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*Supply chain risk management – A case study in the fast moving consumer goods industry*

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## **List of abbreviations**

CEE: Central Eastern Europe

Chi-Sq: Chi-square

Coeff.: Coefficient

EBIT: Earnings before interest and tax

e.g.: for example

ERM: Enterprise risk management

EU 27: 27 membership states of the European Union

FMCG: Fast moving consumer goods

FX: Foreign exchange rate

GBM: Geometric Brownian Motion

GBP: British Pound

HR: Human resources

i.e.: that is

Incl.: including

IT: Information technology

KPI: Key performance indicator

KonTraG: Gesetz zur Kontrolle und Transparenz im Unternehmensbereich

MENA: Middle East North Africa

m EUR: Million Euros

MLE: Maximum likelihood estimators

MR: Mean Reversion

P&G: Procter & Gamble

P&L: Profit and loss statement

P-P: Probability-probability

Q-Q: Quantile-quantile

R<sup>2</sup>: Coefficient of determination

R&D: Research & development

RM: Risk management

SARS: Severe acute respiratory syndrome

SC: Supply chain

SCM: Supply chain management

SCOR: Supply Chain Operation Reference

SCRM: Supply chain risk management

SHEQ: Safety, health, environment, quality

k EUR: Thousand Euros

UK: United Kingdom

US: United States

USD: US Dollar

VaR: Value at risk

WACC: Weighted average cost of capital

WE: Western Europe

### List of symbols

$\widetilde{LM}$  = Lost margin from lost sales

$\widetilde{LS}$  = Lost sales of a month for the supply chain due to a risk  $j$

$C_{Mit}$  = Cost of mitigation of adding finished products with sales value  $x$

$C_{Cap}$  = Cost of employed risk capital

$E[\widetilde{X}]$  = Expected value of variable stochastic  $\widetilde{X}$

$Q_{0.95}$  = 95% risk quantile

$m$  = Gross margin as percentage of sales value

$f$  = Fee for procuring finished products for mitigation externally

$i$  = Interest rate for risk capital

$k$  = Risks not optimized

$j$  = Risk optimized

$s$  = Inventory dedicated to a certain stage of the supply chain allowing for producing finished goods of the value  $s$



## **I. Introduction**

Supply chain risk management (SCRM) has been a subject of intense discussion in academia and practitioner papers. As a result of ongoing globalization and increased competition, companies are facing rising cost pressures and more demanding customers. These pressures often force companies to introduce efficiency initiatives and redundancy reductions - e.g., with just-in-time deliveries or a decrease in the supplier base. Furthermore, factors including outsourcing, relocation and global sourcing create longer and more complex supply chains. Increased service and product complexity, together with difficulties in information exchange and transparency, amplify this effect. These factors lead to increased vulnerability in the supply chain (SC), making supply chain risk management an urgent challenge for many companies (e.g. Wagner and Bode 2006, Sheffi and Rice 2005, Shorten et al. 2008). A further threat is posed by large-scale catastrophic events, such as terrorist attacks or epidemics like SARS or the swine flu, which have become more pronounced in recent years. The insurance company Munich Re (2007) showed in its annual report on natural hazards that the number and severity of natural catastrophes has increased in recent years. The financial crisis and worldwide recession that started at the end of 2008 placed further pressure on supply chains. Economic indicators at the beginning of 2012 show an uncertain economic outlook.

When these trends are considered as a whole, it is clear that supply chain managers are now working with a leaner but increasingly vulnerable supply chain, and that this supply chain is exposed to an increasing number of external shocks. As Hendricks and Singhal (2003, 2005a, 2005b) have shown, supply chain glitches are penalized by the capital market and lead to deteriorating operational and share performance. It is therefore crucial for companies to have an effective supply chain risk management program in place. These concerns are especially relevant in the fast moving consumer goods (FMCG) industry, which is characterized by low margins, high pressure for product availability, innovation and large marketing investments. To date, however, the issue of supply chain risk management in the FMCG industry has not been analyzed in detail (e.g. Weise 2008, Kotler 1999). A prime example of the vulnerability of supply chains in this sector is the West Coast port strikes in 2002, which led to delays for a number of FMCG companies, including Procter & Gamble. Logistics companies called the strikes a “force majeure” but P&G wanted its suppliers to search for solutions, not excuses. As a result, P&G replaced several of its transportation providers with those who better complied with its own urgent and passionate mind-set (Sheffi 2005).

The research presented in this paper is based on the experience of a leading FMCG company – a company that is highly proficient in supply chain management and has received several awards for its supply chain performance. The goal of the research is to understand the value of supply chain risk management beyond the legally required enterprise risk management. Some recent events affecting the case study company (including a supplier bankruptcy and the increased volatility of raw material prices) have led the company to sponsor a dedicated SCRM research project to support scientific research in a topic which is critical for the whole industry. Based on the presented academic research, further application studies are planned by the company at a later point in time.

Before beginning an analysis of the key issues, it is necessary to define “supply chain risk” and “supply chain risk management,” and to differentiate these concepts from the broader theories of “supply chain management” and “supply chain optimization.” A review of the existing literature did not provide a satisfactory working definition for the purposes of this paper. The first part of this research is therefore dedicated to defining and differentiating the above terms. This paper also explores why SCRM has not been holistically implemented at the case study company. In addition, this work sheds some light on the role of departmental barriers involved in supply chain management.

Quantifying the risks in the supply chain makes it possible to better understand the dangers they pose, and thus to appreciate the value of SCRM for the company in question. Quantification is also the basis for devising and assessing mitigation strategies. In the classic supply chain risk management process (identification, assessment/aggregation, mitigation, and controlling), quantification bridges assessment and mitigation and creates the basis for controlling. Quantification is the key to effectively prioritizing risks and to optimizing the level of investment in the mitigation strategy. Since a broad basis of literature discussing identification of risks already exists, the focus of this research project is on quantification and prioritization of risks. Cost and benefit trade-offs and the definition of optimal investments are a standard routine in business sciences. In the field of supply chain risk management, however, there are only a few documented cases of objective quantification. The majority of the available literature relies on subjective risk assessment. This raises the question of whether subjective risk assessment alone is sufficient. If subjective assessment is sufficiently accurate, the lower cost and quicker implementation would provide great benefit. The second part of this research paper will shed light on this question.

A closely related issue is the relationships between various risks (e.g., correlations or cause-and-effect relationships). Several authors have discussed the interrelations between risks and their influences on risk management, but on the whole this issue remains to be clarified. If risks are strongly correlated or if some risks produce others, their effects may significantly alter the results of the quantification process. As a consequence, risk priorities and optimal risk investments may also change. In the final part of this research, a large, unique data set provided by the sponsoring company is used to quantify the relationships and to assess their impact on the risk management process. The conclusions of this research reveal that risk relationships influence supply chain risk management.

Paper 1 defines the common ground for supply chain risk management in the FMCG context, thus forming the basis for papers 2 and 3. Paper 2 compares objective and subjective risk assessment and their values. Paper 3 quantifies risk relationships and derives their impact on supply chain risk management. A revised risk management process is developed and presented as the overall result.

## **II. Paper 1 - Defining a common ground for supply chain risk management**

### **II.1. Introduction**

On March 17, 2000 a thunderstorm triggered a small fire in a Philips semiconductor plant. While the fire itself did not cause major damage, it resulted in the pollution of the clean room production. It was clear that Philips would face several weeks of production loss and that its available stock would soon be depleted. Nokia, one of Philips' customers, immediately recognized the problem and acted quickly. It identified a second supplier and worked actively with Philips to obtain the remaining quantity of products from other locations. As a result of its quick response, Nokia suffered from only minor shipping delays. For Ericsson, another Philips customer, it took about four weeks to realize the extent of the problem. Ericsson was following a single sourcing strategy and had no back-up supplier in place; as a result, they faced major shipping delays that caused losses of USD 500 million. By that point, Nokia had secured all of Philips' spare capacity. Eventually, Ericsson's financial loss forced the company into a joint venture with Sony. In this case, Nokia's advantage was a functioning strategy for supply chain risk management. The company culture allowed the bad news to travel fast. Close monitoring of critical parts, together with a modular engineering design, good supplier relationships and knowledge of the market, allowed Nokia to detect the problem early and facilitated the mitigation of risk. Ericsson, on the other hand, was hampered by a lack of preparation and a company culture of ignoring problems (Sheffi 2005). This example demonstrates the importance of a program of supply chain risk management that is supported by the organization and its various departments.

This research study began with an analysis of the available concepts of general and individual supply chain risk management as well as a review of the existing focused case studies. No common definitions or analysis framework were found. Tang (2006a) found that while most companies are aware of supply chain risks, only a minority had implemented an SCRM policy. Even this paper's case study company, which exceeds its competitors in many areas, has no dedicated SCRM. The present research study seeks to better understand the various issues surrounding the implementation of SCRM. This objective is made particularly challenging by the fact that supply chain risk management, both as a whole and in its component parts, has not been sufficiently defined in the existing literature. To better understand this topic we therefore reviewed managers' understanding of the terms and their implications. We focus on the following research questions: How is risk defined in the organization? How are supply chain and supply chain management (SCM) defined in the

organization? How are supply chain risks defined in the organization? How is enterprise risk management defined in the organization? To what degree is risk management established and implemented in the organization? How is supply chain risk management related to supply chain management and enterprise risk management?

The case study approach was chosen for several reasons: one, because the topic of supply chain risk management is still evolving, and two, because the breadth of the subject makes analysis complex (Manuj and Mentzer 2008). The questions posed have an exploratory character. In the following article we seek to answer those questions and to develop a supply chain risk management framework by compiling and comparing the relevant literature and verifying the developed framework in the case study company.

## **II.2. Literature perspective on key supply chain risk management elements**

### **II.2.1. Risk as general term**

Two definitions of risk dominate the literature: first, risk is comprised of both danger and opportunity, and second, risk is comprised only of danger. In decision theory, risk is defined as the variation of a distribution of possible outcomes, their likelihoods, and their subjective values (March and Shapira 1987). This definition also includes chances, i.e., positive deviations. The KonTraG<sup>1</sup> (a German legal framework that requires risk management for certain companies) also includes both sides; chances and risks (Weber und Liekweg 2004). Harland et al. (2003) define risk as the chance of damage, loss, injury, or other undesired consequences. Many authors define risk as the probability of a given event multiplied by its severity in terms of negative business impact (e.g. Christopher and Peck 2004). Risk also has to be distinguished from uncertainty: the term risk is used if the distribution of the outcome is known, whereas uncertainty describes a unique situation in which the distribution is unknown (e.g. Svensson 2000).

Risk-taking is generally perceived as an integral part of management; that is, all strategic choices have certain risk implications. Norrman and Jansson (2004) define business risk as the level of exposure to uncertainties that a company must understand and effectively manage when executing its strategies. According to Ritchie and Brindley (2007a), risk exists in all

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<sup>1</sup>Gesetz zur Kontrolle und Transparenz im Unternehmensbereich (short: KonTraG), KonTraG requires a system that helps to identify and manage risks that could possibly result in corporate disaster. The statutory requirement for a risk management system is laid down in § 91 II AktG.

business situations. Typically, organizations do not have the capacity to address all potential risks, so in a given situation only the key risks are addressed.

It is clear that that all business decisions contain risks. Almost any event can theoretically become a risk or a disruption; thus, there is clearly no way to develop an exhaustive risk inventory or list. This makes the topic of risk identification and management a very broad and complex area. A truly comprehensive approach might even include risks with potentially positive effects. To make the scope of the present research more manageable, however, it is necessary to limit the focus. Since the goal of risk management is ultimately to mitigate negative influences and ensure the company's success, an analysis of negative risks only is sufficient for this paper.

### **II.2.2. Supply chain and supply chain management**

Brindley and Ritchie (2004) recognize the difficulty in the almost infinite number of definitions of the terms SC and SCM. These definitions are not necessarily inconsistent, but they do have different points of focus. Departmental barriers are still at work, and the term "supply chain" means different things to different people. Despite the large number of definitions, logistics and SCM continue to be seen as alternatives, subsets, or different-but-overlapping disciplines (Peck 2006). While Spekman and Davis (2004) divide the supply chain into three primary channels (goods, information, and money), Cavinato (2004) identifies five sub-chains or networks: physical, financial, informational, relational, and innovational. Juettner et al. (2003) focus only on material and information flows. Christopher (1998) defines a supply chain not as an actual chain, but rather as a network of upstream and downstream organizations with different processes and activities that produce value for the end consumer. He takes an end-to-end perspective from the source of the raw material to the delivery to the end customer.

Peck (2006) describes how SCM has evolved over the last decades. In the 1980s the discipline developed out of logistics and operations management. In the 1990s the field broadened - first with the addition of some aspects of marketing, new product development, order management, and payment, and later with a change in perspective to cross-functional inter-organizational processes. To assure uninterrupted global material availability in a lean operating environment and to deliver a product or service at the right time and price, Elkins et al. (2007) propose cross-functional responsibilities.

Mentzer et al. (2001) and Olson and Wu (2008) distinguish between a strategic and a functional supply chain level. The strategic part defines the coordination and collaboration across firms whereas the functional scope defines the management of logistics and other supply chain processes, across functions and between businesses). Mentzer et al. (2008) offer several definitions. They define supply chain management as applying tools to improve business processes across organizational boundaries. Operations management is defined as optimizing internal functional boundaries and marketing. Finally, they identify logistics and production as separate functions to be coordinated. The task of supply chain management is to match supply and demand while generating the lowest total cost and obtaining the highest level of quality (e.g. Cohen and Kunreuther 2007). Following the suggestions of literature (e.g. Simchi-Levi et al. 2000, Chopra and Meindl 2001), Hendricks and Singhal (2003) developed a framework linking supply chain performance to shareholder value.

For the purpose of risk management, several conclusions can be drawn. Due to the inherent complexity of supply chains, researchers tend to conceptualize supply chains in terms of specific units of analysis (Peck 2006). When developing an approach to supply chain risk management, the scope of the investigation needs to be defined beforehand. A complete supply chain is too large and complex to analyze. Ziegenbein (2007), for example, proposes first classifying the supply chain under investigation, e.g. by end product or geography. Further, it can be seen that the definition of supply chain management is not clear and unique. To properly identify supply chain risks, the term must be narrowed down, amended with regard to its scope and channels, and differentiated from related concepts such as supply chain or enterprise risk management.

### **II.2.3. Supply chain risk and related concepts**

As described above, both risk and supply chain (management) are broadly and to some extent unclearly defined. Authors have consequently arrived at several different definitions for supply chain risk and the related concepts of supply chain disruption and vulnerability. Peck (2006) refers to supply chain risk as anything that poses a risk to the flow of information, material, and product from the original suppliers to the end-users; such risks may lead to a mismatch of supply and demand, ultimately affecting cost or quality, i.e. the deviation from a target value. Wager and Bode (2008) also see risk as a negative deviation from the expected value of a certain performance measure. They, however, refer to supply chain disruptions as

unintended, anomalous events that materialize somewhere in the supply chain or in its environment and which significantly threaten the normal course of supply chain operations. For the affected firm, it is an exceptional situation in comparison to everyday business. Chopra and Sodhi (2004) define supply chain risk as disruption or delay in the flow of material, information, and cash. According to Craighead et al. (2007), supply chain disruptions are unplanned and unanticipated events that disrupt the normal flow. Sheffi and Rice (2005) define disruptions as random events, accidents, or intentional disruptions.

It is also important to understand the closely related concept of vulnerability. Peck (2006) describes a supply chain as vulnerable when some part of the supply chain is at risk or likely to be damaged; this could be the performance, a process, or even an economy or society. Christopher and Peck (2004) characterize supply chain vulnerability as exposure to a serious disturbance that arises from risks present within or external to the supply chain. Svensson (2000) defines vulnerability as a condition affecting a firm's goal accomplishment as a negative consequence of a disturbance. Some authors focus only on certain aspects of the supply chain, such as the supply side (e.g. Zsidisin 2003).

As described above, risk and vulnerability are defined in some sources as a mere deviation from a target value; in others, they are presented as an anomalous, significant event that threatens the normal course of business. Any risk originating in the supply chain or affecting it can be counted as supply chain risk. Risk lists cannot be exhaustive and identify only the main types of risks (e.g. Waters 2007). Juettner (2005) suggests that risk sources include any variable that cannot be accurately predicted and that leads to a supply chain disruption. When both supply chain and risk are so broadly defined, nearly any risk can be counted as supply chain risk. As it is not possible to identify all supply chain risks, it is necessary to focus on the most significant risks. Therefore, an approach that differentiates supply chain risks from other risk management disciplines is required.

#### **II.2.4. Enterprise risk management**

Harland et al. (2003) recognize that modern business management incorporates risk and risk taking. The trade-off depends on an acceptable level of risk weighed against possible benefit, and on the risk appetite of the organization (risk-averse vs. risk-taking). A company's attitude towards risk depends on the nature of the business and on the individual style, behavior, and experience of managers. Risk management therefore has to take every aspect of the business



into account. For Cohen and Kunreuther (2007), risk management involves developing strategies that reduce the probability of negative events and/or their consequences. For Elkins et al. (2007), risk management must also include regular cross-functional, multidirectional information sharing and feedback. Wagner and Bode (2008a) apply a classical risk management process starting with identification, moving to assessment and aggregation, and ending in mitigation and control. Risk management is a field of activity seeking to eliminate, reduce, and generally control risks. Peck (2006) has argued that corporate risk management and strategic management share a common heritage. For Norrman and Jansson (2004), risk management increases the transparency of an organization.

On a governmental level, new legislation has been introduced to ensure the integration of risk management into general business practice. It is hoped that these measures will help to prevent further spectacular corporate crises such as those experienced by Enron, WorldCom and Metallgesellschaft (e.g. Weber and Liekweg 2004, Peck 2006). The United States introduced the Sarbanes-Oxley Act for companies listed on the US stock exchange in 2002<sup>2</sup>. A prominent example in German legislation is KonTraG. The goal of KonTraG is to identify and manage risks that could possibly result in corporate disaster. Therefore, any risk management effort is defined as part of enterprise risk management and issues currently subsumed under it can be differentiated into functional subgroups. This raises the question of which criteria can be used to divide the wide field of ERM.

### **II.2.5. Supply chain risk management**

As discussed above, clear definitions of the terms “risk” and “supply chain management” are lacking; as a result, it is almost impossible to derive a clear definition of the combined term “supply chain risk management”. Haywood (2002) recognized as much, arguing that the absence of a common understanding of the term supply chain represented a significant barrier to the identification of supply chain vulnerabilities and the implementation of appropriate risk management methods. The definitions that have been proposed in the last decade vary considerably. For Juettner (2005), for example, the goal of supply chain risk management is to identify potential sources of risk and to implement appropriate actions to avoid supply chain vulnerability. Handfield et al. (2007) define supply chain risk management as the integration and management of organizations within a supply chain to minimize risk and the reduction of the likelihood of disruptions through cooperative organizational relationships,

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<sup>2</sup> Sarbanes-Oxley describes specific requirements for financial reporting and makes top management directly accountable for policing internal management process controls and documenting procedures.

effective business processes, and high levels of information sharing. Harland et al. (2003) see the supply chain risk management process as a standard risk management process that is applied to a supply network. The risk management process should be established jointly by actors of the network, from identification to strategy formulation (e.g. Bakshi and Kleindorfer 2007, Hallikas et al. 2005). Peck (2006) defines the concept more broadly, and also sees supply chain management techniques as possible risk management strategies - e.g. Six Sigma, process control, or information sharing. Waters (2007) provides a rather narrow definition of supply chain risk management as being responsible for all aspects of risks to the supply chain, especially logistics risks. Kleindorfer and Saad (2005) differentiate between SCRM and SCM. Supply chain risk management, they argue, focuses on disruptions in supply chains, including addressing the effect of alternative supply chain design options on the efficiency and robustness of the supply chain. In contrast, supply chain management mainly focuses on ongoing volume and earnings risks associated with coordinating demand and supply of multiple supply chain actors. Norrman and Lindroth (2004) define the terms risk, uncertainty, and supply chain management very broadly. The diversity of the available definitions makes a general discussion of the concept nearly impossible. It is therefore more feasible and more practical to focus on a review of specific issues in the field of supply chain risk management.

Some authors extend the management of specific individual risks to the development of supply chain resilience. As not all risks can be eliminated, these authors argue, the supply chain as a whole must be made more resilient. Resilience is defined in this context as the ability of a system to return to its original or desired state after being disturbed (Christopher and Peck 2004, Sheffi and Rice 2005). One way for a supply chain to become more resilient is to increase flexibility and redundancy, thus reducing vulnerability. Several authors have proposed measures that can be taken during the supply chain strategy and design in order to increase the resilience of the chain (e.g. Christopher and Peck 2004, Sheffi 2005, Kleindorfer and Saad 2005). Contingency planning, business continuity management, and “near-miss analysis” are often discussed as a part of, or in addition to, supply chain risk management (e.g. Svensson 2000, Norrman and Jansson 2004, Phimister et al. 2003).

Supply chain risk management is related to enterprise risk management in two ways. One, SCRM is a part of ERM in that it focuses on processes within the company that are part of ERM. Further, SCRM broadens standard enterprise risk management by including the upstream and downstream partners in a supply chain. Depending on the scope of the supply

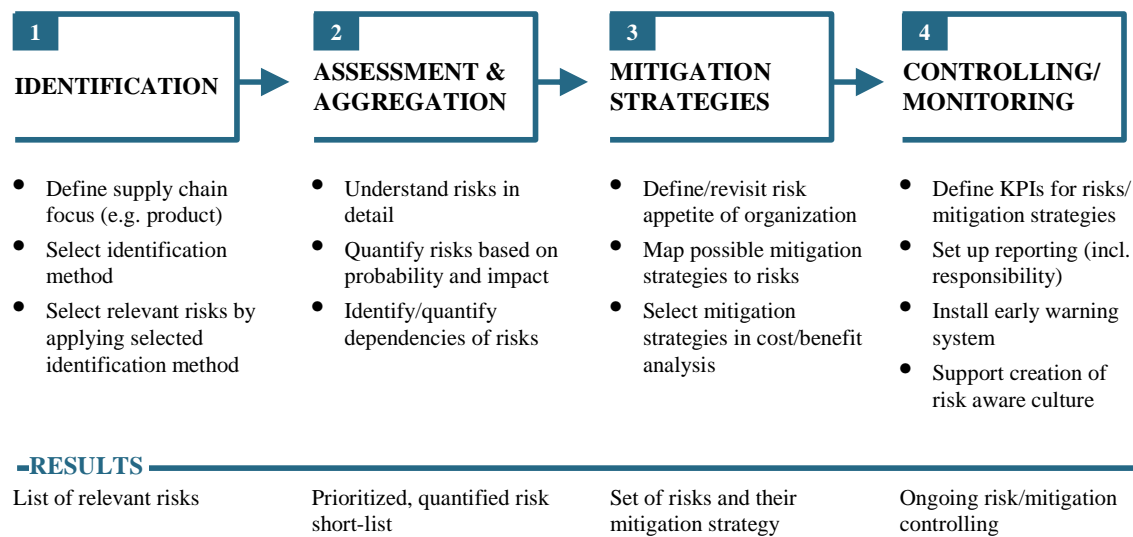
chain of a company, enterprise risk management and supply chain risk management are especially likely to overlap when financial flows, supply chain strategy decisions, and supply chain support processes are included.

#### **II.2.6. Risk identification frameworks and risk management process**

Various authors have proposed different frameworks for risk identification. There are two general approaches: creation of risk lists and categorization of risks. Among those who propose the creation of risk lists, Chopra and Sodhi (2004) propose the following list: disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity. Other authors including Waters (2007), Moder (2008) and Ritchie and Brindley (2007a) likewise present risk lists for the identification process. Among those who propose the creation of risk categories, Svensson (2004) categorizes sources of risk into internal vs. external and atomistic vs. holistic. Kleindorfer and Saad (2005) propose the following risk categories: operational contingencies (equipment malfunctions, systemic failures, abrupt discontinuity of supply, strikes, fraud etc.), natural hazards (e.g. earthquakes, hurricanes and storms), and terrorism and political instability. Peck (2005) defines the following levels as sources and drivers of supply chain risks: process-related, assets and infrastructure dependencies, organizations and inter-organizational relationships, and social and natural environment. Wagner and Bode (2008b) distinguish between demand side, supply side, regulatory/legal and bureaucratic, infrastructure, and catastrophic risks. Ziegenbein (2007) identifies risks by applying a process-oriented approach, specifically by using the SCOR (Supply Chain Operation Reference) model and mapping the risk effects (quality, quantity, default and cost) onto all process steps. Each author included in this review proposes his or her own list or framework of risks.

