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After sales supply chain risk management.

Steffen Luksch 1975-
University of Louisville

AFTER SALES SUPPLY CHAIN RISK MANAGEMENT

By

Steffen Luksch
Dipl. Wirt. Ing. (FH), Heilbronn University, Germany 2001
M.Eng., Heilbronn University, Germany 2008

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By the following Dissertation Committee

Dr. Suraj M. Alexander, Advisor

Dr. Gerald Evans, Member

Dr. William Biles, Member

Dr. John Usher, Member

Dr. Mahesh C. Gupta, Member

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The present work was done during my practical work in the Automotive Industry in the Department After Sales Supply Chain Management and my time as a doctoral student at the University of Louisville in Kentucky, USA. The Department After Sales Supply Chain Management deals with the application related research in the area „*Sustainable Supply Chain Management*" and looked at procedures and methods to ensure a robust supply chain in the post series supply of automobile spare parts.

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ABSTRACT

AFTER SALES SUPPLY CHAIN RISK MANAGEMENT

Steffen Luksch

March 31, 2014

Lean supply chains with cost optimized production and logistics processes in the automotive industry have become a benchmark for other industries. Short delivery times, low inventories and high availability are parameters which assume a robust supply chain. In industrial practice we see, however, that in the After Sales business particularly related to the supply of automotive spare parts, that there are always unforeseen delays in delivery. In order to avoid service level losses on the focal firm level due to missing parts it is necessary to understand the risk structure on the supplier side. For this reason, a risk model for the After Sales inbound SC is developed through this work. Based on an extensive analysis of delivery data a central risk size was derived. Comprehensively researched SC risks are supplemented by After Sales specific risks derived through an empirical supplier survey. A reference network, which is methodologically based on the Bayesian theorem, to control the dynamic relationships was developed. The developed risk model allows for the identification of proactive and reactive measures by top-down and bottom-up analyzes to make lean supply chains for after sales requirements in the best cases robust and resilient. A big advantage of the developed model is not only the ability to quantify the cause and effect of supply chain risks but also to describe the constantly changing risk environment of the supply chain through continuous belief updates within the model. The risk analysis in the developed model potentially reduces the delivery delay of spare parts by 65 percent and diminishes the buffer stock value by 50 percent. To achieve such improvements in the real world organizations must be able to implement measures in explicit SC risk clusters for sustainable supply chain performance and inventory management. Improvements in the internal supplier processes, due to risks like prioritized series supply, or inappropriate after sales supply strategies are necessary. Utilizing the developed After Sales Risk Management Model (ASRIM) organizations will be able to implement proactive risk mitigation strategies, facilitating agile SC performance, while simultaneously reducing buffer stocks.

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1 INTRODUCTION

1.1 Overview

Even small interruptions in one link of a supply chain can cause complete failures. Global chains of delivery are full of potential risks which could extend delivery times. That is why supply chain risk is a key issue in scientific literature, as well as in the industrial practice, gaining an increasing interest. In particular the automotive supply chain has emerged as lean and global networks (Lockamy III and McCormack 2012), (Khan and Burnes 2007), (Faisal, Banwet et al. 2006),(Porter 1998). On the one hand, the practice of global sourcing enhances further cost advantage and strengthens the company's competitive position in the industry. On the other side, global sourcing from countries is subject to threatening risks, such as environmental catastrophes, that could disrupt the well optimized supply stream.

Consequently, supply chain best practices in a global environment may have a reverse effect on the supply chain, leading to the network's inability to supply the demand requirements. A recent example is the nuclear catastrophe in Fukushima, caused by an earthquake and tsunami in 2011. This catastrophe had a huge effect on human lives and caused production problems to all nearby automotive suppliers located in the affected area (Reuters 2011). This is one real-life example for the cause and effect relationship of modern supply chains, where one risk in one level of the supply chain causes another risk in another level of the supply chain. However, it shows that despite numerous developments from theoretical methods and concepts to supply chain risk management, research is still in the initial phase (Jüttner 2005). In particular there still exists a high deficit in quantitative research approaches on risk management in the industrial practice linked to real supply chains (Tang and Nurmaya Musa 2011).

1.2 Problem Statement

In favor of the system and module supply for vehicle production, the spare parts supply for customer satisfaction in the after sales struggled even more. In addition, the automotive supply chain gets leaner and more global, the less room is available to buffer disruptions (Hendricks and Singhal 2005). Subsequently, it is existential to organizations to recognize supply chain risks and their causal effects in advance, in order to take actions that guarantee spare parts availability on time. The awareness of the effect of risks on the supply chain has increased after the disruptive incident in 2011. On average 75 percent of professionals believe that their supply chains are vulnerable to disruptions (Thun and Hoenig 2011). Even though there is a high level of awareness that supply chains are exposed to risks, only 33 percent of responding firms pay adequate attention to supply chain vulnerability and risk mitigation measures (Poirier 2004). Recent research reveals that only 50 percent of industrial firms have implemented an early warning system for capturing warning signals in the supply chain (Schatz 2010).

1.2.1 After Sales Supply

These insufficient numbers might be due to the difficulty to operationalize an effective risk management framework in the supply chain, hindered by the complexity to manage the causal risk structure. Especially in relation to after sales the risks could be even bigger, due to fact that practice shows that the serial deliveries are always more highly prioritized. Based on results of automotive after sales supply chain supplier assessments at a car manufacturer, there generally exists large delivery uncertainties over the ordered spare parts in the form of a wide range of delivery time variation, up to several months. Therefore it is of great economic importance to recognize the risks in the after sales supply chain in their entirety and at an early stage as well as their dependence on each other to minimize these with an appropriate model.

1.2.2 Fields of Action

Above all this is emphasized by the fact that so far there exists a real lack of empirical research into this topic, especially for the automotive after sales supply chain (Sodhi et al, 2012, S. 10f). It should be noted that both in scientific literature and in practice a large interest exists to examine the interaction of risks in the after sales supply chain more intently. This finding was alarming for the supply chain management. For this reason it is necessary for Management to develop an operational **A**fter **S**ales **RI**sk**M**odel (ASRIM) where uncertainties can be evaluated in their cause-and-effect relationships within a real automotive after sales supply chain. Therefore the focus is situated on the supplier side (Inbound) and all the characteristics of the supply chain are for automotive spare parts delivery.

1.2.3 Research Questions

In order to avoid service level losses on focal firm level in the central warehouse due to missing parts it is necessary to understand the risk structure on the supplier side. When we take a closer look, we use the risk network to find risk clusters and can work promptly and preventively on measures to reduce delivery variation on the supplier's side. Based on empirical analysis, a comprehensive picture of vulnerability is provided, as well as the risks in an after sales inbound supply chain. That includes also the differentiated view on the characteristics of supply chain risks for 1st and 2nd tier suppliers. The effectiveness of the developed model has to be demonstrated on a collection of real datasets based on the essential after sales risk drivers. The top-down and bottom-up risk analysis enable a derivation of measures for risk mitigation that reduce delivery delays, and, in turn, optimize the safety stock level without deteriorating the outbound delivery performance.

Therefore the main research questions can be derived:

1. **What are the essential risks within an After Sales inbound Supply Chain?**

2. **How could risks be operationally managed to minimize lead time differences in the focal Firm (Warehouse)?**

It must be the main focus to understand the interactions and uncertainties of the involved After Sales SC suppliers. This research would also identify:

- The after sales spare parts (product group) with high variation in delivery time
- The understanding of the causal interactions within a reference automotive after sales supply chain
- The risk inter-dependencies along the multiple-tier supply chain measured in conditional probabilities.

1.3 Research Contribution

The work is undertaken utilizing the established research process of applied research (Ulrich 1984). The approach involves a dialogue between the researcher and the company involved in the research. The proposed research would focus on assessing uncertainties, or in other words, risks in their causal and dynamic structure allowing for a well-grounded definition of risk mitigation strategies for proactive risk reduction. For this purpose the Bayesian Network Approach will be applied, in combination, within the supply chain risk management framework, to a practical case study. That means the focus is situated on the supplier side (inbound) and all the characteristics of the supply chain are for spare parts delivery.

The main idea of the proposed method takes up the fact that lead time differences on the supplier's side is responsible for buffer stocks in the central warehouse (focal firm) and also higher inventories in the supply chain levels. In order to avoid service level losses in the central warehouse because of missing parts it is necessary to understand the risk structure on the supplier side to manage the safety stock planning in a selective manner.

1.4 Scope of the Dissertation

When we take a closer look we use the risk network to find risk clusters and can work promptly and preventive on measures to mitigate unnecessary stock. The designed after sales supply chain risk model, termed as a Bayesian network, incorporates both the advantages of dynamic risk mitigation to reduce the delivery time variation and selective reduction of warehouse buffers in terms of a continuous service level. Based on an empirical analysis a comprehensive picture of vulnerability as well as the risks in an after sales inbound supply chain of a car manufacturer will be provided.

That includes also the differentiated view of the characteristics of the supply chain risks of the 1st and 2nd tier suppliers. The effectiveness of the developed model has been demonstrated on real datasets based on the empirical analysis and expert knowledge. Simulation results show that the Bayesian theorem applied in a multi stage supply chain risk network achieves excellent results in terms of risk clustering and risk simulation for reducing delivery time variations for more exact buffer stock planning. The work shows that the versatility of the Bayes idea which is illustrated through its application in diverse fields is also useable for after sales supply risk management.

This approach assesses uncertainties or in other words risks in their causal and dynamic structure, and allows a well-grounded definition of risk mitigation strategies for proactive risk reduction. To ensure this, the work is structured into six chapters.

After the introduction and description of the problem formulation in chapter one the theoretical foundation to the subject Supply Chain Management, Risk Management and Supply Chain Risk Management are introduced in Chapter two, it gives also an overview about the specific characteristics of the After Sales and spare parts supply. It provides the reader with theoretical background information on the after sales-specific strategies and challenges in the automotive supply chain management, on how supply chains can be disrupted by risks and how the supply chain risk management is effective for proactive reduction on these risks. Chapter three deals with the present state of the research in SCRM, detects existing gaps and on this basis specifies requirements for further research. In accordance with these requirements, Chapter four investigates in which way and why the risk causality and the Bayesian network are effective for operational risk assessment. Chapter five applies the supply chain risk management framework in a practical case study to a specific operating environment.

Therefore the case study is basically grounded in four essential modules to handle risks in the inbound supply chain in the automotive after sales.

- Module 1: Data analysis
- Module 2: Empirical risk identification
- Module 3: Causal modeling
- Module 4: AS Supply Chain Risk Model

The model's applicability is examined thought simulation and validation based on risk sensitivity and risk scenario analysis.

The research contribution review, the findings and limitations are discussed in Chapter six.

2 LITERATURE REVIEW

First, it is necessary for the ongoing research to analyze the fundamentals of the topic for this work, the combination of the key aspects of SCRM and AS. Hence, the specific features of the After Sales should be firstly explained and then afterwards the definition of SCM and what is a modern SC Network is established. After that the basics in Risk Management will be explained followed by the key elements of the SCRM.

2.1 After Sales

This section will define the term, as well as the role of, After Sales, followed by demonstrating after sales strategies and specific challenges.

For example, a car manufacturer can deliver customer value at the stage of the product design, the vehicle production or the after sales (Cohen, Agrawal et al. 2006). Therefore AS is a feasible business in the automotive value chain. In the automotive industry the aftermarket accounts for almost 30 percent of the revenue, whereas the sale of original parts accounts for 50 to 60 percent of the car maker's total profit (Deloitte 2007). It is the longest-lasting source of revenue that requires the smallest investment (Cohen, Agrawal et al. 2006). Long-term customer contact guarantees great knowledge about their expectations, that then provides further added-value to both the production and the sale of vehicles (Saccani, Johansson et al. 2007). For car makers the AS is the only stable value source and the major business in times of economic stagnation (Wagner, Jönke et al. 2012). For these reasons car manufacturers are advised to pay more attention to their AS management. The AS activities are the company's commitment to respond to the customer's need for support after the vehicle purchase (Cohen, Agrawal et al. 2006). The comprehensive AS business encompasses technical assistance, spare parts distribution and customer care (Saccani, Johansson et al. 2007), where the sale of spare parts is the most beneficial function (Schröter 2006). To be more specific, spare parts logistics is "the market-orientated planning, design, realization, and control of the spare parts supply and distribution, along with associated information flows within a company and between companies and hence in supply chain networks (Wagner, Jönke et al. 2012). The service level is the most important indicator with which to measure the AS supplies performance. It is "defined in terms of either item fill rates or end product availability" in the spares warehouse (Kim, Cohen et al. 2007). As a fact the AS demand is volatile and needs to be predicted based on forecast data, the demand planning alone would not be sufficient to secure the product availability.

Thus, an appropriate inventory strategy is required. The inventory management of spare parts aims to fulfill cost optimal stocking targets for each product that has a pre-determined service level (Kim, Cohen et al. 2007). This target is characterized by a trade-off between the cost optimum and service level (Klug 2010), the higher the service level, the more inventories are stocked. For example, a service level of 98 percent aims to fulfill 98 percent of all demand requirements without any discrepancy in time or quantity. To be able to cope with discrepancies high stock levels are required. Service level and inventory level optimization depends to a certain degree on the warehouse strategy. Pooling spare parts in a centralized way is effective towards total part availability and economies of scale. Consequently, it is feasible to distribute spare parts via a centralized warehouse structure (Cohen, Agrawal et al. 2006, Wagner, Jönke et al. 2012). The central warehouse keeps all spare parts in stock and distributes them in accordance with the demand requirements, individually to regional warehouses (Wholesale) that, in turn, allocate required quantities to dealerships (Vahrenkamp 2005, Saccani, Johansson et al. 2007).

2.1.1 Spare Parts

A spare part is an original part that is either produced by the original equipment manufacturer or its supplier that possesses the customer tool for manufacturing. The main function of the spare part is to replace the firstly equipped part that is damaged or has a high level of wear during its life cycle (Schröter 2006). Consistent with the spare part definition, the demand for spare parts goes hand in hand with the defaulted components of the vehicle in the market. However, the demand for spare parts is not congruent to the number of vehicles in the worldwide vehicle pool. Therefore it is important to align spares supply with the specific life cycle phase and requirements of customers (Wagner, Jönke et al. 2012). The spares supply is divided into three phases (Klug 2010)

1. From the start of production (SOP) until the end of production (EOP)
2. Between the EOP and the end of delivery obligation (EDO)
3. From the EDO until the end of service (EOS)

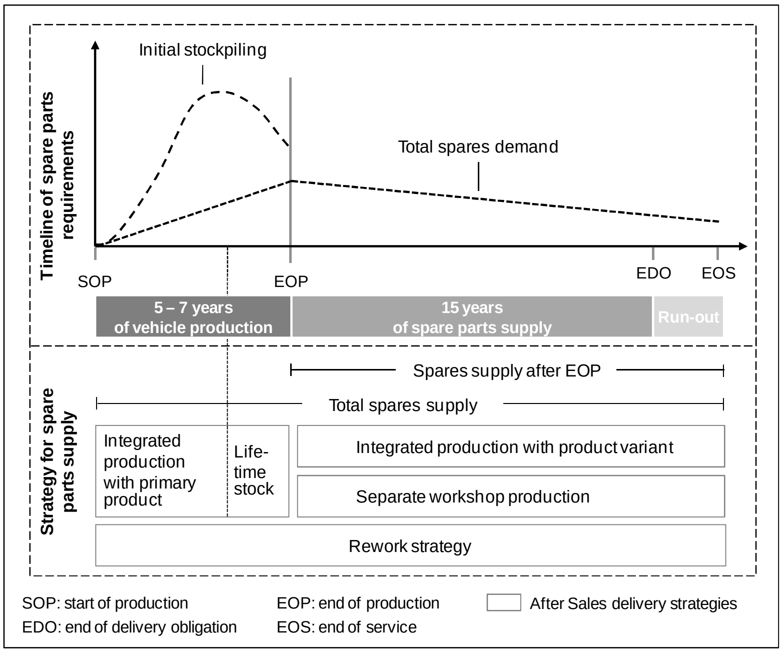


Figure 1 Life cycle of spares requirements and spares supply strategies (Wagner, Jönke et al. 2012) and (Klug 2010)

In the first phase regular vehicle production takes place, where the initial stockpiling is built up. Since no historical data for demand forecasting is available, this is the base for initial stockpiling, the requirements of spares are planned based on the size of the vehicle pool in the market and on historical data taken from former vehicle variants. In general, the level of spares stored is higher than the demand during the initial phase.

The demand for spares gradually increases from the SOP on and decreases slowly at the point of the EOP during the second and third phases. The total spares supply ranges between 15 and 20 years including five to seven years of regular series production with spares availability (Wagner, Jönke et al. 2012). Therefore car manufacturers rely on long-term relationships with their suppliers. Vehicle manufacturers depend on their suppliers when it comes to the spares supply obligation.

2.1.2 Strategies

To secure a long partnership with the suppliers it is necessary for car manufactures to ensure the supply of spare parts by applying one of the following strategies to the suppliers.

Integrated production:

The integrated production strategy is applied to produce spare parts for former car models in a way parallel to the regular production for new vehicle variants (Boone and Quisbrock 2009, Klug 2010). This strategy requires tool changes every time spare parts production is required and leads to high set-up time and costs. The advantage is the ability to bundle spare parts and schedule their deliveries in accordance with demand requirements, without the need of high stock levels, with low capital commitment and with steady responsiveness to sudden demand increases. However, there is high potential for serial parts and spare parts to compete against each other, especially in times of a supplier’s capacity peaks.

The production of spare parts seems less attractive than the series production mainly due to three reasons.

1. The ordered spare parts are comparably low in quantity and generate little benefit
2. The supply of spare parts has to fulfill AS-specific requirements, such as packing and labeling, with the requirements not being planned
3. Suppliers struggle with small quantity increases for serial fulfillment and therefore the pressure of line compensation payments increase

Life-time stocking:

When following the life-time stocking strategy, a large inventory level of spare parts is produced directly before the EOP in accordance with the estimated all-time requirement of the part concerned (Schröter 2006, Boone and Quisbrock 2009, Klug 2010). The major advantage is the benefit of the same cost structure as for serial production. However, life-time stocking leads to high stocks, high cost of capital tied, moderate probability of undersupply linked with long replenishment lead times and the threat of obsolescence especially in the case of short minimum durability.

Separate Spare Parts production:

This strategy implies an individual production of spare parts in a separate plant or hall specialized on the production aligned with the AS requirements (Wagner, Jönke et al. 2012). The benefits are inventory-related because no high stock levels are necessary that avoids capital being up. Moreover, there is no trade-off between the production of spare parts and regular production for a series of the automotive manufacturer. The main disadvantage of separate production is the additional investment in facilities, tooling.

Rework:

A new part that has a defect is called a used part and can be either scrapped or reworked (Vahrenkamp 2005). If the supplier is able to re-work the used part it can be sold as a spare part at a lower price than the original part (Klug 2010).

Since this strategy is not sufficient to guarantee the AS supply in the long run, it is applied in combination with another strategy. Therefore the three main strategies are compared in Table 1.

	Life-time stocking strategy	Integrated production strategy	Separate workshop production strategy
Stock	very high	low	no
Merchandising risk	high	low	no
Threat to delivery capability	longterm feasible	hovering	low
Effort for production planning	no	restructing	replanning
Effort for production steering	very low	disruptive	separate
Invest	no	additional Invest	high Invest
Production cost	low	mean	high

Table 1 Comparison of Spare Parts Delivery strategies (Schröter 2006)

When selecting the appropriate strategy not only resource-related elements need to be taken into account. AS professionals need to adapt the strategy to the parts-specific requirements. One example is an electronic part that has a short life cycle of a few months and therefore would be inappropriate for the life-time stocking strategy. Alternatively, in the case of a small metal part that has low value, low unit price and is slow-moving in its demand, it could be more profitable to put a life-time quantity on stock after the evaluation of production costs, set up costs and warehouse process costs against the overall storage costs.

2.1.3 Challenges

On account of these basic conditions the following challenges arise for the spare parts delivery.

- High part spectrum that accounts for the parallel supply of several product generations (Hagen 2003, Schröter 2006, Boone and Quisbrock 2009).
- Long obligation of delivery of the spare parts for 15 years after the EOP (Boone and Quisbrock 2009)
- Demand time and amount are difficult to forecast, in particular with slow movers (Boone and Quisbrock 2009)
- Low relevance of the spare parts in the commodity purchase departments and linked under prioritization of the quantity in production planning with temporary capacity bottlenecks as a result (Schröter 2006).
- Planning and communication after the end of production (EOP) for further support for a discontinued series and the changes linked with it along the chain of delivery (Schröter 2006).

In particular, with electrical components in the after sales service, these challenges increase based on specific conditions with these parts for example by.

- Quick technological changes of electrical parts often leading to the discontinuation of older construction elements in the discontinued series phase (Schröter 2006)
- Worldwide dispersion of the manufacturing of electrical parts (e.g., semiconductors), so that long routes of transport are necessary and are often affected by natural disasters (Hagen 2003)
- Rare minerals as well as certain plastics as central raw materials to the production of many electronic parts (ISE 2012)

The aforementioned conditions lead to the fact that additional circumstances must be considered which make the SC more complicated, thereby additional uncertainties and therefore additional SC risks, originate.

Based on the previous findings the main differences between the manufacturing SC and AS SC are illustrated in Table 2.

Comparison criteria	Manufacturing SC	After sales SC
Demand	Predictable	Unpredictable, volatile
Parts supply	Based on the production plan	Stochastic estimation of spares
Number of SKUs	Limited	20 times more
Product portfolio	Homogeneous	Heterogeneous
Inventory management	High inventory turn	Low inventory turn
Logistics strategy	Just in time /Just in sequence	Stockpiling
Reverse logistics	None	Return, repair, disposal
Performance metric	Fill rate	Product availability
External sourcing	Up to 70 percent	Almost 100 percent
Supply obligation	None	Spares supply for min. 10 years

Table 2 Comparison of series and after sales supply chains (Cohen, Agrawal et al. 2006)

2.2 Supply Chain Management

2.2.1 SC Definition

Because of the great importance of the term SC in practice, as well as in the research, numerous statements and definitions have already been developed for this term. In the following, three definitions are outlined for the term SC.

> **Mentzer et al. (2001):**
> ,,(…) a supply chain is (…) a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances and/or information from a source to a customer.''

Supply Chain Council (2006):

„The supply chain (..) encompasses every effort involved in producing and delivering a final product or service, from the supplier‘s supplier to the customer.‘‘

Rabelo et al. (2007):

„Supply chains are life cycle processes to support the physical, informational, financial, and knowledge aspects for moving products and services from suppliers to customers’’

These definitions show that with the determination of the concept SC several aspects must be included. The Supply Chain Council (Council 2006) looks, in their definition, primarily at the product traffic regarding several steps (tiers) of the supply chain, i.e. from the supplier’s supplier up to the customer. Rabelo et al. define the SC as a support process to the movement of products, services, funds and information during their whole life cycle. Mentzer et al., on the one hand, define the steps as "individuals" or "organizations" that implies the juridical independency of the SC partners, and, on the other hand, they stress the different directions of the flow of products, services, funds and information.

2.2.2 SC Network

A realistic SC is distinguished according to the flow of direction. That means downstream (Outbound) i.e. from own company (Focal firm) to the customer, (Sell Side) and upstream (Inbound), i.e. from the supplier (Buy Side) to the own company (Focal firm) (Harrison and Van Hoek 2008).

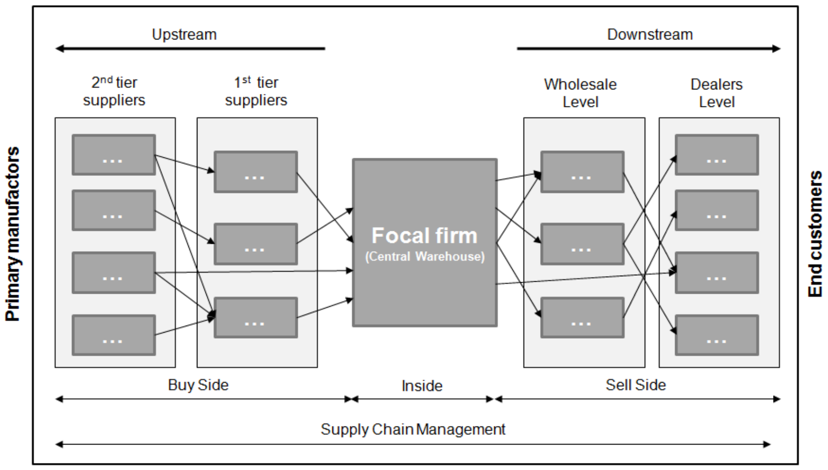


Figure 2 Supply Chain Network (Harrison and Van Hoek 2008)

In conclusion, a modern and realistic supply chain at the current time can be described as a network, where products, services, funds and information, during the whole life cycle and over several steps from legal independent companies, flows accordingly to her determined direction from raw materials to the customer, or vice versa (Wels 2008).

Operational SCM deals with the day-to-day business of SC-related planning, procurement of products and services, manufacturing-related logistics, distribution of finished products and reverse logistics. One objective, is the permanent improvement of the company's internal situation and also the sustained increase of the overall SC performance (Lambert, Cooper et al. 1998, Mentzer, DeWitt et al. 2001). But one of the most important objectives, in particular for the after sales service, can be denoted as the customer satisfaction (Heusler, Stolzle et al. 2006).

This means the SCM planning process has to make sure, for example, a high delivery on time with short delivery times and small stock volumes in the SC. But the other side is smaller stocks and therefore less security, making a chain more susceptible to unforeseen events that cause customer satisfaction to become endangered. That is why control and reduction of the uncertainties must be defined as another aim of the SCM (Davis 1993).

2.3 Risk Management

The concept Risk Management is described in general as the identification and analysis or assessment of the risks as well as their control (Kajüter 2007, Thun and Hoenig 2011). Franck define RM with reference to the definition of Hutchins & Gould (Hutchins 2004) as follows: RM ,,is essentially the process of responding to the existence of uncertainties (….) through controlling variability from an objective, target, specification or standard" (Franck 2007).

2.3.1 Risk Definition

Risk and uncertainty are not identical. Uncertainty is the origin of risk and can be described as a kind of black box where knowledge is rare (Yen and Zeng 2011). Risk arises from uncertainty and can be considered as the probability of the outcome of the uncertainty (Khan and Burnes 2007). Therefore risk is measurable, uncertainty is not (Norrman and Jansson 2004). The occurrence of a risk is called risk event. Risk has different impacts on different stakeholders (Khan and Burnes 2007).

Since there is no exact knowledge about risk events and their impact, the ability to manage risks is limited (Lockamy III and McCormack 2010). For this reason it is important to quantify the entire risk environment (Lockamy and McCormack 2009). Risk reflects the outcome damage and the probability of the outcome damage happening (Harland, Brenchley et al. 2003, Pai, Kallepalli et al. 2003, Norrman and Jansson 2004, Wu, Blackhurst et al. 2006). The loss and the probability of loss occurrence are two essential components, which are also defined by the ISO 2002 requirements (Lockamy III and McCormack 2010).

In this regard risk can be defined as the loss of the risk impact $\mathrm{I(Loss)}$ and the probability or likelihood of the loss to arise $\mathrm{P(Loss)}$ (Manuj and Mentzer 2008):

$$\mathrm{Risk} = \mathrm{P(Loss)} * \mathrm{I(Loss)} \tag{2.1}$$

Consequently, the total supply risk is:

$$\mathrm{Risk_n} = \sum_{i=1}^{n} \{((\mathrm{P_1(Loss_1)} * \mathrm{I_1(Loss_1)}), (\mathrm{P_2(Loss_2)} * \mathrm{I_2(Loss_2)}), \ldots, (\mathrm{P_n(Loss_n)} * \mathrm{I_n(Loss_n)}))\} \tag{2.2}$$

2.3.2 Risk Causality

SC risks "…are related to disturbances and interruptions of the flows within the products, information- and financial network (…) and may negatively affect the objective accomplishment of the individual company, respectively, the entire supply chain, in regards of end user advantage, costs, time or quality…."(Pfohl, Gallus et al. 2011). These disturbances and interruptions are incidents whose occurrences result in the disruption of the overall SC performance (Lockamy and McCormack 2009). Disruptions can arise from the supply side (inbound) and from the demand side (outbound) (Wagner and Neshat 2010). Disruptions from the demand side affect the supply side of the SC. A sudden increase in demand could produce long lead times due to lacking flexibility to respond to the demand increase at both the 2nd tier and 1st tier SC levels. Since one disruption triggers a set of other disruptive events in the SC, the SC risk environment is characterized by an intensive and complex causal structure (Pai, Kallepalli et al. 2003). According to the Oxford dictionary (2012) causality is the relationship of cause and effect. Under these circumstances the term risk needs to be redefined, integrating its causal relationship into the risk system (Yen and Zeng 2011).

