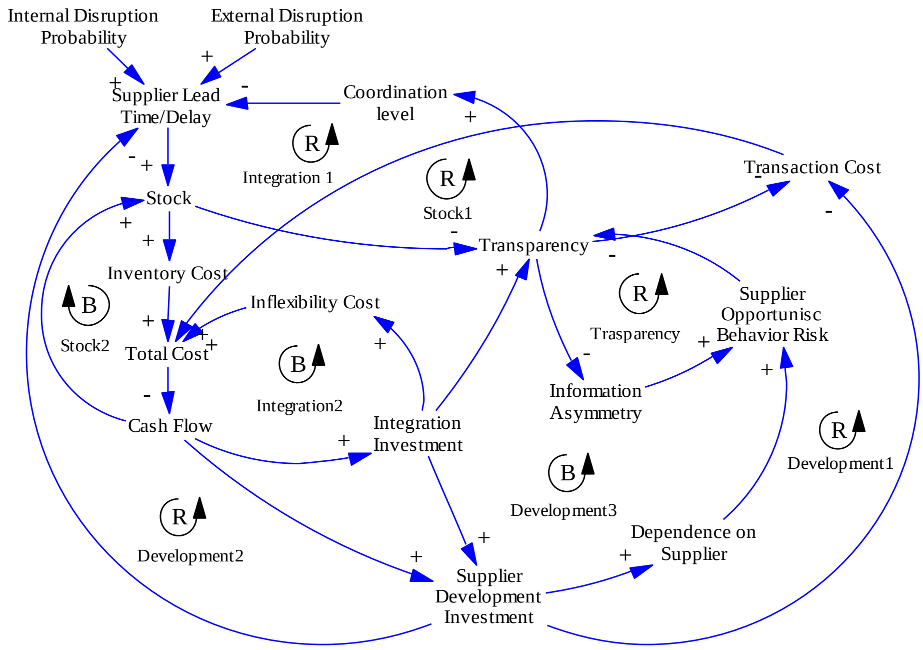

Figure 1 - The proposed model

5. Conclusion

Supply risk has become one of the major concern companies are facing. In this paper, methods and strategies to deal with supply risk are identified and classified in buffer-based methods and behavior-based strategies. A Systems Thinking model, aiming at explaining the logical relationships among these different strategies and at analyzing the impact of different investment mix on supply uncertainty reduction and total cost minimization, is presented. The main limitation of this model is that it does not consider all variables influencing supply uncertainty and the adoption of different strategies. Moreover, relationships among variables are given only by a logical point of view. To solve this last problem System Dynamics methodology can be useful, because it is based on Systems Thinking, but takes the additional steps of constructing and testing a computer simulation model.

Thus, the model presented in this paper is only a first step towards a more comprehensive one, where more variable will be considered and a System Dynamics simulation will be carried out. In order to shift the present model in a System Dynamics one, quantitative relationships among variables should be added to allow a computer simulation. Finally, model validation will be realized through simulation and policy analysis in organizations belonging to different industries to evaluate its value in environment with different risk and uncertainty degrees. Since the supply risk level and the strategy impact depend on firm and market characteristics, this will not be a prescriptive model and it will not suggest a standardized firm behavior and a unique strategy mix. At the contrary, based on context characteristics, it will be possible to set the different parameter values and their reactions to strategies in order to understand the system behavior, its sensitivity to initial and boundary conditions.

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Purchasing strategy under supply risk in a single-period problem

Fabiana Pirola[1], Roberto Pinto[1], Vittorio Moriggia[2], Gaetano Iaquinta[2]

[1] *CELS – Research Center on Logistics and After-Sales Service – University of Bergamo*
[2] *Department of Mathematics, Statistics, Computing and Applications – University of Bergamo*
E-mail: <fabiana.pirola; roberto.pinto; vittorio.moriggia; gaetano.iaquinta>@unibg.it

Abstract

In today's environment, characterized by rapid technological development, globalization and increased competition, procurement management has become a key factor to achieve competitive advantage. Defining a procurement strategy means to identify the optimal number of suppliers, considering both costs and supply risk, and then select the most appropriate suppliers to deal with. The aim of this paper is to identify the strategy a supply manager should follow in order to define an optimal purchasing policy, under demand uncertainty and supply risk. To do this, a two-stage stochastic optimization problem is formulated to help managers in the supplier selection process and in the determination of the quantity to be ordered to each of them, fulfilling the demand and minimizing the total cost.

Keywords

Multiple sourcing, single period problem, supplier selection, supply risk, stochastic optimization

1. Introduction

The rapid technological development, the globalization trend and the increased competition level, push firms towards the attainment of supply chain management improvements in order to achieve lower costs, faster deliveries and higher service level. In this context, procurement management has become a key factor to reach competitive advantage, especially in those contexts where the relationships with suppliers are dynamic, volatile or short-term based (i.e. as in the context of Virtual Enterprise Networks). As stated by Kraljic [8], a supply strategy aims at minimizing supply vulnerability and making the most of potential buying power. Moreover, a proper purchasing strategy impacts on organizational performance not only in term of supply cost and supply reliability, but also by affecting important activities, such as inventory management or production planning and control [6]. Strategy definition encompasses several activities that should be made by purchasing managers, such as purchase's nature analysis, supplier market analysis, potential supplier identification and evaluation, and supplier selection [10]. The increased complexity of today's environment urges for a more systematic and transparent approach to purchasing decision making, especially when it comes to decide to which supplier(s) among those qualified place a new order. At the same time Operations Research offers a range of methods that can support this process (such as multi-criteria decision aid, mathematical programming, data mining techniques and so on), enhancing both effectiveness and efficiency of purchasing decisions [5].

Problem description and goal of the paper

We consider an extension of the classical *single-period problem* (*SPP*, also known as *newsvendor* problem [7]) where the aim is at finding the right size of one-shot order when the demand for the item is unpredictable. It is assumed that if any inventory remains at the end of the period, it is disposed of at a given cost. On the other hand, if the order quantity is smaller than the realized demand, the company forgoes some profit.

Further assumptions are needed in our extension:

- As in the classical setting, the buyer places its order before the starting of the selling period. We let the retailer place a second order after the realization of the demand, at a higher unit price than the first order, to recover from potential backlog occurred. This setting is typical of the fashion sector, but it can be applied in any sector.
- The buyer can place its orders to one or more suppliers (belonging to the set of qualified suppliers) at the same time. We assume that suppliers are not completely reliable and may lose their abilities to supply (i.e. due to their geographical position or intrinsic reliability; we assume that a reliability rating is available to the buyer from internal or external sources); hence, the buyer should decide to which supplier(s) place an order and for which quantity, considering disruption risk.
- We focus on *capacity disruptions* that cause the loss of all of the production at a supplier or group of facilities for a fixed period of time due to a single cause like financial instability, a strike, product quality issues, even fire, earthquake, hurricane, act of terrorism, etc.. The problem can easily be extended to comprise context in which disruption causes the loss of a portion of the production capacity.
- The selection of the suppliers to which place an order involves the definition of the right number of suppliers to deal with. In fact, we assume that a multi-sourcing setting reduces the likelihood of disruption, but at the same time it involves higher costs due to the management of multiple relations.

Given the above problem setting, this paper aims at identifying the main strategy a supply manager should follow in order to define an optimal purchasing policy, considering supplier related risk factors. To do this, a two-stage stochastic optimization problem is formulated to help managers in the selection process under both demand and supply uncertainty. The goal of this problem is to select the most appropriate suppliers and determine the quantity to be ordered to each of them, fulfilling the demand and minimizing the total cost.

This paper is organized as follow: Section 2 gives a brief literature overview about purchasing strategy definition process and supply risk; in Section 3 a two-stage stochastic model, aiming at supporting ordering decisions is proposed and some managerial insights are presented; finally Section 4 concludes the paper with some remarks and practical applications.

2. Selected literature review

Defining a supply strategy means to *identify the optimal suppliers number* and then *select the most appropriate suppliers* to deal with. Regarding the optimal number, a firm can choose among different solutions, ranging from single sourcing to multiple sourcing. In the multiple sourcing strategy, suppliers are in competition with each others and the buying firm negotiates with them; through negotiation, a firm can obtain lower acquisition and shipping costs, but, due to the longer time required, fixed costs related to suppliers management are higher [3]. On the contrary, in the single sourcing situation the buying firm develops a long term relationship with one supplier, allowing a leaner relationship management; thus, fixed costs are lower and the firm can achieve more commitment from supplier, a higher stability on supplied materials quality and even low costs due to economies of scale. Even though the diffusion of lean manufacturing and JIT approaches have favored the use of few suppliers ([4], [11]), the choice depends on several factors, encompassing the impact of acquisition cost on firm revenue (for example if the product has a marginal impact on firm revenue, the most probably strategy adopted will be the multiple sourcing), the type of product (in case of specialized product, few or even one suppliers will be selected), the suppliers availability, and so on.

Another important factor to be considered in supply strategy identification is the *supply risk*. Although there is a lot of literature that study risk in management and operations field, there is limited research that explicitly analyzes risk assessment and risk management in the context of inbound supply [14]. Supply risk is defined as “the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety” [13]. This risk is not represented only by catastrophic events, such as an earthquake or a hurricane, but it is also related to supplier characteristics, such as financial stability, manufacturing capacity constraints or quality and technological changes. Generally, when an organization reduces its supply base, this risk increases [3]. Consequently, from the supply risk point of view, in the multiple sourcing strategy the risk-related cost is lower than in the single sourcing because the probability of supply interruption decreases; in fact, even if one supplier fails, the firm can buy the materials from another supplier.

The second relevant issue in defining supply strategy is suppliers evaluation and selection. This problem has been one of the major topics in operations and supply management literature for decades and researchers suggested different criteria to evaluate suppliers, encompassing organizational (for example financial stability, technology, manufacturing capability) as well as operational (such as quality and delivery) related factors [11]. In addition, different models, both qualitative and quantitative, have been proposed to support the suppliers selection process [5]. In the following section a stochastic programming model is formulated in order to support decision makers in supplier selection process. This kind of model allows the decision-maker to formulate a problem as a function to be maximized or minimized. The main advantage of this approach is the objectivity because the decision function has to be clearly defined; on the other side it consider only quantitative criteria and only hardly takes into account the more qualitative ones 5.

3. The proposed model

Considering the problem setting stated in Section 1, we refer to a company which should buy a single item. Each supplier has its own characteristics, from prices to distance from the company. Moreover, we would take into account the disruption risk of each supplier (that is, when a supplier is not able to supply the committed quantity on time or at all).

In the process we aims at minimizing the total cost given by the sum of acquisition costs (different for each supplier), disposal/backlog costs, fixed costs, supplier risk costs and supply chain risk cost. Given these assumptions, we define the following parameters (Table 1):

Variable	Definition
p_m	Disruption probability of supplier $m \in M$, where M is the set of suppliers
c_m^{NET}	Unit acquisition cost, including transportation cost if bear by the company
c_m	Unit acquisition cost from supplier m, including a risk percentage related to the specific supplier; that is, $c_m = c^{NET}{}_m \cdot (1 + risk_m)$
$risk_m$	Disruption risk of supplier m (see later for the definition)
d_k	Expected demand
F_m	Fixed cost of supplier m, when an order is placed
CAP_m	Expected capacity of supplier m in units
L_m	Minimum batch from supplier m
H	Disposal cost per unit of product
bk	Backlog cost
b_m	Expediting cost from supplier m per unit of product
Cr	Supply chain risk cost tied to the number of suppliers (the greater the number of suppliers, the lower the risk). It could be set equal to the overall losses the company will incur if all the suppliers fail (or if no suppliers is activated)

I_0	Initial inventory level
R	Discount rate, needed since we consider a finite, non-zero interval between the first and the second order

Table 1 - Parameters definition

4. Model formulation

This model is formulated as a two-stage stochastic program [15] that attempts to *(i)* minimize the total cost, considering both the single supplier disruption probability and the supply chain risk tied to the number of supplier, *(ii)* avoid ordering more than actual demand from supplier, which leads to disposal cost and *(iii)* safeguard against ordering less than necessary, which results in backlog and expediting costs.

As in traditional stochastic programming approaches, the objective function consists of the sum of the first-stage performance measures and the expected second-stage performance, and most commonly, the dominant uncertain parameters are the product demands 1. In our approach, not only demand, but also capacity at supplier level is considered as the uncertain parameters, depending on the realization of an adverse event. We assume the empirical reliabilities of suppliers are known in advance, but the actual situations of suppliers become clear after the realization of an event.

Our model uses the following variables:

- x_m = quantity ordered from supplier $m \in M$
- $y_m = \begin{cases} 1 \; if\ an\ order\ is\ placed\ to\ supplier\ m \\ 0 \; otherwise \end{cases}$
- w_{mk} = second order size (quantity to be expedited from supplier m) in order to recover from backlog

Variables that represent the order volumes in both stages are assumed to be continuous non-negative variables to ease the computational requirements to solve the resultant optimization problem. This approximation is minor because the magnitude of these variables will be so large that rounding them has little effect on the solution [11].

Now we can define the two stages of the problem as follows.