Supply chain risk management follows a similar procedure as classical risk management (e.g. Gleissner 2008, Haimes 1998), consisting of (1) risk identification, (2) risk assessment and aggregation, (3) development of mitigation strategies that fit the characteristics and needs of the decision environment, and (4) ongoing risk control and monitoring (Figure 1). The process steps are standardized and applied by various authors (e.g. Kleindorfer and Saad 2005, Wagner and Bode 2008a).

**Figure 1: Risk identification process**



The first step in the process focuses on the accurate identification of the relevant risks and risk fields. Combining a top-down perspective (with the advantage of simplicity and low data requirements) with a bottom-up orientation (more detailed) leads to a fuller picture of the risk landscape (Jorion 2007). The focus of the risk review needs to be defined in advance. Possible perspectives could be regions, final products, materials/inputs, sites, or suppliers (Ziegenbein 2007). Next, the supply chain is mapped, creating a more complete picture of the roles and responsibilities in the network (Harland et al. 2003). A framework is selected and discussed with management to identify any relevant risks for the company. Here, one has to distinguish between creative-intuitive and analytical-structured methods of risk identification. Creative-intuitive measures like brainstorming, interviews, or workshops generate a broad view of risks and make it possible to identify new risks. Analytical-structured methods such as checklists are more practical to handle, but leave little room for identifying new risks (Gleissner 2008, Ziegenbein 2007). For our risk management process, the identification step follows lines similar to e.g. Moder (2008) and Sheffi (2005).

In a second step, the relevant risks are assessed and aggregated. Managers and experts first derive a rough quantification of risk; this is based on the estimated probability of a given event multiplied by the assumed negative business impact. The various risk factors and consequences must be understood in detail in order for managers to quantify risk based on existing data. Managers also identify and quantify the distribution of risks and any dependencies between risks. Once quantified, the risks can then be prioritized. This in turn allows managers to create simulations of risk, as based on the indicators. The result of the

second step is a prioritized and quantified portfolio of risks (e.g. Christopher and Peck 2004, Gleissner 2008).

In a third step, mitigation strategies are developed based on the risk appetite of the company - i.e. on the acceptable risk level. The basic strategies available are risk avoidance, reduction, transfer, diversification, or acceptance. Each risk is mapped to its possible mitigation strategies. The best mitigation strategy for each risk is selected based on cost/benefit analysis and the risk appetite as constraint. After all risk and mitigation pairs are defined, the portfolio is analyzed for possible synergies and interferences (e.g. Chopra and Sodhi 2004, Gleissner 2008).

The fourth and final step consists of the integration of risk management in the supply chain organization. For each risk/mitigation combination, a set of KPIs and threshold values is identified for regular monitoring and reporting. Early warning indicators are set up, and efforts are made to create a risk-aware company culture. In this step it is important to create a monitoring structure, consisting of responsible managers, tasks, and reporting periods. The result of this final step is an established, ongoing risk reporting procedure as well as effective mitigation strategies (e.g. Sheffi 2005). Overall, this multi-step procedure is highly dependent on the availability of sophisticated information.

### **II.2.7. Contribution to the literature**

This paper analyzes factors and obstacles affecting the implementation of a supply chain risk management plan in major companies. It offers insights on how to improve the implementation of such a plan. In this regard we expand upon the work of Haywood (2002), who pointed out that the lack of a clear definition of the term “supply chain” hinders risk identification and implementation of supply chain risk management. We also build on the efforts of Norrman and Lindroth (2004), who considered the unclear definitions of risk and supply chain to be an argument for taking a focused, rather than holistic, approach to this topic. By focusing specifically on the fast moving consumer goods industry, we follow and extend Juettner et al. (2003) in developing risk management approaches for specific supply chains and/or industries. This paper serves as the basis for further research on the quantification and establishment of supply chain risk management. We also follow Peck (2006), who identified the different perceptions of risk by managers of different levels and responsibilities as an area for needed further research. Specifically, managers view supply

chain risks subjectively, as influenced by their own goals. Finally, we respond to Juettner's (2005) research question regarding how the implementation of SCRM processes can be organized within and across companies. With our work we will focus on the intra-organizational perspective, that is, specifically considering departments and their interactions.

## **II.3. Methodology**

### **II.3.1. Case study methodology**

We chose the case study method because we consider it an appropriate approach to the complexity of risk management in the supply chain, especially considering the novel character of the research (Manuj and Mentzer 2008). The strengths of case study research include the likelihood of generating novel theory, the possibility for direct testing, and the resulting empirical validity (Eisenhardt 1989). Further advantages include relevance, understanding, and exploratory depth (Meredith 1998). Boyer and Swink (2008) also suggest that case studies provide richness and first-hand observations in a natural setting, thus providing a foundation for further review. Drawbacks to case study research include a lack of rigor, a low possibility for scientific generalization, and high time and cost requirements (Yin 1989). Eisenhardt (1989) identifies a risk of overly complex theories lacking parsimony. Additionally, Boyer and Swink (2008) identify a risk of bias on the part of the researcher. For Yin (1989), case study research is to be applied when "how" or "why" questions are being asked and when evaluating contemporary, rather than historical, events. Meredith (1998) states that case studies are best for generating and extending theory. In the early stages of theory building, the researcher should be in close contact with the environment being studied (Handfield and Melnyk 1998). Case studies are used to investigate small samples analyzing a large number of variables in order to identify new empirical relationships for an in-depth understanding of the complex external world (Wacker 1998).

Case study methodology is thus appropriate and applicable for explorative theory development, such as the investigations in the present paper. To avoid the shortcomings listed above and to ensure the fulfillment of the above-mentioned criteria, we will follow the clearly defined process developed by Stuart et al. (2002). This process consists of the five stages: (1) define the research question, (2) develop the instrument, (3) gather data, (4) analyze data, and (5) disseminate the results.

### **II.3.2. Sample selection**

After defining our research questions, we developed a research approach and selected the case study company. We used a theoretical sampling approach (Glaser and Strauss 1967) by selecting participants who can provide meaningful data for our research. For our case study object we sought a company that experiences challenges in a competitive industry but demonstrates strong operational and financial performance. We furthermore wanted a company with a heterogeneous structure and with sufficient size to enable us to compare company divisions as sub-case studies. The case study company we selected operates in the highly competitive FMCG industry. Characteristics of this industry include low value, low-involvement goods, impulsive customer purchases, short usage cycles, and high repurchasing need. Customers in this industry tend to make purchasing decisions based on price and availability, and show little brand loyalty. Aside from shelf availability, the market is characterized by high quality requirements (especially for branded goods) and cost pressure driven by private label competition, concentration of retailers, and a high marketing spend (e.g. Weise 2008, Meffert 1999). The case study company is a global player in the FMCG industry. Its supply chain is structured in a global, regional, and local organization with the regions Western Europe (WE), Central Eastern Europe (CEE) and Middle East/North Africa (MENA).

### **II.3.3. Data collection and analysis**

We set up structured interviews to gather data pertaining to our research questions, as defined above. The interviews were analyzed by logical conclusion and small-scale mathematical analysis. We conducted a total of 21 interviews with middle and senior managers at the case study company. The number and content of the interviews were based on emerging theory (Glaser 1978), i.e. upcoming relevant questions were explored and discussed until no further new information resulted from the last interview as compared to the previous ones, and therefore, saturation was achieved. We interviewed two employees in the controlling department at corporate headquarter who were working on the legally required enterprise risk management. We also spoke with four employees in the global supply chain department (head of the SC, supply chain controlling, production steering, and SHEQ<sup>3</sup>). We also talked to the purchasing department, which is mainly responsible for the business unit under review (head of purchasing, employees responsible for purchasing bottles and packaging, raw materials, and transportation) and to one employee from the international sales department. The regional

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<sup>3</sup>SHEQ: Safety, Health, Environment, Quality

perspective of the supply chain in WE, CEE and MENA was obtained in interviews with the head and the employees responsible for the production steering and the logistics and materials management. We fulfill the validity requirements by using multiple sources of evidence, obtained by interviewing different managers at different levels, regions, and departments that differ significantly from each other (e.g. Glaser and Strauss 1967). The interviews were semi-structured and lasted for 1.5 to 2 hours. This structured approach created internal validity by ensuring comparability between interviews. We also requested independent documentation to ensure triangulation of the verbal responses (Stuart et al. 2002). Each interview began with an explanation of the project. The semi-structured questionnaire focused on the managers' view of risk, supply chain management, supply chain risk, and enterprise risk management. All topics were covered first with unaided, open questions and then with aided, closed questions.

Detailed notes were taken during the interviews, as the interviewees felt uncomfortable with recording. The interview write-ups were analyzed and categorized using Microsoft Excel. The grounded theory methodology of systematic organization and constant comparison of data within and between interviews was followed by using open, axial, selective coding (Glaser and Strauss 1967). When appropriate, we used literature as another source of data (Glaser 1978). For internal validity, we reviewed the answers by placing different patterns on the results: we analyzed the results by work experience, region, level, function, and department (Stuart et al. 2002). Following Flint and Mentzer (2000) and Flint et al. (2002), to ensure rigor in the data collection and analysis we applied the following criteria: credibility, transferability, dependability, confirmability, and integrity (Hirschman 1986) and fit, understanding, generability, and control (Strauss and Corbin 1998) (see Appendix 1).

## **II.4. Findings from the case study**

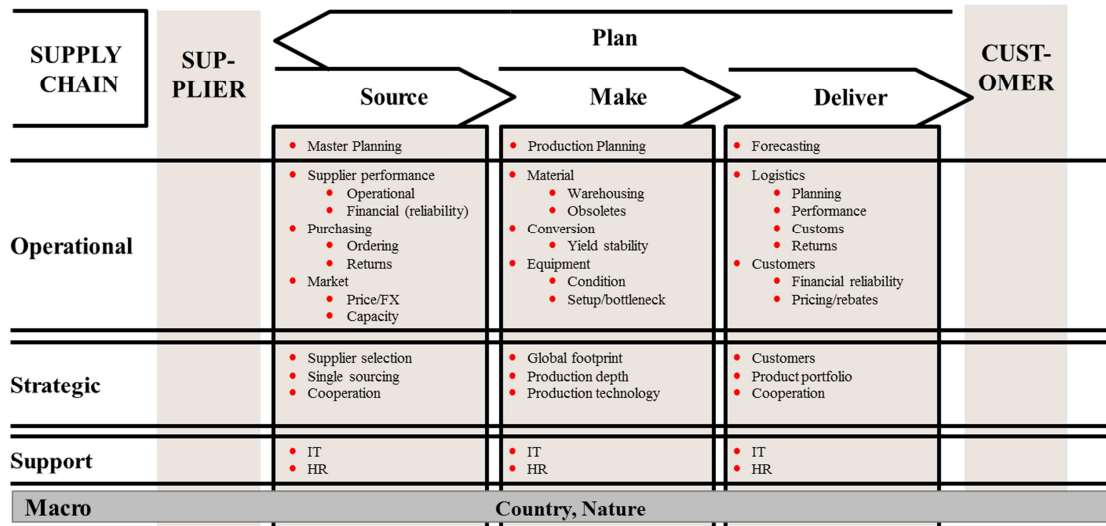
### **II.4.1. Risk identification framework**

When the research project began, no formal risk identification framework was in place in the case study company. As most of the frameworks available in the literature were either overly simple or overly complex, we developed an identification framework of our own that would provide structure but still allow managers to engage in creative-intuitive thinking. The framework creates a common working basis for the interviews and the risk management process. It integrates the findings from the case study and follows and extends the framework of Ziegenbein (2007), as we believe that a process-oriented approach is most promising. Instead of applying the risk consequences to every process step, we map a strategic,



operational, support, and macro view to all process phases. Managers thus have guidance during risk identification but are not overwhelmed with a long list of possible combinations of phases and effects supporting their creative-intuitive thinking. As a list of supply chain risks cannot be exhaustive, the identification framework is used to support the explorative identification process.

**Figure 2: Risk identification framework**



The risk identification framework (Figure 2) is based on the SCOR model (Ziegenbein 2007). It is more strongly focused on process than simple risk lists (e.g. Chopra and Sodhi 2004, Moder 2008). It also relies on tangible examples, rather than on high-level risk categories (e.g. Peck 2006), which encourages the managers' contribution. Risks can have an impact on four major categories in terms of EBIT performance of a supply chain, i.e. indirect cost arising from delays, quality issues, quantity problems, or direct cost (Ziegenbein 2007).

The SC is divided into four main stages of activity: source, make, deliver, and plan. This division is based on the SCOR model and is similar to the distinctions made by Ziegenbein (2007). Planning activities flow from the customer to the supplier. The remaining tasks flow from supplier to the customers. "Source" describes the purchasing and ordering of raw materials; "Make" focuses on the production of the goods; and "Deliver" describes the customer contact and delivery of goods. The steps "Source" and "Deliver" involve contact with suppliers and/or customers. The return process as part of the SCOR model is not included as explicit step in the framework, since it has very limited relevance according to the

interviewees. The model is more flexible than Ziegenbein (2007), as we did not automatically include the attributes of quality, delay, cost, and default on every process step. We avoided this because it would have led to a long checklist of risks; this potentially gives managers the impression that all risks are already on the list and therefore hinders the creative-intuitive thinking process.

The four rows (operational, strategic, support, and macro) represent the management components of each stage. “Strategic” supply chain management includes all decisions regarding network, coordination and collaboration, and process setup (Mentzer et al. 2001). “Operational” management includes the execution of the existing processes including planning. Risks in this area could be problems due to supplier performance, equipment failures, or incorrect forecasting. “Strategic” management focuses on risks that arise from long-term strategic decisions such as single sourcing, production networks, or cooperation. As every strategic decision contains risks (e.g. Norrman and Jansson 2004) we extend the framework of Ziegenbein (2007) to include strategic components. “Support” processes including HR and IT are also necessary for the operational and strategic execution of the supply chain and are therefore also included in our focus. Risks arising in the context of support functions of the supply chain can include system breakdowns or a lack of succession planning. Macro risks arise from the business environment, such as natural hazards or political instability. The framework includes all risks that can have an influence on the supply chain.

The standard SCRM process is used as described above. In the first step, we define the unit of analysis, that is, the scope of the supply chain definition. Norrman and Lindroth (2004) distinguish between a single activity, the company, a dyadic relationship, the supply chain, and the supply chain network. We will focus on the case study company and its dyadic relationships for setting up a supply chain risk management. We will identify risks by reviewing every process step.

#### **II.4.2. Risk in the case study company**

Our interviews revealed that managers and researchers share the same difficulty in developing a definition of risk management. Seven managers viewed risk management purely as a defense against negative threats. Thirteen managers included both opportunities and danger in their definition of risk management. None of the managers, however, mentioned the

potentially positive side of risk unless prompted by the interviewer. When asked whether risk management should also include opportunities, managers offered partly constructed definitions – e.g., “if we have good risk management, this is an opportunity for us.” We mapped the results by region and department/function to discover possible patterns in the answers. All managers working in the CEE and MENA region included opportunity in their definition of risk; this could be because those regions offer a higher growth potential than do saturated markets. In practice, differentiation between risk and uncertainty is not common. Some managers defined risk as an event with unknown outcomes. From a practical perspective, it is not always possible to fulfill the conditions for risk (i.e. knowing the distribution of likelihood and monetary impact); therefore, we will combine uncertainty and risk management. The managers agreed that “all business decisions include risk”. For the sake of theory we can confirm that managers see risk as an event with a negative impact when asked openly (unaided) (March and Shapira 1987). In aided questions, no consensus is achieved. When discussing positive aspects, the term risk should be avoided and chance should rather be used. The differentiation between uncertainty and risk is not recognized in the case study company.

#### **II.4.3. Supply chain management in the case study company**

When managers were asked to provide their definition of a supply chain, the answers largely reflected the organizational view. At the case study company, the supply chain function evolved from the production function. Often, however, based on a common misconception the supply chain department is wrongly defined as logistics department. An anecdote at the case study company illustrates this nicely. When looking for a supply chain manager overlooking the whole supply chain from supplier to inbound logistics, production and out-bound logistics, the head of a regional supply chain was not surprised to find that “50% of applicants were only logistics specialists without a holistic view of the supply chain.” The supply chain organization is structured into global, regional, and local units. Due to product specifics, transportation distances greater than 500 to 700 km are not cost efficient. From an organizational perspective, the responsibilities of the supply chain department start when they receive the sales forecast from the sales department; this forecast includes information such as net demand planning, production scheduling, raw material ordering, production, warehousing, and delivery. The sales department is responsible for the interface to the customer, including both forecasting as well as commercial and strategic customer contact. In some countries customer service (i.e. management of order intake) is part of the sales department; in others it

is part of the SC department. The purchasing department, which is located on the other end of the internal supply chain, is globally centralized and separated from the supply chain organization. Strategic supplier management, including evaluation and integration, is mainly handled by the purchasing department and supported by the global supply chain department, but without the direct involvement of the regional supply chain department. The supply chain department is responsible for the operational aspects of the purchasing process, i.e. the order release for raw materials and supplier evaluation. 75% of the interviewees regard the responsibility of the supply chain department to be only information and material flows. Money flows are controlled by the finance department, including “order to cash” and “purchase to pay” functions. Inventories fall under the responsibility of the supply chain department. Thus, the supply chain department is focused on cost, rather than on monetary flows. The purchasing department, as the front end of the supply chain, also sees itself as responsible for monetary flows, i.e. for handling the price and exchange rate volatility of purchased goods.

Several managers mentioned in the interviews that the different incentive schemes of the purchasing and supply chain departments might lead to problems. While the purchasing department makes decisions based on lowest purchase prices, the supply chain department focuses on the delivery of goods and the service level. Generally, it is not possible to optimize two variables at the same time; one goal will be optimized while the other is a constraint at a certain level. Thus, centralized purchasing’s main goal is to optimize purchase prices while maintaining service and quality. The supply chain department’s main goal, in contrast, is to enforce the service level, and only in a second step to consider the cost perspective. Taking into consideration both the structure of the supply chain and the various goals of the department, it is clear that the responsibilities of supply chain management actually extend beyond the scope of the supply chain department itself. In other words, there is a clear difference between the theoretical and practical scope of activities of the supply chain managers. There are furthermore practical reasons (e.g. purchasing efficiencies) why this difference is maintained.

Summarizing the above, it becomes evident that no single department or responsible manager can entirely manage the supply chain and its risks. In order to successfully manage an end-to-end, multiple flow process, the departments involved must come to a consensus on how to manage supply chain issues. The supply chain involves at least four departments, namely

purchasing, supply chain, sales, and finance. In an extreme case, the supply chain may even function as a chain of small companies within the main company. This is reflected in the statement of one manager in the supply chain department: “The sales department is the customer of the supply chain.” Every company creates its own unique division of tasks along the supply chain and defines the role of the supply chain management department differently. These boundaries and interfaces need to be evaluated before attempting to devise a risk management scheme.

From the literature we confirm that a lack of a common understanding of the supply chain hinders the supply chain risk management process. Buzzwords such as “end-to-end responsibility” were also defined differently by different interviewees. A departmental perspective largely dominates – for example, a central purchasing department was established to increase purchasing power, rather than an end-to-end SC. We additionally observed that an unclear definition of the supply chain contributes to inter-departmental rivalry; that is, the end-to-end supply chain is divided into various departments that each strive to achieve different goals and lack a proper interface. This additionally hinders the implementation of an end-to-end supply chain risk management. We can conclude that the interviewees do not share a common understanding of supply chain management, and that departmental barriers even hinder the development of an end-to-end perspective.

#### **II.4.4. Supply chain risk in the case study company**

When asked to provide their definition of “supply chain risk”, the SC department mainly mentioned risk of lost sales and customer complaints. One interviewee clearly mentioned that the service aspect is ranked most important for the FMCG company, whereas the cost aspect ranks at number two. This focus on service could be clearly seen in the more operative supply chain departments. For the purchasing department, risk was divided into price risk (exchange rate risk and price volatility) and supply risk (non-delivery). Six of the interviewees defined risk as a deviation from a target value; for eleven interviewees, risk existed only if a threshold value was exceeded. These answers were independent of region or department. However, the managers conveyed the impression they tended to look for minor deviations of the target value, as even minor deviations might have extreme long-term consequences; this is true especially in saturated markets with high competitive pressure or if there have been past experiences with a sharp increase in the market prices of raw materials. The main focus for managers was their performance targets, primarily defined in terms of service level and less in

terms of overall EBIT. Supply chain risk is seen differently by all interviewees; their definitions focused mainly on their locus of control (Peck 2006). Several departments have individual risk definitions, which render the definition of SC risk unclear. Risks must be defined in terms of known KPIs (e.g. service level or prices) and then translated to EBIT.

#### **II.4.5. Enterprise risk management in the case study company**

The case study company has implemented an enterprise risk management process, as required by German legislation. However, the efforts of this mandatory procedure did not include the operational departments. Only one of the interviewees was aware of the official enterprise risk management process in the organization. This employee criticized the program as being not well understood or practically implemented in the company. This manager commented, “ERM is something for the management board, not for us.” Interviews with managers responsible for the enterprise risk management indicate that ERM is implemented to fulfill legal requirements. Despite the fact that supply chain managers’ monetary and career incentives ultimately depend on the long-term success of the company/supply chain, which should – at least ideally – depend on a functioning risk management, managers do not perceive the added value of ERM. This lack of understanding shows that the theoretical concepts of SCRM need to be better explained. Managers need to be informed about the processes and concepts of risk management. Given the negative perceptions of risk management, its advantages and potential value should be explained to managers. ERM is not well understood in the organization, or is even viewed negatively, thus hindering an effective implementation of SCRM.

#### **II.4.6. Supply chain risk management in the case study company**

A structured approach to supply chain risk management is not in place at the case study company. However, some procedures are already in place that could be classified as supply chain risk management activities; these include supplier evaluations, market price forecasting or production back-up plans. All managers are proactively working on possible issues and their solutions. However, these activities do not fall under a risk management umbrella. There is no central link to the enterprise risk management. Managers do not have a common basis of discussion and do not cooperate to manage risks. The legal enterprise risk management is insufficient without adaptation to operational units. The term “supply chain risk management” seems difficult to define as every organization has its individual definition of the supply chain department performing different tasks. If supply chain risk management is defined as

managing the risks of these departmental tasks, its contents will automatically differ across organizations. Risk, supply chain, supply chain risk, and enterprise risk management are not clearly understood in the organization. Further, a clear distinction between measures of SCM and SCRM cannot be drawn. Additionally, organizational barriers within the end-to-end supply chain as well as the rather negative perception of the ERM further impede the effective implementation of SCRM.

## **II.5. Conclusion**

The two definitions of risk (opportunity and danger vs. danger alone) that were identified in the literature are also seen in the case study company. We also found varying definitions regarding what is regarded as a risk: a serious event vs. the deviation from a target value. The broad supply chain definition stated in the literature (i.e. including upstream and downstream partners) is not reflected in the company. Rather, an organizational focus prevails, which leads to organizational boundaries and interrupts the end-to-end-processes. Supply chain related flows are mainly seen as material and information. When including the purchasing department, the financial flow is included, as well. Enterprise risk management has not yet been introduced in the organization; currently it remains a topic discussed by the management board but not yet accepted by the operational entities. We have reviewed all relevant definitions that are the basis for supply chain risk management, i.e. risk, supply chain (management), supply chain risk and supply chain risk management. Neither in the literature nor in the case study company are these terms clearly defined. Individual adaptation of the theory is necessary. Further, departmental boundaries threaten to hinder the implementation of a risk management plan (and perhaps even pose some risks to the company themselves). We develop the following proposition:

*The implementation of supply chain risk management is impeded in major companies because of a lack of a common understanding of its terms and implications. Departmental barriers further amplify this issue.*

The need for a common basis for discussion led to the creation of a risk identification framework that can be used as a basis for supply chain risk management. The framework requires a certain level of detail but is designed to not be overwhelming for the manager (for example, it does not include a long list of possible risks). For validation the risk identification framework was explained to the managers and they were asked to give feedback regarding its

consistency and understandability. The framework can be used by different companies and regions as a basis for the identification of main risks, especially in the FMCG industry. Risks along the supply chain are identified according to department, and each department should be made responsible for management of its risks. Any inter-departmental barriers have to be evaluated beforehand. Regarding the definitions discussed above, the following assumptions have been made: Risk is defined by the negative impact multiplied by the probability of an event. We focus only on the negative aspects and ignore the opportunities. The supply chain processes include flows of finances, materials, and information. We consider an end-to-end view of those flows within the company with interfaces to suppliers and customers. We include the purchasing and the customer service departments. Supply chain risk is, therefore, an event that has a negative effect exceeding a certain threshold value. The negative effect is measured in service level or cost. Supply chain risk management encompasses the identification, assessment, mitigation and controlling of risks in the supply chain as defined above.