One possible way is to regard SC risks in a multiple-tier SC dimension. The overall risk at the 1st tier supplier $\mathrm{Risk}_{\mathrm{tier1}}$ could be measured by its absolute risk $\mathrm{P}_{\mathrm{tier1}}(\mathrm{Loss}_{\mathrm{tier1}}) * \mathrm{I}_{\mathrm{tier1}}(\mathrm{Loss}_{\mathrm{tier1}})$ dependent on a second risk emerging from the 2nd tier problems $\mathrm{Risk}_{\mathrm{tier2}}$.

$$\mathrm{Risk}_{\mathrm{tier1}} = ((\mathrm{P}_{\mathrm{tier1}}(\mathrm{Loss}_{\mathrm{tier1}}) * \mathrm{I}_{\mathrm{tier1}}(\mathrm{Loss}_{\mathrm{tier1}}))|\mathrm{Risk}_{\mathrm{tier2}} \tag{2.3}$$

However, risks in the SC do not have to affect different SC partners to the same extent. SC risks are rarely symmetrical (Stecke and Kumar 2009). Unexpected delivery shortage at the 2nd tier supplier have, in almost all cases, a higher negative impact on the 1st tier supplier than on the Original Equipment Manufacturers because the OEM requires in general a safety stock for the final product of its 1st tier suppliers. This example also show that risks in the SC have direct, as well as indirect, effects on each other. In this example, the delivery bottleneck at the 2nd tier would indirectly affect the OEM if no safety stock was available at the 1st tier supplier. Due to lacking transparency of indirect effects SC managers should be cautious that measures to reduce one risk might, in turn, increase another (Khan and Burnes 2007).

2.3.3 SC Risks

SC risks exist inside and outside of the SC (Lockamy III and McCormack 2010, Zsidisin and Wagner 2010). Risks arising from the inside of the SC are internal risks. External risks originate outside of the SC (Thun and Hoenig 2011). SC risks are the subject of numerous pieces of scientific research. The literature review concludes that scholars categorize SC risk into internal and external groups. Appendix A represents an overview of risks that have been identified in the literature review. When studying external risks, scholars mainly focus on the effect of natural disasters, the competitive environment along with economic and political instability. Natural catastrophes are more likely to affect the 2nd tier suppliers due to their geographic location (Blos, Quaddus et al. 2009).

In general, there is a higher risk when sourcing from suppliers in more distant locations from the company (Zsidisin and Wagner 2010). There is no general agreement on how to classify internal risks in the SC. Most scientists study internal risks that can be classified into supply-side, demand-side and organizational risk. The structure of risks and risk impacts vary tremendously depending on the SC structure, the industry and the product. For this reason, in the field of SCM, it is a requirement to tailor research concepts individually (Jüttner, Peck et al. 2003, Wu, Blackhurst et al. 2006).

2.4 Supply Chain Risk Management

2.4.1 SCRM Definition

After the theoretical foundations and definitions for the SCM and the RM this sub chapter concerns itself with SCRM. The integration of RM in the SC is called Supply Chain Risk Management (Blos, Quaddus et al. 2009) and can be defined as follows,

> **(Jüttner, Peck et al. 2003):**
> ….,"the identification and management of risks for the supply chain, through a coordinated approach amongst supply chain members, to reduce supply chain vulnerability as a whole".

This statement makes clear that SCRM is a specific form of the risk management and SCRM seeks to manage the SC vulnerability and SC disruptions towards an agile or robust SC (Figure 3).

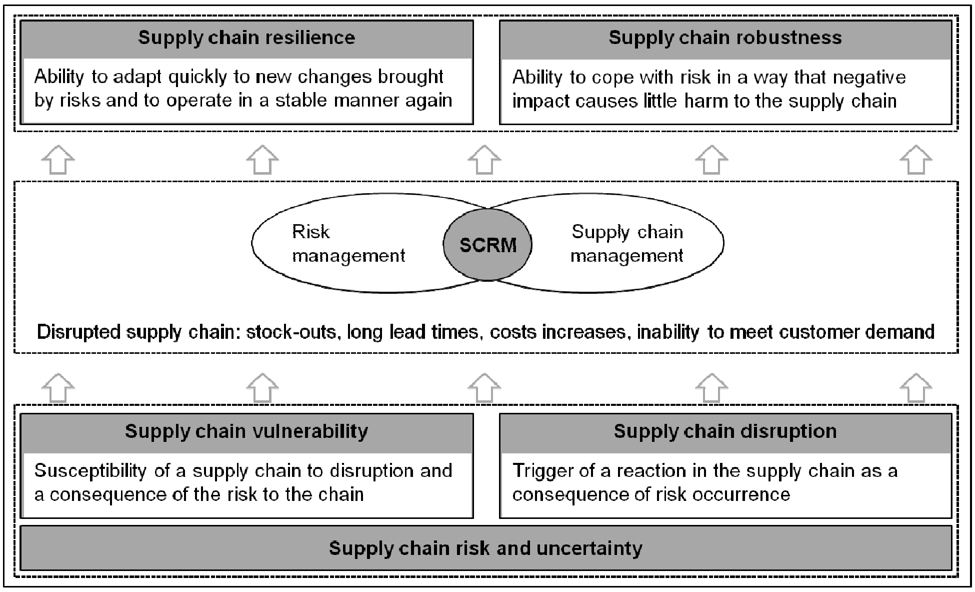


Figure 3 Supply Chain Risk Management

SCRM aims to understand where risks originate in order to predict disruptions, to identify potential losses in order to assign significance to losses, and to develop mitigating countermeasures in order to enable reactive and proactive management (Norrman and Jansson 2004, Zsidisin, Ellram et al. 2004, Trkman and McCormack 2009, Lockamy III and McCormack 2012).

- **Reactive:** SCRM refers to measures taken after the risk occurrence
- **Proactive:** SCRM aims to develop preventative measures before the risk occurrence and is approved to have greater risk reduction potential and benefit (Kleindorfer and Saad 2005, Lockamy III and McCormack 2012)

Thun and Hoenig recognize that reactive SCRM has a higher value when reducing external SC disruptions and proactive SCRM to reducing internal SC disruptions. Furthermore, they explored that proactive SCRM measures provide a higher value to the management than of increased flexibility, decreased stocks, reactivity, and cost reduction. To conclude, proactive and reactive measures both lead to SC resilience.

2.4.2 SCRM Concepts

After the definition of the SCRM, the question now arises how can a SCRM be realized? Therefore the arrangement of the RM processes into SC's should be entered in the following way. According to the definition in this work which the SC is seen as a network of independent "individuals" or organizations (Chapter 2.2.1), it requires for an effective SCRM, a cooperation among the SC partner along the SC (Norrman and Jansson 2004, Kersten 2006). Kajüter (Kajüter 2007) has developed basic approaches to the risk management in SC's to make a distinction regarding the cooperation degree and the level of risk management.

- **RM with orientation towards the SC:**

  This approach has the lowest communication intensity. Because this process is rather transaction oriented and no risk information exchanges are planned that mean asymmetries of information are often the result. Hence, the systematic identification, evaluation and management of the risks is done by the relevant companies (Kaufmann 2002, Kajüter 2007). According to Czaja „this approach is the presently used process in the German automobile industry regarding RM" (Czaja 2009).

- **Risk analyzing within the SC:**

  This approach is considerably more highly integrated because the communication intensity is higher and therefore the lack of information is lower than in RM with orientation towards the SC. With this the risks are analyzed and controlled in the respective SC steps together. The coordination of these common relationships is mostly done by the focal firm but the focus of the RM is controlled by the company itself. In comparison with the first concept this is basically more integrated because of the closer communication exchange.

- **Supply Chain Risk Management:**

  These are the most advanced and developed approaches with the deepest cooperation intensity. The common analysis and control as well as the communication of the risks along the SC take place in a structured frame. All the companies work very close together and sudden disturbances are no problem because of the advanced interlinking of the SC relevant companies. The information is exchanged very quickly. Regarding this comprehensive cooperation this might be the most efficient approach for the management of SC risks.

To run the SCRM approach a trustful cooperation is needed between all the value added partners within the SC. It seems to be very important, that a firm's established SC relations are in the form of those as they in general in the German automobile industry are. However, the other side of the challenging business of automobile manufacturing is, that the quality of the customer – supplier relationships are exceptionally heterogeneous which means that trustful conditions are rare (Czaja 2009). It may be expected that the implementation of a SCRM in the automobile practice still keeps waiting. „(…) companies implement organization-specific risk management, but there is little evidence of risk management in the supply chain level“ (Jüttner 2005).

2.4.3 SCRM Practical Status

Due to the increase of uncertainties within a supply network the enterprise overlapping and comprehensive risk management gains more magnitude in industries. The importance of SCRM in industrial practice progressively went up during recent years.

This appears in a survey from Jüttner (Jüttner 2005) involing 137 managers from different branches 44% of them forecast an increase in vulnerability during the next five years. The result out of Jüttners survey confirms a study from the Fraunhofer Institute (IPA) in 2010, where around 1/3 of the 52 companies expect a strong danger for their chain of delivery (Schatz 2010) and in an empirical analysis from Thun&Hoenig in 2011 asses 75 % of the logistic managers in the SC as vulnerable (Thun and Hoenig 2011). This trend is concerning and underlined by a survey with regard to the importance of SCRM. Kersten et al (Kersten 2006) asked 39 industrial enterprises and 32 logistics service providers with regard to the importance of the SCRM in companies. The result of the survey is shown in Figure 4 and there is a clearly large increase in the importance of SCRM in the years 2000 to 2010 in both the industrial companies as well as logistic services.

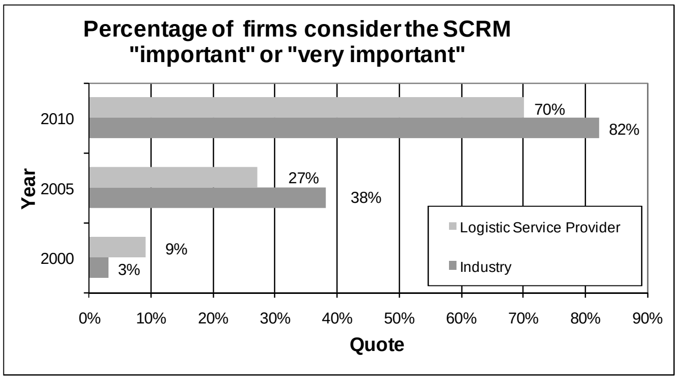


Figure 4 SCRM in Industry and Logistic Services (Kersten 2006)

In spite of these survey results a clear need exists for the implementing of SCRM instruments and strategies in the industrial practice because „(…) the concept of SCRM is still in its infancy, and understanding of SCRM is patchy, both in terms of its key issues and its implementation“ (Jüttner 2005). This means attention is in general mostly dedicated to risk mitigation and countermeasure definitions, whereas the operationalization of SCRM is still in early development stages. One possible cause for the detected discrepancy could be the complexity or almost infinite structural adjustments within the SC concerning enterprise overlapping risk management (Kajüter 2007).

Kajüter gives a short overview about what the most important needs for practical implementation could be in his work in 2003 and 2007 (Kajüter 2003, Kajüter 2007).

- Enlarged action frame over the enterprise and for the whole SC and SC partners (holistic perception/view)
- No missing and different states of information, all SC Partners should have the same data and information (synchronization)
- Same risk readiness of enterprises within the same SC to gain an overall risk (cause-effect view)
- Willingness of the enterprises to adapt to special standards (standardization)
- Keeping things short and simple in global SC's despite the possibly of different national regulatory (practicability)

Further empirical data from the German automotive industry significantly supports the hypothesis that companies with a high degree of SCRM implementation have a higher SC performance (Thun and Hoenig 2011). But it shows also that the arrangement of an enterprise overlapping RM is extremely difficult due to high complexity. One reason is the lack of economic justification for the introduction of a SCRM because it is both difficult to quantify the benefits of SCRM (monetary) and on the other hand, no one is rewarded for solving problems that have not occurred until now (Thun and Hoenig 2011). Because „nobody gets credit for solving problems that did not happen“ (Rice and Caniato 2003).

Norman and Jansson (2004) investigated the impact of a lightning accident that led to a strong fire at the Ericsson U.S. plant. It cost the company 400 million USD, along with an additional 200 million USD insurance payment and three weeks to restart production. The impact became worst when the company was forced to withdraw its key consumer business due to the inability to sell and deliver the product. To protect SC’s from vulnerabilities it is essential to establish a SCRM in relation to an organization’s day-to-day operations. Ericsson has achieved this and runs a very mature SCRM System today.

2.4.4 SCRM Process

In their empirical study (Kern, Moser et al. 2012) prove the strength of traditional RM and it remains significant to the SCRM. Numerous researchers have applied the SCRM Process steps to their risk-related investigations (Pai, Kallepalli et al. 2003, Norrman and Jansson 2004, Kleindorfer and Saad 2005, Faisal, Banwet et al. 2006, Wu, Blackhurst et al. 2006, Manuj and Mentzer 2008, Kern, Moser et al. 2012, Lockamy III and McCormack 2012). The five steps of the SCRM Process from Manuj and Mentzer can be summarized of being composed of three essential steps illustrated in Figure 5.

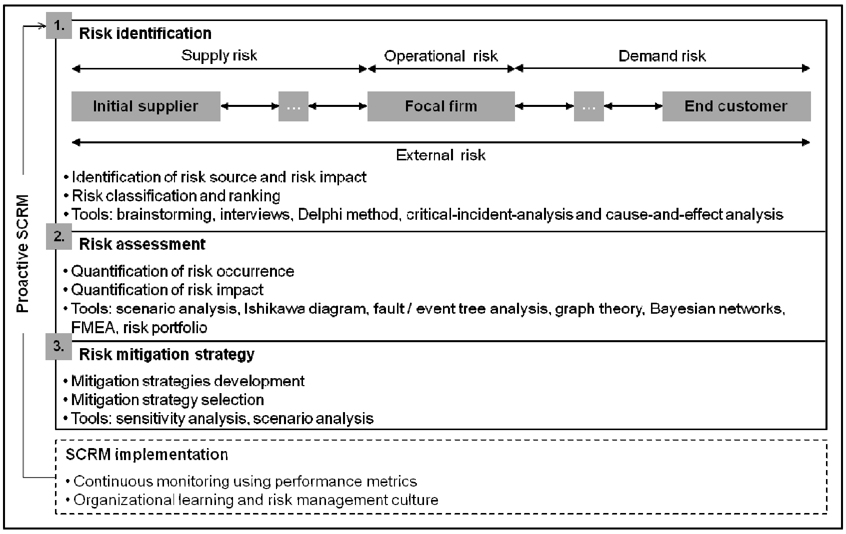


Figure 5 Supply Chain Risk Management Process (Manuj and Mentzer 2008)

1. Risk identification:

The main focus of risk identification is the identification of all relevant risks for the focal firm as well as their SC partners. Therefore it is necessary to understand the risk environment (IBM 2008), followed by the identification of their triggers and vulnerabilities (Kleindorfer and Saad 2005). The classification and ranking of risks enable a structured evaluation of the extent of risks, their sources and their impacts (Wu, Blackhurst et al. 2006, IBM 2008, Kern, Moser et al. 2012). Risks can be ranked according to their acceptance level (Tummala and Schoenherr 2011). Since risk identification is essential to the quality of the entire SCRM process, an accurate methodology is required to predict risks at the earliest stage and in the most precise way (Kern, Moser et al. 2012).

To support and facilitate precise risk identification, all SC processes, SC members and involved components and products should be visualized (Norrman and Jansson 2004). SCRM researchers recommend various methods such as brainstorming, interviews, Delphi method, critical-incident-analysis and cause-and-effect analysis (Ziegenbein and Schönsleben 2007, Tummala and Schoenherr 2011).

2. Risk assessment:

There are various different ways of quantifying risks in the SC. The risk occurrence is generally measured by assigning the probability of the risk of an event (Hallikas, Virolainen et al. 2002, Norrman and Jansson 2004, Kleindorfer and Saad 2005) and the risk impact can be measured by potential losses in terms of monetary value, by recovery time or by a mixture of both (Norrman and Jansson 2004, Manuj and Mentzer 2008). It is especially important to know the causes for certain risks and the most important drivers of SC vulnerability to consider the interrelations of the different risks. In this work we measure the overall risk over the whole SC in term of Lead time differences. That means all possibility events, uncertainties or SC vulnerabilities or in other words risks that will lead to LTD at the focal firm (Warehouse) in time units. To quantify risks and their impact the following methods are seen as appropriate tools, Fault-tree analysis, risk simulation, expert estimation, balanced score card or Bayesian networks and some of them will be further explained in the next section (Norrman and Jansson 2004, Ziegenbein and Schönsleben 2007, Buscher, Wels et al. 2008, Tummala and Schoenherr 2011). Why the especially Bayesian network is appropriate for causal risk assessment will be explained in Chapter four.

3. Risk mitigation:

With risk mitigation the collected and evaluated risks are used to develop proactive risk reduction strategies as well as reactive emergency strategies. Scenario analyses would imply serious and minor risk circumstances (Manuj and Mentzer 2008, Kern, Moser et al. 2012). Even though risk disruptions can be mitigated, it is not possible to completely eliminate them (Faisal, Banwet et al. 2006, Lockamy and McCormack 2009). The appropriate strategy is then selected in accordance with the extent of how the defined scenario is in line with the current SC risk environment.

Comparing strategies against each other and prioritizing mitigating practices support the strategy selection towards fast and effective actions (Pai, Kallepalli et al. 2003, Kern, Moser et al. 2012). Particular attention needs to be dedicated to trade-offs between mitigation strategies and SC efficiency (Sheffi 2001). Furthermore, it is not sufficient to consider risk losses alone when accounting for the total cost. It is required to additionally include the investment in risk mitigation to the total cost of risk. A rule of thumb states that it is required to assess the level of the risk against the cost of the risk mitigation (Chopra and Sodhi 2004). Thus, the expected costs caused by SC risks are the investment to mitigate them, their impact in terms of loss and their likelihood to occur (Kleindorfer and Saad 2005).

2.4.5 SCRM Methods

The actual level of implementation in practice indicates that the requirement concerning SCRM is very extensive and complex and the greatest challenge is the second SCRM Process step, the Risk assessment. In general, the SC Risks could be evaluated in different ways. In the following the methods often applied in practice are briefly introduced.

Scenario analyzes:

A widespread practical instrument for risk assessment is the scenario analysis. This very good method can detect different possible states of risks and give an detailed overview of the current risk situation. All identified factors of influence which would be expected for the changes will be evaluated, quantitatively or qualitatively. It is also possible to consider positive and negative events and take into account opportunities. The field of application of the scenario analyze is extensive. The results of the Scenario analysis enable a determination of the occurring cause effect chains. An essential advantage is the great flexibility of the method, because the respective scenarios can be fixed individually. This is why the method is very useful for the risk assessment. A disadvantage is the rapidly growing complexity on the one hand and on the other hand the ability for humans to think in terms of networks which is an essential condition for a successful outcome.

With a view of the after sales supply chain and the company involved in this research the scenario analysis plays a very important role, as within the framework the right balance between stock keeping units and stock costs on the one hand and service level and therefore customer satisfaction on the other side, must be upheld. It can occur that for short periods inventories must be built up for midterm service level hedging to avoid a delivery bottleneck within the whole logistic supply chain because of a temporary risk. But on the other hand, the method can falter and more eventualities need to be considered depending on the rise of financial expense to develop good scenarios.

Risk portfolio:

For this method there are many different names which can be synonymously used such as "Risk graph", "risk landscape", "Risk portfolio" or "Risk matrix". The author will use the name “Risk portfolio”. The Risk portfolios are very well suited to the measurement of risk positions or risk causes. It is a two-dimensional representation form which illustrates the expected value of the risk (likelihood) as well as the effect (scale of damage) of the risks (Hallikas, Virolainen et al. 2002, Ziegenbein and Schönsleben 2007). One major advantage is that the division of the axes can be configured very differently and makes the method, therefore, very adaptable. The values can be easy evaluated by questionnaires or audits with regard to both dimensions often by the assessment within the scope of a five point Likert scale. Risk portfolios enables us to provide in a two dimensional way the most interesting properties of risk to the reader in a way that is as simple as it is clear.

In similar cases the two dimensions are,

- Expected value or probability of occurrence
- Scale of damage

However, it is also clear that risk port folios are no assessment instruments and are basically only for the representation of already valued risks. Further disadvantages are that, for example, the dependence of the single risks is not illustrated and therefore any representation to draw inference in a temporary context is difficult, because the risks illustrate only the current state of information (Kajüter 2003). From this point of the view the risk portfolio is more suitable for reporting.

Risk simulation:

Fundamental for Risk simulation or Monte Carlo Simulation is the generation of a huge volume of random numbers. This can be very time consuming due to the time needed for calculations. Problems which can be solved by the MCS could be divided into two groups, into problems with deterministic and stochastic nature. There are physical processes which are really stochastic, and theoretical, it is possible to use these figures to generate random numbers. Nevertheless, in practice this does not tend to work and, as a rule, we use the figures from artificially created computer algorithms (Blobel and Lohrmann 1998). With the help of numerous simulation runs we tried to summarize the single risks into one risk so that in the end a likelihood distribution for the respective factor is produced. The Risk simulation method MCS is often used in the financial world and in the business of insurance. Possible objective criteria in this sphere are key performance figures which conceivably have effects on the summarized single risk monetary factors, for example, the Value at Risk (VaR) or the Cash Flow at Risk (CFaR). In the context of SCRM it must be considered that the risk simulation is made over the whole SC and some more major events must be disassembled into smaller single events or sub processes and a detailed assessment of the respective situation must be completed. Risk simulation can be a suitable possibility for analyzing risks when a situation or one sub process can be described in a model and the input dimensions about likelihood distributions can be well estimated. A further positive is that the practical decision process can be supported by risk simulation, but this should not serve as the only method of the decision making (Frey and Nießen 2001). Similar to the Bayesian Nets the risk simulation can be distinguished between static and dynamic simulation. However, in the past a static simulation with continuous and discrete variables could cause substantial issues within a Bayesian Network. Fenton and Neil (Fenton and Neil 2007) describe in their 2007 “Knowledge and Transfer Report” the point of the Bayesian Statistics as follows, ()…“It is because of this historical limitation that even Bayesian statisticians have shunned BNs for problems that involve continuous variables and complex stochastic models. Instead they have used tools like "WinBUGS" (Spiegelhalter, Thomas et al. 1996) to solve these problem. WinBUGS are based on an intensive sampling algorithm known as Markov Chain Monte Carlo (MCMS) method. ”...()…”Fortunately, there have been some recent breakthroughs in development of algorithms.…()…Building on the work of Koslov and Koller (Kozlov and Koller 1997), Neil et.al. (Neil, Tailor et al. 2007) have developed and implemented a dynamic discretization algorithm…()…Users of a software tool such as “AgenaRisk”, which implements this algorithm, can simply define continuous nodes by their range and distribution without any of the complexities associated with the MCS approach and they can achieve results of matching or greater accuracy for many classes of model, especially for models that include discrete variables.” (Fenton and Neil 2007).

Fault tree analysis:

FTA is an appropriate tool to show system and process connections in a logical manner. The complete model is fundamentally a tree-like structure. A so called „Top Event“, e.g. Lead time differences, are fixed in the beginning, followed by the gradual decomposition (branching out) of the possible causes that takes place. Afterwards the single branches of the tree are linked together with help of logical operators AND, OR and NOT. By the end of the FTA it is possible to evaluate probabilities of entrance from independent events, quantitatively, by using the formulas out of the probability theories (Ziegenbein and Schönsleben 2007). Referring to the After Sales SC the FTA should be indicated by how overlapping SC risks have influence on the stock planning process in the After Sales due to LTD as a top event of damage in the focal firm (Warehouse). All AS SC risks are logically linked in the FTA on the basis of the determined expected values weighted with the Top event in order to determine thereby the entire expected value of a LTD by logical interaction of all risks.

For the model three parameters are specified, which have a changing effect on the risks

FTA Parameter:

- Lifecycle status of the part [before/after EOP]
- Inventory range at the 1st tier supplier level [Days]
- Transport time [Days]

Three risks were also specified, which differ strongly for the selected suppliers in this example. These are:

Specified Supplier Risks:

- Critical parts or raw material scarceness
- Natural disasters
- Quality problem on supplier side

When analyzing these parameters and risks the model can be adapted to the respective suppliers or spare parts, in order to compute the supplier or part individual SC risks and total LTD which can be expected. If we establish the total risk in the form of LTD the FTA is also a supporting method to adapt the safety stock amount of the spare parts by adjustment of a few parameters individually. It seems possible for spare parts with a lower risk level to reduce the safety stock and safe money in form of lower capital commitment and on the other side to increase the safety level for parts with higher risk potential to bridge longer delivery times. Finally the FTA represents a first approach, in order to illustrate the interaction of several SC risks where the expected values of the SC risks are summed up according to the bottom up principle to the total risk.

Further methods in practical utilization:

There are additional techniques in use than those methods described in this work. First there is the Risk Balanced Score Card. The general concept is based on the works of Kaplan and Norton, since the early nineties the concept is in enhanced use by many companies. In the context of risk assessment the BSC can be viewed, however, rather as a supporting instrument. However, for the representation, distribution and interpretation of results it is quite applicable. Further techniques are, for example, risk scoring models. With these methods individual risks are combined into a total evaluation to be agreed upon or however the method Analytical Hierarchy Process (AHP), as a systematic procedure for the decision, supports to solve various types of problems in companies. Not to forgot the Failure Mode and Effect Analysis (FMEA), the Event Tree Analysis (ETA) and of course the Bayesian Network (BN), which will be described in more detail in Chapter four.

3 SCIENTIFIC FINDINGS IN SCRM

3.1 State of Research

As in industrial practice and also in scientific research the subject SCRM has become the focus of attention. A good indication is the number of publications on this topic. For this reason a Meta-analysis in the EBSCOhost database was performed (Figure 6). According to the method used by (Vanany, Zailani et al. 2009) the number of articles was established, with the search terms "SCRM", "Supply Chain Risk Management" and "Supply Chain Risk" from 2000 to 2011,annually.

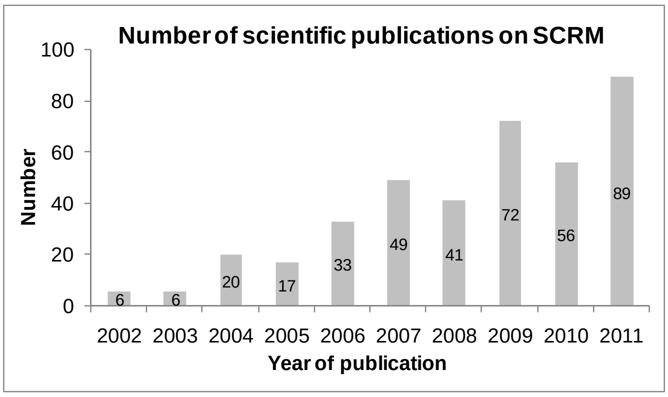


Figure 6 Number of scientific publications (EBSCOhost)

The analysis shows that from 2004 there is a strong increase in the number of published articles and scientific interest regarding this topic until 2011. A trigger for this strong interest in SC risk mitigation could have been the events in 2000 and 2001, which had important effects on the global supply chains (Vanany, Zailani et al. 2009). There was for example the major fire at a supplier for radio frequency chips for Ericsson in new Mexico in 2000, whereby this SC interruption led to Ericsson discounting their mobile communications division (Norrman and Jansson 2004) or due to the country-wide flight prohibition because of the terrorist attacks of 9/11 in the USA, 2001 (Sheffi 2001).

If we have a closer look into publications from recent years about SCRM (Appendix B) we find that three research directions for SCRM can be identified.

The first research area deals with the identification of drivers which increase the SC risks and make in relation to disturbances the supply chains more vulnerable. Peck developed in this context a multilevel model (Peck 2005). In this context the statement from Harland in the year 2003 is relevant that with increasing complexity of products the SC becomes more complex and therefore increases the SC vulnerability. Jüttner et.al established in 2005 by quantitative interviews that essentially six economic trends are responsible for an increase of the complexity in the SC. Additionally the increasing of the globalization and the associated increase of transport risks and cultural risks have their effects. A further issue can be variant variety, increasing outsourcing of manufacturing and assembly steps can also be a reason for a complex SC (Harland, Brenchley et al. 2003, Barry 2004, Bogataj and Bogataj 2007). If we take into account the results from the quantitative empirical analyses of Thun & Hoenig and Wagner & Nashat, economic trends such as SC Globalization, reduction of stocks, centralized distribution, decrease of the supplier basis, outsourcing, shorter product life cycles, rising variant variety can all be identified as risks and therefore as vulnerability drivers in modern SC Networks (Wagner and Bode 2007, Wagner and Neshat 2010, Thun and Hoenig 2011).