First stage: the first stage variables correspond to those decisions that need to be made here-and-now, prior to the realization of the uncertainty. In this case, the first stage decisions are the suppliers selection (y_m) and the quantity ordered to each supplier (x_m). The first stage problem is formulated as follows:

$$\min \sum_{m\in M} c_m \cdot x_m + \sum_{m\in M} F_m \cdot y_m + \left(M - \sum_{m\in M} y_m\right) \cdot Cr + \frac{E\left(G(x,\xi)\right)}{(1+r)} \qquad (1)$$

s.t

$$x_m \le y_m \cdot CAP_m \qquad \forall\, m \in M \qquad (2)$$

$$x_m \ge y_m \cdot L_m \qquad \forall\, m \in M \qquad (3)$$

$$\sum_{m \in M} x_m + I_0 \geq \mu \qquad (4)$$

$$x_m \geq 0 \qquad \forall\, m \in M \qquad (5)$$

$$y_m \in \{0; 1\} \qquad \forall\, m \in M \qquad (6)$$

Regarding the constraints, (2) assures that if supplier *m* is selected, the quantity ordered should not exceed its capacity; (3) defines the minimum lot for each supplier (it could be 0); (4) is a balancing equation between the size of the order, the quantity on hand and the expected demand; (5) and (6) are the usual non-negative and binary constraints.

Second stage: the second stage variables correspond to those decisions made after the uncertainty is unveiled and are usually referred to as *wait-and-see* decision. In this case, the second stage decision is represented by t_k, that depends on disposal/backlog costs and on costs related to the quantity to be expedited (w_{mk}).

For this second stage, we define the scenario $\xi_k = (d_k, \Theta_k)$, where $\Theta_k \in \{0\,;1\}^{|M|}$ is an array of size $|M|$ where each element θ_{mk} when equal to 0 represents the occurrence of a disruption at supplier *m* in scenario *k*; d_k is the actual demand that follows a given probability distribution. Every scenario has a probability p_k to occur.

The objective of this stage is to find out $G(x, \xi)$, that is the optimal value of the following problem:

$$\min \sum_{k \in K} p_k \cdot t_k \qquad (7)$$

s.t.

$$t_k \geq \sum_{m \in M} b_m \cdot w_{mk} + bk \cdot \left(d_k - \left(\sum_{m \in M} x_m \cdot \theta_{mk} + I_0\right)\right) \qquad \forall\, k \in K \qquad (8)$$

$$t_k \geq h \cdot \left(\left(\sum_{m \in M} x_m \cdot \theta_{mk} + I_0\right) - d_k\right) \qquad \forall\, k \in K \qquad (9)$$

$$x_m \cdot \theta_{mk} + w_{mk} \leq y_m \cdot CAP_m \cdot \theta_{mk} \qquad \forall\, m \in M, k \in K \qquad (10)$$

$$\sum_{m \in M} w_{mk} \geq d_k - \sum_{m \in M} x_m \cdot \theta_{mk} - I_0 \qquad \forall\, k \in \qquad (11)$$

$$x_m \geq 0 \qquad \forall\, m \in M \qquad (12)$$

$$y_m \in \{0; 1\} \qquad \forall\, m \in M \qquad (13)$$

$$w_{mk} \geq 0 \qquad \forall\, m \in M, k \in K \qquad (14)$$

In this second stage programming model, (8) and (9) define the expenditure cost due to backlogs and the stock disposal cost, respectively. In fact, a backlog cost is incurred in if the demand overcomes the sum of first stage order and on hand inventory, while otherwise a stock disposal cost for the remaining part arises. (10) ensures that the sum of first and second stage order does not overcome the total supplier capacity; (11) defines the size of the second stage order (expedited quantity); (12)-(14) are non-negative and binary constraints.

About the differences in the structure of backlog and stock disposal cost, expressed in equations (8) and (9), we can state that in case of backlog the company incurs in expediting cost ($b_m \cdot w_{mk}$ that depends on the selected suppliers) for the backlogged quantity, plus a cost due to penalties ($b_k \cdot w_{mk}$ that only depends on the backlogged quantities) for the delays.

We can easily notice that the non-anticipativity is guaranteed by the first stage decisional variables x_m, that do not depend on scenarios.

Computational experiments

In this paper we are interested in the managerial insights that the proposed model can provide rather than the algorithmic aspects for efficient model solving. Hence we do not provide deep discussion about algorithmic strategy in this paper, referring the reader to other specialized sources. To assure a high level of efficiency, we solved our model with CPLEX in GAMS development environment in a standard Intel Pentium IV based Personal Computer.

We assume the following data and parameters:

- Acquisition costs and failure probability (Table 2):

Supplier	Acquisition Cost (c_m)	Failure Probability
1	10	0.4
2	15	0.3
3	25	0.1
4	21	0.2

Table 2 - Acquisition costs and failure probability

- The backlog cost *bk* can be defined considering the average selling price *PR* for the company:

$$bk = PR \cdot (1 + \omega)$$

where *PR* is 30 € and ω is a given spread that depends upon the company. In this paper we let ω varying between 0.2 and 0.5 and considering 4 case-studies to solve the model with different backlogs (Table 3):

ω	Backlog cost
0.2	36
0.3	39
0.4	42
0.5	45

Table 3 - Backlog cost

- The expediting price b_m depends upon the cost as:

$$b_m = c_m \cdot (1 + \gamma_m)$$

where γ_m is the cost spread required by supplier *m*. For the sake of simplicity, we can assume w.l.o.g $\gamma_m = \gamma$ for each *m*. In this paper we let γ varying between 0.1 and 0.4 (Table 4):

γ	Expediting cost supplier 1	Expediting cost supplier 2	Expediting cost supplier 3	Expediting cost supplier 4
0.1	11	16.5	27.5	23.1
0.2	12	18	30	25.2
0.3	13	19.5	32.5	27.3
0.4	14	21	35	29.4

Table 4 - Expediting costs

- The risk cost *Cr* is expressed as the overall losses the company will incur if all the expected demand is not fulfilled:

$$Cr = PR \cdot \mu$$

where the demand follows a normal distribution, with μ = 1500 and σ = 200

- Disposal cost: 25 €

We solve the optimization model for each backlog cost and each expediting cost. In each problem instance we used 100 scenarios. As stated before, we consider only disruptions that prevent the supplier to provide the whole order.

Main results

We can summarize the results of the optimization as follows:

- In general, the total quantity is split especially between supplier 1 and 3, respectively the cheapest and the most expensive ones (Table 5): in particular, the major quantity is ordered from the supplier 3, that is the most expensive one but also the less risky one (except in case of ω= 0.2 and ω= 0.1, where supplier 1 is favored).

Supplier	Expediting cost	Backlog cost = 36 (ω= 0.2)	Backlog cost = 39 (ω= 0.3)	Backlog cost = 42 (ω= 0.4)	Backlog cost = 45 (ω= 0.5)
1	12	426	441	419	390
2	18	0	0	0	0
3	30	992	977	999	999
4	25.2	10	31	41	79
Total quantity		1428	1449	1459	1468

Table 5 - Example of the optimization for ω= 0.2 and different values of ω

- The greater the backlog cost (ω), the greater the total quantity ordered (Table 5).
- The greater the backlog cost, the greater is the quantity ordered from the less risky supplier (supplier 3 and 4), even if they are the most expensive (Figure 1).

- The greater the expediting cost (γ), the greater the quantity ordered from the less risky supplier (supplier 3 and 4).
- Additionally, decreasing the failure probability of supplier 3, all quantity is ordered from this supplier.

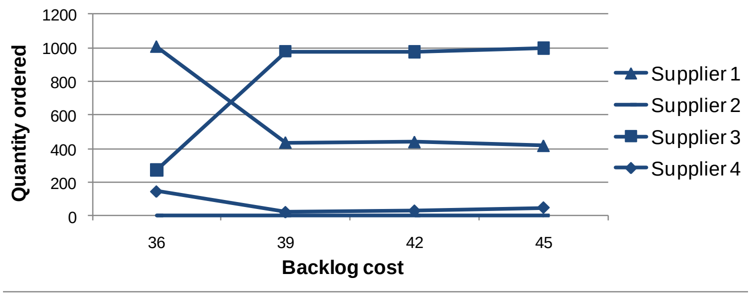

Figure 1 - Quantity ordered from each supplier in case of γ = 0.1 and different backlog costs

5. Conclusions

This paper aims at investigating, through a two-stage stochastic model, the trade-off between costs related to handling multiple suppliers and risk related to manage few suppliers. The computational experiments provide directions for supply strategy formulation in case of four suppliers with different acquisition costs and different failure probabilities. Results demonstrate that the supply risk is the most important factor in order allocation, especially in case of high expediting and backlog costs.

Possible further extensions of this work can be on the following directions: *(i)* considering multi-period problems; *(ii)* considering the loss of only a portion of the production capacity; *(iii)* evaluating how long-term relationship with some suppliers, built in order to reduce supply risk, can affect strategy formulation and total costs; *(iv)* studying sensitivity and post-optimality analysis.

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Investing in Suppliers to Reduce Risk. A Conceptual Model and an Attempt of Quantitative Assessment

Fabiana Pirola, Roberto Pinto, Sergio Cavalieri

CELS – Research Center on Logistics and After-sales Service
University of Bergamo
viale Marconi 5, 24044, Dalmine, Bergamo, Italy
{fabiana.pirola; roberto.pinto; sergio.cavalieri}@unibg.it

Abstract

Suppliers play a key role for the success of a company, whose performance can be greatly improved by the definition of an effective purchasing strategy. An even more relevant factor to be considered in the strategy definition process is the risk related to the inbound flows. Thus, the aim of this paper is twofold: first, a conceptual model providing a comprehensive description of the relationships between company performance, supply risk and the strategies available to reduce impact or occurrence probability of risky events is presented. Secondly, a two-stage multi-period stochastic programming model is proposed, aiming at providing some managerial insights about the advantage of undertaking supplier development investments in order to increase supplier reliability and reduce supply risk.

Keywords

Supply Risk, System Thinking, Stochastic Programming.

1. Introduction

A successful supply chain management entails the definition of an effective sourcing strategy in order to achieve a competitive advantage. Suppliers have become a key component of success because a right choice of supply sources allows the company to reduce costs, increase profits, improve quality and assure on time delivery to customers [17]. For this reason, purchasing is receiving increased attention in many firms and suppliers selection is becoming a strategic level decision, which encompasses different trade-offs; for example, decreasing the number of suppliers can be effective in terms of costs because of scale economies but, on the other hand, can increase the risk of not having sufficient inbound materials if some supply disruptions occur. These disruptions can be caused by natural disasters or by supplier internal problems ([4], [17], [25]). Thus, managing supplier-side uncertainty is today recognized as a relevant factor in developing supply chain strategies, especially due to the complexity and extension that supply chains have reached in the global market. In addition, a recent survey conducted by AMR Research [22] shows that, as a consequence of the today world crisis, perception of risks in most companies managing a global supply chain has shifted in the past 12 months. In fact, while in 2008 the prevailing concerns focused heavily on transportation costs (due to the increasing fuel expenses) and surging commodity prices, in 2009 default of suppliers turned out to be the first perceived supply chain risk.

Common methods employed to manage supply uncertainty are *buffer-oriented* methods, including holding stock to reduce the stock out likelihood in case of delivery delay. These methods represent only an attempt to reduce detrimental effects of risky events, rather than decrease their occurrence probability, and greatly contribute to increase the overall costs.

An alternative and more effective method to reduce supply uncertainty is to deeply analyze its sources and consequently undertake *behavior-based* strategies, that focus on supplier processes rather than on its outcomes and comprise *supplier development activities*, that are any efforts initiated by the purchasing organization in order to better align suppliers' objectives with those of the buyer's [29].

This paper contributes to the discussion on the definition of a suitable supply risk management strategy, for a given supply context, by proposing two models:

1. A *conceptual model*, leveraging on the formal clarity of *System Thinking* approach, in order to provide a general and comprehensive description of the dynamics among the variables involved in the strategy definition process;
2. A *two-stage multi-period stochastic programming model* aiming at provide some managerial insights about supplier selection and quantity allocation when a supply base is available and the company can decide whether to make a supplier development investment aiming at increasing its reliability, sign a framework agreement with suppliers or buy through spot purchasing.

This paper is organized as follows. In Section 2, a literature background on buffer-oriented and behavioral-based strategies is reported. Then, in Section 3, the relationships among these possible strategies, the supply risk and company performance are conceptually modeled using System Thinking approach. Section 4 presents a two stage stochastic programming problem aiming at qualitatively defining a purchasing strategy, using buffer-oriented methods and behavior-based strategies. Section 5 gives some computational results and, finally, some remarks and indications for further research conclude this paper in Section 6.

2. A Literature Review On Buffer-Oriented And Behavior-Based Strategies

Today companies are facing an increasingly complex environment, characterized by different kinds of risks. Among them, supply risk can be defined [30] as "the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety". Starting from this definition, the consequences of supply risk occurrence are delays in supplier deliveries and, then, inbound materials unavailability at the buyer's plant. Furthermore, if appropriate mitigating plans are not in place, possible disruptions in the company's processes and schedules can happen affecting its ability to continue operations, get finished goods or provide services to customers ([3], [11]).

A common way to reduce uncertainty and avoid supply risk is buffering the effect of the risk through stocks, capacity buffers or multiple suppliers, in order to ensure the continuation of the business and on-time delivery to customers ([3], [10], [31]). These methods belong to the so called *buffer-oriented* methods, as defined by Zsidisin [29], where buffers are an outcome-based approach to deal with risks that attempt to reduce its detrimental effects, rather than decreasing the occurrence probability of an undesired event.