## **II.6. Basis and motivation for research on subjective and objective risk assessment**

In paper one we developed common definitions of supply chain risk management and concluded that departmental boundaries can limit or hinder the risk management process. The next step in the research process is to implement the risk management process in the case study company. During this phase we gather the necessary quantitative data. We also compare objective (i.e. quantitative) risk assessment and subjective risk assessment in order to determine whether subjective risk assessment alone is sufficient.

The data of the case study company can be derived based on clear definitions as put forth in paper 1. While the company has extensive data on its supply chain, specific data regarding enterprise risk management is narrowly focused and provides only limited insights into supply chain risk management. With the extended and more precise definitions, we can rely on the supply chain controlling data and derive more relevant information. Lost sales data can, for example, be defined and used in the research. Based on this more complete data set, sophisticated quantitative analysis can be applied to assess the probabilities and the impacts of the risks. Targeted collection of additional, specific data is possible based on the new definition and the access to the organization including different controlling systems across the company.



The managers to be included in the subjective risk assessment were identified based on the work on the common ground of supply chain risk management. The identification of departmental barriers in paper 1 emphasized the importance of including all relevant departments in the study in order not to lose valuable perspectives on the supply chain. Managers in each department were available to discuss risks in their area of the supply chain, their perceptions of financial risk impact, and the probability of a risk event. The scope of the investigation was extended beyond the supply chain itself to include the purchasing, sales and production departments. In this environment, we were able to analyze the differences in risk prioritization from both assessment procedures. The opportunity to interview the managers more than once also allowed for the discussion of possible reasons for differences in the assessment results. Beyond the quality of subjective results the paper explores how subjective and objective assessment can be combined optimally to use the individual strengths.

### **III. Paper 2 - Comparing subjective and objective risk assessment of supply chain risks**

#### **III.1. Introduction**

On February 19, 2001 food and mouth disease was detected in livestock in Essex, England. In response the European Union and several other countries banned the import of British meat outright. British authorities had 300 potentially infected animals in the area killed, but the disease had already spread. Officials put tight restrictions on the British countryside, including closing many roads, tourist parks, and walkways, and cancelled many local activities and sporting events. The battle to control the spread of the disease lasted seven months and resulted in the slaughter of 6.5 million animals, of which only 2,000 had actually been infected. The resulting agricultural loss amounted to 2.4 m GBP. The crisis-control efforts also caused massive losses in other industries: the tourism industry, for example, lost 3.3 m GBP as a result of measures taken against the disease. Would there have been a way to avoid this secondary loss? This example clearly reveals the importance of performing a detailed risk assessment before starting any mitigation strategy.

As described in paper 1, a classical risk management process comprises the following steps: (1) identification, (2) assessment/aggregation, (3) mitigation, and (4) controlling risks (e.g. Kleindorfer and Saad 2005). Our analysis in this paper focuses on the second step, risk assessment. In the literature to date, only a few papers perform a quantitative risk assessment (e.g. Deleris et al. 2004, Buscher et al. 2007); most mainly focus on qualitative risk assessment (e.g. Thun and Hoenig 2011). Khan and Burnes (2007) found that authors often combine objective and subjective risk assessment. We will expand the discussion in the literature with several contributions. First, we provide a comparison of subjective/qualitative risk assessment (as performed by managers) and objective/quantitative risk evaluation (based on internal and external data on supply chain risks). We reveal that managers tend to over- or under-value the probability and the impact of risk types. We identify reasons and decision biases that may explain these differences in the objective vs. subjective risk assessment. Finally, we propose several amendments to the supply chain risk management process that serve to correct the identified weaknesses. For this paper we have decided to use a case study approach similar to paper 1, as the topic of supply chain risk management is still evolving and is highly complex to analyze (Manuj and Mentzer 2008). A proper analysis thus requires direct access to relevant data and management, making a case study ideal.

## **III.2. Literature review**

### **III.2.1. Objective risk assessment**

The most widely cited definition of risk stems from decision theory, in which risk is defined as the variation in the distribution of possible outcomes based on their likelihoods and impacts. In a hazard-focused interpretation of risk, the probability of an event is multiplied by the negative business impact (Christopher and Peck 2004). A number of authors support objective (quantitative) risk assessment without discussing the potential problems arising from this approach. Gleissner (2004), for example, proposes a quantification of risks by determining the scope of the overall risk exposure of a company with a risk analysis. Risks should be simulated in financial terms using Monte Carlo analysis, and this analysis should be integrated into the corporate planning and profit and loss (P&L) statement. Hauser (2003) also proposes a quantitative assessment with financial modeling to simulate adverse events in business processes and to determine the eventual impact on P&L and balance sheet. Potential drawbacks to this approach are not discussed. Deleris et al. (2004) are among the small number of authors who develop a simulation to estimate the probability distribution of supply chain losses caused by disruptions. Their research is focused on one single risk, using an analytic model with simulation but without empirical data. Wels and Winter (2006) also develop an analytic model of dependencies between SC risks.

To quantify risks, risk measures are necessary. Artzner et al. (1999) analyze the coherence of risk measures. A coherent risk measure fulfills the criteria of translation invariance, sub-additivity, positive homogeneity, and monotonicity. Value at risk (VaR) is only coherent for normally distributed losses, as it does not fulfill the criteria of subadditivity for other underlying distributions. However, other measures, such as expected shortfall, are also sub-additive and therefore coherent. For our analysis VaR is sufficient, as we are not adding up risks but merely comparing them.

In risk management in the banking industry, the Basel Committee defines operational risk as the risk of loss resulting from inadequate or failed internal processes, people, and systems or from external events. This risk has to be calculated financially. When compared to the primary risks for which models exist (i.e. market and credit risk), however, operational risk is much harder to calculate. This is due to the difficulty of identifying or assessing all levels of

its many sources. Basel II<sup>4</sup> provides guidelines for three broad methods of capital calculation for operational risk. The Basic Indicator Approach is based on the annual revenue of the financial institution. The Standardized Approach considers the annual revenue of each of the broad business lines of the financial institution. Finally, the Advanced Measurement Approach is based on the internally developed risk measurement framework of the bank, adhering to defined standards (Jorion 2007). In summary, a standardized methodology or theory for the quantification of risks that would allow assessment and comparison of identified risks does not exist. Furthermore, the majority of articles in the literature focus on descriptive/qualitative models, rather than objective/quantitative ones (Tang and Musa 2011).

### **III.2.2. Subjective risk assessment**

Other authors propose a qualitative risk assessment. Oke and Gopalakrishnan (2009), for example, conduct a case study in the retail industry. The authors use a best guess qualitative risk assessment from a manager's perspective by using the frequency during the last six years (low to high) for the probability and the impact in the past and in the future (financial and non-financial). Thun and Hoenig (2011) perform an empirical study in the German automotive industry. Risks are assessed on a five-point scale measuring probability (from very low to very high) and impact (from weak to grave). In a case study of the company Bosch, Moder (2008) applies a qualitative risk assessment using a risk matrix with the units low/middle/high for impact and probability. Sheffi and Rice (2005) propose a qualitative assessment of risk and vulnerability. The vulnerability map defines disruption probability (from high to low) and consequences (from light to severe). Hallikas et al. (2005) assess impact from none (insignificant), minor (single, small losses), medium (short-term difficulties), serious (long-term difficulties) to catastrophic (discontinue business) and probability from very unlikely (very rare), improbable (indirect evidence), moderate (direct evidence), probable (strong direct evidence) to very probable (recurs frequently). Losses are defined in terms of financial consequences (e.g. costs) as well as in terms of immaterial consequences (e.g. trust, reputation, and degradation of knowledge), which are difficult to convert to monetary value but have long-term financial effect. Elkins et al. (2007) construct a subjective risk map without collecting extensive statistical data. Their approach is very pragmatic: a team can subjectively place risk in quadrants based on discussions. The impact should also include an intuitive assessment of how difficult and costly each risk is to mitigate.

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<sup>4</sup> In December 2010 a preliminary version of Basel III was introduced in response to the deficiencies in financial regulation revealed by the global financial crisis (Slovik and Cournède, 2011).

This approach is designed to allow an assessment of the probability and severity of risks without excessive data collection. A subjective risk assessment makes it possible to prioritize risks quickly and cost-effectively.

Qualitative risk assessment, which relies on the judgment of managers, is thus a common tool for risk assessment. Authors recommend this approach for its ease of implementation and quick results. However, its proponents do not cite any of the problems that might arise with purely qualitative risk assessment; neither do they compare their results to objective quantification to judge the quality of subjective assessment.

### **III.2.3. Objective versus subjective risk assessment**

Khan and Burnes (2007) distinguish between a subjective (qualitative) and an objective (quantitative) view of risk. In their opinion, it is not clear how the choice of a subjective vs. objective approach influences the selection of a framework and tools for supply chain risk management. They further discuss whether risks should be measured objectively and agreed upon by all personnel/managers, or if risks are already sufficiently objective when based on individual perceptions. They found that various SCRM authors mix objective and subjective risk assessment: some use the subjective terms “perception” and “perceived,” while others use the term “probability,” indicating an objective risk assessment. Aven and Renn (2009) argue that when risks have potentially major consequences and a high degree of uncertainty and complexity (e.g. terrorism), risk assessment should go beyond probabilities and expected values and should also include a qualitative approach and scenario building instruments, which can provide a more complete picture of the risk. Zsidisin et al. (2005) discuss the concept of expected value as a tool for risk assessment, arguing that focus should be put on risks with the highest expected value. However, they regard the expected value as problematic for low probability, high impact events; such events tend not to be in focus due to their low expected value. Further, the expected value approach requires an awareness of all relevant risks as well as confidence in the estimated probability and potential impact of those events.

Norrman and Jansson (2004) also discuss both methods. They propose a quantitative definition of risk as the probability of an event multiplied by the negative business impact of the event. They suggest placing the risk into a risk map. They also agree that uncertainties have unknown distributions and that as soon as the quantitative definition is abandoned for a broader more business-oriented one, the term “risk” becomes less clear. Olson and Wu (2008)

also discuss qualitative vs. quantitative assessment approaches. Qualitative risk management depends on the management's attitude towards a risk. Managers are often insensitive to probability estimates and tend to ignore events that they perceive to be unlikely. Other studies prefer an objective treatment of risks through quantification and propose an analysis on how managers should make decisions.

Harland et al. (2003) state that risk assessment should take into account intangible losses (e.g. reputation or trust) as well as clearly identifiable financial implications. One result of their case study was the insight that different levels of management have different levels of visibility. It was very difficult for managers to assess probabilities accurately. The managers had to use judgment and creativity. They revealed that the availability of data on risk probabilities and impact was poor and not collected routinely in the supply chain network.

March and Shapira (1987) argue that managers are quite insensitive to probability estimates; managers are more likely to define risk in terms of magnitude of loss, such as maximum exposure. Managers focus on critical performance targets and become more risk averse when performance is above targets. Individuals do not trust, do not understand, or simply do not use precise probability estimates. In various case studies (Rice and Caniato 2003, Zsidisin et al. 2000 and 2004) it was found that companies recognize the importance of SCRM, but invest little time or resources in managing SC risks. Due to the small number of available data points, strong estimates of probability and impact are difficult to obtain; cost/benefit analysis is likewise difficult to perform. Furthermore, managers tend to underestimate disruption risk in the absence of accurate information. They ignore very unlikely events because there is no benefit in solving problems that never happen. Thun and Hoenig (2011) assume a decision bias in their survey: managers estimate a larger impact for incidents with a higher likelihood, because they re-evaluate the magnitude of impact based on the expected value. Ritchie and Brindley (2007a) argue that factors such as attitudes towards risk, previous experiences in similar decision situations, and known or anticipated rewards and penalties can have an impact on the risk perceptions of managers of a given decision, thus influencing their responses.

The results described above collide with the well-known concept of the *homo economicus*, which states that people are capable of rational decision-making and motivated by self-interest to objectively optimize their output of predetermined goals (Simon 1955). This

concept was the basis for the majority of research in the field of supply chain management (Carter et al. 2007). However, many researchers have found that individuals have problems judging probabilities, making predictions, or attempting to deal with uncertain decision environments (Fischhoff 1982, Hogarth 1987, Thaler 2000). To explain those decision biases, Carter et al. (2007) define nine categories for the field of supply management (Appendix 2).

#### **III.2.4. Contribution to the literature**

In this paper we review the questions posed by Khan and Burnes (2007) regarding the implications of the subjective and objective (qualitative versus quantitative) assessment of risk. We investigate how the chosen approach influences the choice of tools for supply chain risk management. We quantify the identified risks and compare the results to their subjective assessment to better understand the value of quantification for supply chain risk management. The nine risk bias categories proposed by Carter et al. (2007) are used to explain the differences between subjective and objective risk assessment. Juettner et al. (2003) identify developing a better understanding of risk assessment along the supply chain and developing more practicable approaches to guide the process as important areas of further research in this field. Further, they assume that systematic differences in the risk concepts are dependent on the specific supply chain and/or industry context. Our research provides new insights in this direction: by focusing on supply chain risks in a specific industry and analyzing the differences between objective and subjective risk assessment, we suggest ways to revise and improve supply chain risk management. This paper specifically focuses on the fast moving consumer goods industry. This research contributes to a better understanding of the most effective assessment tools and steps for use in risk management in supply chains (or supply chain risk categories). This study proceeds along the following steps: first, we compare a subjective/qualitative risk assessment performed by managers against an objective/quantitative risk evaluation based on internal and external data. We then discuss the differences between the objective and subjective risk assessments. Specifically, we identify decision biases that help to explain why managers tend to over- or under-value the probability and impact of risks. Finally, we propose some adaptations to supply chain risk management to correct the identified weaknesses.

#### **III.3. Methodology – Data collection and analysis**

The basic choice of methodology and sampling is described in Chapters II.3.1. and II.3.2. For the research areas defined above, we set up structured interviews to gather data. The results

were analyzed by logical conclusion and quantitative analysis. Our data collection process consisted of the following steps: In the first round, 19 interviews were conducted to identify the risks in the supply chain. In the second round, 16 managers were interviewed to obtain their subjective risk assessment of the identified risks. In the last round, 13 additional interviews were held for the objective risk assessment to gather and understand the objective data. A list of interviewees appears in Appendix 3.

The number and content of the successive interviews were based on the concept of emerging theory (Glaser 1978), that is, exploring relevant upcoming questions until saturation. For risk identification, we interviewed four employees from the global supply chain department in corporate headquarters (head of the SC, supply chain controlling, production steering, and SHEQ). We also talked to the purchasing department mainly responsible for the business unit under review (head of purchasing, employees responsible for purchasing bottles and packaging, raw materials, and transportation) and one employee from the international sales department. The regional perspective of the supply chain in WE, CEE and MENA was obtained in interviews with the head and the employees responsible for the production steering and the logistics and materials management. We fulfill the validity requirements by using multiple sources of evidence; that is, we interviewed different managers at different levels, regions, and departments. The first and second rounds of interviews were semi-structured and lasted for 1.5 to 2 hours. The more structured approach allowed us to attain internal validity by ensuring comparability between the interviews. We also requested independent documentation to ensure triangulation of the verbal responses (Stuart et al. 2002). The semi-structured questionnaire focused on the managers' view regarding the identification and assessment of risks. The third round focused on data collection and explanation. The interviewees selected differ significantly from each other. Interviews were held until saturation had been achieved (e.g. Glaser and Strauss 1967).

Detailed notes were taken during the interviews, as the interviewees felt uncomfortable with recording. The interview write ups were analyzed and categorized using Microsoft Excel. We followed the grounded theory methodology of systematic organization and constant comparison of data within and between interviews by using open, axial, and selective coding (Glaser and Strauss 1967). Where appropriate, we relied on literature as another source of data (Glaser 1978). Regarding internal validity, we reviewed the answers by placing different patterns on the results, i.e. we analyzed the results by work experience, region, hierarchy



level, function, and department (Stuart et al. 2002). To ensure rigor in the data collection and analysis we applied the following criteria: credibility, transferability, dependability, confirmability, and integrity (Hirschman 1986) as well as fit, understanding, generability, and control (Strauss and Corbin 1998) (see Appendix 1).

#### **III.4. Subjective risk assessment in the case study company**

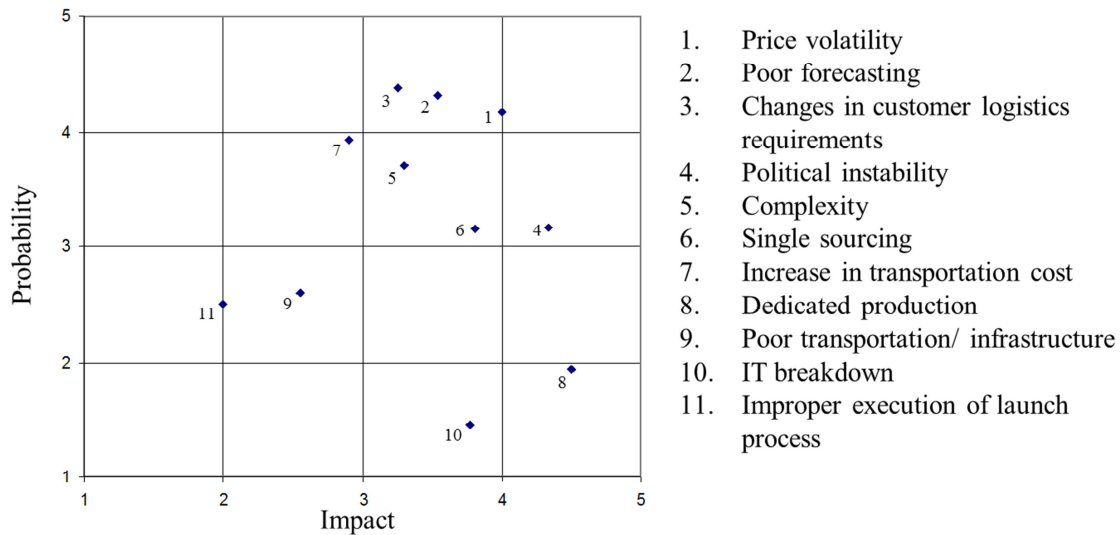
To obtain a subjective assessment of risks in the supply chain, we conducted 16 interviews in the case study company. We used the developed framework as a guide for risk identification (Appendix 4). In a second step, we consolidated and categorized the identified risks. We selected all risks that were named at least twice in the identification phase. We categorized the risks by region/department to ensure that the managers assessing the risks actually work in the corresponding region/department. (For example, poor forecasting was only assessed by the supply chain and sales departments, where the risk is actually applicable, and not by the purchasing department.) The interviewees were then given a 5x5 matrix with impact represented on the x-axis and probability on the y-axis. Interviewees were asked to place the risks on the matrix. The managers were asked to assess the mid-term (i.e. 1-2 year) effect of the risks in terms of probability and impact. Mid-term effects were assessed on a scale from 1 (very low) to 5 (very high), with a focus on managers' responsibility (e.g. Sheffi and Rice 2005) compared to today's performance (Ritchie and Brindley 2007a). At least three managers, each with different areas of expertise and background, assessed each risk. According to Clemen and Winkler (1999), this is necessary when combining experts' probability distributions in risk analysis. Managers assessed one risk at a time.

Based on the completed matrices, we reviewed the risks and selected eleven risks to be quantified further for comparison with the subjective assessments. Figure 3 presents an overview of the mapping of the assessment of selected risks. Every risk can be seen as an independent sub-case study within the case study. Various authors recommend four to ten case studies as sufficient for theory-building purposes (Eisenhardt 1989, Ellram 1996). Here, eleven risks were evaluated due to good data availability and to achieve theoretical saturation (Glaser and Strauss 1967). We selected risks with the highest risk number (probability times impact<sup>5</sup>) (e.g. Christopher and Peck 2004) and further ensured that different key risk categories were analyzed, i.e. operational versus disruptive risks (Tang 2006a).

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<sup>5</sup> FMEA uses a risk priority number calculated by severity times occurrence times detectability (rating from 1 'no effect' to 10 'very high') (e.g. Pujawan and Geraldin, 2009).

**Figure 3: Subjective risk assessment by managers**



The identified risks are listed in Table 1 including the average estimated probabilities and impacts as well as their risk numbers and types.

**Table 1: Subjective risk assessment**

Risk	Impact	Probability	Risk Number	Type
Price volatility	4,00	4,17	16,67	operational
Poor forecasting	3,54	4,31	15,24	operational
Changes in customer logistics requirements	3,25	4,38	14,22	operational
Political instability	4,33	3,17	13,72	disruptive
Complexity	3,30	3,70	12,21	operational
Single sourcing	3,81	3,15	12,01	disruptive
Increase in transportation cost	2,90	3,93	11,41	operational
Dedicated production	4,50	1,94	8,75	disruptive
Poor transportation/infrastructure	2,55	2,60	6,63	operational
IT breakdown	3,77	1,45	5,49	operational
Improper execution of launch process	2,00	2,50	5,00	operational

### III.5. Objective risk assessment in the case study company

A central goal of our study is to compare qualitative and quantitative risk assessment. The goal of quantitative risk assessment is to achieve as realistic as possible approximations with existing data. We do not intend to develop models optimizing the exposure to the respective

risks. The focus is on quantifying risks, relying on internal and external data. When collecting data for the objective risk assessment, we conducted an additional 13 interviews with managers in order to understand the risks as well as the available and derivable data. Then specific data requests as well as dedicated controlling analysis were triggered. For the risks that are analyzed based on sales value and not cost value, we used the contribution margin as the basis for our comparison, multiplying the sales value with an average contribution margin of 45% for a product. By using the contribution margin we included lost EBIT as well as fixed cost, which are no longer covered. For the remaining risks we used the additional cost incurred.

### **III.5.1. Price volatility**

The risk of price volatility is a reflection of the fluctuation in prices of raw materials used in production; materials costs have a direct influence on the cost structure of the company. Reviewing the historic feedstock price development reveals a high degree of volatility, with a peak in 2008. As a basis for its hedging activities, the case study company performs a monthly assessment of feedstock prices. Because the case study company is in the fast moving consumer goods industry, the managers assume that a price pass-through to the retailer is not possible in the short term. The consolidation of retailers in certain countries is very high, so they can exert pressure on the manufacturer (e.g. Weise 2008).

Feedstock prices are described by stochastic processes, which are the basis for derivatives pricing. Short-term supply and demand imbalances significantly impact spot prices. Hamood Al-Harthy (2007) reviews the following stochastic oil price models: the Geometric Brownian Motion (GBM) and Mean Reversion (MR). The main properties of the GBM are that price changes are independent of each other and price changes have a constant mean and volatility. According to Blanco et al. (2001), the following assumptions are not fulfilled when modeling energy prices with GBM: they are not 'exactly' lognormally distributed; extreme price changes may be underestimated by the lognormal distribution; volatilities are neither known nor constant; and results for very high volatilities are not reliable (e.g. above 300%). However, the model is still used, thanks to its simplicity and fewer input parameters (Hamood Al-Harthy 2007, Blanco and Soronow 2001). MR incorporates the tendency of energy prices to revert towards an equilibrium price level that is usually governed by the cost of production and the level of demand. Mean reversion models require the estimation of additional parameters such as the mean reversion level (long-term equilibrium price) and the mean

reversion rate (speed at which prices revert) (Blanco and Soronow 2001). Oil prices tend to follow an MR process in the long term (Bessembinder et al. 1995, Hamood Al-Harthy 2007). As this study is interested in the medium-term risk, we consider GBM the more suitable model.

At the case study company, the forecast for the mean feedstock prices is purchased as an “expert opinion” from petrochemical consulting experts. The forecast also includes the current market developments, i.e. the supply and demand situation of the feedstock. The variation around the mean is derived from historical data. Then, using the software @RISK, cones of uncertainty are calculated per feedstock based on historical volatilities and correlations with other feedstocks. The analysis is performed for 36 feedstocks in three regions. The data has been analyzed and results were provided directly from the purchasing department.

For the main products per region, recipes are provided by the research and development and purchasing departments. Raw materials bought from suppliers are split into feedstocks, conversion cost, and margin, based on supplier information or company knowledge. Alternative recipes can be entered into the model, simulated, and compared. Using the forecasted feedstock data the case study company simulates contribution margins for the respective business unit and region. For our simulation the most volatile raw materials, representing roughly 50% of the contribution margin exposure, are included.

We simulated the cost effect of feedstock volatility for a year. As a reference point for the risk we take the contribution margin of the past year (July 2009 to June 2010, 1,358.9 m EUR). The mean expected contribution margin for the next year (July 2010 to June 2011) lies at 1,320.3 m EUR, leading to a risk of 39.5 m EUR. With a probability of 95% the contribution margin will not fall below 1,309.7 m EUR (risk of 50.2 m EUR) due to increased feedstock prices.