The second relevant area of research is concerned with the preparation of models and concepts for SCRM. In the literature numerous models represent which steps are necessary for a SCRM process (Norrman and Jansson 2004, Kleindorfer and Saad 2005, Ziegenbein and Schönsleben 2007, Manuj and Mentzer 2008). However, the three most important steps for a SCRM process are: risk identification, risk assessment and risk mitigation (cf. chapter 2.4.4). Most models stated in the literature are based on a conceptual approach (Manuj and Mentzer 2008, Tummala and Schoenherr 2011) or they are special case studies which describe SCRM processes already used in the practice (Norrman and Jansson 2004) or concepts which test previously developed concepts (Ritchie and Brindley 2007, Ziegenbein and Schönsleben 2007).

The third relevant area of research focuses on the analysis of SC risks (Appendix A). The aim in this research field is to apply the first two steps of the SCRM process (Risk identification and Risk assessment) ,by identifying the most relevant risks of the considered SC and evaluate their severity (Kersten 2006, Wagner and Bode 2007, Blos, Quaddus et al. 2009, Thun and Hoenig 2011, Vilko and Hallikas 2011). The risk analyses took place on the one hand via qualitative interviews, case studies or in the context of quantitative empirical surveys over standardized questionnaires (Kersten 2006, Thun and Hoenig 2011).

Studying the literature shows that the topic is becoming more scientifically important and is being discussed on qualitatively high level. There is a rapid rise of publications on the subject of SCRM and numerous reports and investigations exist. From Sodhi et al. the different research methodologies can be distinguished in conceptual, empirical qualitative or empirical quantitative (Sodhi, Son et al. 2012).

<table>
<tr><th colspan="3">SCRM Research Methods</th></tr>
<tr><td rowspan="2">conceptual</td><td colspan="2">empirical</td></tr>
<tr><td>qualitative</td><td>quantitative</td></tr>
</table>

Table 3 Overview SCRM research methods

In their two empirical studies Hendricks and Singhal ascertained the impact of SC risks on a company's performance. Both studies show that companies do not recover quickly from the negative effects of disruptions in the SC. On the contrary, the companies that experienced SC disruptions lost 40 percent of their stock return (Hendricks and Singhal 2005). Lockamy and McCormack proved in 2012 that external and operational risks have the most negative impact on a company's revenue (Lockamy III and McCormack 2012). Juettner and Maklan explored the relationship between SCRM, SC resilience and SC vulnerability. They proved that SCRM enhances the resilience of the SC by improving the chain's flexibility, visibility, velocity and collaboration capabilities. That implies, SC resilience has a positive effect on SC vulnerability (Jüttner and Maklan 2011). Today we know that SC risks do not arise statically and in isolation furthermore the SC risks arise dynamically in a modern delivery network. For this reason special techniques are necessary to manage these risks in global supply chains. Hallikas, Virolainen and Tuominen were in 2002 one of the first groups of researchers who tried to model SC risks in a causal relationship (Hallikas, Virolainen et al. 2002). Their causal network thereby is essentially based on the graph theory work of Lauritzen and Spiegelhalter in 1988 (Lauritzen and Spiegelhalter 1988). Rabelo et al. in 2007 took up the causal idea and developed a dynamic system, the very same as Yen and Zeng in 2011 as they also examined the SC risks in a causal SC network (Yen and Zeng 2011). The use of Bayesian Networks in the modeling of SC risks is seen as a very recent branch of research. Lockamy and McCormack have published their work in three essential papers since 2009. They began with the effects of operational supplier risks on revenue over supporting decision making for outsourcing activities in the year 2010, and followed up with the development of an individual supplier portfolio in 2012 (Lockamy and McCormack 2009, Lockamy III and McCormack 2010, Lockamy III and McCormack 2012). Another option to minimize risks in the SC can be established by excluding particular partners from the SC network as part of a proactive SCRM. To achieve SC resilience Zsidisin and Ellram (2003) differentiated between behavior-based management methods, including supplier management practices, e.g. supplier qualification and development of the buffer-oriented methods which imply operation-specific practices, such as inventory management and multiple sourcing.

However the buffer orientated strategies can lead to higher SC costs caused by higher inventories, obsolescence potential or missing economies of scale due to redundant supply sources. Nevertheless, since those practices can be implemented without the need for extensive resources and since their positive impact is short-term, buffer-oriented methods are appropriate approaches towards reactive SCRM (Zsidisin and Ellram 2003). On the other side, behavior-based practices are appropriate for proactive SCRM. In order to decrease delays, Chopra and Sodhi suggested in 2004 to add inventory and capacity to increase SC responsiveness (Chopra and Sodhi 2004). The examinations of IBM provides evidence that the profit loss caused by supply disruptions decreases the higher the safety stock level is kept (IBM 2008). Kim, Cohen and Netessine studied in 2007 the different contract types between the purchasing and supplying organization in the AS. In particular the performance-based contracting was assessed to be effective against moral hazard in terms of product availability and total cost. When implementing the risk mitigation strategy, it is not sufficient to focus on the strategy definition alone. The empirical study conducted by Blos et al. in 2009 shows that SCRM practices need to include strong focus on better SC communication, continuity training programs and from an organizational point of view the creation of a chief risk officer (Blos, Quaddus et al. 2009).

3.2 Gaps in Research

The current state of research shows that it is important to take the risks involved within the Supply chain environment seriously and to develop suitable models for their control in the field of the SCM. An implementable model is the key to agile SCs and effective SC performance. However up to now research efforts are mostly dedicated to risk mitigation and countermeasure definitions, whereas the operationalization of SCRM is still in the early development stages. Only if a risk orientated SC model is implemented in the operations and is continuously improved during the day-to-day business, can measures make a mid or long term effect on risk reduction and risk avoidance. The need for an implementable model in the SCRM area is ever increasing. Companies need practical approaches tailored to the requirements of individual industries and more advanced instruments to identify and assess risk in the entire SC network (Jüttner, Peck et al. 2003, Tang 2006, Wu, Blackhurst et al. 2006, Khan and Burnes 2007). Specific challenges led to broad research on spare parts markets, spare parts characteristics, spare parts supply strategies, warranty, forecasting methods and inventory options (Wagner, Jönke et al. 2012). However, investigations into specific AS SCRM models are scarce. The literature review reveals that there are no frameworks or models that deal with the RM concept in After Sales inbound SC. Despite this there are risks in the AS, they are focused on the contractual relation between the purchasing and supplying firm and they are not affected by the complete delivery structure from the viewpoint of risk theory (Kim, Cohen et al. 2007).

The methodology of Bayesian Networks has been applied to various fields of study, e.g. insurance, financing, statistics, computer science, cognitive science and philosophy (Cowell, Verrall et al. 2007, Darwiche 2010). However, the application of BNs to the overall evaluation of the SC network in terms of RM has been insufficiently examined and is completely missing in the After Sales inbound SC. Therefore, it needs to be further developed to gain deeper insights into the complexity of the AS SC. If the current state of research on SCRM is projected on the After Sales a substantial need for action in all fields of the SCRM process becomes clear. Therefore this work will focus on risks in the inbound SC of the AS. Concretely, the term inbound supply risk means "the potential occurrence of an incident associated with inbound supply from (…) the supply market, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety" (Zsidisin, Ellram et al. 2004). Nevertheless Chen et al. showed that the magnitude of the bullwhip effect are mainly determined by the structure of demand (Chen, Ryan et al. 2000). The outbound risks are less threatening according to almost 80 percent of the purchasing managers in the automotive industry (Blos, Quaddus et al. 2009). It must be a result of today's modern planning systems based on logistical inventory analysis, such as SAP APO and Global Inventory Management Systems which are used as inventory system, to prevent the classic Bullwip effect (Lutz 2002). The today's challenge is to balance the buffer stocks in the warehouse depending on the multiple uncertainties in the after sales inbound SC in a causal context. The cause-and-effect view of risks is effective for proactive and reactive SCRM (Hallikas, Virolainen et al. 2002). Pearl defines requirements which the theoretical approach of causality needs to meet in order to satisfy a scientific approach (Pearl 2009). Consequently, the operationalization of the SCRM requires a qualitative and a quantitative risk analysis (Khan and Burnes 2007). The quantitative assessment and evaluation of causal risks and risk effects will be performed by the application of the graph theory and conditional probability that are integrated in the Bayesian Network.

In summary, the following scientific gaps have been identified:

- No attention to SCRM related to the AS inbound SC network
- The specific AS inbound SC risks are unknown
- Lack of investigation into sustainable SCRM operationalization
- Lack of modeling methodology for risk causality in the After Sales inbound SC
- No application of Bayesian Network within a AS Supply Chain

4 METHODOLOGY

4.1 Bayesian Networks

Bayesian Networks are graphic models which show probabilistic interrelations. In recent decades, Bayesian networks have become increasingly important for practical implementations due to the fundamental works of UCLA Professor Judea Pearl. In addition to his seminal works the computer software to represent very complex problems have improved and today's computers do not have any issues with calculating and representing multi-dimensional problems (Conrady and Jouffe 2011). Basically, Bayesian networks are considered as normative expert systems and they are based on the probability theory (Jensen and Nielsen 2007). These normative expert systems for modeling conditional probabilities concentrate on the uncertainties in problematic fields. In contrast to the rule-based expert systems, normative expert systems do not replace experts they support them only in finding the best decision and reasoning for the particular problem. One of the key features is the ability to model and reason uncertainty in complex problems (Fenton and Neil 2007).

4.1.1 Applications

Today the applications of Bayesian networks are many and varied. Mainly, however, BNs are used in medicine and also, since Basel II (risk protection in the lending business), in the financial world. A few examples are listed in different areas.

- **Medicine:**
  - Pathfinder: Covers approximately 60 lymph node diseases and 100 symptoms and test results
  - MIT-Hearth Disease Program: Therapy of cardiovascular diseases
  - Munin: Used for diagnosis of neuromuscular diseases
- **Economics:**
  - Help Functions, e.g. Microsoft or Hewlett-Packard
  - SPAM filtering
  - Bayes Credit: Risk protection tool. Helps Banks to meet the Basel II requirements
- **Biology:**
  - Prediction of Deoxyribonucleic acid (DNA) structures

- **Meteorology:**
    - Weather forecasting
- **Computer science:**
    - Knowledge representation, fault diagnosis, pattern recognition, heuristic search
- **R&D:**
    - TRACS System: Analyzing systems regarding components, development and manufacturing processes in vehicle design and develop.

The aforementioned examples are of course, incomplete. Numerous other applications of Bayesian Networks can be found e.g. at the Agena, Hugin or Association for Uncertainty in Artificial Intelligence (AUAI) websites. The benefit of the Bayesian approach, particularly when it comes to the calculation of risk probabilities, is its ability to provide a natural way to compute conditional probabilities (Fenton and Neil 2012).

4.1.2 Attributes

In a large number of existing applications, there are essential attributes for the selection of Bayesian networks in risk assessment with complex structures and uncertain knowledge. A Bayesian network can be easily extended with elements of decision theory. This enables, in decision making processes, the established maximum benefit. The list of positive features is extensive. Fenton and Neil have listed some of them in his book “Risk assessment and Decision analysis with Bayesian Networks”.

> **Modeling:** “…*It is important to understand that the key benefit of causal modeling is in stark contrast to classical statistics whereby prediction models are normally developed by purely data-driven approaches.*….“(Fenton and Neil 2012)
>
> **Reasoning:** “…*A BN will update the probability distributions for every unknown variable whenever an observation is entered into any node. So entering an observation in an “effect” node will result in back propagation, i.e. revised probability distributions for the “cause” nodes and vice versa. Such backward reasoning of uncertainty is not possible in other approaches*….”(Fenton and Neil 2012)
>
> **Parameter:** “…*A BN will require fewer probability values and parameters than a full joint probability model. This modularity and compactness means that elicitation of probabilities is easier and explaining model results is made simpler*…”(Fenton and Neil 2012)

Input: "…*There is no need to enter observations about all the "inputs", as is expected in most traditional modeling techniques. The model produces revised probability distributions for all the unknown variables when any new observations (as few or as many as you have) are entered. If no observation is entered then the model simply assumes the prior distribution*…."(Fenton and Neil 2012)

Combination: "…*A BN is "agnostic" about the type of data in any variable and about the way the probability tables are defined*…."(Fenton and Neil 2012)

4.1.3 Structure

Bayesian networks are graphical models and have their origin in statistical modeling. Developed by Pearl in 1988 Bayesian Networks are directed acyclic graphs (DAG) which represent a problem field (Domain) with uncertainties. Probability theory forms the basis for the processing of incomplete or uncertain information. This may also the reason that the probability theory is regarded as the necessary "glue" for modeling and ensures consistent processing of information in the different models (Jordan, Ghahramani et al. 1998).

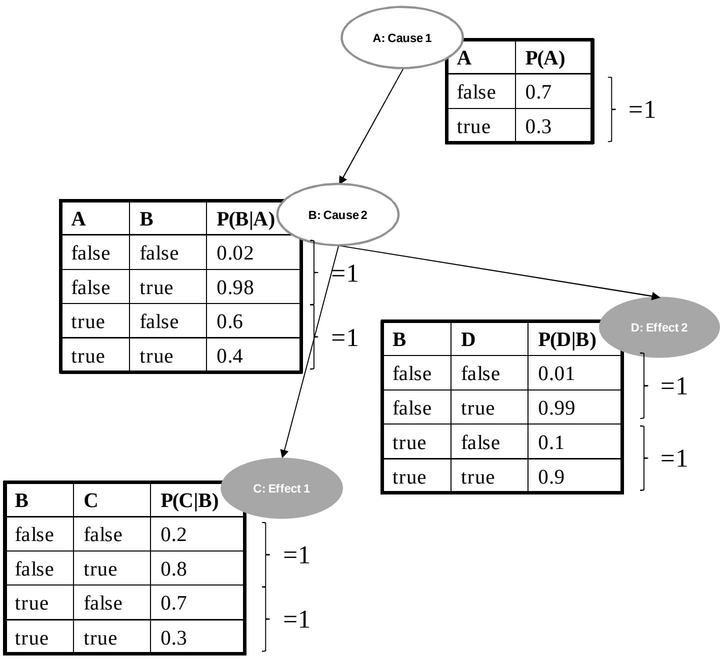


Figure 7 Bayesian Network structure (Fenton and Neil 2012)

The nodes in the BN are the random variables, they represent events or causes and effects and are connected with directed edges, cp. Figure 10. The connections represent statistical or causal dependencies among the variables and show the way of cause and effect graphically. If there is a directed edge between two nodes, the predecessor is called the parent node and the successor node is called a child node. In Figure 7 for example A is a parent node because there is an arrow from node A to node B, so we say A is a parent of B. Informally, an arrow from node X to node Y means X has a direct influence on Y. Root nodes e.g. node A in Figure 7, are associated with a non-conditional or prior probability e.g. P(A). Each node X_i has a conditional probability distribution P(X_i | Parents(X_i)) that quantifies the effect of the parents on the node and the respective parameters are the probabilities in the Node probability tables (NPTs). All parameters must be mutually exclusive and exhaustive and the sum of the probabilities in each NPT must be one. The NPT reflect the strength of the dependencies between the nodes. They can be filled with data (observations, experiments) and with expert knowledge. Further it is possible to map normally distributed continuous density functions or arbitrarily distributed discrete probability functions.

Definition of a Bayesian Network by (Fenton and Neil 2012)

"A Bayesian Network (BN) is an explicit description of the direct dependencies between a set of variables. This description is in the form of a directed graph and a set of node probabilities tables (NPTs):

Directed graph: *The directed graph (also called the topology or structure of the BN) consists of a set of nodes and arcs. The nodes correspond to the variables and the arcs link directly dependent variables. An arc from A to B encodes an assumption that there is a direct causal or influential dependence of A on B; the node A is then said to be a parent of B. We also insist that there are no cycles in the graph (so, for example, if we have an arc from A to B and from B to C then we cannot have an arc from C to A). This avoids circular reasoning.*
NPTs: *Each node A has an associated probability table, called the Node Probability Table (NPT) of A. This is the probability distribution of A given the set of parents of A. For a node A without parents (also called a root node) the NPT of A is simply the probability distribution of A."*

4.2 Calculation

As mentioned in the previous section, the probability theory is the basis for the Bayesian theorem and therefore Bayesian networks. Often two or more events must be linked in order to determine the overall probability. Depending on the type of connection the calculation rules are different in probability and dependence of the different events. The other point is that in probability calculations, there are two different views of the events, the frequentist and the subjective view. A frequentist view draws inferences about data given an unknown parameter but gives little help in quantifying risks. On the other hand the subjectivist approach accepts different beliefs (experts) about uncertain parameters, given new evidence. It happens that a frequentist analysis of a data set often agrees in large part with a parallel analysis based on a subjectivist interpretation of probability (Lindley 1965, Fenton and Neil 2012). However, the probability calculation behind it is quite simple and the rules for both perspectives are the same. The problem in practice is how to select or combine the right rules and axioms when calculating with probabilities. For this reason, the main calculation rules of probability theory should be briefly introduced in the following sub-chapter. These following sub-chapter is based on Fenton & Neil and Montgomery & Runger (Montgomery and Runger 2010, Fenton and Neil 2012).

4.2.1 Probability Primer

Basically, it is important to understand what a random experiment is. It is a procedure which can be repeated any number of times with at least two possible outcomes that we are unable to determine in advance. Common examples are the drawing of lottery numbers or the throwing of a die or a coin. Each possible outcome of a random experiment is called an event. The possible outcomes of a random experiment, which are mutually exclusive and cannot be further divided, are called elementary events or results. Let us denote the outcomes as ω_1, ω_2, ... ω_n (small omega) analogous to the characteristic values of x_1, x_2, ... x_m in the descriptive statistics. The set of all elementary events is called an event space or outcome space, and is defined as $\Omega = \{\omega_1, \omega_2, ... \omega_n\}$. Sometimes we are interested in events that are composed of several elementary events. Consider the event; throwing less than 3 dots when rolling a die. We expect the elementary events "1" and "2" together. This is also known as a composed event and we write formally.

$$A = \omega_1 \cup \omega_2 \tag{1.0}$$

If the event is composed of several elementary events, the following notation is also used:

$$A = \bigcup_{i=1}^{m} \omega_i \tag{1.1}$$

In the following we call composed events only events and we denote them with large letters (mostly A and B), respectively.

Today's probability theories are based on axioms which go back to Kolmogoroff (Kolmogoroff 1933). The axioms by Kolmogoroff give a mathematical foundation for the probability theory. However, the axioms do not make any statements about how the probabilities are to be determined in practice but the probability theory is fundamental for Bayesian Networks.

Imagine an event space and a subset of events. Then:

- The impossible event (∅) is included in the set of events
- The area of the event space (Ω) is the set of all possible outcomes
- For any two events there are also the union (∪) and the intersection (∩) of both events in the set of events included
- For each event there is also the complementary event in the set of events included

In this environment we can define a real valued function P which assigns a real number P(A) to each event This function is called the probability if it has the following properties:

1. P is normalized: $P(\Omega) = 1$
2. P is not negative: $P(A) \geq 0$
3. P is additive: $P(A \cup B) = P(A) + P(B)$, if: $A \cap B = \emptyset$

For the combination of the first and the second points it arises: $0 \leq P(A) \leq 1$

Often, and in particular in risk causality, two or more events must be linked together. To determine the resulting overall probability different calculation rules are available depending on the type of link and dependence of events. In the following the most important rules are introduced briefly; addition rule, the complementary event, conditional probability, independent events, the multiplication rule and the total probability.

Addition rule:

The probability of the union of two mutually exclusive events A and B follows directly from the definition of Kolmogoroff:

$$P(A \cup B) = P(A) + P(B) \; if \; A \cap B = \emptyset \tag{1.2}$$

The probability of rolling a „2“ or a „3“ with a regular dice can be calculated as 1/6+1/6=1/3. For the union of several mutually exclusive events it is therefore:

$$P\left(\bigcup_{i=1}^{n} A_i\right) = \sum_{i=1}^{n} P(A_i), \qquad if \; A_i \cap \; A_j = \emptyset \; for \; all \; i \; \neq j \tag{1.3}$$

In the case that the events are not mutually exclusive to each other, the above formulas do not apply. The problem with the application of the previous formulas is that the overlapping area A ∩ B is counted twice. Therefore we have to subtract one probability. As a result we obtain the following union formula for any two events:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \tag{1.4}$$

Complementary Event:

For each event A, there exists also the complementary event . $\bar{A}$ follows the definition:

$$A \cup \bar{A} = \Omega \tag{1.5}$$

A and $\bar{A}$ are mutually exclusive. And since P (Ω) is 1, it is

$$P(A) = 1 - P(\bar{A}) \tag{1.6}$$

This formula is useful when the probability of the complementary event is simpler to calculate than the event itself. In many cases, the probability of an event B depends on whether an event A previously occurred or not. We call it the conditional probability of an event. This conditional probability is very important in the context of Bayesian thinking.

Conditional Probability:

The conditional probability P(B|A), is the probability of the occurrence of the event B under condition that an event A has already occurred. The conditional probability is calculated as follows:

$$P(B|A) = \frac{P(A \cap B)}{P(A)}; \; P(A) > 0 \tag{1.7}$$

Example:

Consider a University that has a total of 5,000 students enrolled, 300 of them in the industrial engineering program. All in all there are 180 men among them and therefore only 60 in industrial engineering. We define the event A as “studied industrial engineering” and we define event B “is a man”. The probability that a randomly selected industrial engineering student is a male is given by:

$$P(B|A) = \frac{P(A \cap B)}{P(A)} = \frac{\frac{60}{5000}}{\frac{300}{5000}} = 0{,}2 \tag{1.8}$$

A similar problem can be constructed with a bag containing five blue balls and five red. For this example, suppose the probability of B (drawing a blue ball in the second trial?) depends on the occurrence of the event of what color the ball from the first trial had? Let’s take the same example again to explain another important observation in the probability theory, the probability of independent events.

Independent Events:

For example if we put the ball back into the bag after our first trial the probability of B isn’t conditionally dependent on A and if we know that the same number of red and blue balls are in the bag then the probability in this example is always 0.5 (a fifty/fifty chance).

Therefore, it is defined that two events A and B are (stochastic) independent if:

$$P(B|A) = P(B|\bar{A}) = P(B) \tag{1.9}$$

If this equation does not apply then the events are (stochastic) dependent. Together with the Formula 1.7 for the conditional probability it is possible to check by the definition of independence, if two events are independent or not.

Example:
The probability of the in time delivery of Component 1 is P(C1) = 0.9. Component 2 is delivered on time with P(C2) = 0.85. The probability that the two Components are supplied in time is 0.8. We can calculate this on the basis of this information.

$$P(C2|C1) = \frac{P(C1 \cap C2)}{P(C1)} = \frac{0,8}{0,9} = 0,89 \neq P(C2) = 0,85 \tag{2.0}$$

The two events (in time delivery of Components) are therefore dependent. For a practical test it is appropriate to do this in the probability Table (2x2 Table). We found for the example the following table.

	C_2	$\overline{C2}$	Σ
C_1	$P(C_1 \cap C_2) = 0.8$	$P(C1 \cap \overline{C2}) = 0.1$	$P(C_1) = 0.9$
$\overline{C1}$	$P(\overline{C1} \cap C_2) = 0.05$	$P(\overline{C1} \cap \overline{C2}) = 0.05$	$P(\overline{C1}) = 0.1$
Σ	$P(C_2) = 0.85$	$P(\overline{C2}) = 0.15$	**1.0**

Table 4 Probability Table

Let us check the independence, therefore the conditional probabilities of C2 under the conditions of C1 and $\overline{C1}$ must be compared:

$$P(C2|C1) = \frac{P(C1 \cap C2)}{P(C1)} = \frac{0,8}{0,9} = 0,89 \tag{2.1}$$

$$P(C2|\overline{C1}) = \frac{P(\overline{C1} \cap C2)}{P(\overline{C1})} = \frac{0,05}{0,1} = 0,50 \tag{2.2}$$

If the conditional probabilities are different, the two events are stochastically dependent. By transforming the definition of conditional probability we directly obtain the multiplication theorem for any events.

Multiplication Rule:

The probability of the event that both A and B occurs are given by:

$$P(A \cap B) = P(A) \cdot P(B|A) = P(B) \cdot P(A|B) \quad (2.3)$$

Imagine the following example. A bag contains five red balls and five blue. If we want to know what the probability of getting a red ball (A) in the first trial is and also in the second trial (B) we have to use Formula 2.3.

$$P(A \cap B) = P(A) \cdot P(B|A) = \frac{5}{10} \cdot \frac{4}{9} = \frac{20}{90} = \frac{2}{9} = 0{,}23 \quad (2.4)$$

If both events occur independently of each other that means we put the ball back into the bag after the first trial, the calculation can be simplified as P(B|A) = P(B), so that the definitions of multiplication of independent events are:

$$P(A \cap B) = P(A) \cdot P(B) \quad (2.5)$$

And the independent probability is therefore:

$$P(A \cap B) = P(A) \cdot P(B) = \frac{5}{10} \cdot \frac{5}{10} = \frac{25}{100} = \frac{1}{4} = 0{,}25 \quad (2.6)$$

Total Probability Rule:

Let´s assume the following problem. We will know the probability that a randomly selected student at any University is female P(A), and we also know the following.

- From 100 students in Nursing 60 are female
- From 150 students in Industrial Engineering 5 are female
- From 250 students in Business 15 are female

$$P(A) = \frac{60 + 5 + 15}{100 + 150 + 250} = \frac{80}{500} = 0{,}16 \tag{2.7}$$

To stay in the previously used nomenclature the problem can be described more generally as follows. Assume, we have n mutually exclusive events A_1, A_2,...,A_n. The union of these events corresponds to the event space Ω and thus has a probability of 1.

$$\bigcup_{i=1}^{n} A_i = \Omega; \quad with\, A_i \cap A_j = \emptyset\, for\, all\, i \neq j \tag{2.8}$$

If now B is an event in the event space Ω. Then

$$P(B) = P(A_1 \cap B) + P(A_2 \cap B) + P(A_3 \cap B) + \cdots + P(A_n \cap B) \tag{2.9}$$

$$P(A_i \cap B) = P(B|A_i) \cdot P(A) \tag{3.0}$$

This can be illustrated graphically as follows. The rectangle represents the sample space Ω which is covered without the overlapping of the events A_1 to A_4. The event B, which is shown here in grey overlaps with some or all of A_i. The total area of B, which corresponds to the probability, results from the union of the individual intersections $A_i \cap B$.

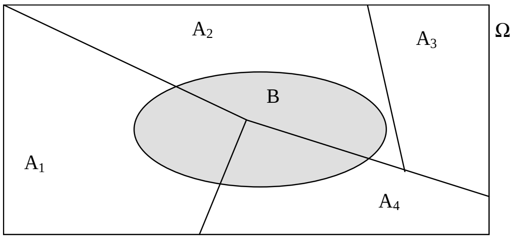


Figure 8 Event Partitioning (Montgomery & Runger)

Now, we are in position to derive the total probability from the previous statements. Consider all the events A_1, A_2,...,A_n and B from the sample space Ω. If,

$$\bigcup_{i=1}^{n} A_i = \Omega \qquad (3.1)$$

$$A_i \cap A_j = \emptyset \; for \; all \; i \neq j \qquad (3.2)$$

Then;

$$P(B) = \sum_{i=1}^{n} P\,(B|A_i) \cdot P(A_i) \qquad (3.3)$$

What does this mean for the previous problem if 20% study Nursing (NUR), 30% study industrial engineering (IE) and 50% study business (BU)? The proportion of the female students in Nursing is 60% in IE 3.33% and in Business 6% and now we are interested in the probability P(F) for whether a random selected student is female.

$$\begin{aligned} P(F) &= P(F \mid NUR) \cdot P(NUR) + P(F \mid IE) \cdot P(IE) + P(F \mid BU) \cdot P(BU) \\ &= 0{,}6 \cdot 0{,}2 + 0{,}03 \cdot 0{,}3 + 0{,}06 \cdot 0{,}5 \\ &= 0{,}12 + 0{,}01 + 0{,}03 \\ &= 0{,}16 \end{aligned} \qquad (3.4)$$

4.2.2 Bayes´ Theorem

Referent Thomas Bayes (1702-1761) was a British mathematicians who was the first scientist to understand probabilities that are conditional upon each other (Jaynesy 1986). The basic theorem can be easily derived by the multiplication of two independent events.

$$P(A) \cdot P(B|A) = P(B) \cdot P(A|B) \tag{3.5}$$

The Bayes Theorem:

$$P(A|B) = \frac{P(A) \cdot P(B|A)}{P(B)} \; and \; P(B) > 0 \tag{3.6}$$

Since this equation is the basis for Bayesian networks, Conrady (Conrady and Jouffe 2011) gives a compact definition of the individual elements of the Bayes Theorem:

- P(A) is the a-priori-probability, also unconditional probability and represents the prior belief, e.g. expert know how, about the hypothesis A.
- P(B|A) is the conditional probability and represents the likelihood of B in A
- P(B) is the total probability that acts as a normalizing constant and represents the evidence, the degree of belief.
- P(A|B) is the a-posteriori-probability and represents the conditional probability, the posterior belief about A depending on the information of B.