One of the main effects related to the occurrence of a supply risk is the delay in supplier delivery. To avoid operation disruptions, an organization can decide to increase buffer sizes, in terms of inventory, capacity and/or backup suppliers. This is a well known remedy in the supply chain management literature, where in the past several authors ([7], [12], [18], [20], [23], [26]) have proposed quantitative models aiming at defining the better quantity to be buffered, especially in terms of inventory. Theoretically, the greater is the risk associated to the inbound logistic flows, the greater is the stock out probability and, then, the greater should be the buffer size. However, as the buffer level increases, the visibility of the upstream and downstream flows and stocks decreases. Due to the lack of visibility, confidence in the supply chain declines and further buffers are taken to cope with uncertainty [5]. As a result, the buffer level would continuously increase and, consequently, it would boost up the production costs for the buying firm (in terms of major inventory costs due to storage space, potential obsolescence and capital investment in stocks, and in terms of additional capacity costs due to the employment of more workforce or lower production yields). Hence, the cash flow availability for further investments would be seriously affected [3].

An alternative and more effective method to reduce supply uncertainty is to deeply analyze its sources and consequently undertake *behavior-based* strategies, that focus on supplier processes rather than on its outcomes [29]. These strategies include the *supplier development* activities, defined by Krause [13] as “any effort by a buying firm to improve a supplier’s performance and/or capabilities to meet the buying firm’s short and/or long term supply needs”. These activities can be characterized by different levels of buying firm commitment. In fact, the buying firm can decide to commit itself only if supplier improves (for instance promising incentive to suppliers) or choose an active involvement in supplier development. “Table 1” reports the possible supplier development activities and the related company commitment.

Activities to improve suppliers’ performance and capabilities	**Buying company commitment**
Increasing communication and information sharing with supplier	Direct involvement
Evaluation of supplier performance	Direct involvement
Certification program by a buying firm representative (no further inspections required)	Direct involvement
Raising performance expectations	Direct involvement
Recognition and awards for outstanding suppliers	Only if supplier improves

Activities to improve suppliers' performance and capabilities	Buying company commitment
Promises of increased present and future business if supplier performance improves	Only if supplier improves
Training and education of a supplier's personnel - providing suppliers with training	Direct involvement
Exchange of personnel between the two firms	Direct involvement
Direct investment in a supplier by the buying firm - providing suppliers with equipment and technological support	Direct involvement

Table 1 - Supplier development activities (adapted from [15])

Research findings ([9], [13], [14], [15]) demonstrate that, through these activities, suppliers increase on-time and complete order fulfillment delivery, as well as reduce non conformities and order cycle time. In addition, from a transaction cost analysis, supplier development practices allow a reduction in both transaction and production costs ([6], [14], [28]). Regarding the former costs, Dyer [6], in its study, shows that lower transaction costs are associated to repeated exchanges, greater total volume of exchange between transactors, higher degree of information sharing and specific investments; these are typical features of relationships where supplier development activities are carried out. From the point of view of production costs, integration with few suppliers allows to take advantage of scale and scope economies and then to reduce unit costs of items. Furthermore, since company investments in suppliers ensure long term relationships and process improvements and optimizations, these activities also contribute to decrease the supplier default probability.

Obviously, investments in supplier development represent also a risk for the buying firm because they are non transferable and benefits are unrecoverable if the relationship is prematurely dissolved ([14], [28]). Furthermore, increasing the investment level increases benefits but also increases the firm's dependence on suppliers and reduces its negotiation power, causing a higher supplier opportunistic behavior risk ([1], [8], [16]). This risk reduces the willingness to share information, lowering the level of transparency and coordination between companies.

Analyzing the literature, while authors studying buffer-oriented methods generally do quantitative studies in order to identify the best quantity to be buffered, researches about behavior-based methods are more qualitative and descriptive. In fact, the different authors that deal with supplier development or similar strategies, typically carry out only surveys and case studies, in order to give some insights into the actual employment of these strategies and their perceived benefits. In addition, an effective comparison model between these two main types of strategies, aiming at supporting organizations in strategy definition considering system complexity and logical relationship among variables, is still missing.

In order to fill these gaps, a System Thinking model, supporting organizations in identifying the impact of buffer-oriented and behavior-based methods on firm's performance, is presented hereafter. Then, in Section 4, a two-stage multi-period stochastic problem is proposed in order to quantitatively describe the decision making problem a firm would face when deciding whether to make investments on the development of a supplier and how much to invest.

3. Modeling The Impact Of Supply Risk Management Strategies

System Thinking methodology has its foundation in the field of System Dynamics, developed in 1956 by Jay W. Forrester at the Massachusetts Institute of Technology (MIT) [27].

Systems Thinking methodology might be thought as a language to depict and understand interactions producing system behaviors. As referred by Senge [24], it aims at seeing interrelationships among system parts rather than linear causal-effect chains and seeing processes of change rather than snapshots. This methodology is based on causal loops diagrams, that are an important tool for representing the feedback structure of systems. They consist of variables connected by arrows denoting causal influences, describing what would happen if there were a change.

Based on this methodology, the model in "Figure " represents both the positive and negative impacts of buffer-oriented methods and behavior-based strategies on firm's performance. The relationships among variables are built based on the literature ("Table "). A plus (+) sign at the end of the arrow between two variables indicates that such variables change in the same direction, while the minus (-) sign indicates that they change in the opposite direction. For instance, when the probability of supplier delay increases, the buffer size to cope with uncertainty also increases, as indicated by the plus sign at the end of the arrow between "supplier delay" and "buffer size" variables. On the contrary, when the total cost increases, the cash flow availability to make new investments decreases, as indicated by the minus sign at the end of the arrow pointing at "cash flow". Furthermore, the plus signs inside the parentheses next to the loop names indicate a positive loop, or a self-reinforcing feedback system, which contains the mechanisms to amplify whatever is happening in the system. The minus signs indicate a negative loop, or a self-correcting feedback system, which, on the contrary, opposes the change and seeks a steady state of the system.

As mentioned in the previous section, one of the main consequence of supply risk is delivery delay, so supply risk is measured as *supplier delay*. This variable includes also the supplier default risk because, if it occurs, the ordered quantity will be lost and the delay will conventionally grow to infinity. In addition, the behavior-based strategies are grouped in the variable "supplier development investment", that encompasses all the different, but not mutually exclusive, available strategies, from information sharing to direct investment in the supplier operations. Obviously, depending on the implemented strategies and on market specific characteristics, the impact on costs and performance would differ. In "Figure 1" the System Thinking model is represented and in "Table 2" the main loops identified are briefly described.

Analyzing the relationships represented in “Figure 1”, a firm can better understand the impacts of its sourcing strategy, especially concerning the adoption of buffer-oriented and/or behavior-based methods.

In this strategy definition process, the main decisions concern supplier selection, including the definition of the number of supplier to use (in this sense, representing a buffer-oriented method), and supplier development investment allocation (behavior-based method), the latter made in order to achieve an improvement in the supplier processes, ensuring its reliability and stability increase.

In the next section, an attempt to quantitatively assess the most suitable strategy considering buffer-oriented methods, behavior-based strategies, supplier delay and default probability is proposed.

	Loop Name	**Type of loop**	**Description**	**References**
Buffer-oriented methods	Buffer1	Positive	Increasing buffer size decreases transparency and coordination among actors and, then, increases supplier delay probability	[5], [26]
	Buffer2	Negative	Increasing buffer size increases costs and decreases cash flow availability to make new investments	[3], [20], [29]
Behaviour-based strategies	Development1	Positive	Increasing cash flow increases the chance to make supplier development investments and, then, decreases transaction and production costs	[14], [6], [19], [28]
	Development2	Positive	Increasing supplier delay probability increases the willingness to improve supplier performance and then to make supplier development investments to reduce supplier delay probability	[9], [13], [14], [15], [29]
	Development3	Negative	Making supplier development investments increases the dependence on supplier and the supplier opportunistic behaviour risk and, consequently, decreases the coordination level, raising the delay probability	[1], [8], [16],[28]
	Development4	Positive	Making supplier development investments increase the transparency and the coordination between firms, reducing supplier delay probability	[1], [5], [19]
	Development5	Negative	Increasing transparency, through supplier development investments, decreases the information asymmetry between a buyer and a supplier and, then, the supplier opportunistic behaviour risk	[19]

Table 2 - Description of the loops in the Systems Thinking model

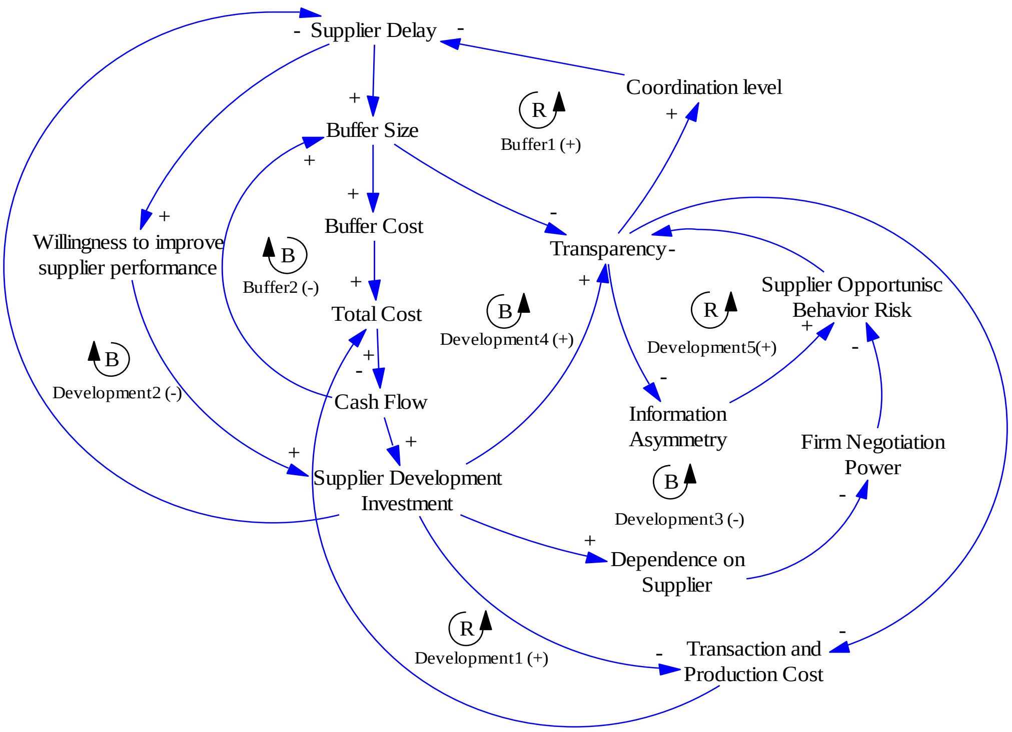

Figure 1 - The System Thinking model

4. A Quantitative Assessment Of Supply Risk Management Strategies

Problem Description

Within a supply chain, suppliers play a key role for the success of a focal company since the selection of suppliers influences costs, profit margins, component quality and timely delivery. In order to choose the right suppliers, a company has to define a *sourcing strategy*, characterized by three key decisions [2]:

1. A criterion for establishing a *supply base*, composed by all the suppliers that meet the quality, delivery, and other objectives of the buying company. Scoring models which rank each supplier in terms of objectives are typically used to evaluate suppliers for inclusion in the base.
2. A criterion for selecting suppliers (a subset of the base) who will actually receive an order from the company. Generally, not all suppliers in the supply base will receive an order; hence, from the approved supply base, a specific subset of suppliers which will actually receive an order to fulfill the demand for a specific product must be determined. Dominant industry practice appears to base this decision primarily on cost considerations.
3. The quantity of goods to order from each selected supplier. Once the selected set of suppliers (a subset of the base) is determined, the firm must allocate product(s) requirements among them. While the supplier's price quote is important, for the allocation decision other factors such as supplier yields (in terms of percentage of ‘‘good’’ units), delivery reliability, order quantity policies, and transportation costs are typically considered.

Focus of this paper is on the latter two decisions about *supplier selection* (i.e. the selection of suppliers among the supply base to which place orders) and *quantity allocation* (i.e. the size of the orders). Hence, we assume that the firm has already established an adequate supply base.

In order to select suppliers from the supply base, we consider a company working with framework agreements. The purpose of a framework agreement is to establish the terms governing contracts to be awarded during a given period, in particular with regard to price and quantity. In other words, a framework agreement is a general term for agreements with providers which set out terms and conditions under which specific purchases (call-offs) can be made throughout the term of the agreement [21]. Through the framework agreement, the buying company and the supplier define a quantity X (*committed* or *contracted quantity*) that should be ordered over the entire planning horizon at a given unit cost c. Once the agreement is in place, in each time bucket of the horizon the buying company will order (call-offs) a quantity x coherent with its specific and contingent needs (thus, even null orders are allowed in some periods). The company should carefully determine contracts and quantities, and rely on spot contracts to cover potential lacks of materials from contracted suppliers.