### **III.5.2. Non-delivery analysis**

The risks related to poor forecasting, improper execution of the launch process, poor transport/infrastructure, and IT breakdown were analyzed together using the same data basis and analysis form. We base our calculation on a common controlling analysis performed by the case study company. The company accounts for every order placed but not fulfilled with a

system of six codes and 14 sub-codes specifying the reasons for non-delivery. The data consists of monthly non-deliveries for 2.5 years (31 monthly non-delivery values from January 2008 to July 2010). The data is on order line level and includes month, country, product, value in Euro, reason, and sub-reason for the non-delivery. Main reason codes are order management and administration, IT, production, sales, supplier, and transportation and warehousing. The customer service department analyzes the reasons and values for the non-deliveries on a weekly basis. Non-deliveries are clearly assigned to reason codes, which are agreed upon by all departments. This process and analysis ensure that the correct reason code is chosen and the non-delivery can be directly linked to one unique reason code. As not all non-deliveries lead to lost sales, they have to be adjusted for follow-up orders, which are not formally documented. Based on their experience in recent years, management estimates that only 30% of non-deliveries result in lost sales, because many customers directly place another order if the current order cannot be fulfilled. To exclude the effects from any increase or decrease in sales (i.e. higher sales may produce higher non-delivery volumes), we relate the monthly lost sales to the sales value in the respective month, creating a non-delivery share of sales per month. We then fit a distribution to the 31 values of the non-delivery ratio using @RISK, relying on maximum likelihood estimators (MLE). The MLEs of a distribution are the parameters of the function that maximize the probability of obtaining the given data set (Aldrich 1997). We compare the input data with the fitted distribution in the same graph and review the probability-probability (P-P) and quantile-quantile (Q-Q) graphs which plot the distribution respectively percentile values of the input data versus the distribution of the results. For a good fit the P-P and the Q-Q graphs are nearly linear (Wilk and Gnanadesikan 1968). Further, a review of the fit statistics was performed: the chi-square test, Kolmogorov-Smirnov statistic and the Anderson-Darling statistic were reviewed (e.g. Stephens 1974, Anderson and Darling 1952). We also reviewed the p-value describing how likely it is that the fitted distribution could possibly have generated the original data set (e.g. Fahrmeir et al. 2001, Schwarze 1997). After the fitting to calculate the yearly risk impact, we simulate the monthly lost sales twelve times by multiplying the fitted distribution with the average monthly sales value and the 30% adjustment factor and add them up for the one year value.

### **III.5.2.1. Poor forecasting**

To calculate objective risk, the risk of poor forecasting is split into an under- and over-forecasting risk. As the product portfolio is diverse and includes a large number of products, a

situation with simultaneous under- and over-forecasting is possible, and both can be analyzed separately.

The risk of under-forecasting is defined as not producing enough products and not being able to fulfill the demand (e.g. Chopra and Sodhi 2004). Penalty costs were ignored in this case, as they are currently only applicable in one country and are insignificant. We fitted a beta general distribution to the non-delivery ratio based on the best fit of the chi-square statistic and a p-value of 0.9902. The lower bound was set to 0. As risk analysis we reviewed the average lost sales per year and the 95 percentile. On average, 9.45 m EUR are lost sales per year caused by under-forecasting. With 95% probability, the lost sales will not be above 11.14 m EUR in one year.

The risk of over-forecasting is defined as the company producing excess quantities and having to store the additional products in the warehouse, thus incurring additional warehousing and capital costs. Based on internal data, in the case study company the inventory is stored for an additional month before it can be sold; on average, 2.6% of the products become obsolete. Inventory holding cost is 20% and cost of capital is 10% for one year of the inventory value measured in manufacturing cost. A monthly analysis is provided with data on the over-forecasted volumes in tons. Due to the limited data availability (only seven data points), we relied on the sample average instead of fitting a distribution. Based on the sales volume per month, the average share of over-forecasted items per month was calculated. According to the case study company, it includes an average value of over-forecasting into production planning and also adjusts the production short term. Consequently, we assume that it can handle the average over-forecasting volume and regard only the positive deviation from the average as a risk. Based on deviations from the over-forecasted values, the production cost for the excess inventory is derived. The company holds this additional value every month on top of the required inventory. It is multiplied with the average inventory holding cost as well as with the average obsolesces rate to calculate cost and write-offs per year. An average risk of 0.7 m EUR per year is identified. To calculate the maximum impact, we took the highest deviation from the average over-forecasting rate and performed a similar calculation. The maximum risk of over-forecasting accounts for 2.4 m EUR per year.

### **III.5.2.2. Poor transportation/infrastructure**

This risk encompasses as all problems that might arise during transportation to the customer, such as shipment or distribution problems resulting in a non-delivery or not fulfilling the promised quality and quantity. The issues can include any delay in transport or damaged goods as well as problems in the distribution between the warehouses that lead to non-deliveries to customers. We also used the non-delivery analysis to quantify the risk and fitted a lognormal distribution based on the best chi-square statistic and a p-value of 0.8356. The mean lost sales lie at 1.01 m EUR; with 95% they will not exceed 1.56 m EUR per year.

### **III.5.2.3. Improper execution of launch process**

The risk of improper execution of launch process refers to issues arising during a launch or re-launch process. Main problems that lead to non-deliveries to the customers are that artworks are not ready, a launch or promotion decision is taken too late, or the relevant master data is not available. As for the risk of poor forecasting we used the non-deliveries analysis as a basis for the risk quantification. We fitted a beta general distribution, which had the best chi-square value and a p-value of 0.8877. The lower bound was set to 0. The mean lost sales lie at 496 k EUR; with 95% probability they will not exceed 676 k EUR per year.

### **III.5.2.4. IT breakdown**

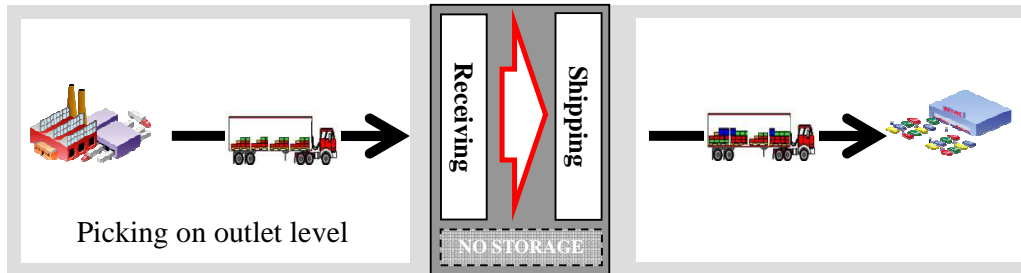
IT breakdown risk refers to problems with the systems that lead to issues in the IT dependent processes, such as master planning or production planning, and which ultimately lead to lost sales (e.g. Jimenez-Rodríguez et al. 2009). We used the non-deliveries data for our analysis and proceeded as described above. We fitted a gamma distribution based on the best chi-square statistic and a p-value of 0.4235. The average lost sales lie at 278 k EUR; with 95% probability they will not exceed 485 k EUR per year.

### **III.5.3. Changes in customer logistics requirements**

The interviews revealed that cross-docking is a key logistics trend in this risk category. Cross-docking is a logistical activity that consolidates shipments from inbound trailers to outbound trailers in buildings known as cross-docks (Yang et al. 2010). The goal of cross-docking is to eliminate storage costs by moving inventory to customers as quickly as possible. Cross-docks can exist in different forms. Bartholdi et al. (2001) suggest classifying forms of cross-docking as either pre- or post-distribution. In a pre-distribution cross-dock (Figure 4), the destinations are predetermined and labeled on the shipments before they arrive at the cross-dock. Workers

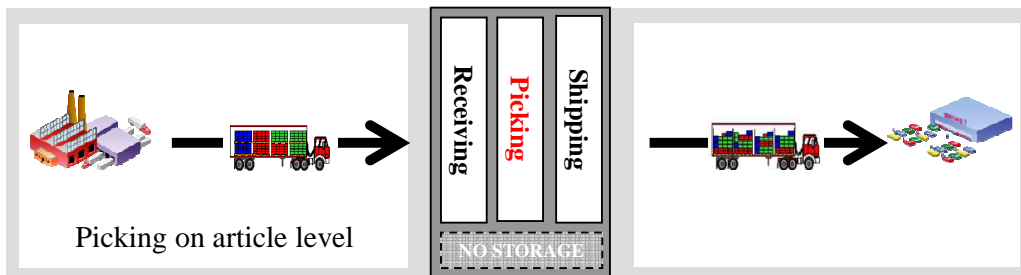
can then transfer the shipments directly from the inbound to outbound trailers. The cost of picking and labeling are thus incurred before the cross-dock – in our case by the manufacturer.

**Figure 4: Pre-distribution cross-dock**



In a post-distribution cross-dock (Figure 5), inbound freight arrives without a pre-determined destination, and workers at the cross-dock assign the destinations to the shipments. This offers several advantages: postponing the final destinations, maintaining confidentiality of the final destinations, and delaying the certain value-adding activities, such as price-tagging and re-packing, to the cross-docks. A post-distribution cross-dock normally requires more floor space for these value-adding activities, in our case incurred by the retailer.

**Figure 5: Post-distribution cross-dock**



An extensive internal analysis at the case study company, including an external expert panel, was used to develop cost scenarios for the two cross-docking options. Based on management information, cross-docking will mainly be performed by large customers, as a certain investment and volume, as well as a fitting store structure, are necessary. According to internal and external information, the share of cross-docking will increase in the next years (Saddle Creek 2008). Management expects that customers will mainly focus on pre-



distribution cross-docking activity, as the company's products have a high volume and rather low value.

For our calculation we analyzed the warehousing and transportation costs for a relevant set of countries. We divided the warehousing cost into warehouse management, storage cost, handling cost, and return handling cost. The internal case study indicates that a cost increase is only expected for the handling cost. We likewise divided the transportation cost into transport management, plant to distribution center, plant to customer, distribution center to distribution center, distribution center to customer, and return transport cost. For cross-docking a cost increase is only assumed for the cost to the customers. Based on the assumption that only large key accounts implement cross-docking, we reviewed the top five customers per country and calculated their share of warehousing and transportation cost based on their volume share. The cost increase for warehousing and transportation are known from on the internal case study.

Based on a survey by the logistics company Saddle Creek Corp. of 547 industry professionals on cross-docking trends and internal information, we expect 25% of the key accounts to invest in cross-docking in the next few years. While this calculation is not exact, it is a solid approximation given the sensitive nature of the information from the key accounts and the uncertain nature of the decision processes behind it. Several authors describe situations in which cross-docking did not have the desired effect (e.g. Jönsson and Silver 1987, Waller et al. 2006). Therefore, we modeled it with a binomial distribution with a probability of 25%, as without better information any key account is equally likely to switch to cross-docking. On average this results in a cost increase of 5.6 m EUR. With a probability of 95% the cost increase will not exceed 9.3 m EUR per year.

#### **III.5.4. Increase in transportation cost**

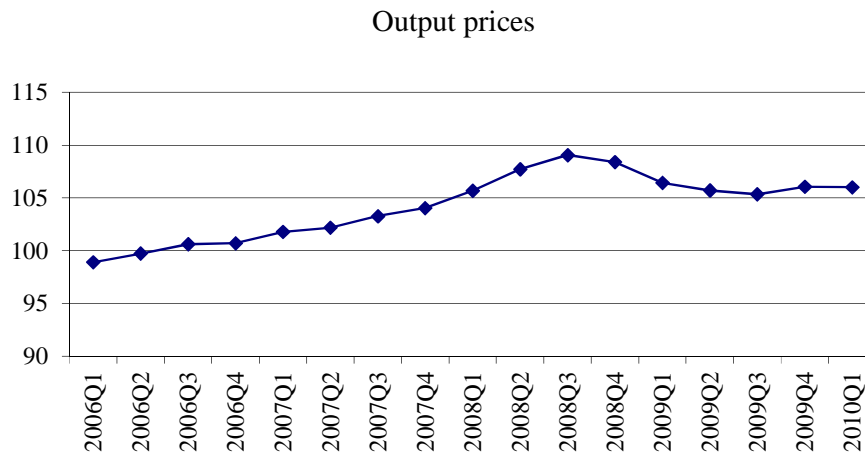
The risk of an increase in transportation cost reflects the growing cost of distributing goods to customers, especially due to increasing energy costs and taxes for CO<sub>2</sub> emissions (e.g. van Hoek and Johnson 2010). This risk is defined as the level of increase compared to the current transportation cost. Based on an extensive analysis of past transportation cost, this risk can be split into the segments shown in Table 2 according to internal company information. The managers assess the likelihood of a short-term price pass through to retailers and customers as low.

**Table 2: Elements of transportation cost**

<b>Cost segments</b>	<b>Cost split</b>
Labor cost	29%
Distance-dependent cost (e.g. fuel, tolls)	26%
Truck maintenance	14%
Fixed cost (depreciation, financing etc.)	17%
Other	14%

Surprisingly, only about one-fourth of the total transportation cost depends on distance-related factors such as fuel prices. A fuel price analysis alone would, therefore, not constitute a full and complete risk assessment. Our analysis is based on external data from the European Commission (Eurostat 2010). Based on this data, the European road freight transport industry is dominated by the major economies - Spain, France, Italy, the UK and Germany (also the core markets for the case study) - in terms of the number of companies, turnover, employment, and investment. Turnover and employment in the European road freight industry have shown a sustained increase between 2003 and 2008. The industry's growth is the result of an increase in both volume and prices. Up to 2007, ton-kilometers followed a similar stable growth path, but suffered a downturn in 2008 under the impact of the wider economic crisis. The presented risk quantification relies on the output prices (producer prices) of the EU 27; these are defined as the average price development of all goods and related services resulting from that activity and sold inside and outside of the domestic market. The data is indexed based on the year 2006. The index of 100 is calculated as average of the whole first year.

**Figure 6: Development of transportation output prices**



Based on the data of Eurostat (2010), a linear trend was derived from the index by a regression analysis ( $R^2$  of 0.6775) and projected to the future. Additionally, we calculated the deviation from this projected value and fitted a logistic distribution to the resulting data based on the best chi-square statistic and a p-value of 0.6625. Using the 2009 transportation cost as incurred by the case study company and the projected index data, we calculated the cost increase for defined points in the future. Transportation cost at the end of 2012 is expected to be 124.2 m EUR, compared to 120.5 m EUR at the end of 2009. There is a probability of less than 5% that the cost will be above 126.6 m EUR. To have a value comparable with the other analysis, we calculate the difference to the actual cost. For the mean, the risk lies at 3.7 m EUR per year; with 95% the risk will be below 6.1 m EUR per year.

### **III.5.5. Complexity**

The risk of complexity refers to problems that could arise as a result of the high complexity of goods and/or processes – for example, an unprofitable product or insufficient process standardization resulting in a lack of economies of scale. Put plainly, this risk describes a lack of knowledge of the costs hidden in inefficiencies of all kinds. Quantification is difficult; for example, according to Perona and Miragliotta (2004), there is currently no known method for defining and measuring the complexity of a manufacturing or a logistics system, and likewise no way of knowing whether and how this complexity will actually affect the system's performance. To quantify this risk we relied on an extensive internal analysis of the complexity involved in purchasing, in the production process, and at the product level. This analysis was conducted over a period of 5 months and with high resource involvement. The

analysis focused on complexity visible to the customer (e.g. brands, packaging) and internal complexity (e.g. processes, recipes). The following process steps were reviewed to assess complexity: raw materials, packaging materials, processing, distribution and logistics, and sales and marketing. This resulted in an average of 15 m EUR (and a maximum 30 m EUR) of potential one-time cost reduction. The main sources of complexity were identified as a multitude of brands, formats, formulas, packaging materials, and raw materials. The case study company has unveiled the detailed steps and data of this analysis to the research team. Due to reasons confidentiality, however, only the two above figures can be released. While these numbers represent a strictly ex post perspective, the data was compiled while the subjective risk assessment took place and, therefore, represent a solid approximation of the risk described by the managers from their perspective.

### **III.5.6. Single sourcing**

The risk of single sourcing is defined as the price and supply risk resulting from dependence on one supplier (e.g. Zsidisin et al. 2004). To gather data about the number of single sources in the case study company, we were given a list of all purchases performed in 2009 including material, supplier, and purchase order value. Based on this list we identified all materials that were sourced from only one supplier. We confirmed the identified single sources with the purchasing department. A purchaser with experience in the main single sources in each category also provided additional information. As we are focusing on the maximum impact of a supplier default, we have chosen to review the critical raw materials and packaged goods, i.e. the raw and packaging materials that are necessary for the core and high sales products of the company.

After identifying the single sources and ensuring that no back-up supplier was in place for those supplies, we linked the raw materials to the finished goods using the bill of material. The net external sales and contribution margin were available for analysis for all finished goods. To estimate the net impact and to test whether the single source was a critical single source, we reviewed the following issues as basis for our quantification: time for qualification of a new supplier/new raw material, bottlenecks in the pre-raw materials, number of plants of the supplier, qualification of second plant, timely information about product discontinuity, and extra stock/inventory of goods.

As stated above, supply and/or price risk are two possible results of a dependency on a single source. For each of the single sources we identified, we assessed whether supply or price risk was likely to be affected. We further assessed how critical the single source really is; that is, whether the effect on price and supply was likely to be minor or significant. According to the purchaser, it takes an average of three months to qualify another plant by the same supplier and about four months to qualify a new supplier. For the identified sources, it can be assumed that there is sufficient finished product inventory for two months. For all single sources except for two, a second plant exists. For the most critical single source the maximum impact is 15.7 m EUR.

### **III.5.7. Dedicated production**

The risk of a dedicated production facility can be defined as the risk of major problems arising in a production plant that is the only source for a particular product. The case study company has one plant that has dedicated production for certain goods. A problem in the plant or even on one line would cause product stock to run out and result in lost sales for these products. To identify critical products, we started by identifying the product groups produced in the plant by line. In a second step, we discussed the possibility of an alternative production line and, afterwards, the possibility of an alternative production site, in management interviews. For all goods that can only be produced in this plant, we checked whether they could also be produced on a second production line, and, if so, how much time and cost would be needed. To better assess the scenario of a full line failure, we conducted management interviews in the plant to identify the required time and investment for rebuilding the line. Afterwards, we evaluated the scenario of a full plant failure, including how much time it takes to switch to an alternative source - e.g. contract manufacturer or internal switch - including R&D qualification time. We also reviewed substitution alternatives for the respective products, e.g. change of bottle size. As a result, we mapped the potential consequences for events stopping one or multiple lines or the entire plant, including all system-inherent mitigation measures and their consequences. Based on this information we calculated the potential risk impact of a line failure and/or a plant failure.

The identified products were matched with their net external sales value. As the average inventory holding time in the company is two months, the inventory buffer was set to this level for all analyzed products. We calculated lost sales per item based on the net external sales and the time required to set up a new line or qualify outside production, and adjusted for

the inventory still on hand. As variable costs do not arise if the line or plant is out of service, they do not contribute to the risk impact. As all fixed costs are expected to remain unchanged, the firm effectively loses the complete contribution margin per product (that is, the net external sales minus the cost of goods sold). The margins corresponding to the lost net external sales described above were, therefore, used as risk impact. The full risk impact was approximated by adding the respective rebuilding investment per product. For total plant failure (including all production lines) the maximum risk impact is 14.9 m EUR. For a single line failure the maximum risk impact is 1.7 m EUR.

### **III.5.8. Political instability**

For the case study company, the risk of border closures due to political instability applies exclusively to its business in the Middle East and North Africa.<sup>6</sup> The risk mainly refers to cross-border business between two or more countries; internal political instability is of less importance, as the products in question are basic necessities. To evaluate the impact of this risk, we mapped and analyzed the company's cross-border business. Most organizations in each country produce for the national market; this is due to the relatively low value of items and the comparatively high cost of transportation. Moreover, country-specific production reduces dependency on other countries, which is important in regions of political instability. To reduce dependency on sourcing from other countries, plants often store a higher share of raw materials compared to finished goods. This ensures that production will not be interrupted, even in the event of political or border disruptions. Three countries in the case study's supply chain, however, depend on imports from other countries: Tunisia, Syria, and Lebanon. Tunisia imports a certain product category from Algeria, while Syria and Lebanon each import one product category from the other.

To quantify this risk, we created a hypothetical scenario involving a complete ban on imports and a full border closing. We used data on the net external sales and contribution margin for the respective product categories and countries as a basis for analysis. Based on interviews with local management and the time required to set up another delivery route via a third country, the delivery ban is set for one month. A one-month import ban would result in a loss of 117.7 k EUR in Tunisia; 458.3 k EUR in Lebanon; and 16.7 k EUR in Syria. In case of a two-month import ban or set-up of alternative supply chain routes, the monthly values are

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<sup>6</sup>The revolutionary events in North Africa in January 2011 took place after the present research study.

added. The risk is calculated as a combination of the risk in Lebanon and Syria, as these two countries depend on each other.

### **III.6. Comparison of subjective and objective risk assessment**

The comparison of subjective and objective risk assessment was executed in three parts. First, we analyzed the ranking of the risks defined by impact and probability assessment and compared these to the mean expected risk value (Table 3). This analysis does not take disruptive risks into account; an expected value comparison is biased due to the low probability of those risks (Zsidisin et al. 2005). To compare cost and sales values we calculated the contribution margin of each risk based on the sales value and on an average product contribution margin of 45% of the sales value. By using the product contribution margin we included not only lost EBIT but also the share of fixed cost not covered by the loss of sales. We ranked the risks and compared them to the ranks of the subjective assessment. In this way it was possible to measure the accuracy of the subjective risk assessment performed by managers against an objective benchmark. Second, we compared the objective and subjective impact assessment of the risks and third, we analyzed the respective probability assessments.

To identify likely reasons for the difference between the subjective and objective assessments, we used the nine risk bias categories of Carter et al. (2007) as an analysis framework. For risks showing a high difference between the subjective and the objective risk assessment, likely underlying decision bias categories were identified and confirmed in interviews with management. Additionally, we reviewed the differences in subjective and objective assessment in relation to the respective probability functions of each risk in order to derive underlying patterns. For example, we analyzed the effects of a positive or neutral skew on managers' risk assessment ability. The probability distributions can be found in Appendix 5.

**Table 3: Subjective and objective risk assessment**

<b>Risk</b>	<b>Subjective assessment</b>		<b>Objective assessment</b>	
	<b>Risk Number</b>	<b>Rank by Risk Number</b>	<b>Mean in m EUR</b>	<b>Rank by Mean</b>
Price volatility	16.67	1	39.5	1
Poor forecasting	15.24	2	5.0	4
Changes in customer logistics requirements	14.22	3	5.6	3
Complexity	12.21	4	15.0	2
Increase in transportation cost	11.41	5	3.7	5
Poor transportation/infrastructure	6.63	6	0.5	6
IT breakdown	5.49	7	0.1	8
Improper execution of launch process	5.00	8	0.2	7

Overall, the managers' ability to judge risks is relatively good: out of a total of eight risks, only two were wrongly assessed, namely poor forecasting and complexity. The managers clearly overrated the risk of poor forecasting. In comparison to the other risks, significantly more management time is spent on forecasting. Forecasting error is closely monitored and intensively discussed in supply chain management meetings in regular intervals. As forecasting is highly prevalent in the department and is in fact one of its daily tasks, it is often in the managers' minds. The managers' overestimation of this risk can thus be attributed to the availability cognition bias.

The product complexity risk, in contrast, was under-rated by the managers. This difference can be explained by two decision biases stemming from the nature of the risk. First, the managers cannot fully comprehend all the detailed financial effects (e.g. the extra cost of higher flexibility in production and more retooling needed) of their broad product portfolio. Information overload causes unjustified simplifications of the risks, which in turn leads to improper assessment. This can be categorized as control illusion bias. Second, a reference point bias seems to be at work. The managers have no point of reference regarding what complexity may cost the company. This is due on the one hand to the inability of controlling systems to measure the effect, and on the other to a lack of previous studies and figures. The foci of management analysis are specific products, inventories, and markets as well as decisions for those. The interactions between these elements are not commonly in focus in management and controlling systems. There is therefore no solid basis for an estimate of the impact or probability of product complexity.