Many common fallacies in probabilistic reasoning arise from mistakenly assuming that P(A|B) is the same as P(B|A) (Fenton and Neil 2011). For that, a small example from the practitioner's perspective explains briefly the Bayesian phenomenon.

Example:

By using the supplier evaluation we found, that 40% of all fuel lines were delivered too late. Furthermore we know from the past analysis that 70% of all lead time differences of the same fuel lines were due to procurement problems of the polyamide (special material PA12 to meet customer requirements) at the second tier supplier. Now the OEM gets the information about general supply problems for PA12. The dispatcher analyzes the delivery schedule, and figure out that 50% of the ordered components use the PA12 according to the BOM.

The definition of the individual elements of the Bayes Theorem can be summarized as follows;

- P(A) represents the prior belief from the supplier evaluation that 40% of all fuel lines were delivered too late. P(A) = 0.4.
- P(B) represents the evidence from the BOM analysis that 50% of the ordered fuel lines are made of PA12. P(B) = 0.5
- P(B|A) represents the likelihood of B in A, that is the amount of fuel lines delivered too late. P(B|A) = 0.7

$$P(A|B) = \frac{P(A) \cdot P(B|A)}{P(B)} = \frac{0.4 \ \cdot 0.7}{0.5} = 0{,}56 \tag{3.7}$$

As a main result, we can see the belief of not in time delivery (previously 40% based on the supplier evaluation) increased to a posterior probability of 56%.

In this example we found by the dispatcher that 50% of the ordered products include the PA12 as a base material. This was, quasi, a happy circumstance. In many practical cases, it is not so easy. In these cases, however, if the evidence probability is not known, we are able to calculate the probability because the event A and its complement always represent a decomposition of the possible outcomes. This process is called marginalization.

$$P(A \mid B) = \frac{P(A) \cdot P(B \mid A)}{P(A) \cdot P(B \mid A) + P(B \mid \overline{A}) \cdot P(\overline{A})} = \frac{0.4 \cdot 0.7}{0.4 \cdot 0.7 + 0.3 \cdot 0.6} = 0.6$$

It is easy to see, the difference of the overall probability whether P(B) is known or not is only 0.04 and this shows us the Bayesian approach is a suitable concept for handling situations under uncertainty.

The lack of raw materials was held responsible in this example for the late delivery. In practice, however, a number of risks in the supply chain can lead to a lack of the inventory and safety stock to supply the customers. Because of today's complexity in supply chains, we have to formulate several hypotheses for the lead time differences in the After Sales Warehouse. For example, transport risks (A_1), a prioritized series production (A_2) or a temporarily higher scrap rate due to a quality problem (A_3). After that we are able to solve such complex problems using the Bayesian approach, we have to make sure that the four events are mutually exclusive and exhaustive. To secure this, we define for this, just the complementary hypothesis of no lead time difference (A_4).

$$P(B) = P(B|A_1) \cdot P(A_1) + P(B|A_2) \cdot P(A_2) + P(B|A_3) \cdot P(A_3) + P(B|A_4) \cdot P(A_4) \tag{3.9}$$

$$\mathrm{P}(A_i|B) = \frac{P(B|A_i) \cdot P(A_i)}{P(B|A_1) \cdot P(A_1) + P(B|A_2) \cdot P(A_2) + P(B|A_3) \cdot P(A_3) + P(B|A_4) \cdot P(A_4)} \tag{4.0}$$

Under the condition that the union of the various events A_1, A_2, ..., A_n are mutually exclusive and the sum of all the probabilities equals one. Now, it is possible to define the Bayes theorem in a general version.

$$\bigcup_{i=1}^{n} A_i = \Omega \tag{3.1}$$

$$A_i \cap A_j = \emptyset \; for \; all \; i \neq j \tag{3.2}$$

Then

$$P(A_i|B) = \frac{P(A_i) \cdot P(B|A_i)}{\sum_{i=1}^{n} P(B|A_i) \cdot P(A_i)} \tag{4.1}$$

4.2.3 Joint Probability Function

In the last sections the basic rules in probability theory and the Bayes theorem were explained. It was shown that various causes can lead to our overall risk lead time difference. One of the easiest ways in small networks to perform the relevant calculations is to use the joint probability function. Due to the joint probability distribution P(U) it is possible to calculate the probabilities of every possible event by the values of all the variables in the Network $A_i = (A_{1,\dots,}A_n)$. Figure 9 show a small Bayesian network example with five variables $(A_1,\dots,A_5)$. Each variable has two states (yes/no) and the variables are mutually exclusive.

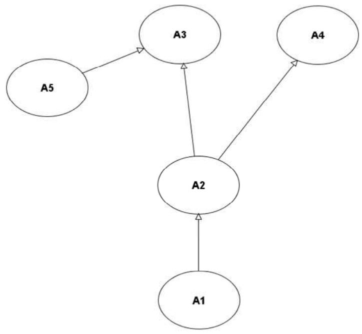


Figure 9 Example of a five node Bayesian Network

Let us apply the multiplication rule to this network to get the following expression:

$$P(U) = P(A_1, A_2, A_3, A_4, A_5) = P(A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5) =$$
$$P(A_5|A_4, A_3, A_2, A_1) \cdot P(A_3| A_5, A_4, A_2, A_1) \cdot P(A_4| A_5, A_3, A_2, A_1) \cdot P(A_2| A_1) \cdot P(A_1) \quad (4.2)$$

If we now take into account the causal structure of the variables, e.g. A_4 which is directly dependent only on A_2 then we get the factorized representation of the joint probability distribution P(U).

$$P(U) = P(A_1, A_2, A_3, A_4, A_5) = P(A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5) =$$
$$P(A_5) \cdot P(A_3| A_5, A_2) \cdot P(A_4|A_2) \cdot P(A_2| A_1) \cdot P(A_1) \quad (4.3)$$

Each variable (node) is independent of the predecessor node if we have an instanced for example true or false parent node. The joint probability distribution over all variables is expressed in Formula 4.4 (Jensen and Nielsen 2007).

$$P(U) = P(A_1, \ldots., A_n) = \prod_{i=1}^{n} P(A_i | Parents\ (A_i))$$

(4.4)

Where Parents (A_i) means the values of the direct predecessors from node A_i with respect to the graph in Figure 9. If we can manipulate the variables in the network, for example set the value of variable A_4 as "yes" or "no" and measure its effect on variable A_1, then the probability distribution of variable A_1 will change under the conditions of the different values of variable A_4. Based on these assumptions we are now able to calculate all probabilities within the whole network. Arising over time through experiments, evaluations or expert knowledge new information about variables, the posterior probability of each variable in the BN can be calculated based on the Bayesian theorem. To bring new knowledge into a network we must have just the basic framework, the so called initial situation. Take the example based on Figure 10. We assume that procurement problems at the first tier (A_1), for example missing components, serve to problems in the 1st tier manufacturing (A_2). Depending on capacity bottlenecks, the prioritization in the 1st tier manufacturing has an impact on the in time shipments for after sales (A_4) or serial delivery (A_3). For delivery delays in serial production (A_3) it is also possible, that the first tier has a lack of series carrier (A_5), with direct influence on the serial in time shipments and which in turn has no direct influence on the after sales due to another packaging concept. That means for the initial situation about ¼ of the products would be usually delivered too late in After Sales (A_3). Now, suppose the following situation. The current supplier rating shows us the supplier has no shipment in time, which means we have a 100% delivery delay (Scenario 1). The BN gives us back the alleged risk cluster and through the joint probability calculation the prior probability of the procurement problem (A_1) increased at the 1st tier from 50% to a posterior probability of 73%. This very simple example shows the importance of the joint probability function in this context.

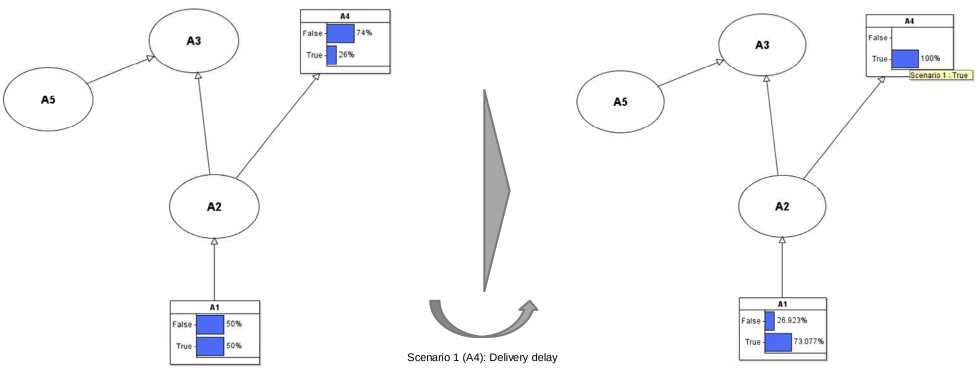


Figure 10 Joint probability calculation

The other side is, in networks with many variables the determination of probabilities in specific variables is more complicated because P(U) grows exponentially with the number of variables (Pai, Kallepalli et al. 2003). For this in the literature, we find two categories of intelligent algorithms. The exact solution algorithms like for example Polytree algorithms (Pearl 1988), Junction Tree algorithms (Lauritzen and Spiegelhalter 1988), or variable elimination algorithms (Zhang and Poole 1994) and the approximation algorithms for example the Markov-Chain-Monte-Carlo algorithms, Likelihood-Weighting algorithms, model simplification methods or stochastic sampling algorithms. A good overview of the inference algorithms can be found in Guo and Hsu (Guo and Hsu 2002).

Finally we can conclude this sub-chapter with the finding that, the Junction Tree algorithm is the most widespread algorithm and for the majority of applications and models completely sufficient. In this dissertation we worked with the junction tree algorithm, since in this work the BN software by AgenaRisk has been used, which underlies the junction tree algorithm (Appendix C).

4.2.4 Node Probability Tables (NPT)

In order to quantify the relationship of causality, an expert must define and quantify the causal dependencies that are all the nodes that have to be characterized by probability values specified in conditioned or unconditioned Node Probability Tables (NPT). Unconditional NPT’s are assigned to nodes that have no parent nodes and require unconditional probabilities (Jensen and Nielsen 2007). Equivalently, conditional NPT’s are assigned to child nodes that are caused by their parent nodes. In conditional NPTs conditional probabilities are determined for the child node dependent on its parent nodes. Many real world problems are effectively represented by a mixture of discrete and continuous nodes (Jensen and Nielsen 2007). Thus, in order to closely represent the real world of the risk environment it is inevitable to incorporate both types, discrete and continuous nodes. A BN with discrete and continuous nodes is also called a hybrid BN (Jensen and Nielsen 2007, Fenton and Neil 2012). The User manual of the Software from AgenaRisk provides various node types and adjustments of each node.

Discrete Nodes:

Boolean:	e.g. “True”, “False”. Or “Yes”, “No”
Labeled:	e.g. “Red”, “Green”, “Blue”
Ranked:	e.g. “Low”, “Medium”, “High”

When applying discrete nodes, each state of the node needs to be defined by a number between zero and one where the probability zero represents an impossible event and the probability one stands for an event being highly likely to happen. However, according to the Cromwell's rule it is less appropriate to assign a value of zero or of one when defining the prior probability (Roskelley 2008). The sum of all state probabilities of one node has to equal one.

Continuous Nodes:

Integer Interval:	e.g. 0, 1, [2, 3], [4], [5 – infinity]
Continuous Interval:	e.g. [0, 10], [10 – 20], [20 – infinity]
Discrete Numeric:	e.g. unordered collection of values -2, 0, 2.5, 3.6, 10

When applying continuous states the probability values of each of the states can be assigned by a probability distribution. Conditional probability densities of continuous nodes can be processed automatically in AgenaRisk by the use of dynamic discretization (Appendix D). To represent continuous nodes the software offers numerous probability distributions.

A correct calculation of discrete and continuous nodes requires compatible adjustments by the use of synthetic nodes. Synthetic nodes have the function of reducing complexity when propagating the probabilities as well as when designing the BN structure. The function also includes the ability to comply with the logic of mutual exclusiveness and common exhaustiveness. For both, discrete and continuous nodes there are three ways of editing NPT; manual, expression and partitioned expression. The manual node is characterized by the necessity to merely assign the prior probability value to each state of the risk node irrespective of the type of the node. The expression node offers mathematical expressions (e.g. IF, AND, OR) for discrete nodes and arithmetic expressions as well as multiple probability distributions for continuous nodes. The partitioned expression can be applied to both node types, where specific expressions can be assigned to the individual combination of node states.

Algebra of NPT:

There are three operations we are interested in and we can use these, along with Bayes' Theorem to compute or derive any measure of interest in the BN. These are; marginalization, multiplication and division. A big advantage of the NPT instead of calculating probabilities, one at a time, we can use tables, containing rows and columns indexed by variable state values (Fenton and Neil 2012).

Adopted from Fenton and Neil the following example should briefly explain the basic calculation logic. For this, we construct a simple BN using the algebra of NPT.

Consider we have the following model, P(A,B,C) = P(C | A,B) P(A) P(B) with the following NPT.

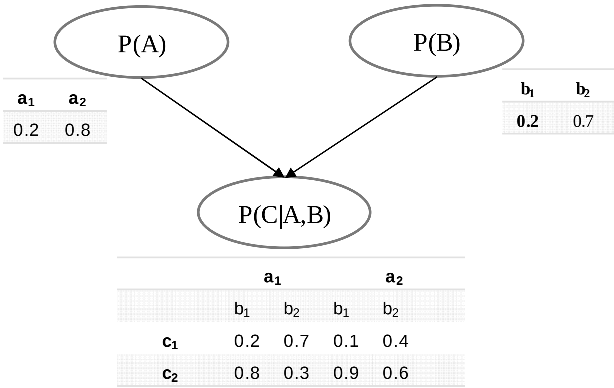


Figure 11 Bayesian Networks calculation logic

Now assume we have new information about B and wish to calculate P(C | B = b_1). To do so, we must solve the posterior probability.

$$P\left(C|\mathrm{B}=b_1\right)=\sum_{A,B}P(A,B=\ b_1,C)=\sum_{A,B}P(C\ |\mathrm{A},\mathrm{B}=b_1)P(B=\ b_1)P(A) \tag{4.5}$$

The first step is set up the NPT and split the calculations.

P(B = b_1) =

b_1	b_2
1.0	0

Now we are able to calculate P(C | A,B = b_1)·P(B = b_1).

b_1	b_2
1.0	0

X

	a_1		a_2	
	b_1	b_2	b_1	b_2
c_1	0.2	0.7	0.1	0.4
c_2	0.8	0.3	0.9	0.6

=

	a_1		a_2	
	b_1	b_2	b_1	b_2
c_1	0.2	0.0	0.1	0.0
c_2	0.8	0.0	0.9	0.0

In the next step we must multiply the result by P(A).

a_1	a_2
0.2	0.8

X

	a_1		a_2	
	b_1	b_2	b_1	b_2
c_1	0.2	0.0	0.1	0.0
c_2	0.8	0.0	0.9	0.0

=

	a_1		a_2	
	b_1	b_2	b_1	b_2
c_1	0.2(0.2)	0.0	0.1(0.8)	0.0
c_2	0.8(0.2)	0.0	0.9(0.8)	0.0

Now we are able to marginalize out A and B leaving C to calculate the final result for $P(C \mid B = b_1)$.

c_1	c_2
0.04 + 0.08	0.16 + 0.72

=

c_1	c_2
0.12	0.88

As this example shows when it comes to the reduction of complex NPT it is essential to keep both the amount of nodes and the amount of states as small as possible. However, in some cases it is more efficient to transform states into individual nodes even if the number of nodes increases. For software processing it can be assumed, that the more states and nodes defined in the BN, the longer the processing takes (Fenton and Neil 2012). For that, it is very important when assigning probability values to the BN to be continuously aware of the objective to create a status quo situation that is as closest as possible to the real world representation.

4.3 Information Propagation

The Information flow is essential for Bayesian Network building. On the one hand for the nodes and on the other hand for the inference process. By the inference process, one or more nodes might be instantiated by new knowledge (Evidence). Therefore dependence is essential when it comes to the application of the Bayes' theorem for conditional calculation of nodes. In directed graphs there are two types of dependence; direct dependence and indirect dependence. In direct dependence there are only two nodes involved. They can be neighbors, completely independent or conditionally dependent. For conditional dependence the parent node has a direct effect on the child node. In the case of indirect dependence there are three nodes involved. They can have one of the three possible relations; serial connection, diverging connection, and converging connection (Kjærulff and Madsen 2005).

4.3.1 Serial Connection

For serial connection (Figure 12), node C is indirectly influenced by node A through node B. Any evidence (b) entered in A gets propagated through to B and then to C, if B is not known.

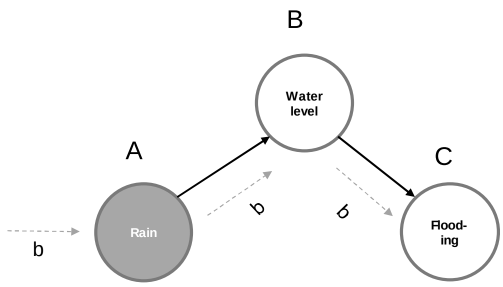


Figure 12 Serial Connection (Fenton and Neil 2012)

For example, if nothing is known about the water level (B), rainfall (A) increases the likelihood that the water level is high and which in turn increases the likelihood of flooding (C). But if the water level is known, the fact that it rained, changes nothing on the likelihood of flooding (Fenton and Neil 2012).

4.3.2 Diverging Connection

In the diverging connection (Figure 13) there exist indirect dependencies between all nodes if (A) is not given. But if we know the state of (A) then the child nodes (B) and (C) are independent and the evidence (a) entered in (A) is transmitted to node B and C.

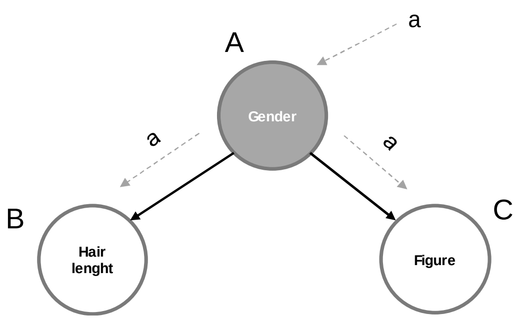


Figure 13 Diverging Connection (Fenton and Neil 2012)

For example, if a person's gender (A) is not known, the hair length affects our belief about the gender as well as our belief in a certain stature. Now we have received hard evidence (a) about the gender, however, the hair length does not change the beliefs about the body type and vice versa. The evidence of (A) blocked the information process between (B) and (C) (Fenton and Neil 2012).

4.3.3 Converging Connection

In converging connections the parent nodes (B) and (C) has a common child node (A). If nothing is known about node (A) expect what can be derived from the parent node, then the parent nodes (B) and (C) are independent. If we enter evidence (b) in the parent node (B) the information is transmitted to (A) as well as we enter evidence (c) in (C).

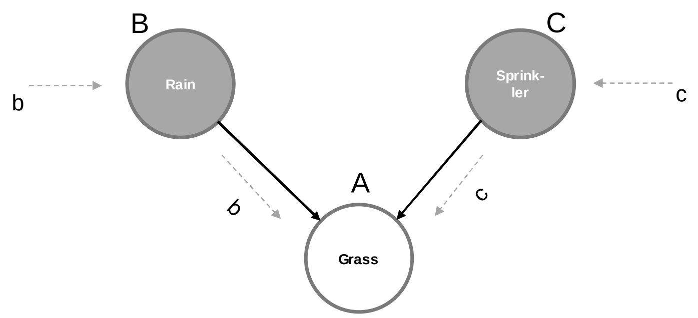


Figure 14 Converging Connection (Fenton and Neil 2012)

For example, if we do not know whether the grass (A) is wet, our observation that it is raining (B) influences our assumption of whether the sprinkler (C) was turned up, or not. But, if we know the grass is wet and the sprinkler is turned on, this will influence our assumption about rainfall. Because we assume that the grass was wet from the sprinkler and not from rain (Fenton and Neil 2012).

It can therefore be concluded that only if nodes are d-connected then they are indirectly dependent or conditionally dependent. Serial connections and diverging connections are d-connected only if the probability of the middle node is unknown. Converging connections are d-connected if the probability of node (A) or of one of its parent nodes, (B) or (C), is known. If there is information about node (A), reasoning about node (B) and node (C) can be inferred. The converging connection is characterized by the so called “explaining way” (Pearl 2001, Kjærulff and Madsen 2005).

If nodes are not d-connected they are d-separated, meaning conditionally independent. Conditional independence is essential for efficient algorithms in Bayesian calculations (Pearl 2001). Nodes are d-separated every time the information flow between them is blocked. Serial and diverging connections are d-separated as soon as information about the node in the middle is available. Converging connections are d-separated if no knowledge about node (A) is available. As shown, d-connectedness and d-separation are required for reasoning with the Bayes' theorem (Fenton and Neil 2012). For detailed information read Greenland and Pearl (2011) or Pearl (2009).

4.3.4 Inference in BN

The most important operation in Bayesian networks is reasoning under uncertainty (Inference) and it serves to predict the effects under consideration of circumstances or the conclusion of an observation of alleged influence factors. Suppose a set of variables is already known, it is also interesting to know how the distribution of one (or several) of the unknown variables looks. We can use the inference therefore for both diagnosis and prognosis, which mean for example reasoning regarding an obvious effect of possible causes or predicting the expected effect on the basis of one or more causes. The underlying process is always the same and is based on the theorem of Bayes. Bayesian networks use the fact that in an initial established net new knowledge in the form of evidence can be introduced. The complexity reduction is achieved by the so called marginalization or variable elimination (Pearl 1988). The basic principle of variable elimination is to factor out the probabilities that are accessed as multiple. A rather long and almost unsolvable process to calculate probability distributions of a particular subset of variables, in Bayesian networks is to establish a common table of probabilities of all variables of the Bayesian network, and then to add together all of the variables. This approach is very inefficient, since the joint probability distribution of all variables is created with significant effort and it is accessed by the multiple of some probabilities. For this reason, nowadays there are various algorithms to exchange messages in a BN. Pearl described the "message passing algorithms" for Bayesian networks in 1986 in his Tech Report. The algorithm is also known under the name Junction Tree algorithm and describes the exchange of messages between the associated parent node and child nodes. Any change in a state leads to a calculation of the individual conditions, and if there is a change, the new message will be passed to the next node. This type of information transfer ensures that only local information-/-states transmitted, significantly reduces the complexity. The operation of the Junction Tree algorithm is presented in Appendix C and can be read in detail in Pearl Tech Report from 1986.

5 AFTER SALES RISK MODEL

The After Sales Risk Model, short ASRIM, follows a practical case study and aims to develop a framework that operates the SCRM process in the After Sales inbound SC risk environment of the research partner. Modeling risks will be the particular focus in the case study. As shown in Figure 15 the practical case study contains four essential modules. The first module limits the field of action based on an extensive data analysis of supplier's delivery data. The results coming out of the data analysis are essential for the ASRIM approach. The second module identifies the most relevant after sales risk per supplier questioning. Module three links the cause and effects of the after sales SC risks to a causal model and module four calculates the operational risk in a Bayesian Network.

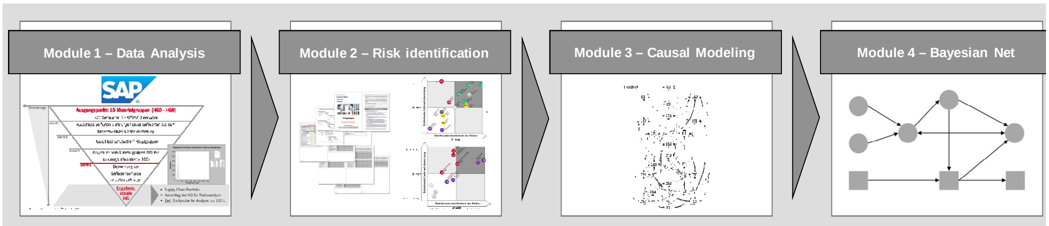


Figure 15 The four modules Approach

But first of all, some background information on this case study must be described briefly. For a better understanding it is necessary to explain the specific framework of the company involved in this research. To be more precise, the essential elements of the After Sales inventory management, the role of safety stock in the company as well as the relevant overall risk for the warehouse and central variable the "Lead Time Difference" will be explained.

5.1 Framework

5.1.1 Central Inventory Management

Warehouse management processes contribute different dispositions that the correct materials are available in the right quantity in stock. As discussed in Chapter two under the stochastic conditions, the uncertainties along the supply chain must be understood.

This may be the delivery date, delivery quantities, demand variances (Hoppe 2012). As the main objectives of inventory management can therefore be called a rapid response to the market changes and determination of the amount and placement of safety stocks. The first step for professional inventory management in the supply chain is already done by the company involved in this research. Under the name "Global Inventory Management" all worldwide stocks are centrally planned and dispatched. The spare part SC spans over three steps from suppliers to the customer. Around 1,400 suppliers shipped all their spare parts into the central warehouse of the focal firm. From the central warehouse the spare parts are sent to the international subsidiaries and the subsidiaries deliver the world wide with the spare parts. The global inventory management controls therefore the stocks of the central warehouse and schedules a fixed range of spare parts for the subsidiaries, which leads to a large gain in information for the inventory planning in the central warehouse. In particular the shorter reaction times in demand fluctuations provide stock savings. But these stock savings in the form of minimization of inventory in the central warehouse have economic limits due to small stocks potentially causing shortage costs.

To avoid cost shortages the basis for global inventory management builds on the stock curves and the logistical warehouse analysis. For the logistical analysis, the storage and retrieval behavior is examined to judge the necessary safety stocks and feasible product availability. Thus, a logistically sensible positioning between a high level of deliverability for the central warehouse due to high safety stocks and low storage costs achieved by low inventory is possible by a central inventory management (Lutz 2002).

5.1.2 Safety Stock

The safety stock is an essential component in the inventory management and serves to bridge supply risks, see Figure 16. In many places within a supply chain, the safety stock is used to meet the delivery to maintain and to avoid delays in delivery. In particular the after sales business does not run without safety stock, the only question is at which level this is to be determined. According to Lutz, the following factors are taken into account when determining the safety stock (Lutz 2002):

- Desired service level
- Lead time (supply risk)
- Quality of demand forecast (operational risks)
- Fluctuations in demand (demand risks)

The higher the service level is, the more safety stock is required. The security costs increase disproportionately with the increasing level of service (Hoppe 2012). Theoretically, achieving a service level of 100% is possible, but this would not justify the costs. However, the profitability of a company should always be the priority typically a cost optimized service level must be the aim. But especially in the After Sales this is not so easy, because the variance in the delivery time (supply risk) has a significant impact on the safety stock and in most cases causes a disproportionate increase. If the delivery time is linked to the complexity of the product it is possible to say that for spare parts with low complexity, a low safety stock can be implemented, while for materials with a complex depth of production and high technological levels more safety stocks should be provided.

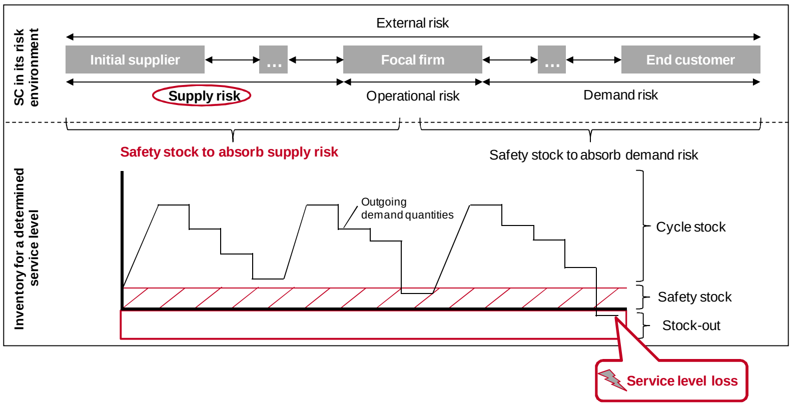


Figure 16 Safety stock

Analysis of the company involved in this research showed that overall the relative safety stocks are very high. For some of the spare parts the target safety stock is up to 200 times that of the cycle stocks. Cycle stocks, which make up only one-twentieth of the safety stock, are regarded as a rule. It is probable that the safety stock is so high because of various uncertainties in the supply chain. But is it necessary? Fluctuation in demand is a special characteristic of After Sales and one risk component of the safety stock which cannot be completely avoided for spare parts. But both the operational risks and the demand risks are considered low due to the systems (SAP APO) and methods (GIM) in use and will not be considered. Therefore it is suspected that the reason for high safety stock is due to the difficulty of estimating After Sales SCs. However, the company involved has a supplier evaluation in use and by assessing the dimensions of quantities and delivery times it is possible to analyze the deviations in the delivery performance. It can be seen that at 90% of the spare parts, the delivery quantity deviations are less than 10% of the target safety stock. The larger shares are the delivery variation and lead time differences. At 20% of the spare parts this is more than one-third of the target safety stock, and is due to deviations of delivery. That is the reason why the lead time differences were defined as a central risk of the inbound SC in this work.