As discussed in the previous section, when a company finds its suppliers lacking in performance it can help suppliers to develop their capabilities ([13], [19]). Buying firms that encounter shortcomings in supplier performance and/or capabilities have several alternatives:

- invest time and resources to increase performance and/or capabilities of their present suppliers (often referred to as *supplier development* or, more generally, behavior-based strategies);
- search for multiple suppliers (belonging to buffer-oriented methods);
- manufacture the purchased item in-house;
- choose a combination of the previous three alternatives [15].

Since supplier development can be a strategic weapon for the buying firm, in this work we focus on the combination of the first and the second option, considering the possibility for the buying firm to invest in the supplier development, in such a way to reduce the disruption likelihood. Clearly, an investment makes sense only for those suppliers that have a framework agreement in place. Hence, the investment is intended to reduce the risk in the medium-short term period, by means of reserving more capacity, or ensuring on time deliveries using dedicated trucks of a fast courier, when possible, and so forth. We implicitly assume that either the company has time to implement the investments in the suppliers or the time required to implement the investment is short.

The resulting classification of suppliers is depicted in “Figure 2”.

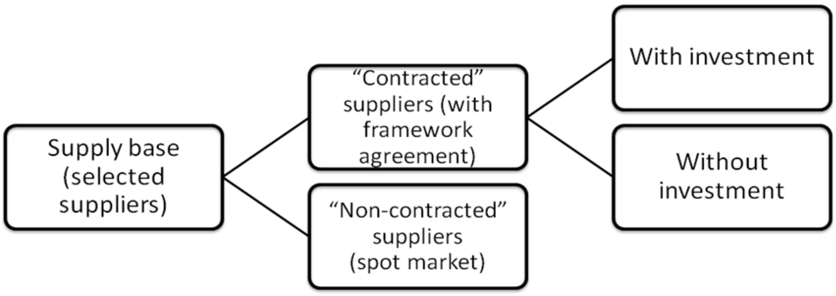

Figure 2 - Classification of suppliers

In order to define the quantity to allocate to each supplier (that is, the actual size of the orders) we have to define how to order the call-off quantities contracted with each supplier. Considering a multi-period planning horizon, we can deal with this problem in at least two ways:

1. An extremely simplistic approach that uniformly spreads the committed quantity X_m contracted with supplier m in equal parts just dividing the contracted quantity by the number of planning periods T, that is:

$$q_{mt} = \frac{X_m}{T} \quad \forall m \in M \tag{1}$$

2. A more realistic approach that explicitly considers the stock holding and backlog cost and the possible demand distribution over the planning periods. We assume this second option, since it leads to a more realistic problem and also includes option 1.

Hence, in the following problem formulation we deal with a single-product/multi-period problem. In the next section, a stochastic programming formulation of the problem is given.

Stochastic Programming Model

We present a two-stage stochastic problem (SP) formulation of the problem discussed so far. The SP model incorporates uncertainties by the inclusion of the recourse problem and probabilistic scenarios for demand and suppliers reliability. We consider two main sources of uncertainty, represented by supplier failure and delivery delay.

In the first stage of the problem, that is before the starting of the planning horizon and the realization of uncertainty, we aim at defining the optimal number of suppliers to deal with among a supply base composed by M suppliers, either signing a framework agreement or investing in their development in order to increase their reliability (that is, to reduce disruptions risk due to delivery delay or default). As stated before, if the company decides to invest in a supplier, it also signs a framework agreement with such supplier. Thus, let y_m be the binary variable representing the supplier m with whom a framework agreement is signed and z_m the variable representing a supplier that benefits from an investment. We assume that signing an agreement with a supplier implies a fixed cost F_m, while an average investment is valued Inv_m (clearly, $Inv_m > F_m$ since it includes the framework agreement cost).

First stage

$$\min \sum_{m \in M} \left(Inv_m \cdot z_m + F_m \cdot y_m \right) + E\left[G(Z, Y, \xi) \right] \tag{2}$$

$$z_m + y_m \leq 1 \qquad \forall m \in M \tag{3}$$

$$X_m \leq \left(z_m + y_m \right) \cdot B \qquad \forall m \in M \tag{4}$$

$$X_m \geq 0 \qquad \forall m \in M \tag{5}$$

$$z_m, y_m \in \{0,1\} \qquad \forall m \in M \tag{6}$$

where Y and Z represent the decisions about "contracted" and "invested" suppliers, respectively, and ξ represents the scenarios.

The objective function "(2)" encompasses all the relevant costs in this stage, comprising the expected cost E of the second stage decisions, while constraint set "(3)" enforces the fact that a supplier m can either benefit from an investment, sign a framework agreement or none of them.

For each contracted/invested supplier the size of the framework agreement X_m is defined before the actual requirements are known (constraint set "(4)", where B is a "big number"). For the sake of clarity, we assume that the size of the framework agreement does not influence the unit cost c_m that only depends on the supplier, even though this assumption can be removed by considering, for example, quantity discounts related to X_m.

It is worth noticing that the cost of the committed quantity X_m does not appear in the objective function of the first stage, since it will manifest itself along the planning horizon, depending upon the realization of the demand in the second stage.

A basic assumption of the model is that the investment in a supplier m leads to a reduction of both default and delay probabilities, while these values are higher in case of no investment. We also assume that the delay probability is not dependent on the framework agreement (i.e. the delay probability does not depend on the fact that a framework agreement is in place). All these probabilities are used in the definition of the scenario set Ξ used in the second stage problem.

Therefore, for a choice represented by a couple (Y, Z) and any scenario $\xi \in \Xi$ (where $|\Xi| = K$) we solve the following second stage problem with the aim at defining the actual orders (call-offs) to place in each period t to each supplier (x_{mkt} to "contracted" suppliers, $xinv_{mkt}$ to "invested" suppliers and q_{mkt} to spot suppliers). This second stage represents those decisions that should be made during the planning horizon when the uncertainties (actual demand, supplier default and delay occurrences) are unveiled.

Second stage

$$\min \sum_{k,t} p_k \cdot \omega_{kt} + \sum_{k,t,m} p_k \cdot c_m \cdot \left(x_{mkt} + xinv_{mkt}\right) + \sum_{k,t,m} p_k \cdot c_m^{SPOT} \cdot q_{mkt} \tag{7}$$

$$\omega_{kt} \geq h \cdot I_{kt} \qquad \forall k \in K, t \in T \tag{8}$$

$$\omega_{kt} \geq -bk \cdot I_{kt} \qquad \forall k \in K, t \in T \tag{9}$$

$$\sum_t (x_{mkt} + xinv_{mkt}) = X_m \qquad \forall m \in M, k \in K \tag{10}$$

$$xinv_{mkt} \leq CAP_{mt} \cdot z_m \cdot \left(1 - defaultinv_{mk(t-1)}\right) \qquad \forall m \in M, k \in K, t \in T \tag{11}$$

$$x_{mkt} \leq CAP_{mt} \cdot y_m \cdot \left(1 - default_{mk(t-1)}\right) \qquad \forall m \in M, k \in K, t \in T \tag{12}$$

$$q_{mkt} \leq CAP_{mt} \cdot \left(1 - y_m - z_m\right) \cdot \left(1 - default_{mk(t-1)}\right) \qquad \forall m \in M, k \in K, t \in T \tag{13}$$

$$\begin{aligned} I_{kt} = & \sum_m xinv_{mkt} \cdot \left(1 - \theta_{mkt}\right) \cdot \left(1 - defaultinv_{mkt}\right) + \\ & + \sum_m x_{mkt} \cdot \left(1 - \delta_{mkt}\right) \cdot \left(1 - default_{mkt}\right) + \sum_m q_{mkt} \cdot \left(1 - default_{mkt}\right) + \\ & I_{k(t-1)} + \sum_m xinv_{mk(t-1)} \cdot \theta_{mk(t-1)} \cdot \left(1 - defaultinv_{mkt}\right) \\ & \sum_m x_{mk(t-1)} \cdot \delta_{mk(t-1)} \cdot \left(1 - default_{mkt}\right) - d_{kt} \end{aligned} \qquad \forall k \in K, t \in T \tag{14}$$

$$I_{kT} = \hat{I} \qquad \forall k \in K \tag{15}$$

$$x_{mkt}, xinv_{mkt}, q_{mkt}, \omega_{kt} \geq 0 \qquad \forall m \in M, k \in K, t \in T \tag{16}$$

The objective function of the second stage considers acquisition costs from contracted suppliers (c_m), stock holding/backlog costs (ω_{kt}, expressed by constraint sets “(8)” and “(9)”, where h is the unit holding cost and bk the backlog cost) and the cost of acquiring the components from non-contracted suppliers (that is, from the market at a higher cost c_m^{SPOT}). In fact, the company can always place spot orders of quantity q_{mkt} to a supplier in the supply base without a framework agreement in place at price c_m^{SPOT}. In this case we assume that $c_m << c_m^{SPOT}$ and, since the contract is cash-based and related to short-term horizon, we assume that spot orders are delivered on time.

Constraint sets from “(11)” to “(13)” define the ordered quantities subject to capacity availability (CAP_{mt}) and supplier operating business. To this end, binary parameters $default_{mkt}$ and $defaultinv_{mkt}$, represent the occurrence of default of supplier m in period t in the scenario k. We assume that if the supplier m defaulted in the period $t-1$, the corresponding binary parameter is equal to 1 and no more orders can be placed to this supplier in following periods. The inventory levels I_{kt} in each time bucket is determined by constraint set “(14)”. It accounts for the actual quantities delivered in each period (we consider a lead time=0), that depends on the occurrence of defaults and delays, represented by binary parameters $default_{mkt}$, $defaultinv_{mkt}$, θ_{mkt} and δ_{mkt}. It is assumed that if the supplier *m* fails to deliver in period *t*, the quantity ordered for such a period will be delivered in the next period *t+1*, unless it defaults. In this latter case, if the supplier *m* defaults in the period *t+1*, the quantity ordered is lost. The demand in each time bucket of each scenario d_{kt} is considered within this constraint set. Finally, constraint set "(15)" defines the required level of inventory $\hat{I}$ at the end of the planning horizon.

Constraint set "(10)" requires further discussion; in fact, it forces the buying company to actually purchase the whole contracted quantity X_m by call-offs; even though this paper is focused on the given formulation "(2-16)", for the sake of completeness it is worth to mention that this assumption can be relaxed in at least two ways:

1. Allowing the buying company to purchase by call-offs at least a portion α of the contracted quantity X_m with no extra-costs for the remaining quantity, leading to the following formulation replacing constraint set "(10)":

$$\sum_{t}\left(x_{mkt} + xinv_{mkt}\right) \geq \alpha_m \cdot X_m \quad \forall m,k \qquad (10')$$

   where $\alpha \in (0,1]$.

2. Introducing a penalty cost γ_m for each unit not being purchased through call-offs, leading to the following formulation of the constraint set "(10)":

$$s_m + \sum_{t}\left(x_{mkt} + xinv_{mkt}\right) = X_m \quad \forall m,k \qquad (10'')$$

   where s_m is the variable representing the quantity not purchased from supplier *m*. In this case, a new penalty term have to be added to the objective function of the second stage problem, that becomes:

$$\min \sum_{k,t} p_k \cdot \omega_{kt} + \sum_{k,t,m} p_k \cdot c_m \cdot \left(x_{mkt} + xinv_{mkt}\right) + \sum_{k,t,m} p_k \cdot c_m^{SPOT} \cdot q_{mkt} + \sum_{m} \gamma_m \cdot s_m \qquad (7')$$

5. Numerical Experiment

In this paper we are interested in the managerial insights that the proposed model can provide rather than the algorithmic aspects for an efficient model solving. In this section, we present some general results derived from numerical experiments with the aim at quantitatively explaining how the purchasing strategy would change in dependency of supplier development investment costs.

Experimental Design

We consider a single buying firm and its supply base composed by M=3 suppliers, each characterized by an item unit cost (c_m^{SPOT}), a delay (Δ_m) and default (DEF_m) probabilities, as reported in "Table 3". We assume without loss of generality that the more reliable is the supplier, the lower are the delay and default probabilities and the higher is the item unit cost. For instance, supplier 1 has the greatest unit cost (13 €/unit) since it is the most reliable one.

Supplier	Unit cost (c_m^{SPOT}) (€/unit)	Delay probability (Δ_m)	Default probability (DEF_m)
sup1	13	0,02	0,01
sup2	12,75	0,05	0,02
sup3	12,35	0,1	0,05

Table 3 - Parameter values without contracts or investments

As argued in the previous section, the buying firm can choose whether signing a framework agreement with some suppliers or investing in supplier development activities. In the former case, the buying company and the supplier define a quantity X_m to be ordered during the planning horizon at a lower cost (c_m). We assume that c_m^{SPOT} is 30% higher than the contracted cost c_m. In addition, if the agreement with supplier m is selected, the buying firm will incur in a fixed cost (F_m) because of the time spent setting up contract conditions and managing the relationship. Considering an annual cost of € 30.000 for an employee in the purchasing function and estimating that he will spend from 2 to 3 hours per week for each supplier with a framework agreement in place, we can estimate that F_m goes from €1.500 to €2.500. In addition, higher fixed costs are assigned to suppliers with higher delay probability because their relationship management requires more efforts due to delays and supply disruptions management. Alternatively, a buying firm can decide to carry out an investment in order to increase the supplier reliability and then to reduce delay and default probabilities. In this case, depending on the activity chosen (see "**Errore. L'origine riferimento non è stata trovata.**"), the firm will incur an investment cost (Inv_m). For the sake of simplicity, we assume that this cost is a multiple (j) of the fixed one. We will analyze how the optimal decisions will change varying the cost multiplier j. Since an investment can be made only in those suppliers with a framework agreement in place, the buying company, as in the previous case, will commit itself to purchase a quantity X_m during the entire planning horizon at a unit cost c_m. The new delay and default probabilities are respectively Θ_m and $DEFIN_m$. The following "Table 4" shows the parameter values in case of framework agreements and development investments.