**Table 4: Subjective and objective impact assessment**

Risk	Subjective assessment		Objective assessment	
	Impact	Impact Rank	Impact/95% percentile in m EUR	Impact Rank
Dedicated production	4.50	1	14.9	4
Political instability	4.33	2	1.0	8
Price volatility	4.00	3	50.2	1
Single sourcing	3.81	4	15.7	3
IT breakdown	3.77	5	0.2	11
Poor forecasting	3.54	6	7.4	6
Complexity	3.30	7	30.0	2
Changes in customer logistics requirements	3.25	8	9.3	5
Increase in transportation cost	2.90	9	6.1	7
Poor transportation/infrastructure	2.55	10	0.7	9
Improper execution of launch process	2.00	11	0.3	10

In order to include the disruptive risks while avoiding the bias in objectively assessing them as described by Zsidisin et al. (2005) – expected value comparison is biased due to the low probability of those risks – we reviewed and compared only the impact of the risks (Table 4). Operative risks do not have a single impact but a joint distribution of probability and impact with an expected value. To approximate impact, we used the 95th percentile (based on the distributions fitted in the @RISK simulation) to achieve a proper comparison with the disruptive risks. While a higher percentile could also be referred to, the 95th percentile is used widely, e.g. in value at risk concepts, and remains fairly stable across simulations (e.g. Jorion 2007). Further, the case study company decided that this risk coverage was sufficient.

The risk of political instability (e.g. closed borders) was over-evaluated by the managers. The base rate bias offers an explanation in this case; it seems that managers tend to remember vivid anecdotes on this topic, instead of judging them objectively. For the directly involved managers from the region, an availability cognition bias was identified, as these risks are widely discussed both at the local level and between local managers and company headquarters.

As stated above, the risk of product complexity was under-evaluated by the managers; this is likely due to a control illusion bias. The impact of cross-docking and transportation cost was also under-evaluated. A likely reason for this is a reference point bias: managers expressed that they see transportation cost as a rather minor issue and outside the core competence of the

company. They therefore set an incorrect reference point. The assessment of the IT breakdown risk is very complex, so managers simplify the situation and over-evaluate the risk compared to the objective risk quantification; again, this is due to a control illusion bias. Additionally, it can be seen that the distribution of the IT risk is highly positive skewed with a long tail on the right (see Appendix 5). The skewness of the distribution makes it more difficult for managers to assess the impact.

As a final step we reviewed the objective and subjective assessment of the probabilities for the risks (Tables 5-7). Due to the nature of the risks, they are not directly comparable and need to be split into three categories: operational risks with frequency data available, operational risks without frequency data available, and disruptive risks. The operational risks with data availability were quantified using the data of the non-delivery analysis. To obtain a finer distinction we performed a frequency analysis of those risks, i.e. analyzed the number of order lines for which this risk was stated.

**Table 5: Probability comparison of operational risks (with frequency data available)**

<b>Risk</b>	<b>Subjective Probability</b>	<b>Frequency index</b>
Poor forecasting	4.31	100
Poor transportation/infrastructure	2.60	44.4
Improper execution of launch process	2.50	6.9
IT breakdown	1.45	5.3

Based on this analysis, we could see that the risk of improper execution of the launch process was over-evaluated. Subjectively, managers evaluated the probability of this risk as being similar to that of the risk of poor infrastructure. The frequency analysis, however, shows a large discrepancy between these two risks. Two likely reasons for this inaccurate assessment are the base rate bias and availability cognition bias, as specific cases remain in the managers' vivid memory and the topic was tackled recently by implementing a pre-defined workflow. This corroborates the indication for both biases found in the analysis of the pure impacts and the impact/probability combination.

**Table 6: Subjective probability of disruptive risks**

<b>Risk</b>	<b>Subjective Probability</b>
Political instability	3.17
Single sourcing	3.15
Dedicated production	1.94

It is difficult to define a probability distribution for the disruptive risks because historical data is not available. Even a method such as extreme value theory, with its goal of deriving extreme or outlying data from regular data, requires a set of data with normal, non-extreme values to derive the extreme values of the distribution (e.g. Furlan 2010); this data was not available to us. At the case study company, an occurrence of these risks has not been recorded or was not known to the interviewed managers. Disruptive risks are dichotomous: either the event takes place, or does not. In this light, the risks of border closures and single sourcing appear over-evaluated. Given that operational risks for which occurrences are known show lower assessment, the impression of over-evaluation is increased. Likely reasons for this are a base rate bias and a control illusion bias. Single instances of such events, even if they did not impact the case study company, are vivid in the managers' memory. Moreover, external risks are seen as more critical than internal risks, because the company does not have the control over them.

**Table 7: Subjective probability of operational risks (without frequency data available)**

<b>Risk</b>	<b>Subjective Probability</b>
Changes in customer logistics requirements	4.38
Price volatility	4.17
Increase in transportation cost	3.93
Complexity	3.70

The probability assessment of operational risks is given in Table 7. Most prominently, the assessment of increase in transportation cost illustrates how uncertainty regarding cost changes creates a risk to the company. All risks show high subjective probability values. For price volatility, product complexity and increased transportation cost information from previous periods is given; however, probability data for the future is not separately available, but only as an expected impact. The subjective ranking conforms to the ranking derived from quantitative assessment as shown in Table 3. The cross-docking risk stands out as an exception as it is rated as the most likely risk. However, it is unclear whether it will come to

bear at all. The case study company has held intense discussions regarding whether or not its retailers will implement cross-docking. Retailers have not yet given any indication of whether they intend to move to cross-docking on a large scale. The cross-docking risk is apparently over-rated due to an availability cognition bias. As the cross-docking issue was very actively discussed in the weeks leading up to the interviews, the managers had a high awareness of this topic.

Reviewing the analyses performed, we arrive at the following propositions:

*Proposition 1: Risk assessment in the supply chain environment based on subjective, qualitative management judgment leads to approximately correct predictions in 70% of risk evaluations (impact and probability individually and the joint risk number).*

*Proposition 2: Risk assessment performed by managers deviates from objective, quantitative assessment. The subjective risk assessment must be reviewed and corrected for known biases in the following risk categories:*

*Proposition 2a: Operational risks with high visibility (e.g. due to a recent focus on them or a recent occurrence in the organization) are over-evaluated due to availability cognition bias.*

*Proposition 2b: The impact of non-core business risks is under-evaluated due to reference point bias.*

*Proposition 2c: Complex risks are assessed incorrectly due to control illusion bias.*

*Proposition 2d: The higher the skewness of a distribution of a risk, the more difficult the subjective assessment of that risk.*

*Proposition 2e: The probability of disruptive risks is over-rated due to a base rate bias and a control illusion bias.*

As a result of the propositions, a revision of the current risk assessment process must be considered. The case study indicates that subjective managerial assessment coupled with targeted de-biasing is sufficient to accurately assess the risk situation of a supply chain. This approach has two advantages. One, management assessment provides a reliable basis for prioritization and development of risk mitigation. Two, especially in the complex environment of a supply chain, this approach results in significant cost saving compared to quantification, which requires massive resources (Ziegenbein 2007). A revised assessment process is formulated as a management implication of this paper.

### **III.7. Managerial implications**

The implications of the above findings for managers are two-fold. On the one hand, subjective risk assessment is in many cases an acceptable alternative to objective risk assessment. On the other hand, managers should be aware that subjective assessment of certain specific risks is likely to be skewed due to decision biases. Therefore, in the standard risk assessment process documented in literature – identification, aggregation/assessment, mitigation, controlling – the step of aggregation/assessment can be amended to include a purely subjective approach that does not rely exclusively on quantitative assessment. While the present paper has included a quantitative assessment of several risks, it has also shown that quantitative risk assessment is not possible for all risks, due to insufficient data availability and the immense personnel resources required. In cases where quantitative assessment is impossible or unfeasible, a subjective approach can be implemented, with strong results.

In the supply chain context, purely quantitative risk management is mainly applied in the field of purchasing price development. In this field, there is sufficient available data on price developments and possible direct mitigation strategies, such as hedging; this data is available thanks to transparent international raw materials markets offering financial products such as options and forwards (Kubis and Nickel 2010). For other supply chain risks, these preconditions do not apply. Both the supply chain and supply chain risk management are less clear-cut than traditional financial risk management (Norrman and Jansson 2004, Ritchie and Brindley 2009).

After identifying the risks in the supply chain, the following steps should be followed. First, risks are categorized as either operational or disruptive risks. Second, operational risks are further divided by high attention risks (intensive management focus within the last year), non-core activities, and degree of complexity (high or low). Third and finally, the probability distributions of all risks are assessed for skewness.

For risks falling into the categories identified above, de-biasing strategies have to be applied based on Kaufmann et al. (2009). The following specific de-biasing strategies are advised. Disruptive risks can be assessed together with external experts, including a thorough briefing on the source of the risk, to recalibrate the perception of managers. For operational risks that have received intensive previous focus, that are non-core activity, and are highly complex, all available quantitative data should be collected, analyzed, and presented to management. If

possible, the risks should be assessed based primarily on quantitative analysis. After the above checks have been performed, it is necessary to identify the risks likely to have a highly skewed probability distribution. This can be done based on the available quantitative data or based on information transfer from literature or other industries.

With the above steps completed, managers assess the risks subjectively – for example, relying on a probability and impact matrix as presented in this paper. All directly available quantitative information on the risks is used to verify or correct the subjective assessment. On the basis of this assessment, it is possible to prioritize risks and defined possible mitigation strategies.

### **III.8. Conclusion**

The goal of this paper was to review and compare qualitative vs. quantitative risk assessment in the field of supply chain risk management. Based on the identification process in the supply chain organization, eleven risks were selected for closer investigation. The comparison of subjective and objective assessment showed that managers are capable of qualitatively assessing risks. When reviewing probability and impact independently, however, managers are often biased in their assessment. Managers tend to recall and therefore over-rate risks which are heavily discussed in the organization. Disruptive risks such as total default of a single source supplier are also likely to be assessed incorrectly due to vivid experiences of managers. Non-core business related risks, such as transportation risks, may be under-rated because of a focal point that differs from that of the core business. Further, it is very difficult for managers to assess very complex risks due information overload. Highly skewed distributions of risks were also difficult for managers to assess. Simplification might lead to improper assessment. In the assessment process, risks belonging to those categories must be identified systematically so that the risk assessment can be adjusted for those risks most likely to be biased.

This paper shows that subjective and objective risk assessments lead to quite similar results for certain types of supply chain risks in the fast moving consumer goods industry. However, it must also be stated that some risks (namely, operational risks with high visibility, disruptive risks, non-core business related risks, complex risks, and risks with a highly skewed distribution) should be re-assessed objectively to ensure proper evaluation of the risk landscape. This could be done by quantitatively assessing those risks, as it was done in this

research. Alternatively, de-biasing strategies could be applied beforehand to correct the assessment. These findings broaden the research of Khan and Burnes (2007) by stating how the risk management process needs to be adjusted for proper assessment of risks.

As a possibility for further research, the stated propositions could be tested within a wider field, e.g. in another industry or through empirical investigation. Another area of further research would be an analysis of appropriate de-biasing strategies. The interdependencies between risks should be taken further into account, as well, although this is very difficult with qualitative risk assessment alone. Some interesting research venues are only available with quantitative analysis. In the field of operational risks, for which a large amount of data is available, it would be interesting to analyze the relationship between risks and the impact on risk assessment, i.e. to identify which risks amplify or mitigate each other.

### **III.9. Basis and motivation for further research on risk dependencies**

The previous paper demonstrated that subjective risk assessment produces results similar to those produced by objective risk assessment for the prioritization of the risk portfolio in the case study company. When de-biasing strategies are applied, as well, the subjective risk assessment provides a solid basis for the risk management process. This raises the question of whether objective or quantified risk assessment is necessary at all, and whether it adds enough value to supply chain risk management to justify the cost and time needed for quantification.

Dependencies of risks are integrated into the quantitative assessment to show its added value. To allow managers to assess risk probability and impact in the subjective assessment, risks are assessed individually. This is a common practice that paper 2 shares with the majority of literature. For proper comparison, the quantitative risk assessment needs to be performed on the individual risk level. For disruptive risks such as natural catastrophes, which impact the supply chain from the outside, this appears to be a reasonable assumption. They may even affect the whole supply chain simultaneously. However, several authors argue that risks are strongly related to each other, either by correlation or by cause and effect. If such relationships exist, they may influence the risk management process during assessment, prioritization, and mitigation. Operational risks impact the supply chain from within. Some risks may therefore impact one step in the supply chain, but trigger a chain reaction of other risks. Even if a single risk is in itself small – as correctly assessed subjectively or objectively – it could still have a powerful influence on other risks. It may, therefore, be optimal to

mitigate this risk first or invest more into its mitigation. The question of whether there are relationships between supply chain risks has already been posed; however, a lack of data has so far prevented a deeper investigation.

There are several possible ways to identify a dependency of risks. Following financial research, relationships between risks in a supply chain could be treated as a portfolio with correlations binding it together. Instead of earnings and their variance of a financial portfolio, the risk portfolio could be analyzed based on risk cost and cost variance. The variance of the risk cost of the portfolio would be higher or lower than the sum of the individual risk variances. The existence of such a portfolio would greatly influence the risk assessment and mitigation process. If risks were negatively correlated, the mitigation of some risks would increase the overall risk cost and variance of the portfolio. Continuing with the portfolio idea, the scenario would require that risks are not related with a direction. However, a standard supply chain model follows directional material and information flows; for example, upstream risks have an impact on downstream processes. Further only the risk variances would be influenced, not the expected risk values.

If risks were related with a direction (that is, upstream risks early in the supply chain influence downstream risks), the correlations would not encompass this effect. Further, if risks not only affected the variance of other risks but also drove the expected value of other risks, cause and effect modeling would be required. If such a model were applicable, the risk management process would be affected in the risk assessment and mitigation steps. It could be ideal to mitigate the crucial risk driving others.

So far, a lack of a consistent data set has prevented an assessment of dependency. Based on our work in paper 1 and 2, we were able to exploit supply chain controlling data to generate a data set with a common risk measure, i.e. lost sales over a sufficiently long period of time. The data set encompasses the operational risks of the case study company and is sufficiently large to support the analysis. The third paper will provide an insight into the value of quantitative risk assessment, which combined with the understanding of subjective risks assessment from paper 2, will allow a realignment of the risk management process.



## **IV. Paper 3 - Analyzing dependencies between operational supply chain risks**

### **IV.1. Introduction**

In 2000-2001, a number of tread separations and tire blowouts on the widely sold Ford Explorer resulted in deaths and injuries. The accidents were attributed to faultily produced tires. In August 2000, Firestone recalled 6.5 million of these tires; in 2001, Ford recalled another 13 million. The recall caused costs of more than 3 billion USD for both companies, who suffered a massive loss in reputation and future sales. The incident caused many to wonder how a leading producer such as Firestone could put such a hazardous product on the market, and whether the testing processes had been missing or insufficient. As it turned out, several interrelated factors had led to the problems. For one, the production plant for the tires used a special production process that led to lower tread adhesion. In addition, the special shoulder pocket design of the tire led to cracking. The design of the Ford Explorer contributed to the problem, as well, because its high center of gravity increased the likelihood of a rollover after a tire blow-out. Further compounding the problem, Ford recommended lower air pressure for the Explorer tires, which increased the rollover tendency even further (Sheffi 2005). None of the individual risks alone could have caused a problem on such a massive scale. The accidents were not triggered by one event alone, but by a string of several interdependent risks.

Supply chain risk management is a very complex challenge, not least because of the complicated relationships that exist between the various internal and external components of the supply chain (Manuj and Mentzer 2008, Peck 2006). To better understand those relationships, this paper undertakes an analysis of operational risks based on company data. Operational risks are inherent uncertainties that arise relatively frequently in the supply chain (e.g. Tang 2006b, Sodhi and Lee 2007). The theoretical framework used for this analysis is the four-part risk management process of (1) identification, (2) assessment and aggregation, (3) mitigation, and (4) controlling of risks (e.g. Kleindorfer and Saad 2005). Our analysis in this paper focuses on the step of risk assessment and aggregation, and specifically on analyzing dependencies between operational risks during those two steps. Based on the discussion in the literature, we developed the following research questions: How do operational supply chain risks relate to and correlate with each other? Which operational supply chain risks correlate with each other? How do risk correlations and relationships change the prioritization of risks for the purpose of risk mitigation? What effect do

correlations and relationships between supply chain risks have on the optimization of mitigation strategies?

Due to the novelty and complexity of supply chain risk management, we have chosen to adopt a case study approach (Manuj and Mentzer 2008). In order to ensure proper analysis, we obtained direct access to relevant data and arranged for management interviews. In the following article we seek to answer the research questions above and to develop propositions for further research in the field of supply chain risk management.

## **IV.2. Literature review**

### **IV.2.1. Risk dependencies**

A number of authors describe the existence of dependencies among supply chain risks. Peck (2006) argues that the risk of a single supply chain decision cannot be viewed independently, but must be integrated into the cumulative outcome. Harland et al. (2003) state that the effects of risks are not easy to manage, as one critical incident may exert a strong influence on others. As the supply network increases in complexity, the number of risks increases, as well. Zsidisin (2003) also states that the sources and outcomes of supply risks are not mutually exclusive, but have a compounding effect. Rao and Goldsby (2009), who develop a typology of risks, note that in the case of environmental risk, uncertainties are not independent, but interrelated. Sodhi and Lee (2007) perform a case study in the consumer electronics industry. They state that in order to effectively manage risks, it is critical to understand the various threats both individually and collectively.

It has also been acknowledged that supply chain interdependencies must be appreciated and understood in order to accurately identify potential risk factors and calculate their likelihood, severity, and consequences (Tummala and Schoenherr 2011). In the four-step risk management process described above, risk interactions impact the assessment phase. Compensating or cumulating aspects can arise if several uncertainties have the same influencing factor or if they depend on each other. When describing the SCRM process, Olson and Wu (2010) state that risks need to be quantified in a disciplined risk assessment procedure that also takes into consideration the links that trigger risks. Mills (2006) identifies the critical nature of risk interdependencies as a key point in value and risk management. Hauser (2003) describes the steps involved in a risk-adjusted supply chain. As one element of the risk quantification step, Hauser proposes a model that captures key assumptions as well as the

relationships and interdependencies of risks. It has also been argued that all risks are interdependent, and effects on earnings are ultimately produced by the combination of single risks; as a consequence, it is crucial to aggregate risks and to take into account the correlation of risks as modeled by risk simulation procedures (Gleissner 2004). Despite the propositions listed above, however, we have not seen many authors explicitly analyzing interdependencies between supply chain risks in a case study or empirically. In their research, Wagner and Neshat (2010, 2012) quantify supply chain vulnerability by developing a supply chain vulnerability index. They also include interdependencies in their index, as vulnerability in one stage of the supply chain can influence the vulnerability of other stages. When supply chain managers inspect the developed vulnerability graph, they can identify the relationship between different drivers, set priorities, and execute appropriate measures for risk mitigation.

Often, however, researchers and organizations approach risk assessment and possible mitigation strategies without any consideration of the issue of possible risk dependencies. Chopra and Sodhi (2004), for example, present a list of risk categories, mapping possible mitigation strategies to each, but do not discuss the aspect of risk dependencies. Likewise, companies themselves often fail to consider risk dependencies when assessing and managing risk. When Zsidisin et al. (2004) analyze the risk assessment techniques of seven companies, they find that correlations between risks are not considered. One example of a study that did take risk dependencies into account was an analysis of correlations of risks performed in the field of raw material price risk. In commodity risk management, the players are well aware that the prices of key feedstocks for plastics are correlated with the basic crude oil price. Mapping those interdependencies through modeling and then applying hedging strategies was shown to offer clear benefits (Cohen and Kunreuther 2007).

For successful risk mitigation, it is critical not only to understand the complexity of a risk portfolio, but also to develop effective methods for an early warning system. An understanding of interdependencies between risks can support early identification. Hallikas et al. (2004) note that risk is not a static measure, and that tools for identification of trends need to be derived. Peck (2005) develops a four-level supply chain framework. An analysis of the complexity of a system, based on appropriate data, is essential for those who must decide how to manage the system. Craighead et al. (2007) analyze reasons how and why one supply chain disruption is often more severe than another. They relate the severity to the SC design characteristics of density, complexity, and node criticality as well as to the two mitigation

strategies of recovery and warning. Sheffi and Rice (2005) define the various stages of disruption; these are preparation, the disruptive event, first response, initial impact, full impact, recovery preparations, recovery, and long-term impact. A single risk that materializes may create a domino effect and result in an increasing escalation of crises.

To shed light on risk interdependencies from another angle, we also approached the subject from a portfolio theory perspective. Markowitz (1952) describes how investors should balance risk and reward by constructing investment portfolios. An efficient portfolio is one where the risk cannot be reduced further without reducing the expected return. In order to apply portfolio theory in this context, it is important to understand the interrelations between risks. Several authors in the field of enterprise risk management describe the effects of portfolio theory. Hommel (2004), for example, states that when portfolio theory is applied, the resulting diversification can reduce the performance risk held by the investor. The total risk associated with an asset can be divided into two parts, systematic and unsystematic (diversifiable, firm-specific) risk. As the number of assets in the portfolio increases with less than perfect correlation, the unsystematic component of the portfolio risk is reduced (e.g. Copeland and Weston 1988). The company's investment portfolio can be seen as a bundle of different but correlated risks; in each case management has to decide between keeping the risks in the company or passing them on, e.g. by using financial derivatives. According to Laux (2004), it is not the risk of an individual asset that is important, but its contribution to the risk of the portfolio and the corporation. The portfolio view thus offers a critical insight into risk management by affirming that the sum of individual risks has different properties than the sum of correlated risks.

According to Ritchie and Brindley (2007a), most companies are operating in a very complex environment. It is possible to create an analogy that applies financial portfolio theory (e.g. Sharpe 1964) to the treatment of a portfolio of risk situations. Essentially, the organization needs to manage a "portfolio" of risks. Supply chain risk management deals with managing the portfolio of risk situations with the dual goals of balancing the aggregated portfolio within an acceptable level while at the same time trying to ensure the generation of an acceptable return on this capital. Ritchie and Brindley (2009) also point out that the aggregation level of a decision often influences the perceived level of risk involved. If decisions are treated independently, the business may remain quite comfortable because they see only the individual risks involved. If these individual decisions are aggregated, however, the overall

perception of risk is likely to change depending on the correlations between them. Related to this is the concept of a portfolio of risk and performance outcomes. Early work in the financial economics field dealing with investment risk and returns resulted in a number of theoretical developments (e. g. Capital Asset Pricing Method – Ball and Brown 1968) that are difficult to apply in the ‘messier, partial and fragmented’ situation found in most organizations (Ritchie and Brindley 2009).

Several authors propose applying portfolio theory to the field of SCRM. Rao and Goldsby (2009) show that portfolio theory has been used extensively in several fields, including SCM, where it has been used, for example, to study vendor portfolios and risks associated with them (Choi et al. 2008, 2004, Gan et al. 2005). Sanders and Manfredo (2002) apply the value at risk concept to a purchasing organization. The risk measure relies on forecasts of the volatility of portfolio returns over a given period. In order to perform proper calculations, the correlations between the returns need to be defined. Kleindorfer and Saad (2005) include diversification to reduce risk as one of their ten mitigation strategies. Gaonkar and Viswanadham (2004) argue that the portfolio model could be used to select a portfolio of suppliers, similar to the way this approach is applied to developing alternative portfolios of investments.

While portfolio theory offers a useful theoretical framework for SCRM, it is important to note several limitations. For one, assets in a portfolio can be traded independently; there is a market to purchase or to sell them. Based on this attribute, each asset can be optimized or hedged separately without an effect on other assets in the portfolio (Markowitz 1952). For some supply chain risks, this condition is applicable – for example, in supplier relationships where one supplier with a specific performance variance can be replaced with another one. Similarly, a raw material with specific price volatilities can be substituted with another material with another volatility profile. Existing SCRM literature, therefore, focuses on the application of portfolio theory to the supply chain risks that fulfill this condition. Other risk properties, however, cannot be easily integrated into the portfolio concept. This would include, for example, a sequential risk correlation in which one risk (e.g. forecasting) amplifies another risk (e.g. raw material planning). Furthermore, some mitigation strategies can have an effect on all risks, or even different effects on different risks (i.e. mitigating some while amplifying others). Increasing inventory, for example, mitigates some risks such as forecasting or production losses, but increases other risks such as obsolescence or high holding cost. Classic portfolio optimization models are not adequate for describing the

complex SC environment, which Ritchie and Brindley (2009) describe as “fuzzy”. As a consequence, the framework of portfolio theory will be considered here as a secondary theory.