5.1.3 Lead Time Difference

As the last chapter considerations have shown there are different risks in the SC which prevent it being robust. The goal in a practical application can therefore be to achieve an agile SC. Generally, numerous risks lead to late deliveries or, at worst, a total lack of stock or just high safety stocks in the form of warehouse buffers, see Figure 17.

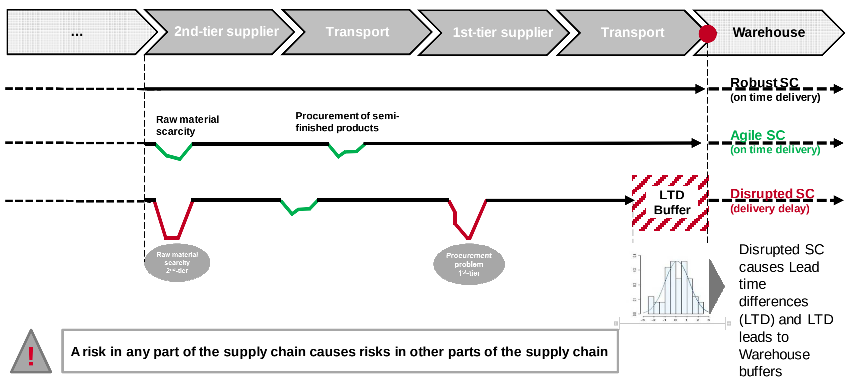


Figure 17 After Sales supply chain electrocardiogram

Since a risk caused at any point in the SC can produce further risks in the following SC, it is important to include the individual risks in a causal relationship. With the LTD, as the overall risk, it is possible to accomplish a causal view of the SC risk (Wels 2008). The greater the lead time differences are, the higher the safety stock amount must be to cover the uncertainties. In the company involved in this research all spare parts delivered to a ‘Central Warehouse’ were measured by the on time delivery. The measurement made by an MRP-System. It counts the day of delivery for each shipment. The lead time difference describes the difference between the scheduled delivery time (SDT) and the date of stock receipt (DSR).

$$LTD = |SDT - DSR| \tag{2.4}$$

If there are any deviations in the chain regarding the delivery time we guess, in the context of supply chain risk management, that the supply chain is disrupted at one or more nodes and that a risk or problem has occurred. To manage these risks and to ensure an agile supply chain the following approach was developed to be put into operation for the company involved in this research.

5.2 Approach

5.2.1 Module 1: Data Analysis

In the first module of the ASRIM approach it is essential to define the supply chain structure and suppliers. An important requirement is that all delivery dates are known. A criteria for the definition in this case study is that we have to select the main material groups from which the spare parts can be classified:

No.	Product group
0	paint & care products
1	engine, clutch
2	fuel tank, engine block heather
3	gearbox, brakes, axes
4	central pipe, lever systems
5	car body
6	electronics
7	utensils, traffic components
8	accessories, custom tailored
9	miscellaneous

The reason for this is that the components are built from a group of materials with similar materials or parts and therefore have similar supply chains and similar SC risks. Using an SAP supplier evaluation all after sales shipments were evaluated by an identical method of measurement concerning date and quantity over a period of one year.

System settings:	Evaluation period: 01/01/2011 – 12/31/2011	
	Products: Automotive Spare Parts	
	All Product groups	
	All shipments	
Figures:	Ø Value each of shipped position:	1,920.45 monetary units
	Ø Distance to first Tier	252.7 km
	Ø Parts weight:	2.5 kg
	Ordered quantity:	3.4 Million Parts
	Delivery quantity:	12.7 Million Parts

Data: 62,102 Data sets
622 Suppliers
16,359 Part numbers

Result: **Almost 70% of all deliveries over all product groups in the evaluation period are not in time.**

This shows the first moment where it seems extremely difficult to deliver the ordered products in the right time and quantity to the central warehouse. It must therefore be risks, or other circumstances in the After Sales, which do not exist in the series delivery and prevent the on time delivery. To find out what is happening we used a four step filter technique to reduce the huge data according to the defined overall risk parameter, the Lead time differences (LTD). The first data filter is utilized to exclude all early shipments and only evaluate the in time and the delayed deliveries. The data sets were reduced from 62,102 to 44,376 and the relevant suppliers from 622 to 589.

No.	Product group	N	Mean	SE Mean	StDev	Minimum	Maximum
0	paint & care products	720	5,947	0,828	22,227	0	305
1	engine, clutch	7.809	7,859	0,284	25,054	0	365
2	fuel tank, engine block heather	314	8,22	1,44	25,53	0	266
3	gearbox, brakes, axes	7.812	8,056	0,249	21,996	0	365
4	central pipe, lever systems	937	7,998	0,731	22,39	0	249
5	car body	16.179	12,452	0,251	31,915	0	364
6	electronics	7.428	8,153	0,235	20,293	0	365
7	utensils, traffic components	1.718	6,952	0,29	12,032	0	155
8	accessories, custom tailored	917	5,736	0,428	12,971	0	153
9	miscellaneous	542	6,5	1,07	25,02	0	322
	Sum of deliveries	44.376	8	1	22		

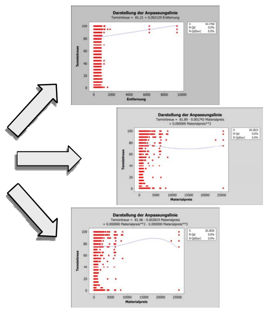
Table 5 Statistical analysis of the delivery data

In table 5, shown as a first result of the data analysis, we find the average value (mean) for the lead time difference (LTD) and standard deviation for each product group. After eliminating all early shipments, the second data filter eliminates specific product groups, like paint and care products (PG 0), utensils and traffic components (PG7) as well as accessories and custom tailored parts (PG 8) or miscellaneous (PG9). The next step for identifying the most relevant product group is to eliminate the product groups with less than 100 suppliers, because for a supplier survey regarding the specified after sales risks it is necessary to have a minimum of 100 suppliers to make an assessment.

Therefore we eliminate the car body (PG5) as well as the engine and clutch (PG 1) because these products would be delivered by internal plants. In the last step the remaining four product groups were examined with respect to their delivery performance. In accordance to the defined cause of risk, the uncertainty, and, the lead time differences this means the average standard deviation of the LTD of the individual product groups were analyzed. To avoid any correlation, diverse regression analysis (linear, quadratics, cubic) with the following obvious quantitative variables was undertaken.

Variables for Regression analysis:

- weight[kg]
- volume [m³]
- distance [km]
- month
- parts prize (spare part) [€]
- material value (shipment) [€]



Result:

No correlation between LTD and the selected quantitative values (R^2< 0.2)!

The four remaining product groups 2, 3, 4 and 6 were further analyzed and discussed with the after sales experts. It was found that the product group electronics has the greatest potential for lead time optimization. With 7,428 deliveries over 149 different 1st tier suppliers, all based in Germany, the statistical analysis showed, that the parts of this product group with an average lead time difference of 8 days and a standard deviation of 20 days, sometimes had the largest supply uncertainty among the remaining four product groups.

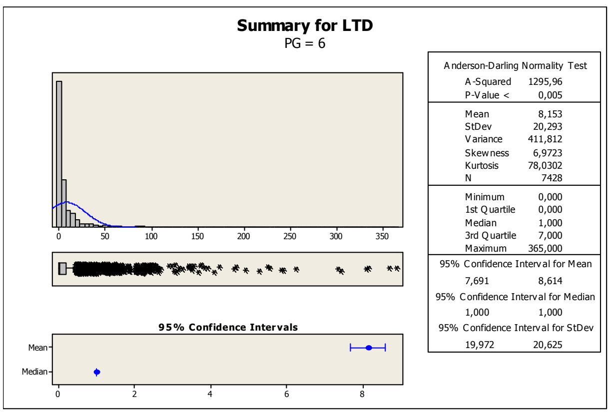


Figure 18 Overall statistics for electronic spare parts

On the other hand, it has been established that this group of materials includes a wide variety of different spare parts. Besides plugs, cable strings, lights and relays this group of materials includes also metal and plastic standard parts, such as metal brackets and other fasteners for electronic parts. This results in a wide range of parts within this group of material, so that it first appeared difficult to derive a representative supply chain. Expert discussions, however, confirmed the assumption that most parts of the selected material group are produced using the same basic components. It could be concluded in consultation with experts that the supply chain of the spare parts and the different suppliers within this SC are similar and the modeled supply chain shows that almost all components and raw material suppliers (2^{nd} & 3^{rd} tiers) in this product group shipped the products from Asia and sporadically from the USA to the 1^{st} tiers in Germany.

Based on this delivery network it is possible to establish the critical paths and the potential sources of risk can be identified. They are:

- **Supply of raw materials:**
  Worldwide, there are only a few major plastics producers for special types of plastics for the automotive industry that are difficult to compensate during a loss of production (Evonik 2012). In addition, the supplies of rare minerals is considered critical because China as a monopolist, has reduced their exports increasingly (Bencek, Klodt et al. 2011).

- **Technological change:**
  Rapid technological development of electronic components in conjunction with limited market power in the automotive industry often leads to early discontinuations of required components (Schröter 2006). In particular, in the automotive after sales where the supply of special qualified components is very difficult (Council 2012).

- **Concentration of electronics suppliers in the Asian region:**
  A variety of electronics suppliers in the 2^{nd} tier level was located in Asia. Risk sources such as long transport routes, different cultures and the high risk of natural disasters in this region can be identified.

- **High quality requirements:**
  Many electronic spare parts, especially in the production of rear lights are made by car manufacturer's very high quality requirements so that these parts have a high vulnerability to quality problems.

The knowledge gained through the modeling of the SC plays an important role for the next step. This representative information on relevant risk sources within the SC of electronic spare parts is the basis for the identification of the SC risks for the supplier survey.

5.2.2 Module 2: Empirical Risk Identification

The second module examined according to the first SCRM Process step, is a complete picture of the After Sales inbound SC in particular used to establish the essential risks. Accurate risk assessment requires precise risk identification in order to derive mitigation strategies which are tailored to the SC. Nonetheless, risk identification remains the most complex and less standardized part of the SCRM framework (Kern, Moser et al. 2012). There are two approaches of how to identify risks. The atomistic approach analyzes a selected fraction of the SC and the holistic approach examines the SC as a whole (Manuj and Mentzer 2008). In this work both approaches are imbedded. The atomistic view allows a detailed focus on the inbound section of the SC. The holistic perspective is then integrated into the SC inbound and multiple tiers of the AS SC. This way of risk categorization models the SC in a detailed and all embracing manner. First, it is important to understand key areas and the risk origin of the SC. To do so, it is required to visualize the SC structure. Figure 19 presents the inbound SC exposed to internal and external risks in the inbound supply.

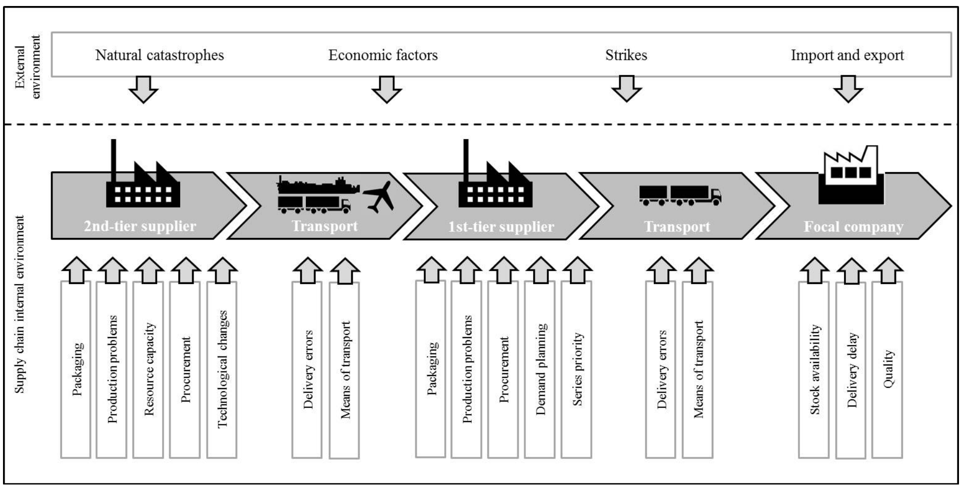


Figure 19 After Sales inbound supply chain risks

To gain an idea of the risks which generally occur within a SC the greatest possible numbers of potential SC risks must be collected. A risk catalogue was established by analyzing well known international journals and books on completed risk assessments. Several studies analyzed risks that arise internally and externally (Appendix A). In total 248 risks could be identified and listed.

Literature source	Number of identified risks
Thun & Hoenig (2011)	16
Lockamy (2011)	47
Vilko & Hallikas (2011)	36
Blos et al. (2009)	41
Rao & Goldsby (2009)	15
Schröter (2006)	9
Ziegenbein (2006)	84
Sum	**248**

Table 6 Identified supply chain risks in literature

Based on the literature risks it was clear that most of them are of a general nature and have therefore only a minimal impact on the supply of spare parts for car manufacturers. Other methods must be used to identify special after sales risks. Utilizing brainstorming and expert discussions other relevant risks for the supply of spare parts, in series or parallel to series delivery, could be found.

Through discussions with experts on the supplier and manufacture sides it was possible to identify the five most significant risks in the after sales supply chain.

1. Inadequate spare parts supply strategies (AS strategies)
2. Low priority in spare parts production and capacity planning (Capacity)
3. Long supply cycles (up to 15 years) and the associated risk of discontinued components and forecast uncertainty (Technological changes)
4. Interlinked manufacturing systems and therefore high set-up times for spare parts based on the small sample size after end of serial production (Production problems)
5. Different packaging of series versus spare parts (Packaging)

Many other potential SC risks or AS SC problem drivers could be identified through discussions with the experts. To get a better overview of the large number of nearly 280 risks, the SC risks must be first classified. For this risk categories are set to meet the requirements of the considered AS inbound SC to derive a specific questionnaire. Accordingly, the questionnaire must be comprehensive regarding the SC risks for the suppliers that we must consider for the planning and production risks (business-related), the procurement and transport risks (network-based) and the environmental risks. Another important point is that in addition to the SC risks of the 2nd tier and 1st tier suppliers must be assessed separately from one another in the questionnaire in such a way that the severity of risk can be assessed at different stages. Further the questionnaire must contain the risks of the supply chain strategies after EOP as these are central aspects of the after sales supply chain. Last but not least, as well as the after sales risks the identified sources of risk for electronic components should also be considered. For this reason, the breakdown by the SCOR model is utilized to extend the view of the AS suppliers and their main processes. These are:

- Planning risks (Inhouse)
- Production risks (Inhouse)
- Procurement risks (Network)
- Transportation risks (Network)
- Environment risks (Environment)

These could be extended by the following categories to fulfill the AS requirements after EOP.

- Risks of long term storage
- Risks of integrated production
- Risks of spare parts workshop

The Questionnaire:

Now we are able to structure the questionnaire in such a way that it could be applied to a practical case study. For this purpose, different criteria were observed. The three most important are listed below:

- The survey must take place anonymously in order to avoid investigation or interviewer bias
- The questioning should be feasible with reasonable effort for all identified suppliers
- The transmission of the questions and returning of the answers should also be simple

Based on this preliminary work it is possible to define the major parts of the questionnaire.

General Information (Section 1)

The first part is used to receive a statistical overview of the companies surveyed, the SC structure and deliveries of spare part types or components.

Drivers of vulnerability (Section 2)

From the perspective of the suppliers we will establish with one question how the suppliers assess the vulnerability of their own supply chain. And how the supplier also evaluate economic trends as direct drivers of SC risks in context of the after sales supply chain.

Specific after sales supply chain risks (Section 3)

The third part identifies the special after sales risks in six different blocks regarding their expected values and their extent of damage in terms of the central element the expected lead time differences. This makes it possible to measure the risks or categories of risks quantitatively and to compare the risks later in a portfolio. According to the requirements we rate the risks according to a five point Likert scale based on input from suppliers of the focal firm which is the "1st tier" and also their sub-suppliers the "2nd tier". That means, the supplier must be able to estimate supply chain risks on the basis of two dimensions, from the perspective of the own company as well as in terms of their key suppliers for each question.

Spare parts supply strategies (Section 4)

The fourth part is designed to ascertain the risks of the after sales supply strategies. Corresponding to the identified spare parts supply strategies, there are three sets of questions. Only the risks of the strategies used depending on the particular spare part strategy in the surveyed companies are valued.

The following Figure shows the structure of the questionnaire graphically.

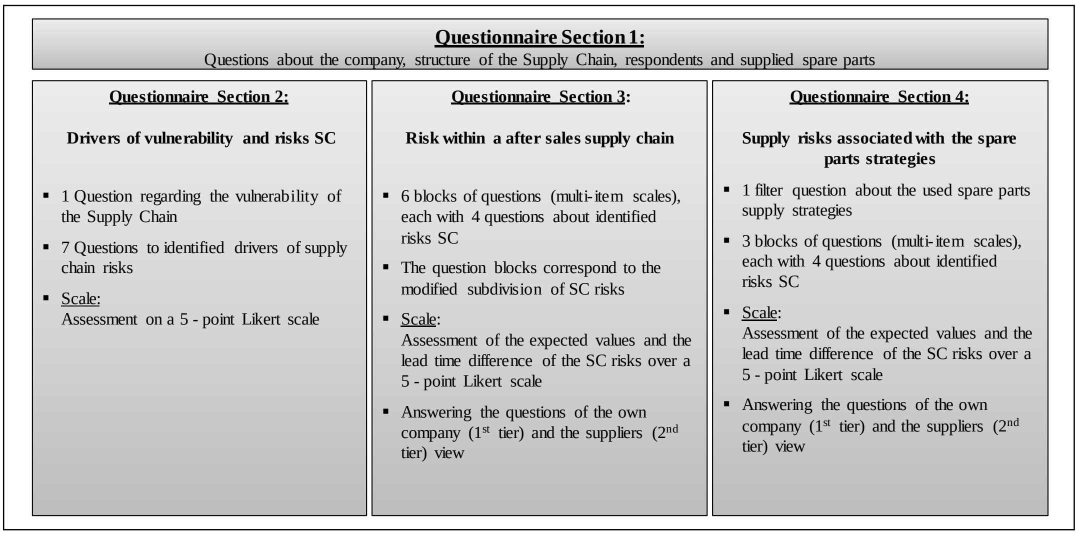


Figure 20 Questionnaire structure

The Pretest:

Before the survey can be undertaken, it is essential to test the questionnaire on its understandability, the technical functionality, the scope and the statistical validity and reliability (Möhring and Schlütz 2010). Therefore, first an internal test of the questionnaire was executed. Based on the gained results, the consistency of the individual questions on the Cronbach's alpha using the statistical program "Minitab", could be calculated (Möhring and Schlütz 2010). The value moved in the individual scales between 0.8 and 0.9, which is a very good result (Rammstedt 2004). The validity of the content was found through the literature search and the numerous discussions with experts.

The Results:

Section 1: General Information

In this empirical analysis a total of 149 suppliers of electronic components were selected, 138 first tier suppliers located in Germany received the AS specific questionnaire and 75 usable questionnaires were returned. Suppliers from different revenue categories participated in the survey. For example in the turnover category from 10 million monetary units to 500 million monetary units, with nearly equal proportions between 16.7% and 26.4%.

Not new, but very interesting to establish was that the majority of the supplier's turnover was not achieved with spare parts or after sales business. The result shows that in all revenue categories more than 50% of the suppliers achieved less than 5% of their turnover with the spare part components. This illustrates the low relevance of after sales business compared to series production. Among the companies surveyed, 19.2% were small companies with less than 100 employees, 34.2% medium-sized companies with between 100 to 500 employees, 12.3% larger companies with 501 – 1000, 9.6% with 1001 to 5000 employees and 24.7% of large companies with more than 5000 employees. Therefore evidence from the two statistics shows that the whole range, from small to large companies participated in the survey. The evaluation of the delivery range showed more than half (53.3%) of the surveyed suppliers deliver peripheral parts of electronic components such as metal or plastic brackets. The direct supplier of electronic components such as relays or semiconductors, with 26.7%, had the largest share. It was also found that the majority of suppliers focused on one type of component, as only eight multiple answers were given.

Section 2: Drivers of vulnerability

To gain a general overview of the vulnerability of the AS SC the suppliers were asked how they assess their SC vulnerability to unexpected supply disruptions. The result is an unexpectedly low average of 1.97 on a five-point Likert scale. That means in contrast, the majority of respondents (75%) assessed the vulnerability of their supply chain to be very low (27.9%) or low (47.1%). Based on this survey result we must assume that the SC vulnerability of the interviewed suppliers and therefore the AS SC of the company involved in this research is surprisingly small. We could further establish that the inventory reduction due to consistent focus on efficiency the increasing globalization and the associated increase in complexity are assessed as the largest risk drivers. These two trends account for 58.9% and 53.5% of the surveyed suppliers, a medium to very large effect on the increase of the SC risks. Similarly, about 40% of the respondents see the increasing outsourcing, or the growing single sourcing as a medium to very high-risk drivers from SC.

The specifics of after sales business, the multiple variations and variety of spare parts along with the long supply obligation and long product life cycles, was rated by over 50% of the supplier with a medium to very high impact on increasing the supply risks. This shows that the characteristics of the AS have an almost equal risk driving effect, such as the economic trends.

Section 3: Specific after sales supply chain risks

All SC risks for the 1st tier and 2nd tier supplier are shown in Table 7. In addition, this table contains according to the five-point Likert scale the realized mean values of the expected values (EV) and lead time differences (LTD) of all AS SC risks and in addition the overall mean of all the EV and LTD for each of the two stages of the SC. The table shows that the EV and the LTD were rated consistently low for the risks surveyed. The average EV of all risks is rated at 1.75 and 1.92 for the 1st tier and 2nd tier. The LTD was rated on average slightly higher. Here, the average was 1.98 and 2.12 for the 1st tier and the 2nd tier. The risks associated with the 2nd tier suppliers, however, tended to be valued higher than the risks for the 1st tier suppliers. The range of realized values for both dimensions extends from 1.43 to 2.67, so that the individual risks can be distinguished at first minimally.

Mean value of After Sales Supply Chain risks according to the Likert scale of 5 levels						
Category	Risk	Index	1st Tier		2nd Tier	
			EV	LTD	EV	LTD
Planning risks	Delayed demand planning	P1	2,12	2,24	2,26	2,39
	Demand planning errors	P2	1,76	1,99	2,04	2,22
	Language barriers	P3	1,47	1,63	1,64	1,73
	System breakdown	P4	1,64	1,9	1,79	1,98
Procurement risks	Material scarcity	B1	2,35	2,38	2,59	2,52
	Quality problems at supplier	B2	1,85	2,27	1,94	2,27
	Technological changes	B3	1,96	2,13	1,99	2,19
	Production problems at supplier	B4	2,11	2,35	2,21	2,34
Production risks	Quality problems	F1	1,68	1,92	1,9	2,15
	Machinery breakdown	F2	1,64	1,87	1,89	2,19
	Capacity bottleneck for spare parts	F3	1,64	1,83	1,84	2,03
	Series priortiy	F4	1,99	2,03	2,11	2,16
Transport risks	Lacking packaging material	T1	1,65	1,76	1,54	1,68
	Lacking means of transport	T2	1,46	1,59	1,43	1,54
	Transportation errors	T3	1,57	1,82	1,61	1,85
	Delivery errors	T4	1,59	1,94	1,76	1,98
External risks	Natural catastrophe	E1	1,57	2,39	1,91	2,67
	Strikes	E2	1,59	1,94	1,93	2,24
	Economic factors	E3	1,68	2,15	2,29	2,57
	Import and export	E4	1,6	1,73	1,8	1,9
	Trade restraints	E5	1,64	1,79	1,8	1,9
Ø EV / LTD all risks		MV	1,75	1,98	1,92	2,12
max. EV / LTD all risks		MAX	2,35	2,39	2,59	2,67
min. EV / LTD all risks		MIN	1,46	1,59	1,43	1,54

Table 7 Empirical results of the AS inbound SC Risks

To be able to make meaningful comparisons the means of the risks are considered relative to each other in a risk portfolio. For this, the risk portfolio needs to be adapted. The range limits for all the risks are determined by the mean values of EV and LTD and the scale runs from the realized minimum value to the maximum value of the EV and LTD. Below, the modified risk portfolio with all 21 risks of the 1st tier, and the 2nd tier supplier is shown. The naming of the SC risks involves the Index contained in Table 7.

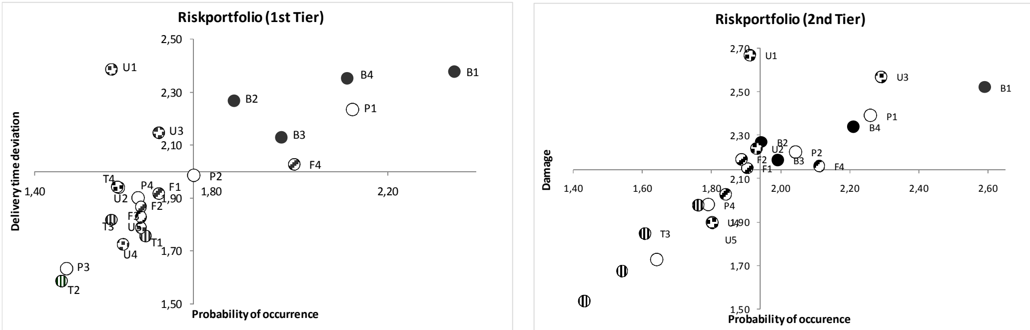


Figure 21 Inbound After Sales SC risks

The risk portfolio shows that among the 21 rated individual risks, the 1st tier suppliers had a total of seven individual risks of particular interest. These so called top AS-risks are illustrated in the box in the upper right field they were rated as above average in both the EV and the LTD compared to the total sample.

Specifically, the top AS-risks are:

1. Scarcity of raw materials (B1)
2. Manufacturing problems (B4)
3. Delayed planning of the supply of spare parts after EOP (P1)
4. Different technological changes in the spare parts (B3)
5. Quality problems (B2)
6. Internal planning errors (P2)
7. Prioritization of series production (F4)

It can be assumed that the 7 top AS first tier risks take place as a large part of the overall risk of AS SC for the focal firm, so that their reduction or control of the overall risk of AS SC is significantly reduced.

The risk portfolio of the 2nd tier shows a similar picture as the risk portfolio of the 1st tier suppliers. In particular, the transportation, planning, and production risks have nearly identical positions. However, only the production risks with an LTD of 2.13 have a slightly higher LTD as the planning risks with 2.08, so that the production risks are now visible in the upper right field in the portfolio. Furthermore, the procurement risks in both the EV with 2.18 as well as the LTD with 2.33, on average, were rated highest. That is, the first tier supplier estimated this risk category at their sub-suppliers as also the highest. The EV of the environmental risks was rated significantly higher in the 2nd delivery stage in relation to the other four types of risk than in the 1st tier delivery stage.

While the environmental risks in the first level are rated with 1.62 and have, therefore, the second lowest value seems that this risk category in the second level has the second highest value with 1.95. It thus appears that, in contrast to the assumptions made, that the environmental risks have both in the first and in the second stage of delivery, a comparatively high LTD.

Section 4: Spare parts supply strategies

The evaluation of section four shows that the most widely used spare part supply strategies are for both, 1^{st} tier and 2^{nd} tier supplier's, the storage is with 66.7% and 49.3% respectively as well as 66.7% integrated production. The scarcest and most used strategy of the large companies is with 17.3%, in the 1^{st} tier and 20% in the 2^{nd} tier the manufacture of spare parts in a separate spare part workshop. In addition, it was found that 1.3% of the 1^{st} tier, or 9.3% of 2^{nd} tier suppliers do not have spare parts supply strategies.

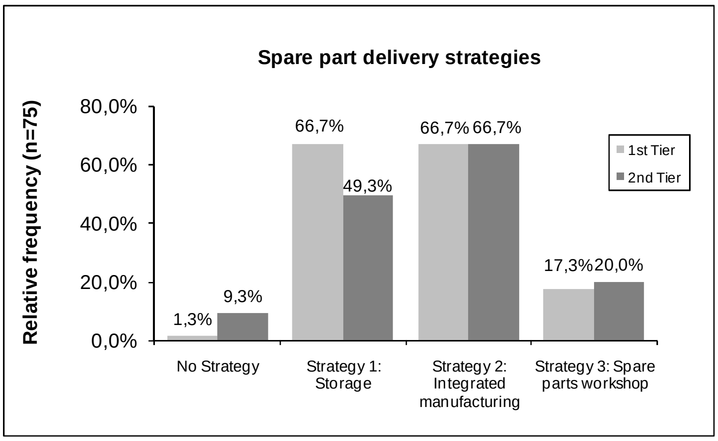


Figure 22 Spare parts supply strategies

If we take a closer look at the 11 risks of the three strategies, the identified risks per spare part supply strategy on a five-point Likert scale, based on the EV and LTD can be assessed. In this way it is possible to calculate for any average risk value for the EV, and the LTD. In Table 8 these are listed for all 11 risks as well as the 1^{st} and 2^{nd} tier.