	Framework agreement				Supplier development investment			
Supplier	Unit cost (c_m) (€/unit)	Fixed cost (F_m) (€)	Delay probability (Δ_m)	Default prob. (DEF_m)	Unit cost (c_m) (€/unit)	Investment cost (Inv_m) (€)	Delay probability (Θ_m)	Default prob. ($DEFIN_m$)
sup1	10	1.500	0,02	0,01	10	j x 1.500	0,01	0,0025
sup2	9,8	2.000	0,05	0,02	9,8	j x 2.000	0,025	0,005
sup3	9,5	2.500	0,1	0,05	9,5	j x 2.500	0,05	0,0125

Table 4 - Parameter values with framework agreement and supplier development investments

We assume that the capacity of each supplier does not represent a constraint. In these experiments, the holding (*h*) and backlog (*bk*) costs are set to € 30 and € 50 per unit, respectively. Furthermore, since the outputs of this problem are tactical decisions and, hence, oriented to the medium period, we decide to consider a planning horizon of 1 year and a time bucket (*t*) of 1 month. Finally, we use a normal distribution to represent the demand (d_{mkt}) for each time bucket. Given the parameter values defined above, we built 100 equiprobable scenarios for each of the 12 time buckets. In each scenario, we let vary the demand, the delay and default occurrence for each supplier. In particular, regarding delay occurrence we set two binary parameters (θ_{mkt} in case of investment and δ_{mkt} otherwise) that are equal to 0 if the supplier *m* delivers on time the quantity $xinv_{mkt}$ or x_{mkt} ordered in the period *t* in the scenario *k*, while are equal to 1 if the supplier *m* delays the delivery. These binary parameters have a probability Θ_m or Δ_m to get the value 1. In the same way, we define two binary parameters that represent the default occurrence ($defaultinv_{mkt}$ in case of investment and $default_{mkt}$ otherwise); in this case, if the supplier *m* defaults in a certain time *t* in the scenario *k*, the parameter $defaultinv_{mkt}$ or $default_{mkt}$ will be equal to 1 from the time when the default occurs until t=12. In this manner, the assumption reported in the previous section, that is if supplier *m* defaults no more orders can be placed in the following periods, is fulfilled.

Results

We ran the two-stage stochastic model varying the investment multiplier *j* from 1 to 75. "Table 5" summarizes the results and shows the different strategies in function of supplier development investment costs.

<table>
<tr><th>Investment cost</th><th>Strategy</th><th>Allocated quantity</th></tr>
<tr><td rowspan="3">From 1 to 14 times fixed cost
($j \in [1, 14]$)</td><td>Investment in supplier 2</td><td>68%</td></tr>
<tr><td>Investment in supplier 3</td><td>23%</td></tr>
<tr><td>Spot purchasing from supplier 1</td><td>9%</td></tr>
<tr><td rowspan="3">From 15 to 24 times fixed cost
($j \in [15, 24]$)</td><td>Investment in supplier 2</td><td>87%</td></tr>
<tr><td>Spot purchasing from supplier 1</td><td>3%</td></tr>
<tr><td>Spot purchasing from supplier 3</td><td>10%</td></tr>
<tr><td rowspan="3">From 25 to 33 times fixed cost
($j \in [25, 33]$)</td><td>Investment in supplier 2</td><td>75%</td></tr>
<tr><td>Framework agreement with supplier 3</td><td>16%</td></tr>
<tr><td>Spot purchasing from supplier 1</td><td>9%</td></tr>
<tr><td rowspan="3">From 34 to 75 times fixed cost
($j \in [34, 75]$)</td><td>Framework agreement with supplier 1</td><td>81%</td></tr>
<tr><td>Framework agreement with supplier 3</td><td>12%</td></tr>
<tr><td>Spot purchasing from supplier 2</td><td>7%</td></tr>
</table>

Table 5 - Results summary

First of all, we can see that the three suppliers are always selected. Thus, the buffer-oriented method of having multiple suppliers represents an effective strategy to deal with supply risk, but supplier development activities are required in order to obtain lower total costs. However, these last type of activities are paying depending on the investment cost and on the specific supplier delay and default probabilities: in fact, through the investment, the improved supplier should get a delay and default probabilities equal or lower than the ones of the most reliable supplier, still guaranteeing a lower unit cost.

In fact, analyzing the results more deeply, we can observe that:

1. In case of investment costs from 1 to 14 times the fixed costs, the best strategy is to undertake supplier development activities in those suppliers with the lowest item unit cost (supplier 2 and supplier 3) and use spot purchasing from the supplier with the lowest default probability, even with the highest unit cost (supplier 1), in case of peak in demand or disruption occurrence of the other two suppliers.
2. In case of investment between 15 to 33 times the fixed costs, the buying company will invests only in supplier 2, while a small percentage of the quantity needed will be supplied through spot purchasing or framework agreement. Supplier 2 is selected for development activities, instead of supplier 3, because its delay and default probabilities become lower or similar to those of supplier 1 and the lower unit cost ensures an economic advantage with respect to supplier 1.
3. For investment costs greater than 34 times the fixed costs, the above economic advantage of reducing delay and default probabilities vanishes and the strategy that minimizes total costs and risk is signing framework agreements for more than 90% of the annual quantity acquired, most of all from the most reliable even if is the most expensive supplier (supplier 1). A lower quantity is allocated to supplier 3, that is the cheapest one. The remaining quantity will be acquired through spot purchasing from the supplier 2

In conclusion, this model quantitatively shows that, if the supplier delay and default probabilities can be reduced through some supplier development activities, the behavior-based strategies together with buffer-oriented methods (in this case having multiple suppliers), could represent an effective way to deal with supply risk and could improve buying firm performance.

6. Conclusions And Further Developments

Given the relevance of risk in supply strategy definition, this paper gives at first a brief overview of available strategies to deal with supply risk in terms of buffer-oriented methods and supplier development activities. Leveraging on the formal clarity of *System Thinking* approach, a conceptual model that analyzes the impact of these strategies on company performance is developed. In the second part of the paper, a two-stage stochastic model that addresses the decision making problem a company has to deal with when it comes to decide a supply strategy is proposed. In particular, this model attempts to (i) select the suppliers, (ii) identify the quantity to be allocated to each supplier and (iii) determine if and under which conditions buffer-oriented methods and behavior-based strategies are effective to face supply risk and reduce total cost. The main results of this method show how buffer-oriented methods can be effectively combined with behavior-based approaches to deal with supply risk, minimizing further the overall cost.

The stochastic model developed so far has some limitations, thus requiring further improvements. First of all, this is an Operational Research model and so it considers only quantitative factors in the definition of the strategies. More qualitative aspects should be considered, such as the level of trust between a supplier and the buying company. This is a necessary condition for establishing long term relationships especially for performing supplier development activities. To overcome this problem, a quantitative measure for these factors should be identified and added to the model. In the current version of the model we do not explicitly address quality problems that might reduce the delivered quantity; nonetheless, this aspect can be easily included in further versions. Another limitation of this model is that there is a general definition of the investment costs without a clear distinction among the different supplier development activities. Thus, in a next version of this model, an association between each available activity and the related investment cost could be done in order to improve the model reliability. Finally, even if the computational experiment is based on realistic data, one or more case studies should be identified in order to validate the model and find out how it could be effective in defining some guide lines to help organizations in the selection of the supply strategy.

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Supply risk management: moving towards a quantitative approach

Fabiana Pirola[1], Roberto Pinto[1], George Zsidisin [2]

[1]CELS – Research Center on Logistics and After-sales Service
Department of Industrial Engineering - University of Bergamo
viale Marconi 5, 24044, Dalmine, Bergamo, Italy
{fabiana.pirola, roberto.pinto}@unibg.it

[2]Department of Management
Bowling Green State University
Bowling Green, OH 43403
gzsidis@bgsu.edu

Abstract

Risk associated with suppliers represents a growing concern, and as a result it has become imperative that firms create resiliency in their organizations and supply chains to ensure business and supply continuity. In this context, this paper lays the foundation for the development of an optimization model for better understanding supply risk and the how the implementation of redundancy and flexibility practices can provide firms greater resilience in their supply chains.

1. Purpose

Supply chains are becoming more complex with the numerous physical and information flows that involve worldwide companies. To succeed in this environment, firms need to pursue a high level of effectiveness while continuously reducing costs. For this reason, practices such as lean manufacturing, just-in-time and low-cost-country sourcing have become familiar to supply chain managers and have gained growing attention in academia.

Nonetheless, if not well designed and managed, these practices can engender potential detrimental consequences due to the risks they induce, which can lead to supply chain disruptions with subsequent financial losses. Among these, the risk associated with suppliers is receiving greater emphasis due to many firms focusing on core activities that increase their dependence on upstream performance, in conjunction with the increasing managers' risk awareness stemmed from the today financial crisis (O'Marah 2009, Thun & Hoenig 2009). Thus, this study focuses on the supply side of the risk and aims at laying the foundation for the development of a quantitative model that supports supply tactical planning for inbound disruptions and determining the most suitable strategies for ensuring supply continuity.

These inbound disruptions can be caused by environmental events, such as calamitous natural phenomena, or by internal supplier problems, such as poor quality products or delivery delays. An effective supply management strategy should ensure supply continuity. In other words, companies should be able to select the best strategy to increase their resilience (Sheffi & Rice 2005) - the ability to return to the original state or to move to a new and more desirable one after being disrupted (Christopher & Peck 2004). Resilience can be achieved by creating redundancy or increasing flexibility (Sheffi & Rice 2005). Generally, these concepts have been investigated considering the overall company point of view (Christopher & Peck 2004, Peck 2005, Pettit et al. 2010, Sheffi & Rice 2005, Tang 2006), but, since this paper deals with supply risk, we focus the analysis on the upstream flows. In this context, redundancy means keeping some resources in reserve (in terms of inventory, time and capacity) to be used to limiting the consequences of a supply disruption (Sheffi & Rice 2005). On the other hand, flexibility is a more proactive approach and comprises any strategy attempting to reduce the disruption likelihood by increasing the supplier ability to respond in a timely and cost effective manner to changing requirements of purchased components (Tachizawa & Thomsen 2007, Tang & Tomlin 2008). Even though they have been named in several different ways, supply risk management approaches broadly leverage on these two concepts, briefly described in Table 1 along with their main impacts on focal company and supplier performance and some literature references.

	Strategy	Definition	Impact	References
REDUNDANCY	Inventory buffer	To keep stocks to mitigate risk occurrence	Reduce the impact of supplier delays Increase buffer and total cost Decrease transparency and coordination level	Caputo 1996, Christopher & Lee 2004, Güllü et al. 1999, Kouvelis & Li 2008, Hung & Chang 1999, Minner 2003, Molinder 1997, Sheffi & Rice 2005, So & Zheng 2003, Van der Vorst & Beulens 2002.
	Time buffer	To include slack time in scheduled time or having longer delivery lead time		
	Capacity buffer	To keep extra internal capacity or have multiple or backup suppliers		
FLEXIBILITY	Supplier integration	To share explicit knowledge or information with suppliers	Increase transparency Improve supplier performance Reduce transaction and acquisition costs Increase plan alignment cost	Bensaou & Anderson 1999, Burke et al. 2007, Caputo 1996, Christopher & Lee 2004, Costantino & Pellegrino 2009, Das et al. 2006, Dyer 1997, Giunipero et al. 2005, Humphreys et al. 2004, Joshi 2009, Krause 1997, Krause et al. 1998, Lee et al. 2009, Modi & Mabert 2007, Sheffi & Rice 2005, Stevenson & Spring 2007, Zsidisin & Ellram 2003
	Supplier development	To share know-how with suppliers		

Table 1 - Overview of flexibility and redundancy practices

Flexibility and redundancy are generally investigated as two different and unrelated practices. In addition, authors studying redundancy practices usually perform quantitative studies in order to identify the optimal quantity to be buffered, while researches on flexibility are more qualitative and descriptive, giving insights into the actual employment of these strategies and their perceived benefits, based on surveys and case studies. To overcome these gaps, we first analyze some of the conjoint effects of redundancy and flexibility practices on the system made up of buyer and supplier (Figure 1). Then, we attempt to quantitatively interpret these relationships, as described in the following section.