#### **IV.2.2. Contribution to the literature**

Our goal is to analyze interdependencies among operational risks. So far, risk interdependencies have been described theoretically but have never empirically documented (e.g. Kleindorfer and Saad 2005, Chopra and Sodhi 2004). Traditional risk management techniques show weaknesses in their assessment of the complexities of supply chains and their evaluation of the interdependencies of threats (Pettit et al. 2010). Juettner et al. (2003) state that network-related risk sources can either absorb or amplify the impact of events arising from environmental and organizational risk sources. They see a need for research investigating risk management in different industries. The development of tools to help managers anticipate risks is seen as a crucial task in this regard. Christopher and Peck (2004) furthermore reveal a need for analysis of the risks internal to the supply chain, i.e. supply and demand. They point out that while many external disturbances to the business environment are already acknowledged as risk sources, risks arising within the supply and demand network are not as obvious. We therefore focus in this paper on operational risks internal to the supply chain. Ritchie and Brindley (2007b) see a need for research developing causal pathways for risk sources in order to gain a better understanding of the nature and scale of risks. While analyzing the correlations between risks, we will thus also review causal relationships. In doing so we will extend the work of Sheffi and Rice (2005), who identify the stages of disruption with an explorative analysis of the triggers and correlations affecting the initial and full impact phase. Khan and Burnes (2007) identify an area for further research in integrating concepts of other disciplines to supply chain risk management. We will borrow concepts from financial portfolio theory by simulating the risk portfolio with and without correlations to observe the difference. Further, we analyze potential optimization strategies for how to best reduce operational risks and simulate the effect of different mitigation strategies. We repeat the process with a regression-based cause and effect model and describe the differences. As a final result we suggest several improvements to the traditional risk management process, specifically to the steps of assessment/aggregations and mitigation. In their investigation of the research developments in supply chain risk management, Tang and Musa (2011) discover a large amount of mainly descriptive and conceptual literature and only very few quantitative models. They identify a need for research that studies risk management issues from an

industry perspective and develops quantitative models that enable managers to make fact-based decisions in risk management. With our proposed models this will be possible.

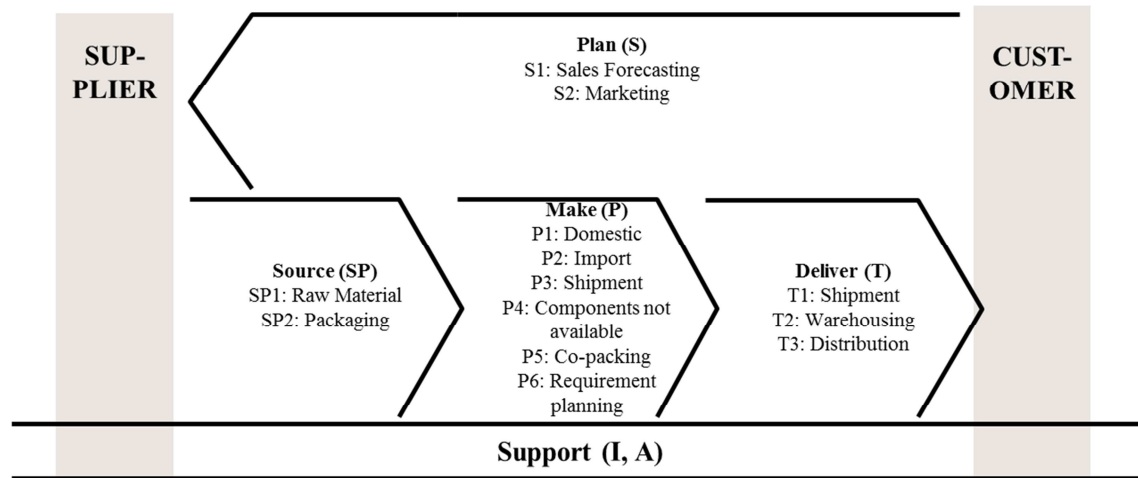
### **IV.3. Correlations between operational supply chain risks**

#### **IV.3.1. Data collection**

The basic choice of methodology and sampling is described in Chapters II.3.1 and II.3.2. A perfect risk analysis would be able to describe all aspects of a risk, from cause to effect, and accurately predict the impact the risk may have on the company. In practice, however, the root causes of risks are often external to the company itself and therefore not observable. Further, complex risk interrelationships of a parallel or sequential nature make it nearly impossible to realize this ideal analysis. Therefore, an analysis can be started from a standardized effect or impact measure, identifying similar effects, deriving correlations, and combining the findings with management insight to uncover interrelations as well as proposing cause and effect chains. As the basis for our analysis we use a unique company report listing the details of all non-deliveries over a period of 2.5 years. In the context of the report, a non-delivery is defined as an unfilled order line that led to a decrease in service level. In our analysis we adopt the definition of Juettner et al. (2003), who describe supply chain risk as the possibility and effect of a mismatch of supply and demand that exceeds the safety inventory threshold.

The non-deliveries report contains information about all order lines that cannot be fulfilled, each categorized according to a pre-defined reason code. All departments involved in the supply chain process or with delivery to the customer are involved in assigning the reason codes; these are purchasing, production, logistics, sales, and supply chain. The reason codes are quite specific, and the different departments have to agree on only one reason code. The data for each non-delivery consists of the month, year, country, region, product name and number, the value not delivered, and the reason code. In total, the reports list a value of 199.7 m EUR in non-deliveries in the years 2008, 2009 and January to September 2010. Non-deliveries are not necessarily permanently lost sales, as the customer may choose to complete the purchase at a later time when the products are available again. However, every non-delivery is an order that had been accepted and was not fulfilled; it is therefore a negative event for the case study company.

**Figure 7: Supply chain process and risk categories**



The macro reason codes can be mapped into four regions, following the SCOR model (e.g. Tang and Musa 2011, Ziegenbein 2007): purchasing (source), production (make), transportation (deliver), and sales/marketing (plan). The support functions administration and order management and IT (A and I) also form a part of the non-delivery analysis<sup>7</sup> (Figure 7). The model is further divided into a total of 13 sub-reason codes. The highly specific SCOR model thus covers the complete supply chain, from customer information to supplier interaction, and all internal processes in between. Table 8 lists the sub-reason codes with explanations.

**Table 8: Sub-reason codes with explanation**

Code	Name	Explanation
P1	Domestic production	Loss, quality problems, delay, insufficient capacity, change in production priority for domestic production
P2	Import production	Loss, quality problems, delay, insufficient capacity, change in production priority for import production
P3	Production shipment (internal)	Delay in transport, insufficient capacity, wrong loading, damaged goods, thermo truck not available
P4	Components not available	Lead time of raw, semi-finished or packaging goods is not kept
P5	Co-packing/external	Loss, quality problems, delay, insufficient capacity, change in production

<sup>7</sup> For our analysis we will not integrate the support function, i.e. IT and administration and order management. Non-deliveries due to administration and order management are initiated by the case study company, e.g. orders are blocked due to an exceeded credit limit of the customer. For the IT problems the data basis is not sufficient.



	producers	priority for external production
P6	Requirement planning	Change in the requirement plan, replenishment order posted too late, quantity of the replenishment order not enough, order for the co-packer was given too late or quantity for the co-packer was not sufficient
SP1	Raw material supply	Missing raw material due to problems with the supplier
SP2	Packaging materials supply	Missing packaging material due to problems with the supplier
S1	Sales forecasting	Wrong input by key account manager for promotion quantities or timings, sales forecast deviation
S2	Marketing	Film/artworks are not ready for the production, decision for a launch or promotion was taken too late
T1	Shipment	Transport cannot be started due to missing thermo truck, delays, insufficient transport capacity, mistakes during the loading of the truck, goods not found in the client warehouse, damaged goods during shipment
T2	Warehousing	Inventory inaccuracy compared to the system, product not found, wrong picking, damaged goods at the warehouse
T3	Distribution	Delivery of the products to the warehouse was too late, incorrect split of goods between different company warehouses

The records list the total value of non-deliveries categorized under each sub-reason code over the period of 33 months. Table 9 presents the value of lost deliveries organized by sub-reason code, listed in descending order of total value. Sales forecasting represents a disproportionately high source of non-deliveries, followed by domestic and import production.

**Table 9: Reasons for non-deliveries with value in k EUR**

<b>Code</b>	<b>Description</b>	<b>Value</b>
S1	Sales forecasting	91,245
P1	Domestic production	25,591
P2	Import production	18,855
SP2	Packaging materials supplier	14,564
P6	Requirement planning	6,834
P5	Co-packing/external producers	6,151
SP1	Raw materials supplier	5,642
T1	Shipment	6,008
P4	Components not available	5,378
T2	Warehousing	5,117
P3	Production shipment	4,755
T3	Distribution	4,336
S2	Marketing	5,226
<b>Total</b>		<b>199,707</b>

### IV.3.2. Data analysis

A first round of interviews was conducted at the case study company to identify the main risks in the supply chain and to develop an understanding of the steps of the supply chain process. Together we conducted high-level process mapping and processes analysis (Vlajic et al. 2011). We then developed a process model of the supply chain in accordance with the SCOR model (e.g. Tang and Musa 2011, Ziegenbein 2007, as shown in Figure 7). In addition, we analyzed the non-delivery report (described above) in order to better understand the relationship between the various operational risks. The risk effects we identified impact the supply chain at specific process steps. We next analyzed the relationship between the identified risk pairs. The correlation between the risk pairs was calculated and the risks categorized within the process model. The findings were presented and discussed in a second interview wave with managers. The analysis provides a way to better understand the risk landscape in an organization as well as in dependent companies. With the interviews it was possible to identify cause and effect relationships between different operational risk types as well as possible causes of supply chain risk.

The goal of the analysis is to calculate the correlations between the monthly risk impact sums for the individual sub-reasons in Microsoft Excel. A common measure of dependency between two variables is the Pearson product-moment correlation coefficient, as shown in equation (1). This coefficient is calculated by dividing the covariance of the two variables by the product of their standard deviations. The correlation coefficient  $\rho_{X,Y}$  between two random variables  $X$  and  $Y$  with expected values  $\mu_X$  and  $\mu_Y$  and standard deviations  $\sigma_X$  and  $\sigma_Y$  is defined below (e.g. Fahrmeir et al. 2001).

Pearson's correlation coefficient:

$$\rho_{X,Y} = \text{corr}(X,Y) = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X - \mu_X)(Y - \mu_Y)]}{\sigma_X \sigma_Y} \quad (1)$$

The Pearson correlation coefficient is defined only if both of the standard deviations are finite and nonzero. It is symmetric:  $\text{corr}(X,Y) = \text{corr}(Y,X)$ . The correlation is +1 in the case of a perfect positive (increasing) linear relationship (correlation) and -1 in the case of a perfect decreasing (negative) linear relationship (anticorrelation). Some value between -1 and 1 in all other cases indicates the degree of linear dependency between the variables. As the value approaches zero, there is less of a relationship (closer to uncorrelated). The closer the

coefficient is to either  $-1$  or  $+1$ , the stronger the correlation between the variables (e.g. Fahrmeir et al. 2001).

The Pearson product-moment correlation coefficient further requires the following: dichotomous or interval scale, normal distribution, linearity, and significance. To fulfill the requirement of a normal distribution, we transform all monthly sums by natural logarithm, resulting in a good approximation of the normal distribution to calculate the correlations. We fit a distribution to the data using @RISK. The normal distribution is a good approximation of the data based on the reviewed quality indicators (p-values, chi-square statistics). For the simulation of the risks of the company, we fit a log-normal distribution to the monthly data and use the correlation coefficient of the bivariate lognormal of equation (2) to ensure that mean and standard deviation remain the same (Johnson and Kotz 1972).

Correlation coefficient of the bivariate lognormal:

$$\rho = \frac{e^{\rho N \sigma_x \sigma_y} - 1}{\sqrt{(e^{\sigma_x^2} - 1)(e^{\sigma_y^2} - 1)}} \quad (2)$$

To analyze the relationship between the different risk types, we perform a correlation analysis among all risks. We focus on all correlations exceeding an absolute value of 0.35, as the t-test shows significance for this value in the case of 33 data points. We split the data by region. The mature market of Western Europe (WE) was compared to the still-evolving market of Central Eastern Europe (CEE). Out of the total of 199.7 m EUR of non-deliveries, CEE caused 168.3 m EUR (84.3% value of non-deliveries), whereas WE only caused 31.4 m EUR (15.7% value of non-deliveries). In CEE, non-deliveries represented 5.82% of the net sales, whereas in WE the non-deliveries represented only 0.68% of the net sales. The WE region is already very mature, as personnel are experienced and processes are well developed and sophisticated. In the case study company, production and supply chain setup take place on a regional level; therefore, to ensure a proper analysis of risks and interdependencies, a regional focus has been taken in the analysis, as well. As the majority of problems arising for the company originates in the CEE region, we focus on this region first. To adjust the data for trends and peaks caused by an increase or decrease of the sales value, the monthly data was divided by the monthly net sales, creating a sales ratio as analysis basis.

### IV.3.3. Results of the correlation analysis

Table 10 shows the results of the correlation analysis for the Central Eastern Europe data. As the results reveal, it was possible to derive significant relationships between the correlated risks. In a second step, the results of the analysis were discussed with management in order to inquire whether there were any explanations.

**Table 10: Correlation analysis for Central Eastern Europe**

CEE		P1	P2	P3	P4	P5	P6	S1	S2	SP1	SP2	T1	T2	T3	Total
P1	Domestic production	1.00	0.49	0.03	0.45	0.07	0.22	-0.21	-0.05	0.19	0.27	0.19	-0.02	0.43	0.42
P2	Import production	0.49	1.00	-0.14	0.53	0.05	0.07	-0.48	0.21	0.18	0.17	-0.14	0.04	0.07	0.01
P3	Production shipment	0.03	-0.14	1.00	-0.07	-0.15	-0.15	-0.09	-0.14	0.18	0.15	-0.01	-0.09	0.02	-0.04
P4	Components not available	0.45	0.53	-0.07	1.00	0.02	0.20	-0.03	0.19	-0.04	0.30	0.26	0.27	-0.18	0.32
P5	Copacking/external producers	0.07	0.05	-0.15	0.02	1.00	0.31	0.03	0.46	-0.13	0.27	0.02	0.28	-0.14	0.15
P6	Requirement planning	0.22	0.07	-0.15	0.20	0.31	1.00	0.18	0.26	0.02	0.38	0.01	0.19	0.21	0.32
S1	Sales forecasting	-0.21	-0.48	-0.09	-0.03	0.05	0.18	1.00	0.32	-0.06	-0.05	0.45	-0.32	0.01	0.73
S2	Marketing	-0.05	0.21	-0.14	0.19	0.46	0.26	0.32	1.00	-0.08	0.00	0.22	-0.15	-0.14	0.40
SP1	Raw materials supplier	0.19	0.18	0.18	-0.04	-0.13	0.02	-0.06	-0.08	1.00	-0.12	0.05	-0.37	0.10	0.02
SP2	Packaging materials supplier	0.27	0.17	0.15	0.30	0.27	0.38	-0.05	0.00	-0.12	1.00	-0.01	0.47	0.17	0.27
T1	Shipment	0.19	-0.14	-0.01	0.26	0.02	0.01	0.45	0.22	0.05	-0.01	1.00	-0.34	0.08	0.56
T2	Warehousing	-0.02	0.04	-0.09	0.27	0.28	0.19	-0.32	-0.15	-0.37	0.47	-0.34	1.00	-0.31	-0.28
T3	Distribution	0.43	0.07	0.02	-0.18	-0.14	0.21	0.01	-0.14	0.10	0.17	0.08	-0.31	1.00	0.30
<b>Total</b>		0.42	0.01	-0.04	0.32	0.15	0.32	0.73	0.40	0.02	0.27	0.56	-0.28	0.30	1.00

In the following, we provide a list of the correlated pairs, including both risk names and sub-reason codes. In the second line, potential explanations, as derived from management interviews, are provided in detail.

**Pair:** Domestic production/import production (P1/P2)

**Explanation:** Domestic and import production are positively correlated. As both are on the same process level, they are substitutes. Any risk impacting one of these also increases pressure on the other.

**Pair:** Domestic production/components not available (P1/P4)

**Explanation:** When components are not available, it is likely to increase the pressure on production, and existing problems in production are revealed or amplified.

**Pair:** Domestic production/distribution (P1/T3)

**Explanation:** The correlation between domestic production and distribution to internal warehouses indicates that production problems cause additional issues in the warehouses, such as late deliveries or incorrect distribution.

**Pair:** Import production/components not available (P2/P4)

**Explanation:** When components are not available, it is likely to increase the pressure on production, and any existing problems in production are revealed or amplified.

**Pair:** Import production/sales forecasting (P2/S1)

**Explanation:** Sales forecasting is negatively correlated with import production. This finding is somewhat surprising, as one would assume that poor sales forecasting would increase the pressure on the production and even lead to an increase in production issues. However, because only one reason can be entered for each issue, managers assume that either production *or* forecasting is chosen as reason for non-delivery, thus producing the negative correlation.

**Pair:** Co-packing, external producers/marketing (P5/S2)

**Explanation:** Promotions and special products are often manufactured at external producers. If marketing decides too late on product or promotion specifics, co-packers have to react in a very short timeframe, and may in some instances be unable to do so quickly enough.

**Pair:** Requirement management/packaging material supplier (P6/SP2)

**Explanation:** Problems in the production requirement planning and late delivery of packaging material are positively correlated. Late deliveries might lead to late replenishment or co-packer orders or increase the pressure on the replenishment process. Packaging materials are delivered late, and as a result the requirement orders are planned in a rush and with insufficient quality.

**Pair:** Sales forecasting/shipment problems (S1/T1)

**Explanation:** Incorrect forecasting and distribution of goods between the warehouses are positively correlated. Problems with the forecast could also have an impact on the division of goods between different warehouses and lead to late deliveries to the warehouses due to incorrectly forecasted production. Both process steps have a direct link to the customer, so customer issues could also be underlying causes.

**Pair:** Raw materials supplier/warehousing problems (SP1/T2)

**Explanation:** Problems with the raw material suppliers and warehousing problems are negatively correlated. Managers believe that both steps are too far apart in the supply chain to influence each other.

**Pair:** Packaging materials supplier/warehousing problems (SP2/T2)

**Explanation:** Problems with packaging materials suppliers and warehousing problems are positively correlated. Increased pressure due to late deliveries of packaging material might lead to problems in the warehousing.

Based on our analysis, it is possible to identify a clear relationship between operational risks in the analyzed supply chain. The direction of the dependencies can be derived using the SCOR process model and management interviews. We are thus able to develop our first proposition:

*Proposition 1: Operational risks show a dependency on each other. The direction and cause-and-effect relationship is based on the flow of information or goods.*

*Proposition 1a: Planning risks (forecasting and marketing) have an influence on source, make, and deliver risks.*

*Proposition 1b: Source risks have an influence on make and deliver risks.*

*Proposition 1c: Make risks have an influence on deliver risks.*

An understanding of these relationships is critical for the prioritization and selection of risk mitigation strategies. Given that each mitigation strategy is likely to affect multiple risks, it is advisable to begin applying mitigation strategies to upstream risks.

*Proposition 2: Correlated risks cannot be resolved individually. Mitigation strategies should focus on the risks at the beginning of the dependency chain to have the highest possible impact.*

We then reviewed our propositions in light of the analysis for Western Europe. Table 11 shows the results of the correlation analysis for the Western Europe non-delivery data.

**Table 11: Correlation analysis for Western Europe**

WE		P1	P2	P3	P4	P5	P6	S1	S2	SP1	SP2	T1	T2	T3	Total
P1	Domestic production	1.00	0.45	0.00	0.05	0.26	0.29	0.69	0.02	0.25	0.34	0.21	-0.10	-0.04	0.76
P2	Import production	0.45	1.00	-0.22	0.05	0.08	0.43	0.29	0.04	0.02	-0.36	0.09	-0.19	-0.03	0.47
P3	Production shipment	0.00	-0.22	1.00	0.09	-0.27	-0.13	-0.14	-0.01	-0.33	0.02	0.32	0.14	0.34	-0.10
P4	Components not available	0.05	0.05	0.09	1.00	0.36	-0.41	-0.18	-0.14	-0.39	-0.28	-0.22	0.10	-0.29	-0.16
P5	Copacking/external producers	0.26	0.08	-0.27	0.36	1.00	0.19	0.01	0.18	-0.22	-0.06	-0.05	-0.03	0.07	0.35
P6	Requirement planning	0.29	0.43	-0.13	-0.41	0.19	1.00	0.20	0.12	-0.14	-0.03	0.05	-0.05	-0.08	0.37
S1	Sales forecasting	0.69	0.29	-0.14	-0.18	0.01	0.20	1.00	0.05	0.28	0.45	0.14	-0.16	-0.09	0.82
S2	Marketing	0.02	0.04	-0.01	-0.14	0.18	0.12	0.05	1.00	-0.18	-0.02	0.24	0.01	0.20	0.24
SP1	Raw materials supplier	0.25	0.02	-0.33	-0.39	-0.22	-0.14	0.28	-0.18	1.00	0.15	-0.14	0.13	0.31	0.21
SP2	Packaging materials supplier	0.34	-0.36	0.02	-0.28	-0.06	-0.03	0.45	-0.02	0.15	1.00	0.20	-0.16	0.17	0.36
T1	Shipment	0.21	0.09	0.32	-0.22	-0.05	0.05	0.14	0.24	-0.14	0.20	1.00	-0.41	0.41	0.41
T2	Warehousing	-0.10	-0.19	0.14	0.10	-0.03	-0.05	-0.16	0.01	0.13	-0.16	-0.41	1.00	0.07	-0.21
T3	Distribution	-0.04	-0.03	0.34	-0.29	0.07	-0.08	-0.09	0.20	0.31	0.17	0.41	0.07	1.00	0.20
Total		0.76	0.47	-0.10	-0.16	0.35	0.37	0.82	0.24	0.21	0.36	0.41	-0.21	0.20	1.00

While the individual strengths and risk gravity centers are different, the general propositions also hold for WE, thus supporting their general applicability. It is clear that risks depend on each other in the WE market, as well. The differences can be explained by factors such as different market conditions, infrastructure, or maturity stage. It is crucial to understand the different dependencies at work on the most influential risks. The CEE market is still in a developing phase, and the share of non-deliveries is much higher in CEE (roughly 6% of net sales) than in WE (only 1% of net sales). In WE, some problems do not occur at all in several months. Furthermore, it is possible that dependencies are more stable and more clearly visible in WE as a result of there being less noise in the data and a less volatile process.

*Proposition 3: The magnitude of correlations between operational supply chain risks is supply chain specific; that is, it depends on specifics of the market, such as the maturity stage, size, and customer structure.*

**IV.4. Risk simulation**

Following Proposition 1 and the logic of the SCOR model, the relationship between risks as underlined by the correlations is assigned a direction of flow. In their research describing different supply chain flows, Tang and Musa (2011) state that the direction of the material flow is from supplier to customer. A risk that occurs at an earlier supply chain step may therefore influence or even trigger a downstream risk. The previous risk is, therefore, assumed to be the cause for the later risk as described by Olson and Wu (2010). This follows Harland et al. (2003), who see incidents influencing each other heavily. Vljajic et al. (2011) stress that the cause and effect relationship of events should be included in the analysis.

A risk at an early stage of the supply chain causes distress on the downstream supply chain and can cause an increase in risks at a later stage. Any downstream risk, therefore, has two

potential causes: it may be triggered externally by the impact of a previous risk, or by internal causes independent of any previous risk. For example, a P1 risk (domestic production) may be triggered by a P4 risk (components for production not available). The P1 risk might also be caused by a machine failure in domestic production itself, i.e., independent from P4. To describe the cause and effect relationship, a linear regression is fitted to each pair of sequential risks forming the supply chain. The linear regression is calculated with the lost sales of one risk as regressor and the risk of the second, down-stream risk as the regressand using least square regression (Greene 2002). The model with its four risks and three regressions is presented in Figure 8.

The residuals of the regression, i.e., the difference between observed data and the data calculated by the regression model, are fitted with a distribution describing the remaining variance of a risk. The sum of both the regression result and the distribution result describes the complete risk. By building a sequence of these regression and residual variables, a supply chain can be described as seen in Figure 8. As the basis for the fitting we rely on 30 observations of monthly lost sales events in the CEE supply chain of the case study company as described above. The 30 observations represent the complete data history available at the time of research at the case study company excluding 3 data points, which feature missing values for several risks. Regarding the predictive power of the sample, two observations can be made. On the one hand, following Speed (1994), the small sample will result in overly conservative tests for the validity of the regression, i.e., the likelihood of rejecting a true relationship increases. Second, the structure of the supply chain is under constant change; hence, collecting more data, e.g. by doubling the sample duration to five years, may result in a lack of comparability of the first and last period.