Mean value of After Sales Supply Chain spare part strategie risks according to the Likert scale of 5 levels						
Category	Risk	Index	1st Tier		2nd Tier	
			EV	LTD	EV	LTD
Storage	Sudden exhaustion of inventory	L1	1,84	2,42	2,14	2,71
	Unplanned material changes	L2	1,84	2,40	2,03	2,57
	Exceeding the best before date	L3	1,70	2,04	1,78	2,11
	Undersizing of the warehouse	L4	1,90	2,19	1,89	2,29
Integrated manufactoring	Prioritization of series production	I1	2,52	2,20	2,32	2,35
	Disproportionately high set-up times	I2	2,78	2,27	2,50	2,35
	Shortage of staff for spare parts production	I3	1,88	1,94	1,98	2.06
	Coordination problems in the production planning	I4	1,74	1,88	2,02	2.04
Spare part Workshop	Initial difficulties in manufacturing	W1	1,54	1,75	2,00	2,15
	Missing or incomplete documents	W2	1,62	1,67	2,27	2,23
	Low effects of experience at the staff	W3	1,62	1,67	1,93	2,00
Ø EV / LTD all risks		MV	1,88	2,04	2,08	2,31
max. EV / LTD all risks		MAX	2,78	2,39	2,50	2,69
min. EV / LTD all risks		MIN	1,54	1,67	1,78	2,00

Table 8 Empirical results of the AS supply chain spare part strategies

The table above shows that the mean differences are minimal. Thus, it is also difficult to compare the various risks associated with the supply of spare parts strategies in the table. Therefore, the 11 risks of 1st tier suppliers are represented in a risk portfolio.

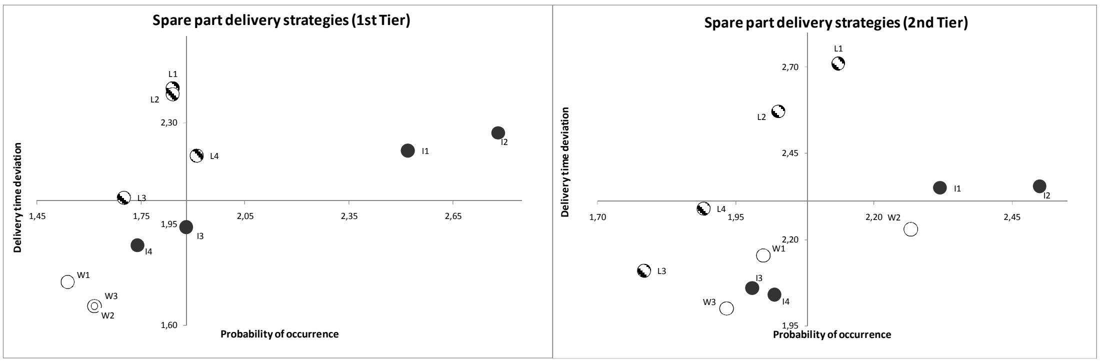


Figure 23 Spare parts supply strategy risks

The risk portfolio shows that among the 11 rated individual risks, the 1st tier suppliers had a total of three individual risks of particular interest. These so called top AS-risks are noted in the box in the upper right field and were rated as above average in both the EV and the LTD compared to the total sample.

Specifically, the top AS strategies risks are:

1. Under-sizing of the warehouse (L4)
2. Prioritization of series production (I1)
3. Disproportionately high set-up times (I2)

Furthermore, two risks were identified in the EV although the LTD were rated particularly high. These risks are:

1. Sudden exhaustion of inventory (L1)
2. Unplanned material changes (L2)

The risk portfolio of risks in the 2nd tier shows that the majority of the risks were evaluated, relatively, slightly higher. For the L1 and L2 risk have been assessed significantly higher than in the 1st tier SC level.

The overall risk of the three supply strategies can be determined by multiplying the sum of EV with the sum of LTD. We show that in particular the two most popular spare part supply strategies with risk figures of 4.6 during long-term storage and 4.1 in the integrated production have the highest risk potential for the after sales SC. In contrast, the spare part workshop strategy with the risk figure of 2.678 was considered the most stable.

5.2.3 Module 3: Causal Modeling

After the identification of the most relevant SC risks it is necessary to investigate their relationship in the AS SC. The evaluation of risk interactions is based on human knowledge and judgment that are subject to human limitation of logical consistence (Warfield 1974). In this work all risks interactions have been proven by cross functional expert judgment.

The aim of the cross impact analysis is to obtain an interrelated graph. There are five steps to follow.

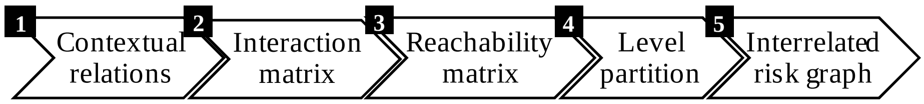


Figure 24 Cross Impact analysis process

Before we start the process we must clarify some important rules. There are four different ways of how one risk can affect another risk. Forward interaction means that risk R_i affects risk R_j (Interaction variable V) and correspondingly backward interaction means that risk R_j affects risk R_i (Interaction variable A). If two risks, risk R_i and risk R_j, affect each other simultaneously they have mutual interaction (Interaction variable X). There is no interaction if they do not affect each other at all (Interaction variable O). One particular characteristic of the complex relationship between elements in the cross impact analysis is called transitivity (Warfield 1974). Simply put, transitivity can be paraphrased as indirect dependence of two risks (Pfohl, Gallus et al. 2011). The reasoning behind transitivity is as follows: If production problems at first level cause a delivery delay at the focal company and a delivery delay at the focal company leads to negative stock availability then production problems at first tier level indirectly cause negative stock availability. In order to highlight indirect causality an asterisk has been assigned to the variable (V*, A* and X*).

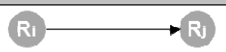
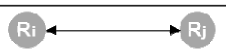
Interaction type	**Interaction variable**	**Example of interaction**	**Explanation of interaction**
Forward	V		Risk Ri has influence on risk Rj.
Backward	A		Risk Ri is influenced by risk Rj.
Mutual	X		Risk Ri and risk Rj influence each other.
None	O		There is no interrelation between risk Ri and risk Rj.
Transitivity	*		Risk Ri has direct influence on risk Rj and indirect influence on risk Rk.

Table 9 Interaction typology in the cross impact analysis

The cross impact analysis process:

1. Identify contextual risk relations:

For standardization reasons three principals must be determined. First, the logic for the identification of contextual relations between risks is one dimensional. For example, there is no interaction between delivery quality at the focal company and procurement at the 1st tier supplier, even though when considering multidimensional interrelation quality issues at the 2nd tier supplier might be passed to the 1st tier supplier and consequently cause poor quality performance at the focal company. In this particular case, it is assumed that quality revision takes place at the 1st tier supplier to avoid any quality problems caused by the 2nd tier.

The second principal deals with the higher attention on after sales business in bad times. For example, in economic recession the AS became the main pillar for companies. Low production at the car manufacturer level positively affects the production capacity at the supplier. Then spare parts orders receive more attention, this is reflected in terms of production and delivery reliability. Such positive interrelations are not considered in the cross impact analysis because the purpose of it is to design a graph of critical relations only.

And finally, if there is both direct and indirect interaction, direct interaction has higher priority, since all indirect interactions are logically embedded in transitivity. First tier suppliers procure semi-finished components from 2nd tier suppliers for final module assembly. Raw material scarcity caused by natural catastrophes directly affects the production at the 2nd tier supplier and indirectly the procurement of semi-finished goods at the 1st tier supplier. Due to there being a direct relation between the production at the 2nd tier and procurement at the 1st tier, the raw material problem would also reach the 1st tier. Even though those principles facilitate the judgment upon causality of risks, their identification is demanding in terms of time and the number of elements.

2. Risk interaction matrix:

Since the contextual matrix is formed in rows (R_i) and in columns (R_j). The contextual risk relation matrix is transferred to a standardized risk interaction matrix (Appendix F). Identified risk relations are encoded into causality direction variables:

- Direct (indirect) forward interaction is V*
- Direct (indirect) backward interaction is A*
- Direct (indirect) mutual interaction is X*
- No interaction is O

3. Risk reachability matrix:

The systematically structured interaction matrix is encoded into a binary matrix where V* and X* are represented by entries of 1 and A* and O by entries of 0. After Warfield the new matrix is called the reachability matrix where transitivity is implied. The binary reachability matrix enables quantitative evaluation of risk causalities. There are two indicators for quantitative analysis; risk dependence power and risk driving power (Faisal, Banwet et al. 2006, Pfohl, Gallus et al. 2011).

Dependence power is the potential of a risk to depend on other risks in the risk system. Driving power is the potential of a risk to affect other risks in the risk system. The entries of 1 in the reachability matrix represent the number of edges for hierarchical ordering in the final graph design (Warfield 1974). For example the risk demand planning (1S4) in Figure 25 scores 21 points, which is the maximum score for dependence power and scores five points for driving power, whereas a maximum score is 21 (Appendix G). For qualitative analysis it is better to transfer the results from the reachability matrix into a portfolio. To do so, we allocate the dependence power values to the horizontal dimension and the driving power values to the vertical dimension in the portfolio. Figure 25 illustrates the completed portfolio of risk dependence power and risk driving power. For interpretation purposes the portfolio has been divided into four quadrants. Weakly dependent risks with low driving power are situated in quadrant III. Weakly dependent risks with high driving power are situated in quadrant IIa. Strongly dependent risks with low driving power are depicted in quadrant IIb. And eventually, risks with both high dependence and high driving power are found in quadrant I. However, no risks have been identified to fulfill the requirement of quadrant I. One indicator for this is due to the sequential logic of the SC. Risks ascends along the SC from one risk to another risk, from one SC level to another. This phenomenon is explained by transitivity. Consequently, transitivity reduces both the driving and dependence power. In quadrant IIa risks of external factors (E1, E2, and E3) are positioned. External risks have a very high driving power since they occur outside the SC and subsequently have an effect on each level of the SC. Quadrant IIb includes risks from the focal company (C1, C2 and C3) as well as risks form the 1st tier supplier (1S2, 1S3, 1S4 and 1S5). Risks at the level of the focal company and of the 1st tier supplier have the greatest dependence power because any risk occurring at any level of the SC is passed on to the top level of the SC. These risks can be regarded as the outcome of any other risk that emerges in the SC, and for that reason they have the greatest potential for mitigation actions.

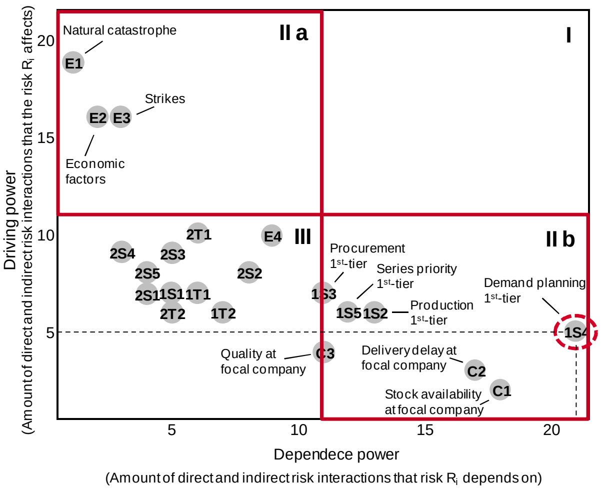


Figure 25 After Sales reachability portfolio

This work will focus on risks in the quadrants IIa and IIb (cp. Figure 25) of the dependence and driving power portfolio. Even though no 2nd tier risk has been identified as significant by the portfolio, it would be incomplete and unrealistic to totally disregard the 2nd tier SC-level in further analysis. Since the procurement of raw material affects the production performance at the 2nd tier and any production problems would again directly affect the 1st tier suppliers, it is reasonable to include them in further research

4. Level partition and causal graph:

The reachability matrix is used for level partitioning that enables hierarchical ordering of risks for the construction of the graph (Pfohl, Gallus et al. 2011). Partitioning of elements is compatible with the iterative process (Warfield 1974). The iteration requires the establishment of the reachability set and the antecedents set of all 21 risks. The reachability set represents all entries of 1 in the row and the antecedent set represents all entries of 1 in the column of the risk R_i. It is required to establish an intersection of both sets for all 21 risks. If elements in the reachability set equal the elements in the intersection set of risk R_i the hierarchical levels of risk R_i can be determined. To determine the next hierarchical level the first assigned risk has to be removed, then the next equal sets need to be identified. The hierarchically ordered risks can now be arranged into a risk network as shown in Figure 26. The causality between the risks is determined by the arc directions among the risks. To overcome redundant directions, as criticized by Pfohl, Gallus et al. 2011, only forward interactions (V) and mutual interactions (X) are considered. It is important to disregard transitivity interactions (V* and X*) since they are indirectly included in direct interactions among risks.

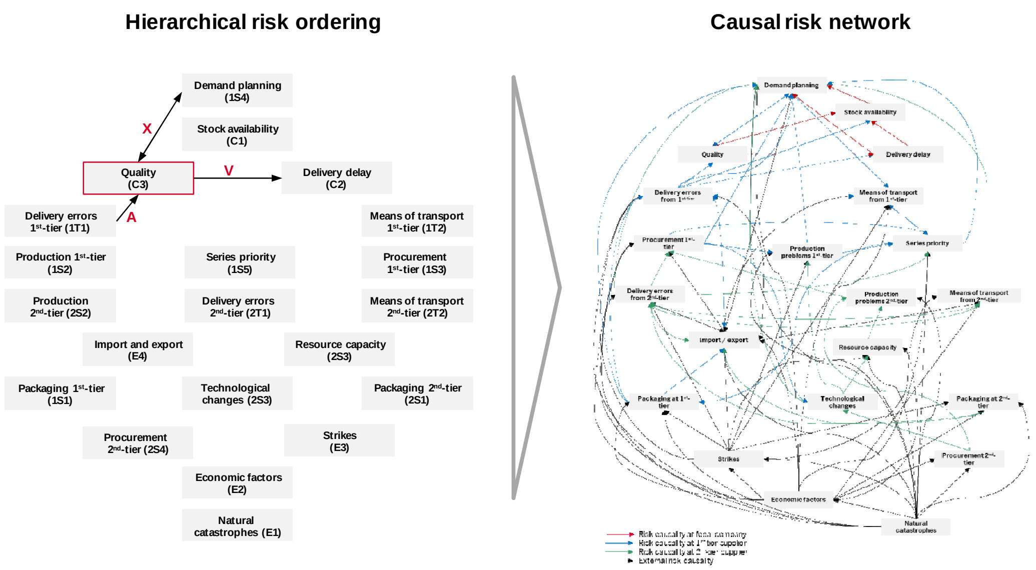


Figure 26 Hierarchical risk ordering

Because the SC is a sequence of activities, the identified risks are assumed to have the same structure as the SC. In fact, the structure of the graph is identical to the structure of the SC as demonstrated in Figure 26. The graph is extensively interrelated and indicates the complexity of the SC risk environment. However, contrary to the above assumption the cross impact analysis method recognizes a hierarchical shift of certain risks away from the sequential logic of the SC.

This finding means that there are risks that require a distinctive focus. The top level of the graph is represented by the focal company. As expected the risks of stock availability (C1), delivery delay measured in LTD (C2) and delivery quality (C3) are located here. Unexpectedly, the risk of demand planning (1S4) is also found here. Furthermore, it has the highest hierarchical position in the graph and therefore the highest potential for risk mitigation. Consistent with the above assumption 1st tier risks are situated within the level of the 1st tier supply. Production related risks from the 2nd tier scale up in the graph encapsulating all remaining 2nd tier risks. This finding implies the high potential for risk mitigation down the SC. Export and import (E4) is the only external risk that enters the SC, although it is expected to be found outside the SC. This is because 2nd tier suppliers are mainly located in regions with geographically long distances from the 1st tier. Procurement at the 2nd tier (2S4) is the only internal risk that is positioned outside of the SC. This is because the procurement of raw material is greatly dependent on external conditions. Packaging risks of the 1st tier and 2nd tier have a low hierarchically position in the graph and are less disruptive to the SC.

In summary, the following risks have been identified as having high mitigation potential against SC disruptions:

- Focal firm risks (Warehouse): stock availability (C1), delivery delay (LTD) (C2), quality problems (C3)
- 1st tier supplier risks: production problems (1S2), procurement bottleneck (1S3), demand planning (1S4), priority of series production (1S5)
- 2nd tier supplier risks: production problems (2S2), procurement bottleneck (2S4)
- External risks: natural catastrophes (E1), economic instability (E2), strikes (E3)

To effectively handle the Bayesian calculation, the first adjustment will require an essential complexity reduction of directed interrelations.

5.2.4 Module 4: AS Supply Chain Risk Model

When building the BN, there are two challenges to be taken into account. First, it appears to be impossible to model the AS SC in the same details as in module three. For this reason simplification of the SC risk model in comparison to the results of the cross impact analysis that is needed. Conrady and Jouffe (2011) confirm that simplification techniques such as generalizations, approximations and implicit assumptions of probabilities are accepted in complex systems of causality. These techniques can be used in the BN that in spite of everything still ensures exact calculations (Lauritzen and Spiegelhalter 1988). Second, it is essential to keep both the amount of nodes and the amount of states as small as possible. However, in some cases it is more efficient to transform states into individual nodes (synthetic nodes) even if the number of nodes increases. As shown in Figure 27 the AS SC Risk model as a Bayesian network, can be visually divided into three major components according to the three level supply chain. The transport stages are respectively located as an interface between the supplier levels. The block of after sales specific strategies will settle at the stage of 1st tier supplier and at each SC level there are tier specific risks.

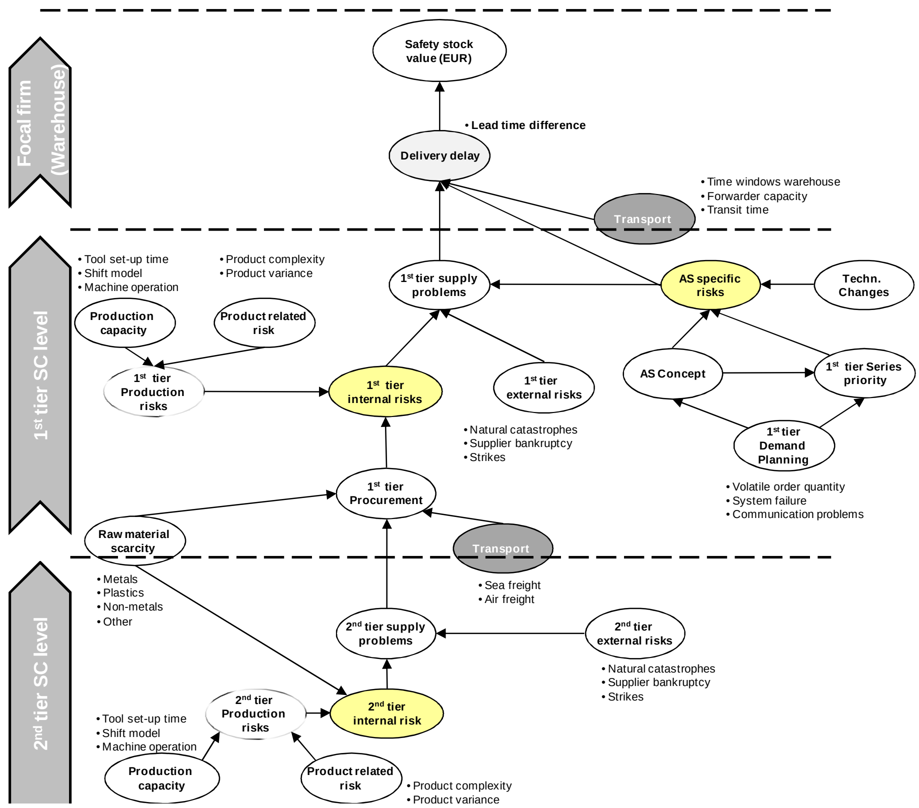


Figure 27 The After Sales RIsk Model

In order to get a better understanding of the established model in a first step, the individual nodes of the network need to be explained. Following the direction of the material flow we start bottom up with the 2^{nd} SC level.

SC Level: 2^{nd} tier

The 2^{nd} tier supply problems as the overall risk in the second SC level are expressed by the nodes 2^{nd} tier external risks and 2^{nd} tier internal risks. The node's internal risks are conditional and multidimensional or in a modeler's language according to Fenton and Neil a so called synthetic node which is characterized by the following Conditional NPT.

Node settings:

Name:	**Internal risks 2^{nd} tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Production risk; Raw material scarcity
NPT mode:	Manual
NPT:	Conditional NPT

Internal risk at 2nd-tier

Raw material scarcity	High			Low		
Production risk	High	Medium	Low	High	Medium	Low
High	0.95	0.6	0.5	0.8	0.5	0.1
Low	0.05	0.4	0.5	0.2	0.5	0.9

Table 10 Conditional NPT – 2^{nd} tier internal risk

The internal risk at 2^{nd} tier SC level contains risks in the production capacity, product related risks respectively and risks regarding raw materials.

The production capacity node is characterized by the following events. Man power capacity risks, tool set-up time risks and the use of the machine explicitly for focal firm productions. The event, "Man power" refers to the risk that adequately trained personnel, for the manufacturing of spare parts, is available. The control of this event is achieved via shift models. The event, “tool setup time” is the risk that in a multi-machine operation and in an additionally integrated manufacturing strategy, the time for tool changing must be as low as possible. The higher the set up time the higher the risk no spare parts are produced in times of capacity scarcity. Finally, the event “multiple-machine operation” provides information about whether other customers share the whole or part of the assembly line. The risks are characterized in a ranked way where risk is low, medium or high.

The probabilities are assigned manually based on expert knowledge.

Node settings:

Name:	**Production capacity 2nd tier**
Node type:	Ranked
States:	High - Medium - Low
Conditioned on:	Man power capacity risk; Tool set-up time risk; Multiple-machine operation
NPT mode:	TNormal
NPT:	"Mean: wmean(1.0, second_tooling, 3.0, second_capa, 2.0, second_multiple_machine)
Variance:	0.01
Interval bound:	0.0 - 1.0"

Name:	**Man power capacity**	**Tool set-up time**	**Multiple-machines**
Node type:	Ranked	Ranked	Ranked
States:	Low (5 shifts / week)	Low (0-1 hours)	Low (yes)
	Medium (10 shifts / week)	Medium (1-2 hours)	Medium (other)
	High (15 shifts / week)	High (>2 hours)	High (no)"
Conditioned on:	-	-	-
NPT mode:	manual	manual	manual
NPT:	0.1	0.6	0,1
	0.3	0.3	0.1
	0.6	0.1	0.8

Product related risks consist of the events product complexity and product variance risk. The product complexity is described by the number of BOM items. The greater the number of BOM items the greater the complexity and production risk. In addition, they do not make variants manufacture of spare parts easier. For example, color variants, country specific features or functional variants in ECUs. As a rule we define the greater the number of options the greater the product related risk. In the second level of delivery, this risk is not quite as serious, since the final variant is formed usually in the first tier SC level.

Node settings:

Name:	**Product related risks 2nd tier**
Node type:	Ranked
States:	High - Medium - Low
Conditioned on:	Product complexity; Product variants"
NPT mode:	TNormal
NPT:	"Mean: wmean(3.0,second_product_complex,2.0,second_product_variants)
Variance:	0.01
Interval bound:	0.0-1.0"

Name:	**Product complexity**	**Product variants**
Node type:	Ranked	Ranked
States:	Low (<8 steps) Medium (8-15 steps) High (>15 steps)	Low (<3 variants) Medium (3-8 variants) High (>8 variants)
Conditioned on:	-	-
NPT mode:	manual	manual
NPT:	0.7 0.2 0.1	0.7 0.2 0.1

Raw material scarcity is comprised of the procurement bottleneck of plastics, metals, minerals and non-metals and other raw materials. Their Boolean probabilities are assigned manually in accordance with expert judgments.

Node settings:

Name:	**Raw material scarcity 2nd tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Plastics; Metals; Minerals and non-metals; Other
NPT mode:	Expression
NPT:	"if(raw_mat_metals == ""Yes"" || raw_mat_plastic == ""Yes"" || raw_mat_minerals == ""Yes"" || raw_mat_minerals_other == ""Yes"", ""High"", ""Low"")"

Name:	**Plastics**	**Metals**	**Minerals**	**Non-metalics**	**Other**
Node type:	Boolean	Boolean	Boolean	Boolean	Boolean
States:	No - Yes	No - Yes	No - Yes	No – Yes	No - Yes
Conditioned on:	-	-	-	-	-
NPT mode:	manual	manual	manual	manual	manual
NPT:	0.9 - 0.1	0.9 - 0.1	0.9 - 0.1	0.9 - 0.1	0.9 - 0.1

The external risks are characterized by natural catastrophes, strikes and supplier's bankruptcy. Their probabilities are manually quantified in the Boolean way, namely the probability of whether the risk occurs or not (yes or no). Among the external risks there is only one interrelation. Natural catastrophes have an effect on a supplier's bankruptcy because the outcome of catastrophes in the geographical regions where 2^{nd} tier suppliers are located, is assumed to be especially severe as demonstrated by the earthquake in Japan in 2011.

Node settings:

Name:	**External risks 2^{nd} tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Natural, 2nd-tier Bankruptcy, Strikes
NPT mode:	Expression
NPT:	noisyor(second_eco_fac, 0.4, second_nat_cat, 0.3, second_strike, 0.5, 0.1)

Name	**Natural catastrophes**	**Bankruptcy**	**Strikes**
Node type:	Boolean	Boolean	Boolean
States:	No - Yes	Low - High	No - Yes
Conditioned on:	-	Natural catastrophes	-
NPT mode:	manual	manual	manual
NPT:	0.75 - 0.25	Conditional NPT *	0.9 - 0.1

Bankruptcy 2nd-tier

Natural catastrophes	Yes	No
High	0.7	0.2
Low	0.3	0.8

Table 11 Conditional NPT – 2^{nd} tier bankruptcy

The final 2nd tier supply problems node is caused by 2nd tier internal and 2nd tier external risks. SC professionals reviewed the validity of the conditional NPT.

2nd-tier supply problems

External risks	High		Low	
Internal risks	High	Low	High	Low
High	0.95	0.7	0.8	0.05
Low	0.05	0.3	0.2	0.95

Table 12 Conditional NPT – 2nd tier supply problems

SC Level: 1st tier

The 1st tier supply problems as the overall risk in the second SC level are expressed by the nodes 1st tier internal risks, 1st tier external risks and the After Sales specific risks. According to the material flow the nodes 1st tier internal risks are modeled as a conditional and multidimensional synthetic node which is characterized by a Conditional NPT.

Node settings:

Name: Internal risks 1st tier

Node type: Boolean

States: Low - High

Conditioned on: Production risk; Procurement bottleneck

NPT mode: manual

NPT: Conditional NPT

Internal risk at 1st tier

Procurement bottleneck	High			Low		
Production risk	High	Medium	Low	High	Medium	Low
High	0.9	0.7	0.3	0.7	0.3	0.1
Low	0.1	0.3	0.7	0.3	0.7	0.9

Table 13 Conditional NPT – 1st tier internal risk

The internal risk at 1st tier SC level contains production capacity risks, product-related risks and risks regarding procurement bottlenecks. The production capacity risks and product related risks are assessed in a similar way as in the 2nd tier. The difference, however, lies in the individual node settings. In the majority of cases the products are essentially only assembled. The availability of sufficient production capacity is in most cases a central after sales problem in a series parallel production-/-assembly because the probability of becoming a bottleneck in terms of staff or equipment availability is much higher as in the lower levels of the SC.

Node settings:

Name:	**Production capacity 1st tier**
Node type:	Ranked
States:	High - Medium - Low
Conditioned on:	Man power capacity risk; Tool set-up time risk; Multiple-machine operation
NPT mode:	TNormal
NPT:	Mean: wmean(1.0,first_tooling,3.0,first_capa,2.0,first_focal_firm_mach)
Variance:	0.01
Interval bound:	0.0 - 1.0

Name:	**Man power capacity**	**Tool set-up time**	**Multiple-machines**
Node type:	Ranked	Ranked	Ranked
States:	Low (5 shifts / week)	Low (0-1 hours)	Low (yes)
	Medium (10 shifts / week)	Medium (1-2 hours)	Medium (other)
	High (15 shifts / week)	High (>2 hours)	High (no)"
Conditioned on:	-	-	-
NPT mode:	manual	manual	manual
NPT:	0.4	0.4	0,7
	0.5	0.5	0.1
	0.1	0.1	0.2

Product related risks are assessed in a similar way at the first SC level as in the second level. The difference, however, lies in the individual node settings. The number of variants is determined by the logistical complexity in the assembly of all products, because the variants (e.g. colors, software, and country specific features) are most often made in the last stages of production lines. If an error occurs in the last stages of the whole production line then it is quick to reach the maximum capacity. Another point is that the higher the number of varieties the less an assembly line can be used for spare part production.