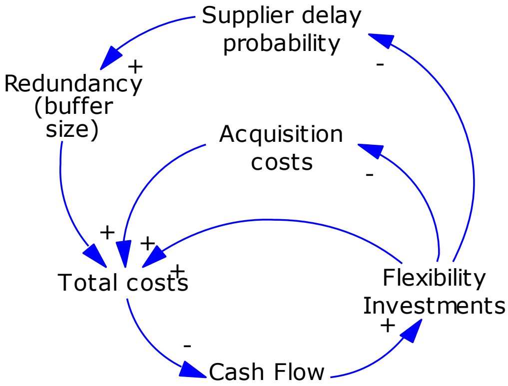

Figure 1 - Conjoint effects of flexibility and redundancy practices

2. Research Approach

The qualitative model presented in Figure has been translated in a two stage mixed-integer stochastic programming model (Birge & Louveaux 1997). Due to space constraints, we report only the description of the model without the analytic formulation. In a two-stage stochastic optimization approach, the uncertain parameters are considered as random variables with an associated probability distribution and the decision variables are classified into two stages. The first-stage variables correspond to those decisions that need to be made prior to the realization of the uncertainty. The second-stage corresponds to those decisions made after the uncertainty is unveiled. After the first-stage decisions are taken and the random events realized, the second-stage decisions are subjected to the restrictions imposed by the second-stage problem. Due to the stochastic nature of the performance associated with the second-stage decisions, the objective function, traditionally, consists of the sum of the first-stage performance measure and the expected second-stage performance.The objective of the stochastic model is to support the selection of the best medium/long term strategy (or mix of strategies) among those available, considering the impact of possible risky events that could affect the inbound flow. In particular, we consider only the risks that affect the incoming product availability and delivery timeliness, while we purposely neglect those ones that cause uncertainty in terms of the price to be paid for inbound supplies, such as price volatility and currency rate fluctuation.

Thus, the main consequences of a supply risk occurrence can be classified as follows:

- *Delay*: supplier delivers late the entire quantity ordered.

- *Short-shipment*: supplier delivers on time only a portion of the order and the remaining quantity is delivered at a later time.
- *No shipment at all*: all the quantity ordered is lost and no more order can be placed to this supplier because it does not provide supply anymore. There can be several reasons for this, such as natural disaster, going out of business, being bought out by another firm, changing the direction of its business and customer market, or determining that the customer is no longer profitable.

This classification contemplates also quality problems and wrong part deliveries. In fact, both cases require supplier intervention in order to repair or substitute the defective/wrong products and this can result in a delay in the final delivery.

Considering these risk occurrences and an uncertain demand, the objective of this model is *(i)* to define the optimal number of suppliers to deal with among a supply base composed by *M* suppliers, *(ii)* select the best strategy (or mix of strategy) to be implemented (in terms of redundancy practices and flexibility investment) and *(iii)* allocate the needed quantity to the selected supplier(s) in order to negotiate a framework agreement.

Flexibility practices generally require substantial investments in the buyer-supplier relationship and, for this reason, a proper assessment of supplier characteristics and the external environment should be carried out. In particular, research findings suggest that investments in suppliers make sense when there is a significant impact of the delivered product on company profitability (Cannon & Perreault 1999, Handfield & Bechtel 2002, Kraljic 1983, Krause 1999, Leeuw & Fransoo 2009, Modi & Mabert 2007), high supply market complexity (characterized by low number of suppliers available, high customization level, high technological level and so on) (Bensaou & Anderson 1999, Giunipero et al. 2005, Hallikas et al. 2004, Kraljic 1983, Lee et al. 2009, Leeuw & Fransoo 2009) and high importance and capability of the supplier (Bensaou & Anderson 1999, Humphreys et al. 2004, Krause 1999, Leeuw & Fransoo 2009). Consequently, the supplied items in this model cannot be commodities but should be some custom products with the above mentioned characteristics. Based on this assumption, when the buying company selects a specific supplier it also signs a framework agreement with it, meaning that the two companies define a quantity *X* (called committed or contracted quantity) that should be ordered over the entire planning horizon.

We also assume that each supplier is characterized by an acquisition cost, an urgent shipment cost (in case of emergency, the buying company could require some shipments with a shorter lead time but higher cost), a fixed cost, a lead time, a given probability to delivery late all the quantity ordered or only a portion of the order, and a given probability to not ship at all the required order. When the buying firm decides to make an investment to improve supplier flexibility, the fixed cost associated with the supplier will increase, including also the investment cost. The acquisition and expediting costs, and the probabilities that the supplier will be late or will not ship at all should decrease. These reductions will depend on the type and amount of investment and should be assessed before running the model.

In summary, the quantitative model is divided in two stages, each of which has different decision variables.

First Stage: Before the beginning of the planning horizon and then before the uncertainties are discerned, the buying company has to define whether to sign a framework agreement with one or more suppliers, or to invest in one or more suppliers in order to increase their flexibility and subsequently their reliability (decreasing delay and supplier loss probability). In both case the buying company should also determine the total quantity that should be ordered during the entire planning horizon from each selected supplier. This decision should be made considering the fixed and investment cost associated with each supplier and the second stage expected cost.

Second stage*:* During the planning horizon the uncertain parameters become known, which include on time and completeness of supplier delivery, loss of suppliers, and actual demand. In this stage, we will define k scenario for each of them with an associated probability p_k to occur.

The second stage decision variables are the quantity to be ordered each period for each selected supplier and the frequency of urgent orders. These decisions should be determined based on inventory/backlog costs, acquisition cost and expediting costs. However, the main objective of this second stage is not to define the right quantity to be ordered each time (this would be the aim of a following operational planning), but is to define the theoretical optimal quantity to be ordered in each scenario in order to calculate the expected cost allowing to select the best strategy and the contracted quantity.

3. Findings And Originality

As mentioned above, flexibility and redundancy practices are usually presented in isolation. However, since flexibility and redundancy are mutually dependent practices, a systemic approach that analyzes the system holistically (de Rosnay, 1997) is considered by the authors more appropriate to describe the impact of these risk management practices on supplier and buying company performance. In this regard, this study represents an attempt to analyze supply risk management following a systemic approach, with the main differences between analytic and systemic approaches being presented in Table 2.

Analytic approach	Systemic approach
Isolates elements	Unifies elements
Emphasizes the precision of details	Emphasizes global perception
Focuses on one variable at a time	Focuses on groups of variables simultaneously
Validates facts by means of experimental proof within the body of a theory	Validates facts through comparison of the behaviour of the model with reality
Deals with linear and weak interactions	Deals with non-linear and strong interactions

Table 2 - Analytic vs. Systemic approach

4. Research Impact

From a research point of view, this stochastic model contributes to fill the gap identified in the first section and, then, to propose a more comprehensive and quantitative model to evaluate the economic advantage of investing in suppliers to increase their flexibility. Further, this model evaluates the impact of investments on redundancy practices, which include inventory, time, and capacity. In addition, through a sensitivity analysis of the results, it will be possible to better understand when and under which conditions flexibility practices are useful to reduce the total cost. Finally, considering the option of vertical integration, this tool can provide some evidence of the impact of supplier reliability on make or buy decisions.

5. Conclusions

This model, through a two stage stochastic programming, aims at support the tactical supply planning of a firm when it comes to decide the best strategy to be implemented considering supplier-oriented risk. Since it is an Operational Research model, the main limitation is that all the qualitative factors that can influence strategy selection process should be translate in monetary value. Furthermore, this model takes into account flexibility only from supply point of view, without considering any other possible intervention on the internal or downstream processes to increase resilience.

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Supply Chain Risk Commonalities and Differences Between Italy and Switzerland/Germany

Gandolf R. Finke[1], Roberto Pinto[2], Fabiana Pirola[2], Bruce Arntzen[3]

[1]ETH Zurich - BWI Center for Industrial Management
Logistics, Operations and Supply Chain Management
Kreuzplatz 5 / F9 - CH-8032 Zurich
gfinke@ethz.ch

[2]CELS – Research Center on Logistics and After-sales Service
Department of Industrial Engineering - University of Bergamo
viale Marconi 5, 24044, Dalmine, Bergamo, Italy
{roberto.pinto, fabiana.pirola}@unibg.it

[3]MIT Center for Transportation & Logistics
77 Mass Ave, E40-365, Cambridge, MA 02139
Corner of Amherst & Wadsworth Streets
barntzen@MIT.edu

Abstract

In this paper, we introduce a survey with companies from Italy and Switzerland/Germany. The survey questions address issues around supply chain risk, mitigation and management approaches as well as cultural aspects that play a role. We briefly discuss and compare some of the data of the survey results.

1. Purpose And Background

Supply chain trends continuously change the risks companies have to face day by day, from supply disruptions to demand upsurge and downturn. However, the approach to these different types of risk is generally not homogeneous moving from one country to another. As argued in Douglas and Wildavsky (1983) each form of social life has its own typical risk portfolio, and cultural differences and local habits might shape risk perceptions in different ways.

The purpose of this paper is to present some of the main results of a global survey about experiences and attitudes toward supply chain risks and risk management in companies based in different countries. The survey was set up by the MIT Center for Transportation & Logistics as part of the global scale risk survey at MIT (ctl.mit.edu/research/global_scale_risk_initiative). This initiative was aimed at understanding regional and cultural differences in the way that supply chain risk is perceived globally. For this purpose, the survey was conducted in different countries in Europe, North America, South America, Africa and Asia.

Both, the CELS – Research Center on Logistics and After-sales Service and the BWI Center for Industrial Management contributed to the survey managing dissemination and data collection activities in Italy and Switzerland/Germany, respectively. Thus, the questions were translated to Italian and German language and companies within the countries were contacted and asked to participate in the survey.

The main goal of this paper is to compare some of the data collected in these European countries, underlining the differences and commonalities in approaching supply chain risk management in the surveyed countries. Switzerland and Germany have been grouped together to represent one region here because of cultural and regional proximity. Also comparatively few Germans (less than 10%) were among the respondents.

2. Research Approach

The results presented in the remainder come from the above mentioned international survey. Due to the scope of the paper and the extent of the data, we only analyze the survey results partially. Moreover, due to some confidentiality agreements and restrictions on sharing data, the cross-analysis will be performed only considering aggregated data.

Survey questions were mainly based on Likert-like scales, while some open questions were included too. The raw survey data was cleaned for incomplete answers before processing and further analyzed by taking averages and counting percentages. The sample size for Italian companies was 74 and for Switzerland/Germany 141, providing a broad enough base to derive a general understanding and perception of supply chain risk.

3. Findings And Originality

In this section we report some of the key findings of the comparison of the survey results. Figure 1 shows the aggregation of the answers given to the question whether mitigation efforts should focus on prevention or event response. The graph shows a strong tendency towards risk prevention (about 60% of both samples) as a preference, which is not surprising: risk taking especially with unclear outcomes is not part of either country's management culture and not encouraged through incentives. Nonetheless, about 25% of both samples consider prevention and reaction to be equally important, which could be interpreted as an undecided position where no clear management approach has been taken. Swiss/German survey respondents tend to answer less extreme than their Italian counterparts which aligns with common stereotypes. From the analysis emerges that from the respondents' view, the general focus of risk management should be on the preventive side.

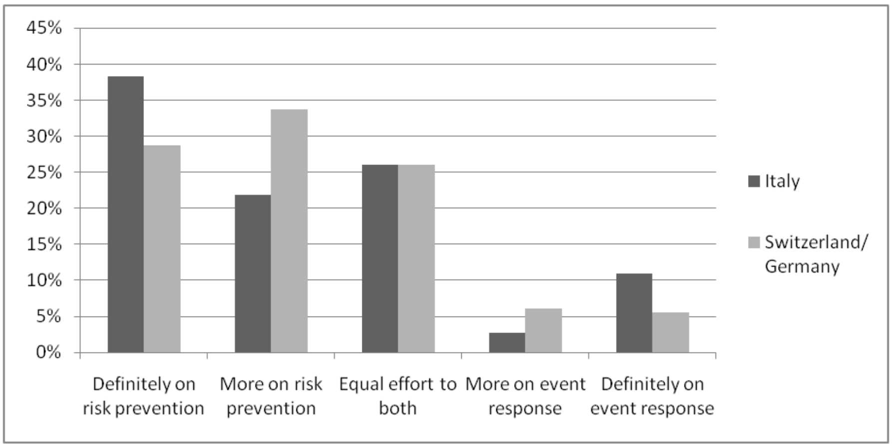

Figure 1 - How companies spend their efforts in managing risks

The following graph depicts results about the best position in an organization to manage risks. The two extremes of the Likert-scale are the complete centralization on one side and complete decentralization on the other, with two intermediate levels in between. Considering the radar-like graphs in Figure 2, the closer to the center of the square the line is, the more centrally the activities should be performed. For example, in both countries the ”Planning of risk prevention measure” should be performed in a decentralized manner, while “Performing event response” actions should be deployed more centrally.

The main implication of these results is twofold: first, Italy and Switzerland/Germany appear to have a similar attitude towards the centralization/decentralization dilemma; secondly, planning activities show a slight tendency to be favored as a central activity as opposed to implementation of response or prevention measures. This second observation seems to be aligned with expectations: assuming a centralized point of view can favor a broad perspective about risks, while actions should be taken locally wherever a disruption occurs.

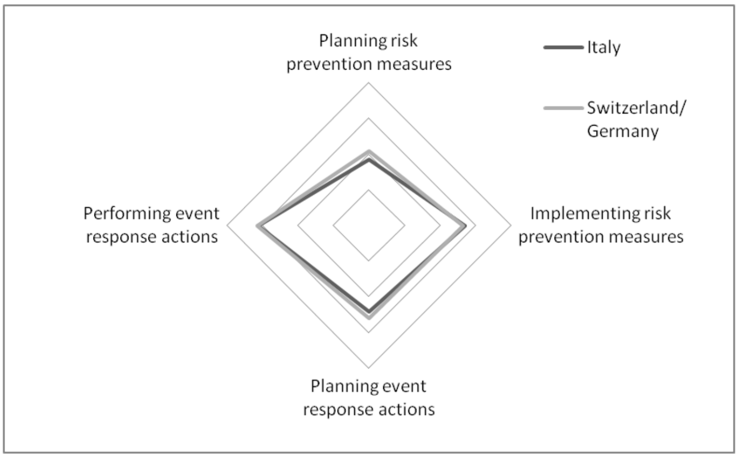

Figure 2 - Where is the best position to plan or implement actions?