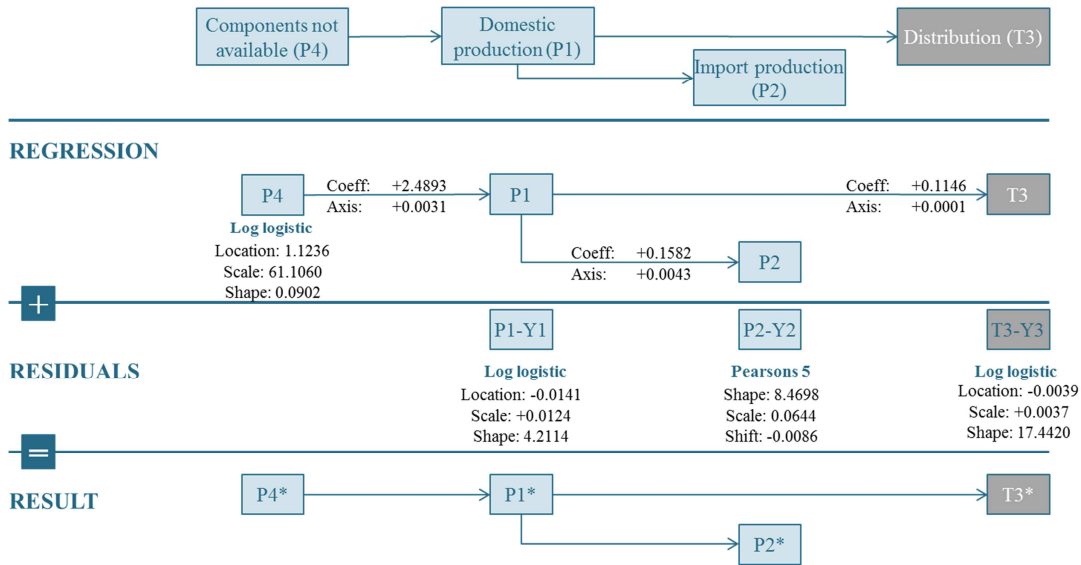
We assume a single-product supply chain, based on the data granularity at the case study company. The case study company produces and sells a variety of packaged, fast moving consumer goods in several business units. Production is a chemical flow process resulting in large bulk volumes; these are broken down into packages of few kilograms or liters for consumer use. Sales are only handled via retailers, who are defined as the customers for the company. The retailers handle sales and logistics to the individual retail outlets and exclusively control contact to the consumers. Demand for the products of the case study company is fairly stable, growing at a yearly rate of 1% before inflation. There has been only a negligible reaction to the economic crisis of -1% in 2009. The key driver of demand



variance is customer choice at the point of sale, driven by the customer's brand preference as well as by promotions with aggressive pricing or extra value offers such as larger packs for the same price (Weise 2008). Considering the industry position of the case study company - with very similar, packaged products and comparable demand structures regarding time and quantities - the single-product assumption has limited impact. For the regression analysis, this will result in more conservative findings, as multiple products result in higher noise levels in the data and therefore in lower regression coefficients. Combination effects between several risks must also be considered. If, for example, several products are manufactured on the same machinery, this potential conflict can present an additional risk. One example scenario will make this risk clear. For example, material needed for product A is delivered too late due as a result of a certain risk. As a consequence, the production machinery, e.g. the packaging line, is pushed to its limit in order to attempt to minimize the impact of the risk. The packaging line is then reconfigured in a rush to produce product B, and the line breaks down due to configuration errors. Thus, the risk of product A has effectively triggered a risk event of product B. If both products are analyzed separately, the two risk impacts would be separated and their relationship would be invisible in the analysis. A combined analysis, in contrast, reflects these relationships.

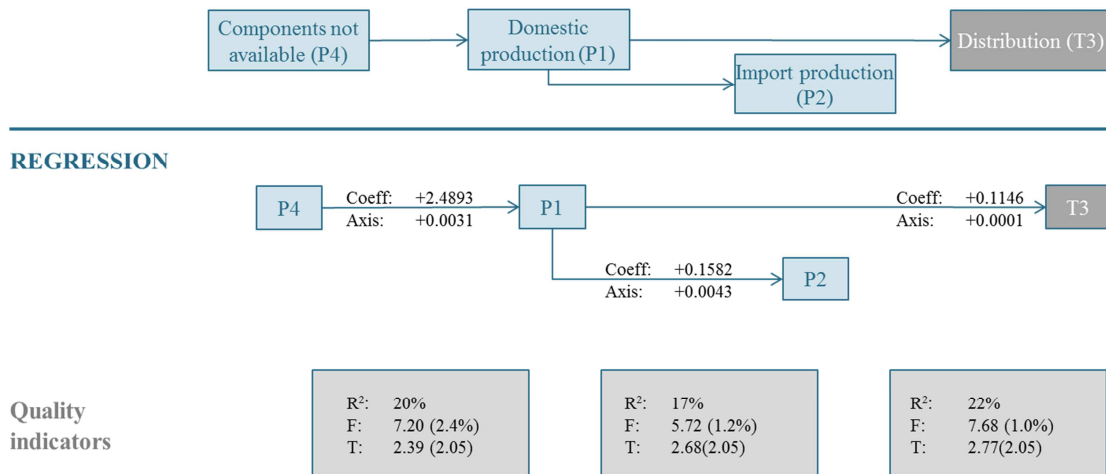
The best fit for P4 (components not available) can be shown to be the log logistic distribution. Figure 10 contains the parameters of the log logistic distribution fitted to the case study data for risk P4. The quality of fit indicators (p-value and chi-square value) show that the distribution is a meaningful approximation of the observed risk values. Risks P1, P2 and T3 are then each a combination of a dependent variable and an independent residual term.

**Figure 8: Regression and residual model**



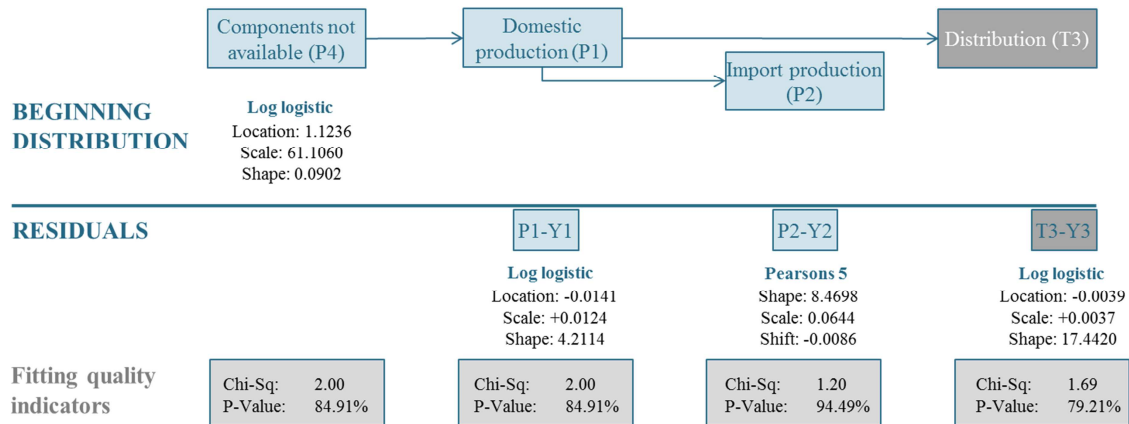
All regressions as described in Figure 9 show valid F-values with low probability of randomness, significant correlation coefficients, and t-values above the benchmark level of 5% for significance (Greene 2002). With  $R^2$  values of 20%, 17%, and 22% the regressions are meaningful. It is obvious, however, that a significant portion of variance is not explained by the regressions. To capture this portion, distributions are fitted to the residuals.

**Figure 9: Regression model and fitting quality indicators**



As shown in Figure 10, the fitted distributions provide satisfying approximations of the distributions of the remaining variance. The p-values of all distributions are above 79%, while chi-square values are equal or less than 2.

**Figure 10: Residuals and fitting quality indicators**



#### IV.4.1. Optimization of risk mitigation

In order to further explore Proposition 2, we will optimize the mitigation of two risks: one at the first stage of the supply chain (P4) and one at the second stage of the supply chain (P1), based on the above model. We will compare the optimal mitigation based on results of the regression/residual model with the limited perspective of an uncorrelated and correlated model to reveal the differences. The risk event is defined as a loss of sales: a certain value of sales in EUR already contracted with a customer is lost due to a risk event in the supply chain. As a mitigation strategy, the case study company buys dedicated inventory to compensate for a specific potential risk impact (P1 or P4). For P4, this can be, for example, an extra supply of raw materials or semi-finished goods. For domestic production this could be a stock of unlabeled products. Given the case study company's available data on lost sales, this inventory is not described in terms of production cost, but in terms of the sales value  $s$ . For example, the company stores a certain amount of inventory of semi-finished product without scenting or packaging. If a risk impacts the supply chain at this stage, the semi-finished inventory can be finalized and thus allow the production of goods with the sales value  $s$ . As all risks are measured in lost sales value, this maintains comparability. Lost sales directly correspond to absolute margin by the factor  $m$ . The object of optimization is either the cost of the single risk or the cost of all risks in the supply chain (consisting of the mean lost margin, the cost of mitigation, and the cost of holding capital) to ensure that the value at risk (95th percentile) of the mean lost margin distribution is covered (Jorion 2007). The 95th percentile of the risk impact and probability distribution is the risk limit that the case study company wants to "insure" by holding sufficient capital. If a manager considers only his part of the

supply chain, e.g., the domestic production, he will use the cost of the single risk. If a supply chain manager is in charge of the total supply chain, i.e. he is responsible for all risks under review, he will rely on the cost to the total supply chain for optimization. Under each model – regression/residual, correlated, and uncorrelated supply chain models – both cost figures can be calculated and used as the basis for the optimization of the mitigation. Each optimal value of inventory in sales value  $s$  under the uncorrelated, correlated and regression models is employed in the regression model to calculate the resulting risk cost. The regression model is used as the benchmark for comparisons across the three risk models.

To mitigate one risk  $j$  of the four risks (P1, P2, P4, T3) in the supply chain, semi-finished inventory is added to allow for the production of finished goods of sales value  $s$ . It is added on a monthly basis with the goal of minimizing the following cost of the risk to the supply chain<sup>8</sup>:

$$\min_s E[\tilde{C}_j(s)] = C_{Mit_j}(s) + E[\tilde{LM}_j(s)] + E[\tilde{C}_{Cap_j}(s)] + \sum_{k=1}^3 (E[\tilde{LM}_k] + C_{Cap_k}) \quad (3)$$

The cost function consists of four parts:  $C_{Mit_j}(s)$  which are the cost of mitigation for risk  $j$  (cost of acquiring semi-finished inventory with the sales value of  $s$ ),  $E[\tilde{LM}_j(s)]$  representing the expected lost margin due to the risk  $j$  and  $E[\tilde{C}_{Cap_j}(s)]$  describing the expected cost of holding risk capital for risk  $j$ , as well as  $E[\tilde{LM}_k]$  forming the expected lost margin, and  $C_{Cap_k}$  describing the cost of risk capital for the other three risks  $k$ . For the uncorrelated model of the supply chain,  $\tilde{LM}_k$  and  $C_{Cap_k}$  do not depend on the value  $s$ . On the one hand,  $s$  is only applicable to the risk  $j$  and can, for example, be understood as unpacked, semi-finished products for domestic production. This can be seen from equation (4) defining the expected value of the margin loss  $\tilde{LM}_j(s)$  as the product of the product contribution margin  $m$  with the expected value of the lost sales  $\tilde{LS}_j(s)$  due to the impact of the risk  $j$ :

$$E[\tilde{LM}_j(s)] = m * \max(E[\tilde{LS}_j] - s; 0) \quad (4)$$

---

<sup>8</sup> The stochastic parameters of the model are indicated by a tilde.

Equation (5) describes the expected value of the distribution of  $\widetilde{LM}_k$  similar as the product of the product contribution margin  $m$  with the expected value of the lost sales  $\widetilde{LS}_k$  which are independent of  $s$ :

$$E[\widetilde{LM}_k] = m * E[\widetilde{LS}_k] \quad (5)$$

The probability distributions are fitted to the lost sales  $\widetilde{LS}$  entailed by each individual risk  $j$  and  $k$  in the sub-supply chain of P4, P1, P2 and T3. Distributions and fitting quality indicators are found in Appendix 6. The distribution is only fitted to the lost sales  $\widetilde{LS}$ , as they are the risk measure in the data available. The basis for the fitting of distributions is the monthly lost sales as a percentage of total sales, excluding sales increase or decrease effects (i.e. higher absolute sales may produce higher absolute non-delivery volumes). To assure the best possible fit and improve interpretability, the values are transformed as described in Section IV.3 into their lognormal form (Greene 2002). On the other hand, in the uncorrelated supply chain, a reduction of the impact of risk  $j$  (the loss of margin  $\widetilde{LM}_j(s)$ ) by purchasing inventory of the value  $s$  as mitigation does not affect the likelihood of the other three risks  $k$ . Equation (4) indicates that an increase in  $s$  decreases the expected value of the total margin loss  $\widetilde{LM}_j(s)$ .

Similarly, holding the incremental capital, which is needed to compensate the potential margin loss, has to be financed; this is reflected in the interest cost  $i$ . The constant  $i$  describes the weighted average cost to the case study company necessary to attain the risk capital. The company has decided to hold capital sufficient to compensate 95% of all margin losses, i.e. the capital equivalent to the 95th percentile  $Q_{0.95}(\widetilde{LM})$  of the margin loss distribution. Equation (6) describes the cost of capital:

$$E[\widetilde{C}_{cap_j}(s)] = i * Q_{0.95}(\widetilde{LM}_j[s]) \text{ and } E[C_{cap_k}] = i * Q_{0.95}(\widetilde{LM}_k) \quad (6)$$

Based on the assumption of an uncorrelated supply chain, the distributions of the risks are assumed to be independent and hence uncorrelated. Further, as  $s$  can only be employed to mitigate the risk  $j$ , it does not impact the capital needed for the three remaining  $k$  risks.

The cost of the mitigation is driven by the price premium  $f$  the case study company has to pay to the contract manufacturers supplying the goods with the sales value of  $s$ .

$$C_{Mit}(s) = s * f \quad (7)$$

At the beginning of each month, the case study company buys inventory with a value of  $s$ , which the contract manufacturer produces and keeps as stock ready to be requested by the company in order to cover the risk  $j$  for a particular supply chain stage. For this service he charges the fee  $f$ , which is a percentage of the inventory value  $s$ . The cost of producing the inventory is carried by the contract manufacturer until  $s$  is requested and sold by the company. If an occurrence of risk  $j$  prevents the company from using its own production, it can utilize the backup inventory at the contract manufacturer and compensate any lost sales up to the value of  $s$ . As this inventory is dedicated to one risk cause, it can only be used for the particular risk. The fee  $f$  effectively reduces the margin of the case study company for any good sold under this arrangement to  $m - f$ . As  $f$  is smaller than the margin  $m$ , any product from this extra stock sold provides a net gain to the company, although the profit is reduced. In the presented case,  $f$  amounts to 30%. The fee  $f$  is comprised of 14% inventory holding cost (i.e. physical holding cost (handling and warehousing), damage, loss, and obsolesces); 10% increased production cost for the contract manufacturer due to smaller batch sizes and higher need for retooling; and 6% as a profit margin for the contract manufacturer itself.

If the supply chain risks are assumed to be correlated, then the lost margin distribution  $\widetilde{LM}_j[s]$  for the risk  $j$  impacts the expected values of the distributions of  $\widetilde{LM}_k$  for the  $k$  remaining risks. The correlation coefficients as derived above in Section IV.3. are applied in the correlated model.

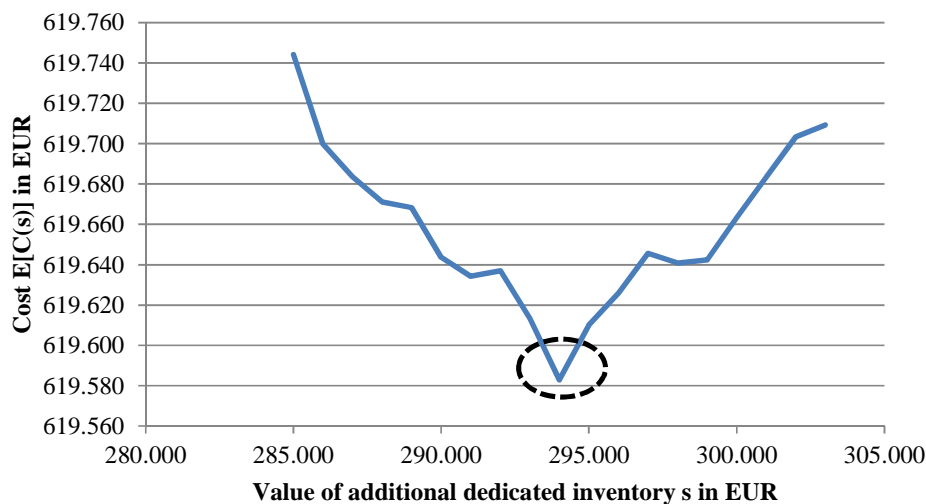
If risks are connected by cause and effect relationships in a regression model, then any mitigation by the value of  $s$  influences the variance and the expected value of the lost margin distributions  $\widetilde{LM}_k$ . Equation (5) now has to be adapted, as the expected lost margins  $\widetilde{LM}_k$  of the other  $k$  risks are dependent on the expected value of the mitigated lost margin  $\widetilde{LM}_j[s]$  of risk  $j$  with the value  $s$  of additional inventory, as shown in Equation (8). Further, the cost of risk capital of Equation (6)  $\tilde{C}_{Cap_k}$  now also depends on the change of the variance of the distribution of  $\widetilde{LM}_j$ .

$$E[\widetilde{LM}_k(s)] = m * E[\widetilde{LS}_k(\widetilde{LM}_j[s])] \text{ and } E[\tilde{C}_{Cap_k}(\widetilde{LM}_j[s])] = i * Q_{0.95}(\widetilde{LM}_j[s]) \quad (8)$$

The required mitigation value  $s$  cannot be determined in closed form. Therefore, Monte Carlo simulation is used to numerically derive the optimal value  $s$ . As in our case all risks are either uncorrelated or positively correlated, an investment in  $s$  reduces both the mean and variance of the total cost of the risks<sup>9</sup>.

As shown in Figure 11, the value of additional inventory is varied in steps of 1,000 EUR. A distinct minimum expected value of the cost  $\tilde{C}_{P4}(s)$  of 619,583 EUR can be identified at a value of 294 k EUR for  $s$ .

**Figure 11: Identification of optimal mitigation value, example risk P4**



For the simulation, the interest rate  $i$  for any incremental capital is set to 10%, which approximately equals the WACC of the company considered. The profit margin  $m$  is set to 50%, which is an average across multiple products of the case study company ranging from 45% to 60%. Additional cost premium  $f$  for purchasing inventory to assure the production of extra goods with the value of  $s$  to avoid lost sales is set to a value of additional cost of 30% and then varied to explore sensitivity.

#### IV.4.2. Comparison of mitigation results for different supply chain perspectives

We start by mitigating the largest risk in the supply chain, P1. In a first step, P1 is optimized individually – that is, based on the cost of this risk alone, without consideration of its

<sup>9</sup> In a classical financial investment portfolio individual elements may be correlated positively or negatively. An optimization may, therefore, reduce the mean return yet may increase the variance of the return of the portfolio. So either the variance of returns or the mean return is optimized while the other element is held constant (Elton and Gruber 2011).

interdependence with the rest of the supply chain. In Table 12, below, we compare the baseline case without mitigation, optimal mitigation in the uncorrelated and correlated supply chain, and the regression model. We assume a remaining margin of goods purchased externally of 20%, instead of 50%, as is normally the case. This difference corresponds to a price premium of 30% paid to the contract manufacturer to provide the semi-finished inventory in a very short time.

In the baseline case, no additional goods are purchased. The total financial risk on the whole supply chain is 806 k EUR. This consists of the lost margins on all risks under review as well as the cost of risk capital, i.e. the cost of the additional capital that the company has to hold in order to ensure (in our case, with a probability of 95% (95th percentile)) that the company could cover its losses with equity. According to the correlated and uncorrelated model, the case study company would purchase semi-finished inventory with a sales value of 448 k EUR at incremental cost of 134 k EUR. As only one risk is mitigated here, there are no correlations between the risks to affect the optimization in this case. Therefore, the values for the correlated and uncorrelated case show the same figures. For the single risk perspective, we optimized the cost of the single risk, not including the interdependencies of P4, P2, and T3. The total financial impact is 719 k EUR as measured with the regression model. Applying the regression model for optimization, the case study company will buy 473 k EUR of goods in sales value, i.e. 5% more, but with a resulting total supply chain cost of only 718 k EUR. The incremental cost of 142 k EUR in this case is higher than in the correlated case, 134 k EUR. The regression model includes all observable relationships and is, therefore, more accurate. The correlated and uncorrelated perspectives thus produce a suboptimal result.

**Table 12: Mitigation optimization of risk P1 based on single risk perspective in EUR**

<b>Single risk</b>	Additional units in sales value	Cost of mitigation	Cost (incl. capital cost, lost margin, cost of mitigation)
No mitigation	0	0	806,201
Regression	472,000	141,600	717,951
Correlated	448,000	134,400	719,420
Uncorrelated	448,000	134,400	719,420

It is now possible to pose the question of whether an optimization based on a single risk is still optimal when considering the whole supply chain. After broadening the perspective to include the whole supply chain, i.e. also including the risks P4, P2, and T3 in the optimization of cost, we arrive at the results shown in Table 13.



**Table 13: Mitigation optimization of risk P1 based on complete supply chain in EUR**

<b>Supply chain risk</b>	Additional units in sales value	Cost of mitigation	Cost (incl. capital cost, lost margin, cost of mitigation)
No mitigation	0	0	806,201
Regression	640,000	192,000	712,059
Correlated	444,000	133,200	719,760
Uncorrelated	434,000	130,200	720,662

For the correlated case we arrive at an optimal purchase of finished goods with a sales value of 444 k EUR, leading to total supply chain risk cost of 720 k EUR. For the uncorrelated case the model suggests a purchase of 434 k EUR of additional goods in sales value, creating a total cost of 721 k EUR. In the regression model the optimal purchase of goods is 640 k EUR, leading to a total risk cost of 712 k EUR. Total costs always include capital cost, lost margins, and cost of mitigation. To cover the 640 k EUR of sales value, the case study company has to invest an additional 192 k EUR. Compared to the single risk case described above, in the regression model, the case study company invests more, yet arrives at a lower cost to the supply chain: 712 k EUR for the regression model compared to 718 k EUR in the single risk case. A perspective that considers the complete supply chain, therefore, results in a superior mitigation solution.

The mitigation optimization is repeated for risk P4 from the two perspectives of single risk and supply chain perspective. The mitigation solution derived from the regression model and based on the complete supply chain is revealed to be optimal (Appendix 7). This underscores the result of the optimization of risk for only P1, domestic production, as shown above.

*Proposition 4: Managers who ignore the cause and effect relationship of risks will make suboptimal mitigation investments, resulting in inefficient supply chain risk management.*

#### **IV.4.3. Comparison of mitigation results in different supply chain stages**

To better understand the implications of Proposition 2, we optimize a mitigation strategy for a smaller risk that occurs earlier in the supply chain. P4 is mitigated based on the total supply chain risk cost. Similar to the optimization of the risk P1, the regression model leads to an optimal value compared to the correlated and the uncorrelated models. The results can be seen in Table 14, below.

**Table 14: Mitigation optimization of risk P4 based on complete supply chain in EUR**

Supply chain risk	Additional units in sales value	Cost of mitigation	Cost (incl. capital cost, lost margin, cost of mitigation)
No mitigation	0		806,834
Regression	300,000	90,000	619,032
Correlated	103,000	30,900	681,009
Uncorrelated	100,000	30,000	683,445

According to Proposition 2, the mitigation of risk P4 should be preferable to the mitigation of P1, as P4 is positioned earlier in the supply chain. To validate this proposition, we compare the optimization results for the total supply chain cost for P1 and P4. To mitigate P1 the case study company should purchase 640 k EUR of sales value at cost of 192 k EUR, resulting in total supply chain risk cost of 712 k EUR. When mitigating P4, which is upstream on the supply chain, the case study company would have to purchase additional items accounting for 300 k EUR in sales value at 90 k EUR of additional purchasing cost. This leads to a total supply chain risk cost of 619 k EUR. Thus, an optimization of an earlier risk is more cost efficient and should be preferred over an optimization of a later stage risk, even if the later stage risk is significantly larger than the early stage risk. Proposition 2 is therefore strengthened.

To better understand the stability of the result, we performed a sensitivity analysis for the cost of mitigation. The incremental cost of purchasing additional finished goods in the short term, initially set to 20%, was varied from 15% to 45%. The finding was stable across all parameter sets. Results can be found in Appendix 7 and 8.

Taking into consideration the mitigation strategies of Chopra and Sodhi (2004), our example could be applied to the mitigation strategies of adding inventory (as seen in the model above), adding capacity, and having redundant suppliers. These mitigation strategies lead to extra costs per unit of product produced; these are captured in the fee  $f$ , e.g., depreciation cost or an extra margin for the supplier. The mitigation strategies of increasing responsiveness, increasing flexibility, and increasing capability are more difficult to apply because their implementation and cost structures are very broadly defined. These strategies must be further specified and detailed for individual situations before being applied. An increase of customer accounts would only mitigate the receivables risk, which is not investigated in this case. Aggregation and pooling of demand is, in our case, the fast moving consumer goods industry,

already exploited to a large extent, as the manufacturer faces a concentration of retailers and high degree of information sharing (Weise 2008).