Node settings:

Name:	**Product related risks 1st tier**
Node type:	Ranked
States:	High - Medium - Low
Conditioned on:	Product complexity; Product variants"
NPT mode:	TNormal
NPT:	Mean: wmean(3.0,first_product_complex,2.0,first_product_variants)

Variance: 0.01

Interval bound: 0.0-1.0

Name:	**Product complexity**	**Product variants**
Node type:	Ranked	Ranked
States:	Low (<8 steps)	Low (<3 variants)
	Medium (8-15 steps)	Medium (3-8 variants)
	High (>15 steps)	High (>8 variants)
Conditioned on:	-	-
NPT mode:	manual	manual
NPT:	0.2	0.2
	0.6	0.5
	0.2	0.3

The procurement bottleneck at the 1st tier supplier depends on raw material scarcity, the interrelated 2nd tier supply problems and transportation delays from the second level supplier to the first level supplier.

Node settings:

Name: **Procurement bottleneck 1st tier**

Node type: Boolean

States: Low - High

Conditioned on: Raw material scarcity; Transportation delay; 2nd-tier supply

NPT mode: manual

NPT: Conditional NPT

Procurement bottleneck at 1st-tier

Raw material scarcity	High						Low					
Transportation delay	High		Medium		Low		High		Medium		Low	
2nd-tier supply	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
High	0.95	0.8	0.9	0.7	0.85	0.6	0.8	0.4	0.7	0.2	0.6	0.05
Low	0.05	0.2	0.1	0.3	0.15	0.4	0.2	0.6	0.3	0.8	0.4	0.95

Table 14 Conditional NPT – 1st tier procurement bottleneck

Scarcity of the raw material affects the 1st tier to the same magnitude as at the 2nd tier and therefore the raw material risk is defined in the same way as at the 2nd tier.

The transportation delay can be caused by low, medium or high risk level of the sea and of the air freight. The transportation delay follows the Tnormal distribution with a mean weighted once by the sea freight and twice by the air freight. This weighting has been determined due to the fact that in any case of a sea freight bottleneck there is a possibility to compensate delivery delay of the sea freight by sending additional ordered parts by special delivery or via air freight.

Node settings:

Name:	**Transportation delay 1st tier**
Node type:	Ranked
States:	High - Medium - Low
Conditioned on:	Sea freight; Air freight
NPT mode:	TNormal
NPT:	Mean: wmean(1.0,transport_sea,2.0,transport_air)
Variance:	0.01
Interval bound:	0.0 - 0 .1

Name:	**Sea freight**	**Air freight**
Node type:	Ranked	Ranked
States:	Low: 0-4 weeks	Low: 0-3 days
	Medium: 5-8 weeks	Medium: 4-7 days
	High: >9 weeks	High: >8 days
Conditioned on:	-	-
NPT mode:	manual	manual
NPT:	0.1	0.2
	0.6	0.5
	0.3	0.3

The interrelated 2nd tier supply problems directly affect the procurement of semi finished components at the 1st tier. AS specific risks is the special risk cluster that causes in most cases the final supply problems on the 1st tier level. The implementation of nodes in the AS concept, series priority and change management concepts sum up the AS risks.

Node settings:

Name:	**AS specific risks 1st tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Series priority; Change Management concept; Implemented AS concept
NPT mode:	Expression
NPT:	noisyor(series_prio, 0.5, first_change_mngt, 0.55, AS_concept, 0.5, 0.05)

Compared to mass production small and sporadically ordered quantities provide for almost any massive production planning problems as long as no after sales concept is aligned with the focal firm. If we delve one step deeper another problem on the supplier's side are the inconsistent and not always considered scrap rates out of the supplier's assembly line which effect the total demand in the end. It comes down to the quantity, or in most cases, to lead time differences in the delivery to the customer. This is why problems in demand planning conditionally affect the node AS Concept. The implementation of an AS supply strategy is dependent on whether there is an accurate or imprecise demand planning. The Boolean probabilities of whether the supplier has an implemented AS supply strategy or not are assigned manually based on data provided by Module 2 (cp. Figure 22).

AS concept

Demand planning	High	Low
High	0.75	0.35
Low	0.25	0.65

Table 15 Conditional NPT – 1st tier after sales concept

Manual probability quantification is also assigned to the node states of technological changes and the series priority risk.

Node settings:

Name:	**Change Management 1st tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	-
NPT mode:	Manual
NPT:	0.6 – 0.4

The After Sales specific risks are interrelated to each other and the degree of the series production priority depends on both the availability of an implemented AS supply strategy and also on the availability of an accurate demand planning.

Node settings:

Name:	**Series priority 1st tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Demand planning; Implemented AS concept
NPT mode:	manual
NPT:	Conditional NPT

Series priority at 1st-tier

Demand planning	High		Low	
AS concept	Low	High	Low	High
High	0.8	0.3	0.7	0.1
Low	0.2	0.7	0.3	0.9

Table 16 Conditional NPT – 1st tier series priority

The demand planning risk includes the sub risks of volatile orders from the focal company, possible system failures and communication problems for both between the 2nd tier as well as for the focal company.

Node settings:

Name:	**Demand planning 1st tier**
Node type:	Boolean
States:	Low - High
Conditioned on:	Volatile order quantity; System failures; Communication problems
NPT mode:	Expression
NPT:	noisyor(order_qty, 0.2, sys_fail, 0.4, comm_prob, 0.4, 0.1)

Name:	**Volatile orders**	**System failures**	**Communication problems**
Node type:	Boolean	Boolean	Boolean
States:	Forecast error < 0.3	EDI errors < 0.1	Low - High
	Forecast error > 0.3	EDI errors > 0.1	

Conditioned on:	-	-	-
NPT mode:	manual	manual	manual
NPT:	0.3	0.9	0.7 – 0.3
	0.7	0.1	

The 1st tier external risks are composed similarly to those of the 2nd tier level. The only difference is that for the 1st tier supplier that there are no interrelations between the external risks because of the following reason. The supply chain structure in the first level of the investigated product group and the suppliers of the company involved in this research are mainly located in regions, where the impact of natural catastrophes is less likely to have an effect on the supplier's financial performance.

The overall 1st tier supply problems node is caused by specific AS risks, 1st tier internal and 1st tier external risks with the following node settings.

Node settings:

Name:	**1st tier supply risks**
Node type:	Boolean
States:	Low - High
Conditioned on:	AS-specific risks; External risks; Internal risks
NPT mode:	Expression
NPT:	noisyor(first_ext_risks, 0.5, first_internal_risks, 0.5, first_AS_risks, 0.5, 0.1)

SC Level: Focal firm (Warehouse)

The final stage of the inbound SC describes the extent of total damage expressed by lead time differences in days. The 1st tier supply problems, the AS specific risks, and the transportation delays are responsible for the delivery delay at the focal firm (Warehouse).

The 1st tier supply problems sum up risks that originate in the SC from the 1st tier level considering the risk effect from the 2nd tier level and the transportation problems.

The lead time difference at the focal firm follows a Tnormal distribution based on historical SAP data from Module 1.

Node settings:

Name:	**Delivery Delay (Focal firm)**
Node type:	Continuous interval
States:	0 - 90
Conditioned on:	1st-tier suppliers; Transportation; AS-specific risks
NPT mode:	TNormal
NPT:	Conditional NPT

Delivery delay at focal company

1st-tier supply problems	High (30; 90)				Low (2;7)			
AS-specific risks	High (21; 60)		Low (7;14)		High (21; 60)		Low (7;14)	
Transportation delay	High	Low	High	Low	High	Low	High	Low
Expression	TNormal(27,75,1,360	TNormal(25,75,1,360	TNormal(21,52,1,360	TNormal(19,52,1,360	TNormal(14,34,1,360	TNormal(12,34,1,360	TNormal(7,11,1,360	TNormal(5,11,1,360

Table 17 Conditional NPT – Focal firm lead time differences

The AS specific risks are also triggered to a certain extent, by the focal company due to contractual requirements, small batch sizes and long internal process times in technological related product changes and therefore directly influence this node based on product availability.

Transportation related risk is a multilevel node with five events which are measured in hours of the capacity limits at the warehouse and the transportation risk (e.g. transit time risks caused by external factors like traffic congestion, truck maintenance) during the transportation from the first tier SC level to the focal firm.

Node settings:

Name:	**Transportation delay to focal firm**
Node type:	Boolean
States:	Low - High
Conditioned on:	Transport-related delay
NPT mode:	Expression
NPT:	if(val(total_transport_delay)<12, "Low", "High")

Node settings:

Name:	**Transport related delay**
Node type:	Continuous interval
States:	0-100
Conditioned on:	Lacking time window capacity; Lacking forwarder capacity; Transit-time related delay
NPT mode:	Arithmetic
NPT:	lacking_capacity_forwarder + lacking_time_windows + transit_time

Name:	**Total Time window**	**Lacking Time window**	**Total Forwarder Capacity**
Node type:	Continuous interval	Continuous interval	Continuous interval
States:	0-24	0-24	0-24
Conditioned on:	-	Total time window	-
NPT mode:	Tnormal	Binominal	Tnormal
NPT:	Mean: 6.75	Trial: total_capacity	Mean: 6.75
	Variance: 5.1	_time_window	Variance: 10.6
	Interval bound: 0-24	Success: 0.01	Interval bound: 0-24

Name:	**Transit time related delay**	**Lacking forwarder Capacity**
Node type:	Continuous interval	Continuous interval
States:	0-24	0-24
Conditioned on:	Total forwarder capacity	-
NPT mode:	Tnormal	Binominal
NPT:	Mean: 2	Trial: total_capacity_forwarder
	Variance: 25	Success: 0.01
	Interval bound: 0-24	

To illustrate the impact on the safety stock we hold that the delivery delay expressed by lead time differences is the overall uncertainty on the inbound side of the SC. From the point of view of the inventory management, demand-related uncertainties are managed by means of the safety stock. Consequently, the safety stock can be strategically implemented to buffer risks emerging from the supply side of the SC. Based on the framework assumptions the lead time difference in days at the focal firm is assumed to be equivalent to the safety stock in days kept in the spare parts warehouse of the focal firm. This is how the safety stock secures the stock availability from the inbound perspective.

In order to make results comparable when it comes to the simulation it is useful to assign monetary units to the safety stock. The node safety stock value in monetary units is obtained by multiplying the total amount of days where orders have been delivered late by the average cost of keeping the equivalent orders on hand.

Node settings:

Name:	**Safety stock value**
Node type:	Continues Interval
States:	-30,000-3,500,000
Conditioned on:	Delivery delay
NPT mode:	Arithmetic
NPT:	stock_value*behind_schedule

The stock value is expressed by a constant of the total amount of stock keeping units in the warehouse in monetary units. Finally, Figure 28 illustrates the initial After Sales Risk modeled in agenaRisk.

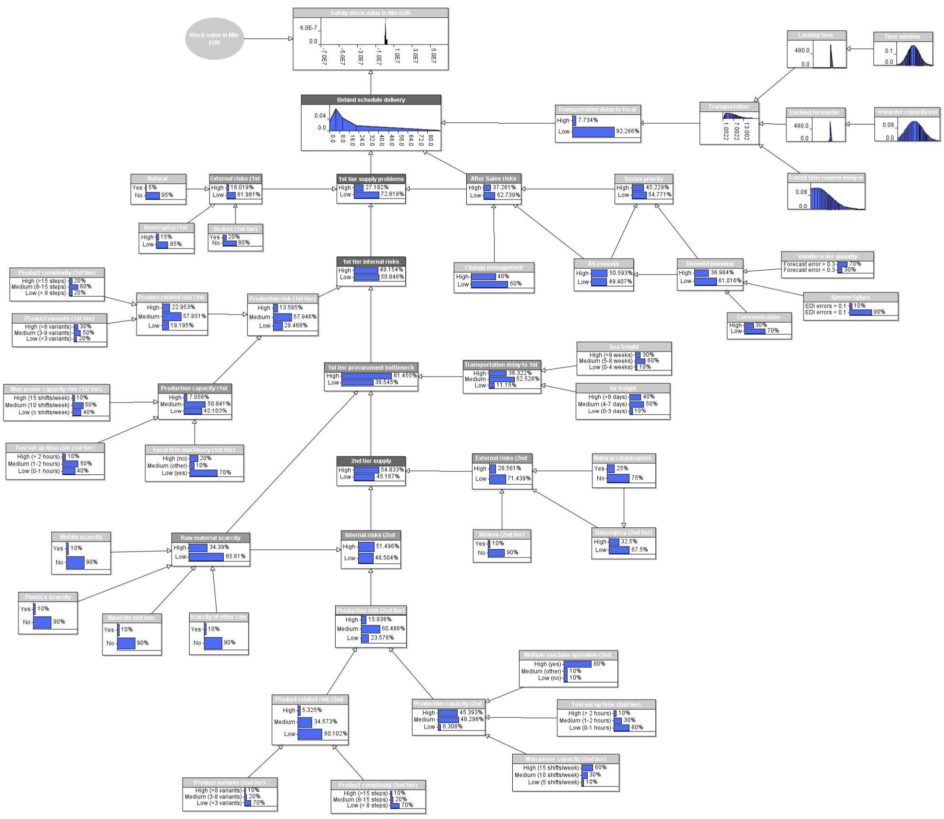


Figure 28 The After Sales RIsk Model in agenaRisk

5.3 Model Validation

In order to meet the requirements of the ASRIM it is necessary to drawn a zero line in the initial model. Based on the real SAP delivery data only late deliveries of spare parts can be considered in the validation of the ASRIM because only the delayed deliveries are risk relevant. In summary the 7,428 spare part deliveries from product group number six (electronic parts) must be limited because only 4,399 delivery data sets were delivered late. As shown in Figure 29 the mean lead time difference of the SAP delivery data analysis for late delivered spare parts is 13.77 days with a standard deviation of 24.86 days. In comparison the initial causal model with the risk specification of each node and the multiplication of corresponding conditional probabilities in the model results in a mean of 13.659 days for total lead time difference over the whole SC inbound structure.

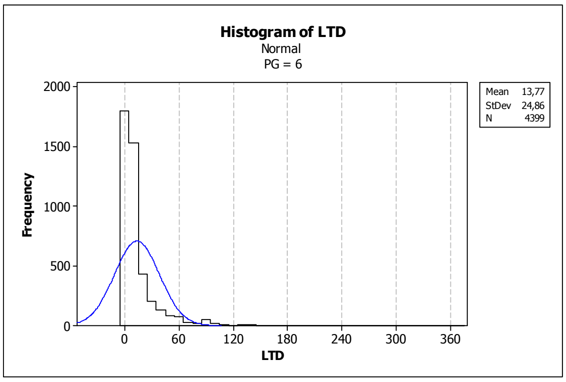


Figure 29 Validation of the After Sales RIsk Model

The difference between the ASRIM and the system data analysis is only 0.11 days this comparison confirm the validity of the ASRIM.

5.4 Scenario Analysis

The scenario analysis has been applied by several scholars (Chopra and Sodhi 2004, Kleindorfer and Saad 2005, Stecke and Kumar 2009, Lockamy III and McCormack 2010, Yen and Zeng 2011). For risk analysis in the Bayesian network there are two main relevant approaches. The bottom-up analysis examines the effect of risks at any level in the SC referring to the central risk size. The top-down analysis is equivalent to the sensibility analysis and detects those risks that cause the central risk size. The sensitivity analysis has been proven to be appropriate to detect the root cause of risks (Jensen, Aldenryd et al. 1995, Rabelo, Eskandari et al. 2007, Lockamy and McCormack 2009).

Scenario 1: Raw material scarcity

We propose that a particular material due to resource constraints over an extended period is no longer available. Under this condition the 2nd tier supplier is not able to produce and deliver a specific module component to the 1st tier supplier. To overcome the supply bottleneck, the 1st tier supplier decides to initiate a spare part redesign in coordination with the customer. After entering the new information in the model we are able to calculate the new situation regarding lead time differences on the focal firm level. Based on this new situation the probabilities of the SC risks in Table 18 are updated in the ASRIM.

Supply chain risk	**Prior probability**	**Evidence probability**	**Posterior probability**	**Delta Posterior - Prior**
Change management	40.0%	70.0%	60.9%	**+20.9%**
Series priority	45.2%	80.0%	76.8%	**+31.6%**
Procurement 2nd tier	10.0%	100.0%	100.0%	**+90.0%**
Financial risk 2nd tier	32.5%	60.0%	41.9%	**+9.4%**
Product complexity 2nd tier	30.0%	0.0%	0.0%	**-30.0%**

Table 18 Scenario 1: Effects of belief updating in the ASRIM

The prior probabilities represent the initial status of the model. The evidence probabilities reflect the risks that have been entered into the risk model for belief updating based on the new knowledge from the suppliers. The posterior column represents the new risk situation after the processed belief updating in the ASRIM. In the last column the changes between the prior and posterior probabilities are presented. The decision for the spare part redesign requires undergoing the process of change management, which is exposed to additional risk in the After Sales. This knowledge leads to a higher risk perception. Thus 70 percent of the estimated risk evidence is entered into the risk node change management. After recalculation the network the posterior probability for this risk node increases by 20.9 percent and results in 60.9 percent of the new risk perception. The spare part redesign reduces product complexity. For this reason the evidence probability for the risk node product complexity 2nd tier is supposed to decline. The evidence probability for this risk is zero percent that reduces the posterior probability of the perceived risk by 30 percent. In this manner the risk nodes series priority, procurement 2nd tier and financial risk 2nd tier were inserted into the risk model.

The first outcome of the evidence updating is a significant change of the posterior probabilities of the scenario relevant risk nodes. The second outcome is the change in posterior probabilities of conditional risk nodes. These six further nodes do not receive a direct evidence update but they are also affected. AS-specific risk, in particular the AS supply strategy, and procurement problems at the 1st tier level have the highest affected probability change.

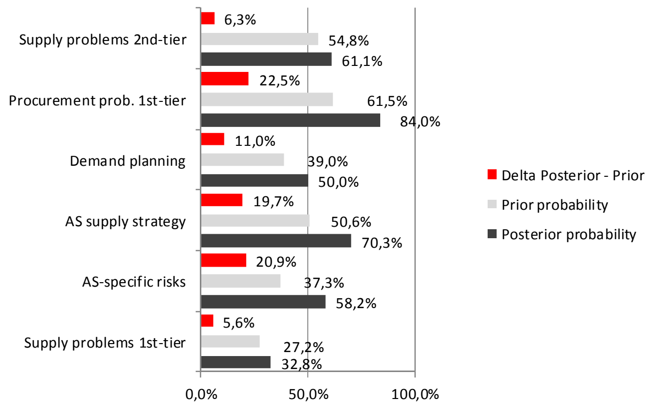


Figure 30 Scenario 1: Raw material scarcity risk cluster

The most relevant information update is that the probability changes end up in the central risk node. We have to expect an additional 2.7 days of lead time difference which is equivalent to a stock value increase of an additional 19.8 percent to bridge the waiting time due to the spare part redesign.

Supply chain risk	**Prior probability**	**Posterior probability**	**Delta Posterior - Prior**
LTD (Warehouse)	13.7 days	16.4 days	**+2.7 days**
Safety stock value	100%	119.8%	**+19.8%**

Table 19 Scenario 1: Posterior effects on the central risk element

The new situation in this scenario is that with the overall information from the ASRIM, is that the operations are now able to work specifically on minimizing the risk in the individual clusters or find other internal measures in the central inventory management for example increasing specifically and temporarily the stocks of the affected spare parts.

Scenario 2: New Parts

Entirely new and specialized parts are designed and affect the investigated SC and part group for an extent scale. The new parts were delivered from new suppliers and this new suppliers in the SC are not familiar with the processes of the focal firm. Beside the challenge a lack of experience, the supplier struggles with high machinery and tool investments. In addition, the new technology is more susceptible to quality issues and requires long term change management processes on the one hand (in general, one change in one part requires a change in another part), and on the other hand it is subject to a higher demand for spare parts due to the higher probability of damage to vehicles already on the market. Therefore, six months before the SOP there is a requirement to build up a stockpile of spare parts. The AS specific requirements, such as packaging and labeling, make the supply process of spare parts more complex than the standardized supply of series modules. This leads to the cannibalization phenomenon between the series and the AS quantities. Through discussions with experts we found the eight most relevant SC risks for this scenario. After entering the new evidence in the ASRIM for belief updating and their corresponding posterior probability in the risk model, we established the new risk structure in the SC. (cp. Figure 31)

Supply chain risk	Evidence probability
Series priority	80.0%
AS supply strategy	70.0%
Change management	60.0%
System failures	60.0%
Communication problems	60.0%
Financial risk 1st-tier	55.0%
Product complexity 1st-tier	90.0%
Product variants 1st-tier	95.0%

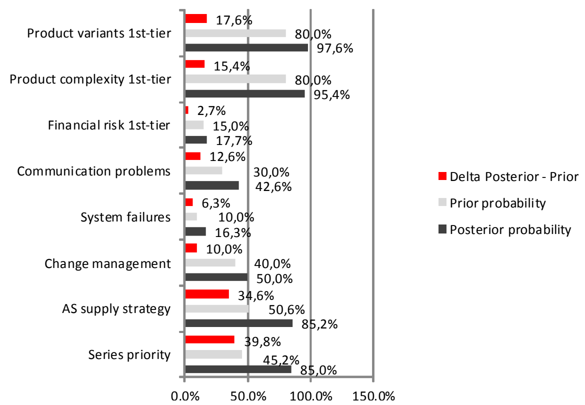


Figure 31 Scenario 2: Effects of belief updating in the ASRIM

The ASRIM belief updating over all SC levels shows seven further risk nodes which are exposed to a probability change (Appendix H). The demand planning risk and the total AS specific risks show the strongest risk effect among all observed. The dynamics of all affected risks lead to additional 2.7 days in lead time difference and to an increase of 20.1 percent in the value of the stock.

Scenario 3: Demand increase

There are multiple reasons for unexpected increases in demand. For example customers from a new market order the basic product and after the purchase they upgrade the basic product with original parts in order to avoid additional tax payments for luxury goods when importing the primary product. Such purchasing behavior is difficult to forecast since no previous data is available. Second, for promotion purposes in Middle Eastern countries a high number of special products are ordered within a short time period. Late communication leaves little room for appropriate supply planning. Finally, an increment of unplanned demand for primary products increases the series production. At the same time a particular supplier reaches its production capacity peak and therefore prioritizes the deliveries for series production. Prior Risk probabilities, evidence probabilities for belief updating and posterior probabilities of this scenario are presented below in Table 20.

Supply chain risk	Prior probability	Evidence probability	Posterior probability	Delta Posterior - Prior
Transportation delay 1st-tier	7.7 hours	55.0%	9.3 hours	**+1.6 hours**
Series priority	45.2%	80.0%	77.3%	**+32.1%**
Volatile order quantity	70.0%	90.0%	95.6%	**+25.6%**
Production capacity 1st-tier	57.9%	80.0%	76.6%	**+18.7%**
Product variants 1st-tier	80.0%	90.0%	95.1%	**+15.1%**
Procurement prob. 1st-tier	61.5%	75.0%	82.7%	**+21.2%**

Table 20 Scenario 3: Effects of belief updating in the ASRIM

The belief updating of the expected risks affects further risk nodes in the overall ASRIM. The risk of AS supply strategy shows the highest risk affect. All six risks for the belief update and seven additionally affected risks produce a delivery delay of an additional 1.8 days and a stock value increase of 13.6 percent.

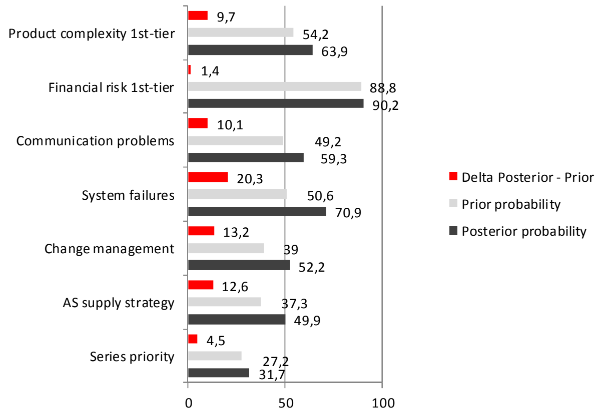


Figure 32 Scenario 3: Demand increase risk cluster

Supply chain risk	Prior probability	Posterior probability	Delta Posterior - Prior
LTD (warehouse)	13.7 days	15.5 days	**+1.8 days**
Safety stock value	100%	113.6%	**+13.6%**

Table 21 Scenario 3: Posterior effects on the central risk element

5.5 Sensitivity Analysis

Another type of analysis is the observation of a Bayesian network for the purpose of determining the value of information, or the determination of the influence individual variables have on the overall system or other variables. In both cases we are referring to a sensitivity analysis (Laskey 1995). Such analyzes allow on the one hand, cost-benefit assessments, for example, in evaluating the accuracy of a diagnosis (e.g. development of the buffer stock value) to derive how the collected evidence affects the accuracy of a diagnosis and how the evidence must be improved (e.g. more accurate data by adding or exchanging a risk sensor in the modeled SC). On the other hand, a sensitivity analysis, is the accurate determination of weak points in the system, through the provision of essential influences on desired or undesired risk clusters.

In the sensitivity analysis, either a series of scenarios are generated by the default of evidence, and then are compared to the results of the inference process, or an aggregation of various scenarios assessed by considering their similarities. Both methods are counting on the influence of some (less) parameters considered targets. In this work a best case and worst case scenario have been developed to test the risk sensitivity in the ASRIM. The following table illustrates the sensitivity analysis results of a mean of 22 days lead time difference for the worst case scenario and the results of a mean of only 5 days lead time difference for the best case scenario. The initial risk situation in the modeled inbound SC represents a mean of 14 days lead time difference and is also listed for comparison purposes.

			Focal Company (central warehouse)		1st-tier SC level							2nd-tier SC level
Delta buffer stock value	Delta LTD in days		Safety stock value	LTD in days	Series priority	Change Management	AS concept	Demand planning	AS-specific risk	Internal risk	1st-tier supply problems	2nd-tier supply problems
+ 100%	+57%	↗	2,089,800	22	57.4	49.2	62.4	44.3	66.5	56.7	66.5	55.8
-	-	●	1,044,900	14	45.2	40.0	50.6	39.0	37.3	49.2	27.2	54.8
- 50%	- 64%	↘	522,450	5	34.3	31.8	40.0	34.2	11.1	44.7	2.1	54.3

Table 22 Sensitivity analysis: Effects on LTD in a worst case and best case scenario

In the worst case scenario the delivery delay increases from a prior of 14 days to a posterior of 22 days and leads to the safety stock doubling. As indicated by the probability increase, this result is mainly due to the AS specific risks, especially the risk of series priority and AS supply strategy, and due to 1^{st} tier supply problems. In the best case scenario the delivery delay decreases from a prior of 14 days to a posterior of 5 days and leads to a safety stock reduction of 50 percent. Also, the best case scenario indicates AS specific risks, especially the risk of series priority and AS supply strategy, and 1^{st} tier supply problems which strongly affect risk probabilities within the ASRIM. This shows that the lead time differences can be traced back to a few After Sales specific risks in the SC. Until here and from this point of view we can conclude, it's quite possible to achieve a low mean of lead time differences by eliminating or steering the right risks in the after sales inbound supply chain with the developed model.

6 SUMMARY

The major objective of this research was the development of a flexible and practically usable After Sales SC Risk Model (ASRIM) which is based on the SCRM process described in the literature. The developed risk model based on the Bayesian concept evaluates risks in an exact way as it captures all risk interrelations by means of conditional probabilities when determining their impact on the SC. Furthermore, the developed risk model is more flexible and more accurate when it comes to analyzing SC risks because new information can be integrated in a simple and efficient way providing a different perspective on the total SC risk. It supplies SC experts with a reliable overview of the affected supply chain. The idea to include the lead time difference as a central risk size in the ASRIM with a direct impact on the stock makes it possible to derive mitigation strategies and manage after sales warehouse buffers in a selective and temporary manner. It is possible to run the ASRIM based on risk symptoms in the SC network to make an exact diagnosis of expected lead time differences and their direct impact on the buffer stock value on a focal firm level. On the other hand it is possible to manage the SC in a preventive manner, which means going from a lead time target down to the risk symptoms in the multistage SC.

6.1 Findings

In terms of a critical evaluation of the results within this work the research questions of Section 1.2.3 will be revisited in this chapter. To answer the central research questions a four step approach was applied. The first two modules concentrate on answering the first research question. To get a comprehensive picture of the vulnerability and the risks of the affected AS SC it is first important to ensure transparency. Based on output from different suppliers, approximately 60,000 delivery data sets from a MRP – System was investigated. From this extensive data it was possible to exclude correlating relationships and to define the LTD as the central risk size. As a further result of the data analysis, a reverence supply chain was modeled and subjected to 75 suppliers from the same category of an empirical survey. New knowledge for the research area and for the company was collected and the first research question could be answered.