Figures 3 and 5 depict the frequency of different disruptions to the supply chain caused by either internal or external risk. They are derived from Likert-like scales which range from answer possibility 1=”Never” up to 5=”Almost Daily”. The informational value of the results are of course limited due to the nature of the scale. Especially the comparison of results has to be executed carefully, as the perception of items is likely to vary between respondents. Nonetheless, we used average values to derive basic implications.
Product quality failure, transportation carrier failure, as well as inventory write-off, raw material cost and major software system failure are among the most common internal disruption causes. Generally, Italian companies are more affected by transportation carrier failure with respect to their Swiss/German counterpart. On the other hand, Swiss/German companies suffer more demand downturn and problems related to raw material suppliers and costs. Nonetheless, the differences are not so eminent.

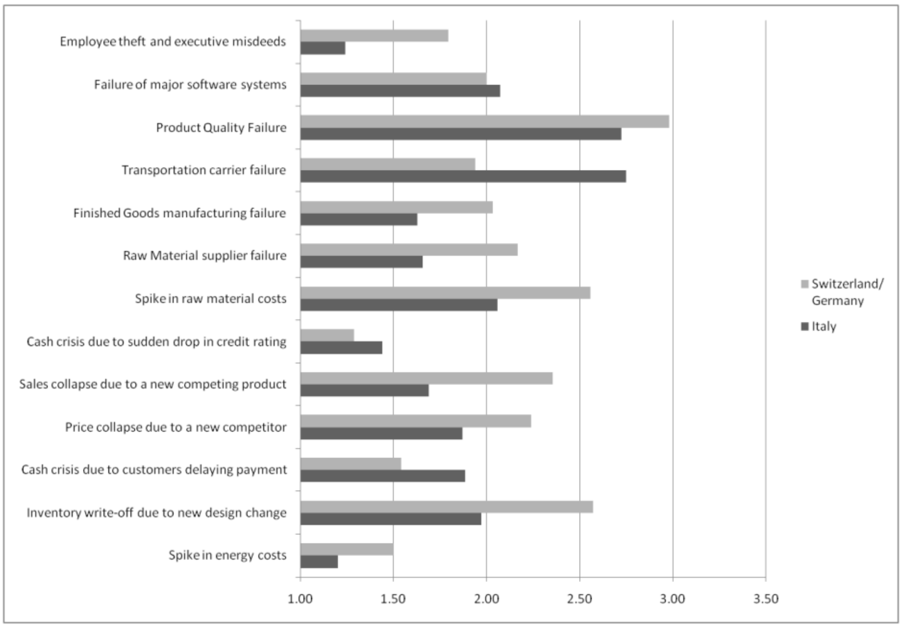

Figure 3 - Frequency of supply chain disruption due to internal events

It is interesting to cross-analyze the frequency of occurrence of disruption due to internal events and the approach adopted to risk management, discussed in Figure 1. In Figure 4 the vertical axis measures the frequency of occurrence of the specific events reported on the horizontal axis; as depicted there, risk prevention and event response approaches almost always dominate the undecided approach of respondents who declared to put equal effort to both.

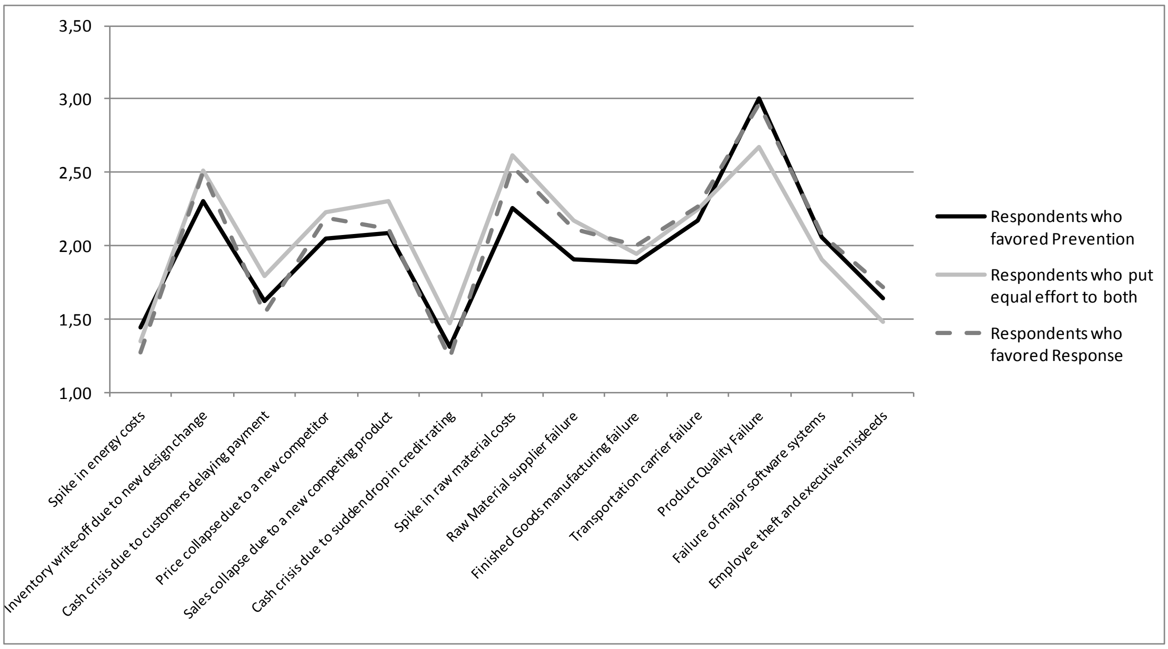

Figure 4 - Comparison of disruption occurrence in companies adopting different risk management approaches

Considering external events, economic recession and currency risk – probably strongly influenced by the recent global economic turmoil –, product tampering, labor disputes and virus or cyber attacks are the most prominent reasons for disruptions.

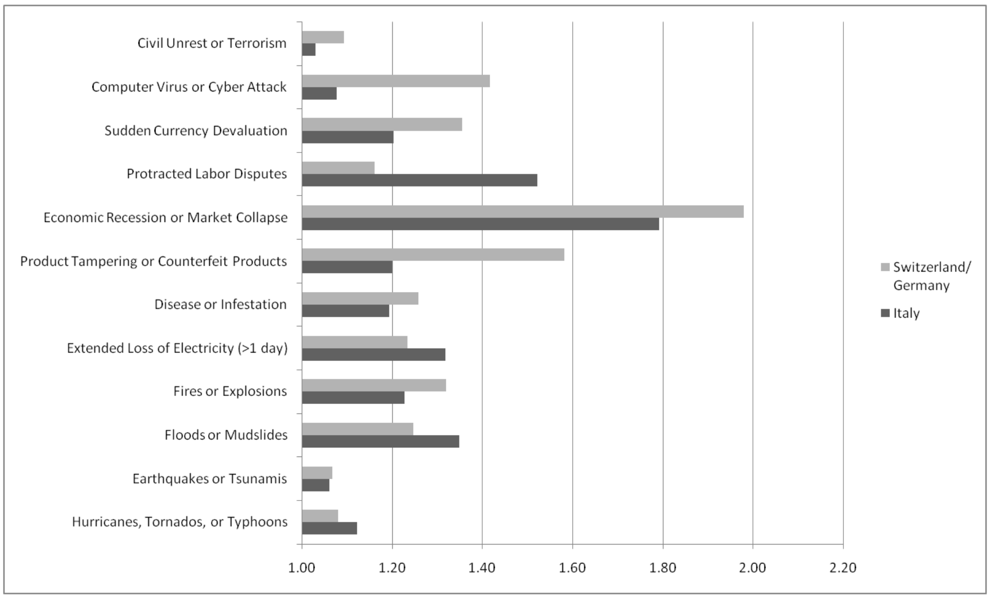

Figure 5 - Frequency of supply chain disruption due to external events

Again, differences between the two countries are not immense. However, Swiss/German companies face product tampering more often than Italian ones, who have experienced protracted labor disputes more often than their Northern neighbor.

This also reflects the different situations at the two labor markets and the strong focus on branding of Swiss/German companies with regard to quality.

Next, Figure 6 describes which types of risk management instruments, procedures or staff are implemented and employed. The answer possibilities included ”Yes and its is effective”, ”Yes but it is not very effective” and ”No”. This scale therefore represents answer possibilities in decreasing effectiveness of supply chain risk management. The data is aggregated for both regions, as only minor differences were detected. However, we see that available risk management tools are for the majority not used effectively, considering that an ineffective or no use of the corresponding risk management method was claimed for almost all methods listed. This shows how much effort is still needed in spreading and implementing the available methods effectively as well as developing new and effective ones.

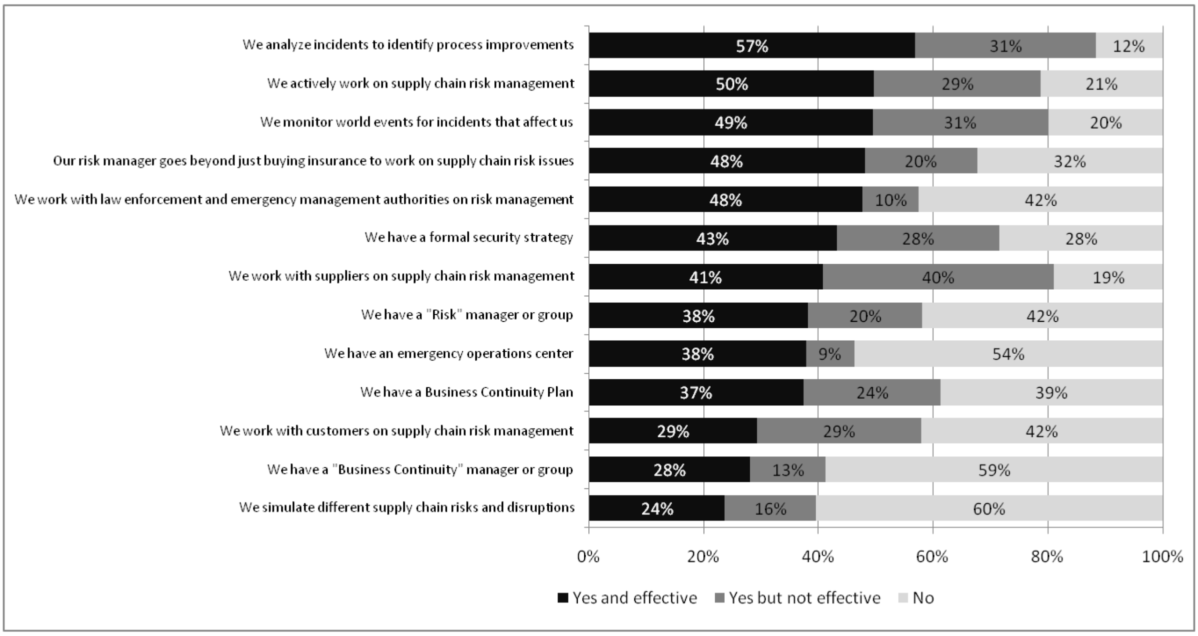

Figure 6 - Supply Chain Risk Management approaches at surveyed companies

4. Research Impact

This research can provide an inside into how supply chain risk is managed and experienced by managers in different countries. The survey generally helps to identify where industry needs and research gaps are in terms of effective supply chain risk management approaches. However, more analysis including an analysis of the statistical significance of results should follow on the data available.

5. Conclusions

As also reported in Oltedal and Rundmo (2007) different worldviews did not lead to extremely different perception of risk in the two countries, and the relations between culture and risk perception seemed somewhat sporadic and unsystematic. Cultural and geographic proximities are an obvious explanation of the shown similarities.

Further analysis of the data with regard to for example the correlation of industries, individuals and surrounding culture with the answers provided in different questions could lead to meaningful results.

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An Investigation of the Relationships Between Supply Risk Awareness, Assessment, Management, and Supply Disruption Occurrence

Fabiana Pirola[1], George A. Zsidisin[2], Stephan M. Wagner[3]

[1]CELS – Research Center on Logistics and After-sales Service
Department of Industrial Engineering - University of Bergamo
viale Marconi 5, 24044, Dalmine, Bergamo, Italy
fabiana.pirola@unibg.it

[2]Department of Management
Bowling Green State University
Bowling Green, OH 43403
gzsidis@bgsu.edu

[3]Department of Management, Technology, and Economics
Swiss Federal Institute of Technology Zurich
Scheuchzerstrasse 7, 8092 Zurich, Switzerland
stwagner@ethz.ch

Abstract

The today supply chain trends along with the current financial crisis have increased the awareness among professionals that risk assessment and mitigation play a crucial role in successfully managing supply chains. This increasing emphasis on risk management and the even more predominant trend to focus on core activities that creates greater dependencies on upstream supply, emphasizes the importance of the supply risk management. This study focuses on the supply side of the risk, looking at the relationships between top management awareness, supply risk assessment, supply risk management, and disruption occurrence. In particular, through a structural equation model, this research will demonstrate that increasing the top management awareness of supply risk raises the employment of risk assessment tools. Risk assessment allows a company to better understand risk sources increasing the implementation of risk management techniques in order to improve enterprise resiliency and decrease disruption occurrence.