#### **IV.5. Managerial implications**

The above findings have clear implications for managerial practice in the context of a large supply chain. In theory, the integration of cause and effect models and adjustment of mitigation strategies is easily executed. In reality, however, a manager is likely to identify and accept only those risks and effects that fall within his responsibility and, only to a lesser extent, their secondary risk effects outside of his department. In other risk management disciplines that are limited to specific functions or industries, e.g. financial risk management, the issue of the limited perspective of managers may not be as important. Supply chain risk management, however, often spans the entire value creation process of the company; this makes coordinated management efforts crucial. To counter the tendency for managers to work in departmental silos instead of as a team, companies must integrate all relevant departments (i.e. purchasing, supply chain/logistics, production, marketing/sales planning, finance/controlling) into the risk management process. Companies should also aim for transparency of analysis; this can help ensure acceptance with all managers and an incentive (e.g. unified quantified cost targets) for managers to cooperate with each other and to work to manage risks beyond their purview.

In this paper we developed a simulative, regression-based approach that makes it possible to quantify the effects of risk interdependencies. We have also offered an approach to optimizing risk mitigation strategies that can be easily transferred from an academic to a managerial application. The simulation presented allows managers to prioritize related risks in order to choose a targeted application of mitigation strategies. Applying the proposition that early stage risks influence later stages of the supply chain and should thus be mitigated first, managers can focus their risk management practice on the most critical risks. Furthermore, with the simulative analysis of mitigation strategies, managers can apply the optimal degree of risk capital provision and mitigation to, for example, select the optimal amount of additional inventory. This combination extends the existing literature on risk mitigation in its development of applications for managerial practice by industry, as demanded by Juettner et al. (2003).

#### **IV.6. Conclusion**

The analysis of risk relationships as recommended by several authors (e.g. Hauser 2003) is difficult to achieve in supply chain risk management due to the complex nature of the supply chain. The supply chain complexity results in a low standardization and limited data availability compared to other risk management disciplines such as, for example, financial risk management (Ritchie and Brindley 2009). In the present paper, we analyze risk interrelations using non-delivery data from a major FMCG company. This analysis yields several interesting insights. For one, our analysis identified correlations in the non-delivery data collected for two regions. For 13 analyzed risks, 10 out of 78 risk pairs show a significant correlation for the CEE region and also 10 out of 78 pairs show a significant correlation in the WE region. This has several implications for the risk management process. For one, in order to understand their full potential effects, risks cannot be quantified individually, but have to be analyzed together. When an impact analysis of risks also includes the correlations of those risks, the prioritization of risks for mitigation may more heavily emphasize risks that have only a low individual impact, but which are highly correlated with others in the supply chain. Further, risk dependencies are revealed to be supply chain specific; they may depend, for example, on market maturity stage or market conditions.

Additionally, reviewing the individual correlations in search of a general pattern, it becomes apparent that upstream risks influence downstream ones. An upstream risk with a small, direct financial impact may cause a domino effect and result in larger financial impact further down the supply chain. This finding influences risk mitigation priorities, as counter-measures should prioritize addressing the upstream or triggering risks to reduce their influence on downstream risks. Only later should resources be invested in relieving risks at a later supply chain stage. When planning mitigation strategies it is thus critical to focus on the risks that arise earliest in the supply chain structure. A cause and effect model makes it possible to plan an optimal risk mitigation strategy and to avoid suboptimal mitigation strategies based on a simple uncorrelated or correlated supply chain model, as shown in the examples above. This is an especially crucial change, as risk management priorities are traditionally derived from the absolute value of the individual negative impact of a risk. As shown in the examples, this is not necessarily optimal.

The research presented here expands the traditional risk management process, which served as the underlying theory of this work. Correlations and cause and effect models such as the

regression and residual model have been shown to influence not only the assessment step, but also the aggregation and mitigation steps. This further strengthens previous arguments (e.g. by Peck (2006)) that understanding interdependencies is a vital part of effective supply chain risk management. This paper provides the first proof, in the limited environment of a case study, of the importance of understanding risk interdependencies.

The results suggest several interesting opportunities for further research. To strengthen the findings regarding how risk relationships influence supply chain risk management, two research avenues can be considered. The first would be to collect similar, but more extensive data on risk impacts in a simpler environment with a less complex product and country setup; this would make it possible to quantify the influence of correlations and cause and effect relationships with less noise in the data. To better understand the validity of the results, we suggest an investigation of supply chains with different correlations between risks, different risk values, or different lengths of the observation periods. This could be effectively achieved by investigating supply chains in other industries. In a second promising avenue of research, supply chains could be explicitly modeled to not only derive relationships between the risks from observations, but also ground them further in supply chain theory. For example, shocks in an explicit model of a production line could be relied upon to show how a risk on an early stage of the line triggers a risk later on in the line by stretching the line to its capacity limit. This would, however, require a simple, well-controlled supply chain environment with dedicated measuring and controlling points and would quite possibly have the character of an experiment.

This research paper illustrates the importance and insight value of extensive data collection in the supply chain environment. We thus hope that this paper may offer encouragement to other researchers to invest time and effort in obtaining detailed data about supply chains - however complex and tedious that process may be - to more accurately quantify risk impacts and their relationships. More extensive data collection would allow the currently under-researched area of cause and effect relationships to be examined more closely. The execution of the research presented here in the case study environment illustrates the relevance and importance for companies of further academic work on risk relationships.

## **V. Overall conclusion**

Considering the results of all three papers as a whole, it is possible to suggest some important modifications to the supply chain risk management process. Paper 1 provides a common ground for supply chain risk management by defining the terminology under the special circumstances of the FMCG industry. Paper 2 reveals that subjective risk assessment is a valuable part of risk assessment that can complement and even expand upon objective, quantified risk assessment. Paper 3 illustrates the impact of relationships between risks for the example of operational risks. Together, these three research perspectives provide indications for how to improve the supply chain risk management process.

The first part of this research project revealed the need for a common understanding of the concepts and definitions in the fields of supply chain and supply chain risk management, e.g. with regard to the four-step process of identification, assessment/aggregation, mitigation, and controlling. The term “supply chain” must be defined with regard to its use in each particular environment in order to provide a more precise scope of discussion. Further, all departments with a relevant responsibility in the supply chain need to be included in the discussion and definition process; otherwise, as is often currently the case in companies, departmental barriers limit the perspective of individual managers to their area of responsibility. Only when an agreed-upon set of definitions is clearly communicated to all relevant managers, it is possible to ensure that all crucial risks are identified and mitigated.

The second part of this research illustrates the value of subjective risk assessment compared to objective risk assessment. In the case study company, the managers demonstrated a strong ability to accurately prioritize risks, even compared to a quantitative assessment performed on the basis of controlling and external data. However, subjective risk assessment shows biases that require corrections by targeted de-biasing strategies, e.g. if risks have strongly skewed distributions. We demonstrated that when combined with de-biasing strategies, subjective assessment is a reliable tool for prioritizing the overall supply chain risk portfolio of the company. Furthermore, as seen in the case study company, there is often only scant, if any, quantitative data available for some kinds of risks, especially disruptive risks. This emphasizes the importance of systematic, de-biased subjective risk assessment for prioritization.

The third part of the research provides insights into the impact of risk interdependencies. By comparing risk priorities and optimal mitigation investments in three optimization models – independent risks, correlated risk, and risks with a cause and effect relationship – the clear effects of dependencies in the case study example becomes obvious. When risk prioritization takes into account risk correlations as well as supply chain flows, the sequence of prioritization is shifted: rather than focusing on the risks with the highest expected cost, managers must prioritize those risks that occur at an early supply chain stage and that have a high correlation to the later risks. The analysis based on a cause and effect model further reveals the clear advantages of investment in risk mitigation early in the supply chain. In the example of the case study company, it can be shown that a higher investment early on may offer cost advantages over investing in the larger risk at a later stage of the supply chain.

Combining the insights of the second and the third parts of this research, we conclude that subjective risk management can be recommended as the first step in prioritizing risks, especially in order to assess disruptive risks with limited data availability. An objective risk assessment, however, is of greater value for risks for which good data is available – for example, for operational risks well covered in controlling systems of the company. Finally, a strong case can be made for including risk interdependencies in the risk mitigation planning. We recommend that the risk assessment be split into two parts: one, a broad and subjective assessment covering all risks, and two, a focused and objective review of those risks for which sufficient data is available. The derivation of mitigation strategies is strongly influenced by the cause and effect model, which shifts the focus of mitigation efforts towards the beginning of the supply chain and changes the optimal amounts of investment. The sequential application of both subjective and objective assessment appears to be most beneficial for supply chain risk management.

This research project suggests several opportunities for further academic work. Overall it can be said that there is still a critical need to improve traditional risk management techniques, particularly in light of the complexities of supply chains as described by Pettit et al. (2010), and that this need is particularly felt in the assessment phase. As our research only focuses on the fast moving consumer goods industry, a similar approach could also be applied to other industries as proposed by Juettner et al. (2003) to identify the specific needs and characteristics of each. The potential benefits of combining subjective and objective risk assessment should also be investigated further. As proposed by Khan and Burnes (2007), the

implications of the subjective (qualitative) versus and objective (quantitative) risk discussion with respect to their impact on tools for supply chain risk management could be further investigated. For example, our approach could be adapted to large-scale empirical research, to another industry, or to other case studies in order to explore the applicability of our conclusions in other environments. Further, the nine risk bias categories and de-biasing strategies as proposed by Carter et al. (2007) should be tested on a large scale to provide general proof for their suitability for use in the context of objective and subjective supply chain risk assessment.

The most interesting field for further research, however, is the growing body of evidence revealing the importance of risk dependencies and their effects. Based on Ritchie and Brindley (2007b), further research should investigate causal pathways for risk sources to gain a better understanding of the sources and effects of risks. As shown in our case study, these relationships strongly influence the sequence of mitigation and optimal investment into risk mitigation. If other companies could be encouraged to collect more data, especially on operational risks systematically across departmental boundaries, a more general investigation could be started. This would also clearly follow Tang and Musa (2011), who identify a research need to provide managers with more quantitative models on which they can make fact-based decisions, as opposed to more descriptive or conceptual literature.



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## Appendix

### 1. Evaluation criteria (Flint and Mentzer 2000, Flint et al. 2002)

Trustworthiness Criteria	Method of addressing criteria in the study
<p><i>Credibility</i></p> <p>Extent to which the results appear to be acceptable representations of the data</p>	<p>One year of conducting interviews and analyzing data.</p> <p>Participants reviewed the findings and provided feedback.</p>
<p><i>Transferability</i></p> <p>Extent to which the findings from one study in one context will apply to other contexts</p>	<p>Participants chosen based on theoretical sampling.</p> <p>Diverse sample representing variations in type of responsibilities, position level and region.</p>
<p><i>Dependability</i></p> <p>Extent to which the findings are unique to time and place; stability or consistency of explanations</p>	<p>Experiences covering recent and past events were reflected upon by the participants, core categories existed across responsibilities and regions.</p>
<p><i>Confirmability</i></p> <p>Extent to which interpretations are the result of the participants and the phenomenon as opposed to researcher bias</p>	<p>All findings reviewed by researcher and advisors.</p> <p>Findings supported by quotes.</p>
<p><i>Integrity</i></p> <p>Extent to which interpretations are influenced by misinformation or evasions by participants</p>	<p>Confidentiality assurance to participants.</p> <p>Non-threatening interviews by researcher.</p>
<p><i>Fit</i></p> <p>Extent to which findings fit with the substantive area under investigation</p>	<p>Addressed through the methods to establish credibility, dependability and confirmability.</p> <p>Concepts more deeply described, capturing complexities of social interactions discovered in the data.</p>
<p><i>Understanding</i></p> <p>Extent to which participants by into results as possible representations of their worlds</p>	<p>Executive summary of findings to participants; asked if they reflected their stories and perspectives.</p> <p>Presented summary to colleagues and practitioners.</p>
<p><i>Generality</i></p> <p>Extent to which findings discover multiple aspects of the phenomenon</p>	<p>Interviews had sufficient lengths and openness to elicit many complex facets of the phenomenon.</p>
<p><i>Control</i></p> <p>Extent to which organizations can influence aspects of the theory</p>	<p>Some variables within the theory are aspects over which participants would have some degree of control.</p>

## **2. Decision biases according to Carter et al. (2007)**

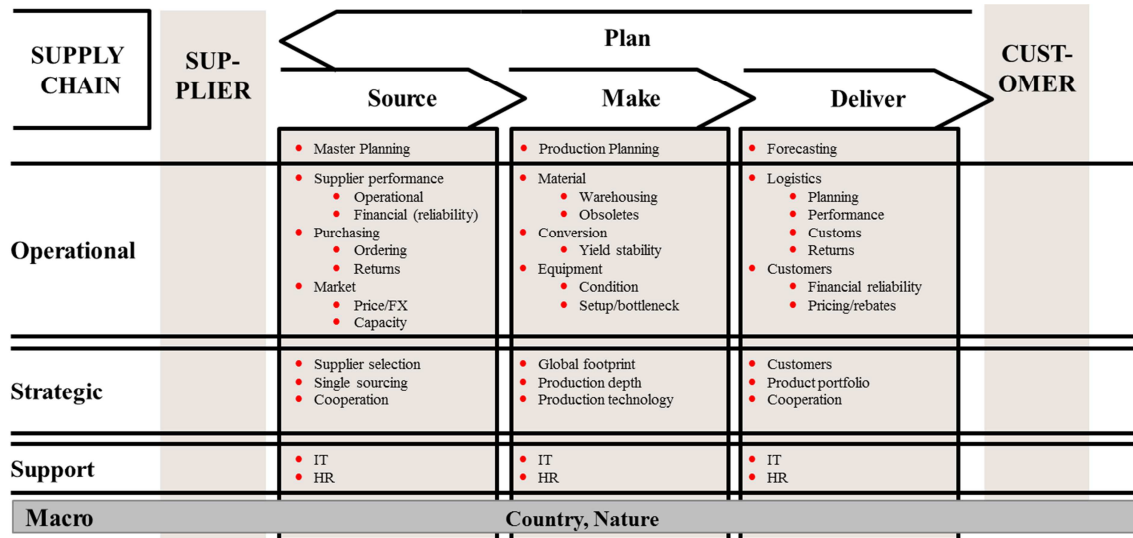
- Availability cognition bias, i.e. information is more easily recalled from memory and, therefore, more probable.
- Base rate bias, i.e. managers rely more on an anecdote or personal experience, i.e. on few or even a single vivid data points.
- Control illusion bias, i.e. a sequence of random events or non-representative samples can be mistaken as essential characteristics of a process leading to unrealistic confidence in judgment, especially when task is complex, i.e. information overload.
- Output evaluation bias, i.e. in retrospect the degree to which an event would have been overestimated, failure is seen as bad luck and success as ability of the decision maker.
- Persistence bias, i.e. an alternative is chosen because this was also done in the past. Managers show bounded rationality and limit the search for new options.
- Presentation bias, i.e. the sequence of the presentation of events influences the value of data.
- Reference point bias, i.e. evaluation from initial reference point are insufficient, judgments are biased in the direction of a relevant comparison point.



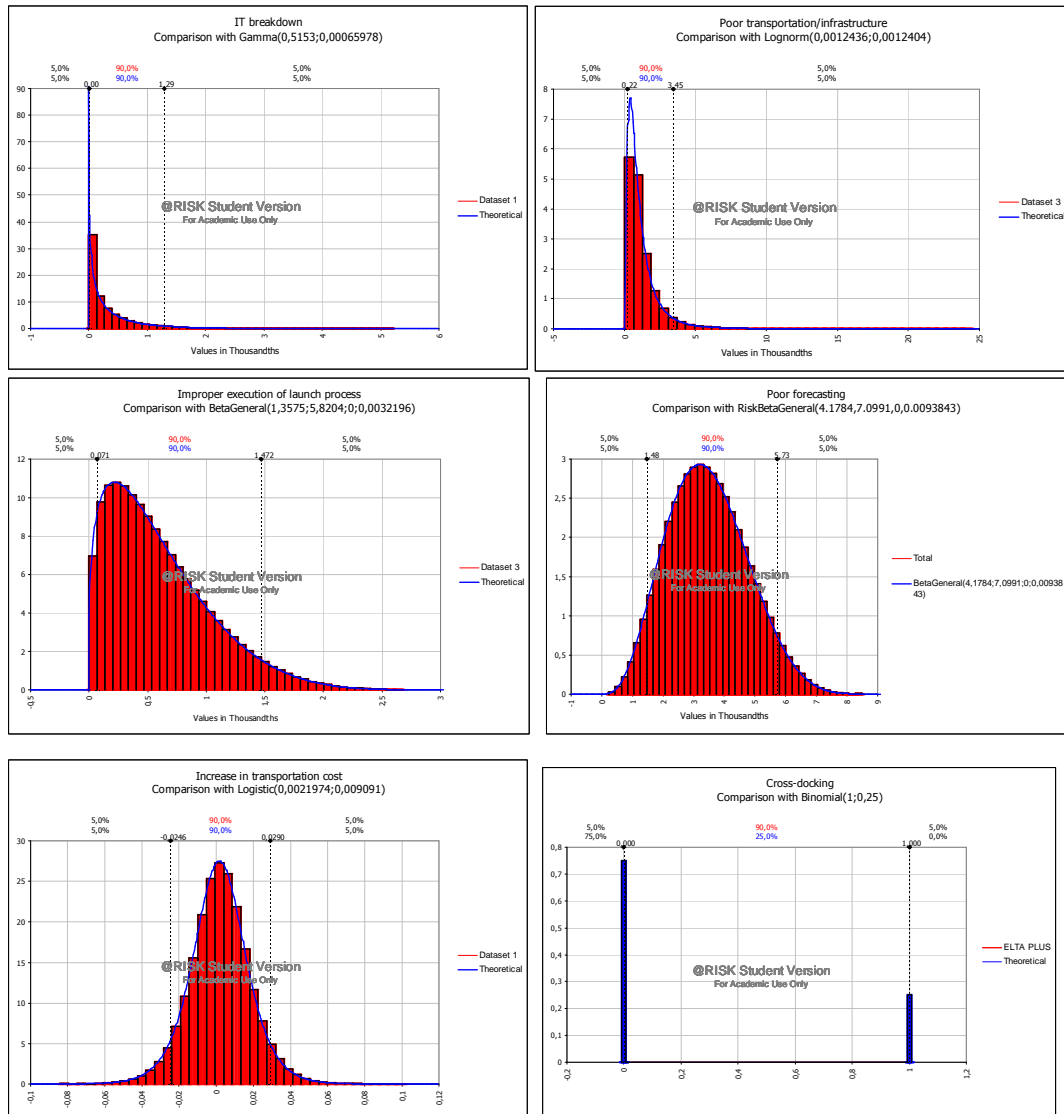
### 3. List of interviewees

Region	Position	Round 1	Round 2	Round 3
Global	SHEQ	x		
MENA	Logistics and Planning	x	x	
WE	Head of SC	x	x	
Global	Head of Purchasing	x		
CEE	Production Steering	x		
Global	Production Steering	x	x	
WE	Logistics and Planning	x	x	
CEE	Head of SC	x	x	
Global	Sales	x	x	
CEE	Logistics and Planning	x	x	
Global	Purchasing	x	x	
Global	Purchasing	x		
Global	Head of SC	x	x	
WE	Production Steering	x	x	
CEE	Logistics	x	x	
MENA	Head of SC	x	x	
MENA	Production Steering	x	x	
Global	Controlling	x	x	x
Global	Purchasing Logistics	x	x	
Global	Projects		x	
Global	Planning			x
Global	Purchasing			x
WE	Planning			x
Global	Purchasing			x
Global	Logistics and Planning			x
Global	Purchasing			x
Global	Purchasing			x
Global	Purchasing			x
Local	Head of SC			x
Global	Purchasing			x
Global	Purchasing			x
Global	Logistics and Planning			x

#### 4. Risk identification framework



## 5. Probability distributions of operational risks



## 6. Fitting results for the correlated and uncorrelated supply chain

	Components not available (P4)	Domestic production (P1)	Import production (P2)	Distribution (T3)
<b>DISTRIBUTION</b>	<b>Normal</b> Mean: -6.8559 Variance: 1.1273	<b>Normal</b> Mean: -5.27503 Variance: 0.88227	<b>Normal</b> Mean: -5.345610 Variance: 0.43155	<b>Normal</b> Mean: -8.2738 Variance: 1.6165
<b>Fitting quality indicators</b>	Chi-Sq: 3.70 P-Value: 71.76%	Chi-Sq: 1.58 P-Value: 95.43%	Chi-Sq: 3.74 P-Value: 44.25%	Chi-Sq: 3.70 P-Value: 71.76%

## 7. P4 Components not available

Single risk perspective (Additional units in sales value varied in steps of 25,000 EUR)

Incremental cost for additional units	45%	40%	35%	30%	25%	20%	15%
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Regression	Additional units in sales value	25,000	50,000	75,000	100,000	150,000	175,000	225,000
	Cost of mitigation	11,250	20,000	26,250	30,000	37,500	35,000	33,750
	Cost	770,383	737,692	708,870	682,936	642,317	621,598	591,531

Correlated	Additional units in sales value	50,000	50,000	75,000	100,000	150,000	175,000	225,000
	Cost of mitigation	22,500	20,000	26,250	30,000	37,500	35,000	33,750
	Cost	740,578	737,692	708,870	682,936	642,317	621,598	591,531

Uncorrelated	Additional units in sales value	50,000	50,000	75,000	100,000	150,000	175,000	225,000
	Cost of mitigation	22,500	20,000	26,250	30,000	37,500	35,000	33,750
	Cost	740,578	737,692	708,870	682,936	642,317	621,598	591,531

Total supply chain perspective (Additional units in sales value varied in steps of 25,000 EUR)

Incremental cost for additional units	45%	40%	35%	25%	20%	15%
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Regression	Additional units in sales value	250,000	250,000	275,000	325,000	350,000	400,000
	Cost of mitigation	112,500	100,000	96,250	81,250	70,000	60,000
	Cost	659,249	646,425	633,317	603,591	586,899	567,743

Correlated	Additional units in sales value	50,000	50,000	75,000	125,000	175,000	200,000
	Cost of mitigation	22,500	20,000	26,250	31,250	35,000	30,000
	Cost	740,578	737,692	708,870	658,115	621,598	601,132

Uncorrelated	Additional units in sales value	50,000	50,000	75,000	125,000	150,000	200,000
	Cost of mitigation	22,500	20,000	26,250	31,250	30,000	30,000
	Cost	740,578	737,692	708,870	658,115	634,966	601,132

## 8. P1 Domestic Production

Single risk perspective (Additional units in sales value varied in steps of 25,000 EUR)

Incremental cost for additional units	45%	40%	35%	25%	20%	15%
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Regression	Additional units in sales value	100,000	225,000	350,000	625,000	800,000	1,025,000
	Cost of mitigation	45,000	90,000	122,500	156,250	160,000	153,750
	Cost	793,255	773,837	748,555	680,894	635,832	583,368

Correlated	Additional units in sales value	225000	275000	350000	550000	700000	950,000
	Cost of mitigation	101,250	110,000	122,500	137,500	140,000	142,500
	Cost	784,066	769,733	748,555	686,395	642,004	586,116

Uncorrelated	Additional units in sales value	225,000	275,000	350,000	550,000	700,000	950,000
	Cost of mitigation	101,250	110,000	122,500	137,500	140,000	142,500
	Cost	784,066	769,733	748,555	686,395	642,004	586,116

Total supply chain perspective (Additional units in sales value varied in steps of 25,000 EUR)

Incremental cost for additional units	45%	40%	35%	25%	20%	15%
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Regression	Additional units in sales value	325,000	425,000	525,000	775,000	950,000	1,125,000
	Cost of mitigation	146,250	170,000	183,750	193,750	190,000	168,750
	Cost	782,155	764,842	741,531	676,458	632,891	581,916

Correlated	Additional units in sales value	225,000	275,000	350,000	550,000	700,000	875,000
	Cost of mitigation	101,250	110,000	122,500	137,500	140,000	131,250
	Cost	784,066	769,733	748,555	686,395	642,004	590,523

Uncorrelated	Additional units in sales value	200,000	275,000	350,000	525,000	650,000	825,000
	Cost of mitigation	90,000	110,000	122,500	131,250	130,000	123,750
	Cost	785,308	769,733	748,555	688,774	646,431	594,475