Keywords

Top Management Awareness, Supply Risk Assessment, Supply Risk Management, Supply Chain Disruptions

1. Introduction and Aim of the Paper

Today supply chain trends such as global sourcing, lean manufacturing, and just-in-time inventory management have had a great impact on supply chain management. One of the potential detrimental consequences of these practices is the increasing risk companies encounter if disruptions occur in their supply chains and their subsequent financial losses. The $400 million loss incurred by Ericsson after the fire in its sole microchip supplier in 2000 or the estimated $2 billion loss of Toyota due to gas pedal problem in 2010 [12] are only few examples of the impact of risk resulting in supply chain disruptions and external quality failures that originate in the upstream supply chain.

Considering a supply chain, risk can be classified in five categories [3]: process risk, control risk, supply risk, demand risk and environmental risk. The first two categories are internal to the firm and depend on how value-adding and managerial activities are managed and controlled. Demand and supply risks, those that are external to the firm but internal to the network, entail potential disruptions in the upstream and downstream flows in the supply chain. Finally, environmental risk comprises external disruptions due to socio-political, natural or economical events.

The current financial crisis that has been slowing down the global economy has further increased the awareness among professionals that risk assessment and mitigation play a crucial role in successfully managing supply chains [17]. This increasing emphasis on supply risk, along with the even more predominant trend to focus on core activities that creates greater dependencies on upstream supply, emphasizes the importance of the supply side risk management.

Thus, this study focuses on the supply side of the risk, defined as the probability of an incident associated with inbound supply in which its outcomes result in financial losses for the firm [21]. In particular, this study will look at the relationships between top management awareness, supply risk assessment, supply risk management, and disruption occurrence.

This paper is organized as follows. Section 2 presents a brief literature background on supply chain risk management in order to support the proposed research model and hypothesis formulation. Then, in Section 3 the research methodology is described, including data collection and model evaluation. Finally, Section 4 concludes the paper with a discussion of the research findings and some limitations.

2. Literature Background and Hypothesis Formulation

Several authors have proposed frameworks to support companies' risk management considering both generic supply chain risks ([1], [18]) or, more specifically, supply risk ([8], [9], [15], [20]). Even if some differences exist, all these frameworks are based on the same four phases, that are (i) *risk identification* that gives rise to awareness of risk an organization is facing, (ii) *risk assessment* to evaluate the potential impact and the occurrence probability of a risky event, (iii) *decision and implementation of risk management actions* aiming at reducing the impact or decreasing the occurrence probability of a disruption, and (iv) *risk monitoring* to ensure that risks are effectively identified and assessed and that appropriate controls and responses are in place.

Although these frameworks have been developed based on literature review or best practices and validated through case studies, quantitative evidences regarding the actual relationships between all the phases have been scarce. Consequently, this paper aims at analyzing if in the supply management practices the above-mentioned phases are sequentially correlated and if they effectively lead to a reduction in supply disruptions impact.

First, we argue that implementing tools and techniques to identify risk will increase the organization awareness of the risks that exists with their respective purchases. Then, the more the supply management professionals are aware of these risks, the greater the extent they will implement tools to assess that risk. These risk assessment tools can be embedded in the supplier evaluation process, and may also focus on creating estimates of the risk dimensions of probability and impact. When buyers implement risk assessment tools to a greater extent, they will improve their knowledge of the supply risk that exists, and subsequently seek to manage that risk. The greater the utilization of supply risk management tools by supply management professionals, the less likely disruptions will occur in the company due to supplier problems. In other words, the aim of these risk management tools is to enhance the enterprise resiliency [19] by returning to its original state or moving to a new, more desirable one after a disruption occurrence [3]. Resiliency can be achieved by either creating redundancy or increasing flexibility [19]. Redundancy practices aims at limiting or mitigating the negative impact of a disruption, while flexibility leads to reduce its occurrence probability. In the supply management context, building redundancy means, for instance, keeping extra stock, maintaining multiple suppliers or running operations at low capacity rates, while flexibility practices include supplier certification and monitoring, strong buyer-supplier relationships, information sharing and even investing in supplier operations to improve its performance. While several studies demonstrated the positive impact of flexibility practices on supplier performance ([10], [14], [16]) and then on reducing supply disruption occurrence, redundancy has been generally analyzed in a quantitative way, namely developing models identifying optimal inventory quantities ([6], [11]). Thus, regarding supply risk management, this paper focuses on redundancy practices aiming at evaluating if they are actually effective in limiting the impact of supply disruptions and, then, reducing the consequent buying company disruptions. This study will test a research model, as depicted in Figure 1, that is based on the following hypothesis:

- H1: Supply management professionals that have a greater awareness of supply risk will employ supply risk assessment tools to a greater extent
- H2: The greater the extent that supply management professionals employ risk assessment tools, the greater the extent those individuals will implement supply risk management techniques to reduce their exposure to supply disruptions.
- H3: The greater the extent that supply management professionals implement supply risk management techniques, the less likely buying company's disruptions will occur as a consequence of upstream disruptions.

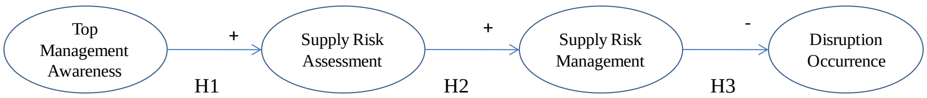

Figure 1 - The research model

3. Research Methodology

Data Collection

In order to obtain data for testing the research model, an on-line supply risk audit instrument was developed and administered to a convenience sample of 499 supply management professionals employed at five organizations belonging to three different industries. In total, a sample of 297 respondents was collected, which corresponds to response rate of 59.3%. Table 1 shows the company demographics and the sample characteristics. The questions used in the survey instrument asked respondents to report their answers with respect to a specific purchase they manage. Multiple-item measures were used to assess the focal constructs on 5-point scales (1= strongly disagree – 5= strongly agree). The survey was segmented into (i) awareness of supply risk, (ii) supply risk assessment, (iii) supply risk treatment, and (iv) supply disruption occurrence.

Industry	Home country	Sample	Responses	Response rate
Home construction and improvement materials	U.S.	156	53	34.0%
Home construction and improvement materials	U.S.	56	34	60.7%
Paper and other capital equipment	Germany	41	33	80.5%
Aircraft manufacturer	U.S.	201	141	70.1%
Material handling equipment	Germany	45	35	77.8%
	Total	499	296	59.3%

Table 1 - Company demographics and response rates

Data Analysis

Data were analyzed following the two-step approach recommended by Anderson and Gerbin [2]. First, a measurement model was tested using Confirmatory Factor Analysis (CFA) in order to provide a confirmatory assessment of convergent and discriminant validity of the scales. Then, the structural equation model depicted in Figure 1 was assessed and the hypothesis tested.

The measurement model is composed of the linkages between the observed variables (measurable indicators) and the latent constructs (that in this case are top management awareness, supply risk assessment, supply risk management, and disruption occurrence) and of curved arrows representing correlation between every pair of latent variables. This model was run in LISREL program and the resulting indicator's loadings and t-value are reported in Table 2.

Convergent validity, that indicates how well the observed variables are indicators of the corresponding latent variables, can be assessed from this measurement model by determining whether each indicator's estimated loading on its construct is significant

[2]. As shown in Table 2, all the loadings have significant t-values providing evidence of convergent validity.

Discriminant validity describes the degree to which the constructs that should not be correlated one each other are, in fact, not correlated. It can be evaluated by constraining the estimated correlation between the latent constructs to 1.0 and then performing a chi-square difference test on the values obtained for the constrained and unconstrained models. This test should be performed for one pair of factors at a time, rather than as a simultaneous test of all pairs of interest [2]. The increase of the chi-square in every constrained model with respect to the unconstrained one was always more than 100 with an increase of 1 degree of freedom. This means that the differences in the chi-square statistic are always significant, providing support to discriminant validity.

Reliability tests were also performed for each construct using Cronbach's alpha [4], as shown in Table 3. Cronbach's alpha is over the value 0.7 for all factors, demonstrating a sufficiently high reliability of the four scales analyzed.

Observed variables for each latent variable	**Loading**	**t-value**
Top Management Awareness		
We have a formal system for making supply risk visible to our top management	0.93	19.75
We have a formal system for making supply risk visible to our purchasing management	0.84	17.08
Top management regularly reviews our supply risk exposure	0.58	10.53
Top management explicitly considers supply risk when evaluating our purchasing group's performance	0.57	10.1
Supply Risk Assessment		
We use a formal process for rating suppliers based on the level of risk they pose	0.82	15.87
We use a formal process for identifying and assessing supply risk	0.79	15.04
We regularly use tools such as supply chain mapping to identify sources of supply risk	0.66	11,75
We generate estimates of probability of potential supply disruptions	0,59	10.2
We use supplier councils to identify and discuss potential sources of supply risk	0.51	8.48
Supply Risk Management		
Supply continuity / contingency plans	0.79	13.3
Ensure that excess supplier capacity exists to deal with unplanned increases in demand	0.72	12.07
Dual or multiple supply sources	0.53	8.48
Require suppliers to immediately report all supply disruptions irrespective of their impact	0.45	6.99
Require suppliers to hold inventory for you to prevent stockouts	0.42	6.52
Disruption Occurrence		
Operations disruption due to a late delivery	0.86	17.53
Operations disruption due to a quality problem	0.84	16.85

Expedited shipments to avoid a disruption due to a late delivery	0.81	15.77
Late deliveries	0.77	14.81
Unacceptable delivered quality	0.76	14.52
Excess cost due to a supplier's failure to perform	0.68	12.37
Use of an alternate source for this product because the primary sourced failed to perform	0.38	6.37

Table 2 - The measurement model loadings and t-values

Construct	Cronbach's alpha
Top Management Awareness	0.822
Supply Risk Assessment	0.713
Supply Risk Management	0.713
Disruption Occurrence	0.89

Table 3 - Cronbach's alpha

Once we provided support for convergent and discriminant validity of the scales, the proposed structural equation model was tested. Figure 2 presents the path coefficients along with the t-values, resulting from running the structural equation model analysis using LISREL 8 program. All the path coefficients between the latent variables are significant with $p < 0.001$.

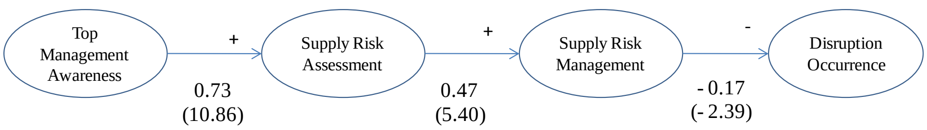

Figure 2 - Results of the structural equation model

Regarding goodness-of-fit indices, the traditional measure is the chi-square fit index. The chi-square statistic provides a test for perfect fit in which the null hypothesis is that the model fits the population data perfectly. A statistically significant chi-square causes rejection of the null hypothesis, implying imperfect model fit and possible rejection of the model [5]. However, this statistic has been criticized on several grounds because it is influenced by the sample size, such that model evaluations with large samples will almost always lead to model rejection [13]. As expected, we obtained a significant ($p<0.001$) chi-square statistic of 496.1 with 186 degrees of freedom. For this reason, other indices were considered to evaluate the structural equation model. Among them, the RMSEA (Root Mean Square Error of Approximation) is generally regarded as one of the most informative fit indices [5]. The RMSEA of this model is 0.075 that indicate a reasonable fit of the model to the observed data ([5], [7]).

Since the goodness-of-fit indices demonstrated that the model fits the data and the path coefficients are all significant, this model provides strong support to the three hypotheses formulated in the previous section (H1, H2 and H3).

Thus, there are positive relationships between top management risk awareness and supply risk assessment and between supply risk assessment and its management while there is a negative relationship between supply risk management and disruption occurrence.

4. Discussion and Conclusion

Focusing on supply risk, this paper provides a confirmation of the research model and then empirically demonstrates that the four phases that generally characterize a risk management framework (namely risk identification, assessment, management and monitoring) are sequentially correlated. Thus, the more the top management is aware of the risk that exists with their purchases, the greater the extent supply risk assessment tools will be employed in the purchasing department. These tools allow a company to identify the main risk sources and estimate both occurrence probability and impact. If the main risk sources and their potential consequences are known, risk management techniques can be implemented in a more effective way because a company is able to better identify where and how to intervene in order to prevent operation interruptions and/or economic losses. In particular, this study focuses on redundancy practices that improve enterprise resiliency by limiting the impact of possible risky events. The research findings empirically demonstrated that creating redundancy is effective in decreasing company's disruption occurrences due to supplier problems and, then, in limiting the impact of upstream disruptions.

Obviously there are some limitations with the current study. First of all, data are gathered from only three industries and this can limit the generalizability of the findings, even if establishing the unit of analysis as the purchased items reduces this problem. Another limitation is that we did not analyze the cost related to the implementation of redundancy practices as well as the cost associated to disruptions. So the economic trade-off of having some redundancies and the decreased cost of disruptions has not been considered in this analysis.

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