Question 1: What are the essential risks within an After Sales inbound Supply Chain?

We empirically confirmed four increasing risk trends for the investigated AS SC of the company and also identified the high variety of parts and the long parts supply cycles as special risk drivers of the AS SC. Through the comprehensive literature review of the general SC risks we could demonstrate that the network risk can be seen as a serious risk of After Sales Supply Chains. It turned out that in particular the risks of discontinued components as well as the shortage of raw minerals for spare parts are particularly serious risks. In addition, the location dependent effect of the 2nd tier suppliers and especially the increasing risk awareness of environmental risks due to the dramatic event of a natural disaster in Fukushima have been outlined. Through the survey of suppliers and the results of the risk portfolio it was possible to identify ten severe AS SC risks that were all rated above average in both the EV and in the LTD. Overall, there were seven AS SC risks and three risks for special spare part strategies identified on the direct supplier level, cp. Chapter 5.2.2. It was shown in particular that a large part of the ten After Sales inbound supply chain risks corresponded to the findings and assumptions made in modeling the AS SC and from previous expert discussions.

The second research question is answered by the content of module three and four and based on the results from the first two modules. For the risk identification the results from the empirical study, in total 21 AS risks, cp. Table 7, were restructured towards a representative after sales multiple suppliers SC. To manage AS SC risks efficient in the operations it is necessary to understand their causal interrelation over all SC levels. Therefore a 21 by 21 interrelation matrix was constructed with the aim to identify causal relationships between risks and visualize them in a causal risk network. For risk evaluation the risk network was transferred to an acyclic graph where risk probabilities were assessed individually in conditional and unconditional probability tables. The peculiarity of mapping conditional probabilities in a network and integrating new knowledge into a network were the main constraints for the development of the After Sales Risk Model. The applicability of the Bayesian logic for causal SC risk evaluation was chosen and proven in Chapter four. The developed model is flexible and dynamic not least for the belief updating. It can be adapted for other purposes if risk clusters, in the form of the network nodes are specifically redefined. The risk analysis of the developed Bayesian Network provides following SCRM insights scientifically and practically. The second question can be answered as follows.

Question 2: How could risks be operationally managed to minimize lead time differences in the focal Firm (Warehouse)?

The scenario and sensitivity analyzes of the developed model verify that the occurrence of one risk has an impact on other risks in the SC. The risk structure in the modeled SC accumulates risks on the focal firm level on the top of the SC causing the central risk size LTD. The main impact on the LTD is caused by AS specific risks and by 1st tier supply risks. In this regard, if AS specific risks are mitigated first, they would simultaneously mitigate risks originating in the first supplier level. The third result is that a reduction of the delivery delay has a positive effect on the buffer stock. In the modeled BN it is possible to reduce the stock on the focal firm level up to fifty percent. To reduce the LTD this requires a reduction of AS specific risks from a prior of 37.3 percent to a posterior of 11.1 percent, and 1st tier supply risks from a prior of 27.2 percent to a posterior of 2.1 percent. In particular risk reduction measures related to the risk of series priority, to the risk of insufficient AS supply strategy and to the risk of lacking change management would reduce the AS specific risk and automatically diminish the supply risk from the first SC level.

To preventively manage AS specific risks the following strategies need to be further developed for operational implementation. The capacity assignment at the supply source according to the value stream would enable a requirement tailored production strategy for spare parts supply. This would not only reduce the risk of an unaligned strategy for spare parts production but would also diminish the risk of series priority where series and spare parts production are subject to cannibalization in favor of series quantities. It is shown that not only risk impacts have causal effects on each other, but also risk mitigation strategies, meaning that a mitigation action for one risk has the potential to mitigate another risk. At this point it is crucial to be aware of possible mitigation measures having a positive effect on one risk but a reverse effect on another risk. This is essential to pay attention to when selecting appropriate mitigation strategies. In this context, it is also important to be aware that there is not only one mitigation strategy that might be appropriate. The quantity harmonization is another countermeasure to control the risk of series priority. If a series is harmonized and spare parts quantities are managed, then the supplier is able to plan and forecast possible production capacity bottlenecks in advance and proactively respond to threatening delivery delays. We conclude that the ASRIM is able to control the SC risks with a SC expert.

6.2 Discussion

This work incorporated numerous methods, concepts and theories from scientific research and checked them for applicability in the specific area of After Sales. Based on the identified research gaps listed in chapter three the new knowledge gained with this work are now reflected and discussed in detail and in a scientific context.

No attention to SCRM related to the AS inbound SC network:

The three main phases of the SCRM process for proactive SCRM are a central part of this work. Concepts described in the literature, along with process steps and tools of SCRM (cp. Chapter 2.4) were adjusted to the research topic in the context of a practical case study which enables the development and implementation of a concrete approach for identifying, evaluating and controlling inbound AS SC risks (cp. Chapter 5.2). It was possible to gather new information about a well-chosen spare part product group and their essential supply risks provided by the practical implementation of the main elements of the SCRM process within the case study. In summary, the company gets a wide range of instruments for SCRM based on empirical analysis of the AS SC risks. With the development of the ASRIM as a Bayesian network, it is possible to develop proactive measures to mitigate the identified SC risks and to immediately decrease the overall risk of AS SC to improve the overall After Sales inbound delivery performance. Since Bayesian networks are in principle learning systems it was possible to demonstrate a new approach for SCRM on the supplier side of an AS inbound SC network. Now a sustainable SCRM is implemented to realize a risk based inventory and supplier management within the After Sales organizations.

The specific AS inbound SC risks are unknown:

However, no general agreement exists on the risk typology because risks are not the same (Zsidisin and Wagner 2010) and vary across industries, companies and products. In the automotive industry risks that stem from the supply side contribute to SC disruptions to a higher degree than the demand side (Wagner and Neshat 2010). Similar to other studies (Chen, Xia and Wang 2010, Zsidisin and Wagner 2010, Zsidisin et al. 2004) the inbound supply risks are the main research object.

For this reason, the author first examined how suppliers assess the vulnerability of the AS SC of the company involved in this research. The results showed that the vulnerability of the AS SC is generally rated as low. This is in great contrast to the general SC results presented in the literature by Jüttner (2005), Schatz et al. (2010) and Thun & Hoenig (2011). These authors have identified a consistently high level of vulnerability of the SC in its investigations. On the one hand storage in the AS is more common than in the general SC, investigated by Thun & Hoenig (2011) so that disturbances of the SC can be initially compensated by the warehouse stock and thus does not directly result in interruptions of AS SC. Furthermore, it was shown that the increasing complexity trends, identified in the literature, such as globalization and the increasing efficiency trends such as inventory reduction, outsourcing or single sourcing in the AS SC are also significant risk drivers. In particular, the inventory reduction and the resulting associated increasing dependence on the smooth functioning of the SC as well as globalization, due to cultural differences and the increased transport distances were evaluated as the largest risk drivers. These results are similar to the results of various empirical studies on the risk drivers of the general SC from Thun & Hoenig (2011), Jüttner (2005) and Wagner & Neshat (2010). It can therefore be empirically confirmed that increasing complexity and efficiency in both general SC's and in the AS SC are relevant risk drivers.

In addition to the trends mentioned above additional factors like the high spare part variants and the long product life cycles of spare parts which result from the difficult conditions of AS, were studied with respect to their risk driven effects. The investigation showed that these two factors have a nearly identical risk increasing influence as the general trend has attributed. Possible reasons for this are the increased need for coordination and the greater complexity due to the high variations of spare parts and the need to maintain the AS SC's due to long supply cycles. This leads to an overall increase in complexity and thus risk increases. Therefore, these two factors can be confirmed as special risk drivers of the AS SC empirically.

After consideration of the risk drivers the actual AS SC risks were investigated. It emerged that both the 1st tier and 2nd tier suppliers of the investigated SC scored highest for the network related procurement risks, against another five types of risk in relation to the EV as well as the LTD. This result corresponds exactly to the result already gained in the empirical studies of Kersten et al (2006), Wagner & Bode (2007), Thun & Hoenig (2011). In these studies, the network risk was also the highest, dependent on a value added focus. We can conclude that in both SC's general or After Sales specific, and independent of the value level, the supply network risks from Jüttner (2003), arising from the interaction of SC partners, will assess most severely. In contrast, the environmental risks were evaluated very differently in the two value added stages of AS SC as well as compared to the survey risk analysis. Thus, the EV of the environmental risks, in the second SC level was rated significantly higher than in the first SC level.

This is to a large scale due to the different locations of the suppliers. While the production plants of the first tier suppliers were mainly in Germany the second tier suppliers have their plants in the SC mostly in Asia and thus from areas where environmental risks, particularly natural disasters, occur much more frequently than in Germany. The extent of damage from these risks were in the past risk analysis studies rated low but now the environmental risks have reached the second highest level for LTD in this risk analysis. One explanation for this could be the disaster in Fukushima in 2011. The Fukushima disaster may have, in relation to the disastrous consequences for global SC, resulted in the suppliers having a higher sensitivity and risk awareness of environmental risks.

As part of the risk analysis it was further demonstrated that the risks of the investigated product group compared with those of the standard spare parts, are not significantly different. This result, surprisingly, is very different from the assumptions derived in the literature that due to the special nature of electronic spare parts which SC would have a greater risk than other parts. However, this confirmed, the statements of experts which have similar problems in delivery time deviations for crash and maintenance spare parts. It turned out that the two most commonly used spare parts supply strategies, the long term storage and the integrated manufacturing have the highest overall risk for an AS SC. This confirms the view that, with this strategy, the risks usually relate to the entire stock and can be, in the case of exhaustion only, very slow, when responding to production of new spare parts. The risks of integrated production have the highest EV on average. This result in particular emerged due to the integration of the spare parts in series production, additional sources of risk arise such as long changeover processes or difficult production planning because of small batch sizes which make the manufacture of spare parts as a whole unstable and thus increases the likelihood of manufacturing faults. In contrast the spare part workshop, as the second spare parts supply strategy seems to be the most stable supply strategy.

Lack of investigation into sustainable SCRM operationalization:

Czaja (2009) and Zsidisin et al. (2004) propose the identification of early warning indicators for effective risk mitigation. Czaja (2009) carried out a broad empirical study on early warning indicators for supply interruptions in the automotive industry. Several risks could be identified in the multiple level SC that are consistent with the data obtained from SC professionals in this work. The empirical results of Czaja provide important information but provide little insight for specific action because risks are considered locally and not in their global SC context.

For a target oriented risk analysis Blackhurst, Scheibe & Johnson (2008) as well as Norrman & Jansson (2004) classify the wide range of products into groups. In a similar way a local and global approach has been developed in this work for the operation of the SCRM framework. The local SCRM focuses on particular groups of parts. The global SCRM is the result of the local SCRM weighted by a specific factor. Wu, Blackhurst and Chidambaram (2006) also integrated a weighting factor to evaluate risks. Because a weighting factor is efficient for differentiating quantitatively between subsets of one system, it has been applied to weight the impact of each AS critical component group on the total delivery delay. Organizational adjustments are required in terms of additional resources for SCRM implementation. Norrman and Jansson (2004) give solid recommendations of how to reorganize multinational enterprises in order to integrate the SCRM. The main obstacles to the implementation of RM are investigated by Kersten, Hohnrath & Winter (2008) and are due to the lack of adequate tool coordination, management capacity and willingness to share information and trust towards SC members. Only if managers recognize SCRM to be part of their responsibility will they understand how their decisions affect the SC as a whole. Therefore, to exploit the potential of the SCRM it is necessary to create a collective willingness and cross-functional acceptance of RM in the AS SCM. The integration of SCRM in daily business is especially successful when it is readjusted regularly (Kern et al. 2012, Lockamy and McCormack 2009, Manuj and Mentzer 2008). It requires the coordination of processes, information systems and organizations (James 2011).

Lack of modeling methodology for risk causality in the After Sales inbound SC:

Moreover, no particular attention was dedicated to the aftermarket or to risk causality. There is plenty of research that did not assess the causality within their SCRM, Tummala & Schoenherr (2011), Zsidisin & Wagner (2010), Blackhurst, Scheibe & Johnson (2008), Manuj & Mentzer (2008), Stecke and Kumar (2007), Wu, Blackhurst & Chidambaram (2006), Chopra & Sodhi (2004). This is assumed to be due to the challenge to investigate the dependence of more than two variables. The After Sales has been scarcely researched in terms of RM. The investigation from Hagen (2003) emphasizes service parts management where risk analysis is scarce and rather theoretical. He identified that supply risks exist in the SC from the initial tier to the end-customer. On the demand side, meaning the supply from the focal firm to the customer, the supply risk is secured by legal obligations. The supply from the first supplier level to the focal firm by contractual obligation, and from the second supply chain level to the first level involves minimal power to control risks. Only one paper has been found to use the Bayesian approach for the aftermarket in the automotive industry. The model of Meixell, Shaw & Tuggle (2008) is founded on the Bayesian concept and demonstrates how new knowledge about the outbound minimizes the forecast error when planning the spare parts demand. In contrast to this work, the scholars do not emphasize the RM of the inbound SC for the AS.

Instead they proved the affect of new knowledge in the uncertain AS environment and support the applicability of BN for SC risk analysis. In summary, to the author's best knowledge no solid modeling methodology has been developed for the inbound SC risk evaluation in the After Sales inbound SC.

No application of Bayesian Network within a AS Supply Chain:

In their research agenda about SCRM Khan and Burnes (2007) come to the conclusion that a wide range of tools have been explored by researchers, however, these tools have not been adapted for use in managing SC risks. The most practice oriented framework for operative SCRM was developed by Norrman & Jansson (2004). It is one of the most cited scientific works in the field of SCRM. The research provides mature tools to facilitate the definition of risk mitigation strategies and their tracking, and therefore can be recommended as supplementary reading. In addition, Manuj & Mentzer (2008) develop tools to support the selection of the most effective risk mitigation measures, which are assumed to provide an additional value to the elaborated SCRM model. In contrast, this work regards risks emerging from multiple tiers of the AS SC and analyzes their causal interrelations. In particular the top down and bottom up risk analysis in the BN provides an added value because it enables the identification of root caused risks for a target-oriented definition of mitigation measures. Root causes of risks are effective for preventive risk mitigation Tummala & Schoenherr (2011), IBM (2008), Wu, Blackhurst & Chidambaram (2006) because they can serve as early warning indicators. Yen & Zeng (2011) investigate SC risks in their causal relationships and not in the upstream or downstream structure as generally applied in research. Similarly to this work, they assess the risk causality by means of conditional probabilities and joint distributions. However, they specify risks nodes in a Boolean fashion, meaning the risk is either active or inactive. Such an approach is less reliable for the AS SC because the risk environment in the SC is generally uncertain to the extent that no SC risks can be defined to with any certainty as per the Cromwell's rule. Stecke & Kumar (2007) assess risks in a Ranked fashion, where risks can have a low, medium or high state. To rank risk states is a more precise approach for risk impact evaluation, however, they evaluate risks qualitatively and this is not sufficient for an effective SCRM. In this work, risk nodes have been quantitatively specified by probability distributions and, if reasonable and necessary, by Boolean or ranked states. This is how the real domain of the SC is modeled in a more representative and accurate way. Pai et al. (2003) were the first to analyze SC risks and their cause and effect interrelations by means of the BN. In their approach they evaluate relevant risks with a major focus on the impact of external risks. For this reason the risk network appears incomplete. Buscher, Wels & Winter (2007) revived the importance of the SCRM and concluded that the assessment of risk causality was new.

IBM (2008) developed an example of how the BN illustrates root causes of risks and how they may impact SC operations. The design of a risk network is difficult to apply to the multiple supplier SC in the automotive industry and to the requisites of spare part supply presented in chapter 2.1. Greenland & Pearl (2011), Wagner & Neshat (2010) applied the graph model to understand risk interdependencies and adjacency matrices, and to assess the total risk. The graph model is the structural element of the BN and therefore less complex and less precise for risk modeling. Lockamy and McCormack (2009 & 2012) modeled SC relevant risks by means of BN to evaluate the supplier's impact on the car manufacturer's revenues. The same risk network was applied to create supplier risk profiles to facilitate outsourcing decisions Lockamy & McCormack (2010) and to internally benchmark suppliers, Lockamy (2011). The use of the same risk network for different situations indicates not only the applicability of the BN in the SCRM but also the flexibility of a BN based model to be adapted with little effort to different purposes. As demonstrated, researchers increasingly recognize the benefits of the Bayesian concept for causal SC risk evaluation. The application of the Bayesian logic enables constructive results for the risk modeling. However, the risk modeling appears incomplete because risks are considered in a one-dimensional SC structure. In comparison, this work provides an advanced SCRM where risks are aligned in a multiple AS SC.

To conclude, the elaborated After Sales Risk Model is able to evaluate causal AS SC risks by means of conditional probabilities in the Bayesian concept. It provides a solid potential to preventively derive risk mitigating actions for a proactive SCRM in the After Sales. The lack of a comparable approach in the research are speaks in favor of the elaborated model. The validity of the ASRIM has been proven by an analysis of mean lead time differences based on MRP-System data of the company involved in this research.

6.3 Limitations

In spite of the numerous new findings in this research we had to be careful due to the complexity and diversity of the topic and its limitations. Firstly, it can be assumed that there is a certain proportion of empirical study bias, since the supplier survey was performed in a dependent relationship between customer and supplier. Presumably this was the reason why the results given on the five point Likert scale consistently had very low values. This led to an absolute view of the realized average values which were limited for example to the question of vulnerability of AS SC or the proof of the difference between two types of parts and the spare parts strategies.

Furthermore, only the procurement or the inbound side of AS SC was considered in the empirical analysis and in the determination of the network related risk categories as well as the viewing direction of the AS SC. Thus, only the procurement relevant risks could be compared as representative network risk with the results of other empirical studies. A further limitation is based on the questionnaire design. In order to evaluate the SC risks of the first and second stages of delivery, the first level supplier had to assess any risk from their own company and from the perspective of their experience in cooperation with their sub-suppliers. By doing so the risks of the respective levels could be compared with respect to their relationship with each other. An absolute comparison of the respective risks of both value chains and thus an accurate study of how to develop certain risks along the SC, however, was not possible because of the general deviation between self-assessment and external assessment.

With a view of the ASRIM we can conclude whether the entire supply chain would be considered in the model deviations and whether distortions in the central risk size are possible. The reason is that the established model is specifically developed on the selected product group and the modeled AS SC. Nevertheless, the elaborated ASRIM takes a broad view on the supply risks of the AS SC but does not regard SC members individually. The model is an accurate approach for risk evaluation; however, it is not absolutely exact. This is because the complexity of the SC risk environment is complicated by the incorporation of all relevant risk aspects into the model. Furthermore, even though the probabilities of the risk occurrence are defined by SC experts, the values are estimated and could lead to a distortion of the real picture. In addition to this, Fenton & Neil (2011) warn against a stationary model. To avoid this limitation, the BN based ASRIM provides the option to continuously adjust risk node specifications, add new risk nodes or simply update the risk related knowledge. For this reason it is existential to continuously maintain relevant information in the model. However, if new information is available and relevant to the SC performance, it is required to be entered into the ASRIM. This means that the AS SC environment must be constantly observed. This is difficult to implement in practice, as this responsibility lies with the company to keep the ASRIM up to date.

6.4 Research recommendations

Given the limitations of this work and in combination with the contributions made for science and practice, further research recommendations can be given in different directions.

Initially, the general approach applied in this work could be transferred to other industries for modeling supply chain risk structures. However, modeling Supply Chain Risk structures is a challenge and the ASRIM can be considered as a complex model. Therefore focusing on single product categories or well-chosen suppliers would be conceivable to enhance the understanding of relationships from single risk clusters in complex supply chain structures.

Also, the ASRIM focuses on protection of the buyer side (Inbound) of a selected After Sales Supply Chain. By further empirical analyzes on the sell side (Outbound) other risk sensors may exist, which can be incorporated into the developed model or in additional models. Such research on the outbound side would clarify the risk structure of the complete supply chain.

In addition, the transferability of specific after-sales supply chain risks to other product groups could be examined further. Such research would provide further support for the validity of the developed ASRIM within the investigated after sales supply chain and industry.

Finally, the idea to implement the risk control with the Bayesian approach in practice can be pursued. Since data is available in real time it is not sufficient to calculate the risk value in external systems, such as "Agenarisk". For this reason, it is recommended to investigate how applications or programs can be integrated into the IT systems of the companies.

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APPENDICES

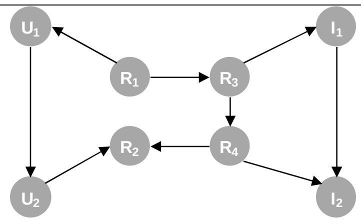
A. Literature review of supply chain risks

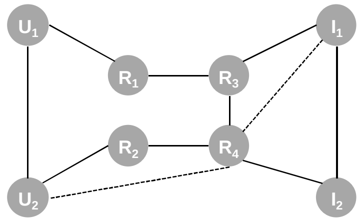
SC risk scholars	Internal SC risks	External SC risks
(Harland, Brenchley et al. 2003)	Supply-related risk, demand-related-risk, production-related risk, financial instability, business strategy	Legal issue, political instability, competitive-related risk
(Chopra and Sodhi 2004)	Procurement, inventory, delivery delay, production-related risk, demand-related risk, IT, intellectual property	-
(Zsidisin, Ellram et al. 2004)	Supply-related risk, production-related risk, quality problems, cost, design	Natural disaster, legal issues, safety, health
(Faisal, Banwet et al. 2006)	SC-related risk, organizational risk	Natural disaster
(Wu, Blackhurst et al. 2006)	Delivery delay, 2nd-tier supplier, demand-related risk, production-related risk, quality problems, financial instability, management-related risk	Natural disaster, economic instability, political instability, legal issues, security
(Blackhurst, Scheibe et al. 2008)	Procurement, inventory, transportation, demand-related risk, production-related risk, quality problems, IT, organizational risk, management-related, intellectual property	Legal issues
(Manuj and Mentzer 2008)	Supply-related risk, production-related risk, demand-related risk	Political instability, economic instability, legal issues, security, competitive-related risk
(Lockamy and McCormack 2009)	Delivery delays, production-related risk, quality problems, information flow	Economic instability, competitive-related risk
(Stecke and Kumar 2009)	Supply-related risks, production-related risk, demand-related risk	Natural disaster, political instability, legal issues, security
(Lockamy III and McCormack 2010, Lockamy III and McCormack 2012)	Delivery delay, 2nd-tier supplier, production-related risk, quality problems, financial instability, organizational risk, management-related risk	Natural disaster, political instability, legal issues
(Zsidisin and Wagner 2010)	Transportation, quality problems, management-related risk, financial instability, information flow	Natural disaster, political instability, physical distance
(Pfohl, Gallus et al. 2011)	Supply-related risk, transportation, demand-related risk	Natural disaster, employee strikes, security
(Tummala and Schoenherr 2011)	Delivery delay, inventory, transportation, procurement, demand-related risk, production-related risk, IT	-
(Yen and Zeng 2011)	Supply-related risk, delivery delay, inventory, cost, procurement	-

B. After Sales related scientific paper overview

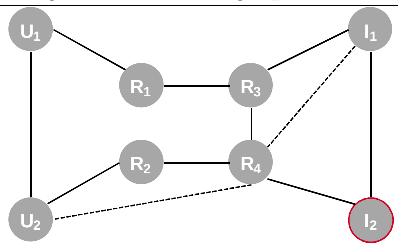
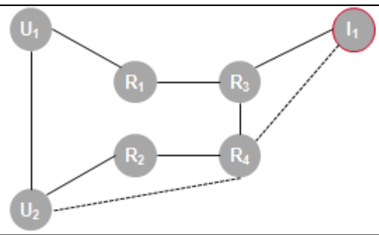
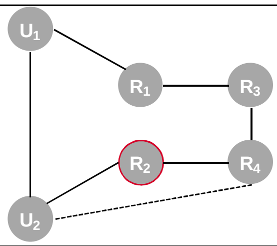
Published	Author(s)	Titel of work	Methode	Journal Rating	Related to AS SC
2011	Thun & Hoenig	An empirical analysis of supply chain risk management in the German automotive industry	empirical (quantitative)	B	No
2011	Tumalla & Schönherr	Assessing and managing risks using the Supply Chain Risk Management Process	conceptional	C	No
2011	Vilko & Halikas	Risk assessment in multimodal supply chains	empirical (qualitative)	B	No
2009	Blos et al.	Supply chain risk management: a case study on the automotive and electronic industries in Brazil	empirical (qualitative)	C	No
2009	Wagner & Neshat	Assessing the vulnerability of supply chains using graph theory	empirical (quantitative)	B	No
2008	Manuj & Mentzer	Global Supply Chain Risk Management	conceptional	B	No
2007	Bogataj & Bogataj	Measuring the supply chain risk an vulnerability in frequency space	conceptional	B	No
2007	Kajüter	Risikomanagement in der SC: Ökonomische, regulatorische und konzeptionelle Grundlagen	conceptional	-	No
2007	Ritchey & Brindley	Supply Chain Risk Management and performance - A guiding framework for future development	conceptional /empirical (quantitative)	B	No
2007	Ziegenbein	Identifikation, Bewertung uns Steuerung von SC-Risiken - eine Methodik	conceptional /empirical (quantitative)	-	No
2007	Wagner & Bode	Empirische Unteruchung der SC- Risiken und SC-Risikomanagement in Deutschland	empirical (quantitative)	-	No
2006	Kersten et al.	Supply Chain Risk Management - Developement of a Theoretical and Empirical Framework	conceptional /empirical (quantitative)	-	No
2005	Jüttner	SCRM: understanding the business requirements from a practitioneer perspective	empirical (quantitative) / (qualitative)	D	No
2005	Kleindorfer & Saad	Managing Disruption Risks in SC	conceptional /empirical (quantitative)	A	No
2005	Peck	Drivers for supply chain vulnerability, an integrated framework	empirical (qualitative)	B	No
2004	Barry	Supply chain risk in an uncertain global supply chain environment	conceptional	B	No
2004	Norrman & Jansson	Ericsson's proactive supply chain risk management approach after a serious sub- supplier accident	empirical (qualitative)	B	No
2003	Harland et al.	Risk in supply networks	conceptional /empirical (qualitative)	-	No

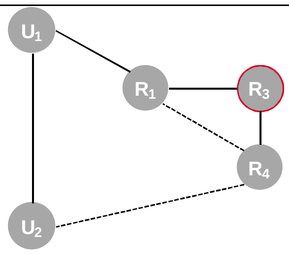
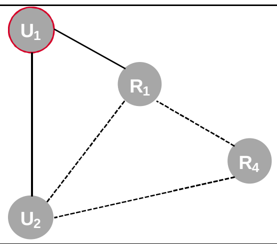
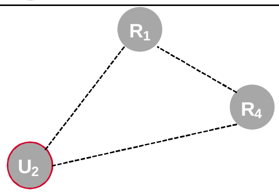
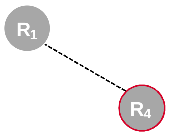
C. Junction Tree Algorithm (adapted from Fenton and Neil (2012))

<table>
<tr><td colspan="2">1. Construct the moral graph</td></tr>
<tr><td>

Example of a Bayesian network</td><td>Identify the parents of each node:
• R_2: (U_2, R_4)
• I_2: (I_1, R_4)</td></tr>
<tr><td>

Moral graph</td><td>Link the parents of each child:
• R_2: (U_2, R_4) → arc between U_2 and R_4
• I_2: (I_1, R_4) → arc between I_1 and R_4

Remove the direction of all arcs.</td></tr>
<tr><td colspan="2">2. Triangulate the moral graph</td></tr>
<tr><td>
</td><td>• Need to identify subsets of nodes called clusters and eliminate it
• Starting with the node where the maximum number of edges has been added to, in this case R_1 and I_1
• Start with I_2 → cluster: I_2, R_4, I_1</td></tr>
<tr><td>
</td><td>• Continue with I_1 → cluster: I_1, R_3, R_4</td></tr>
<tr><td>
</td><td>• Continue with R_2 → cluster: R_2, R_4, U_2</td></tr>
</table>

	• Continue with R_3 → cluster: R_3, R_1, R_4
	• Continue with U_1 → cluster: U_1, R_1, U_2
	• Continue with U_2 → cluster: U_2, R_1, R_4
	• Continue with R_4 → cluster: R_4, R_1
	• End with R_1 → cluster: R_1
3. Summary	
Identified clusters:	• $I_2R_4I_1$, $I_1R_3R_4$, $R_2R_4U_2$, $R_3R_1R_4$, $U_1R_1U_2$, $U_2R_1R_4$, ~~R_4R_1, R_1~~ • Disregard cluster R_4R_1 and R_1 since both are already included in $U_2R_4R_1$
Identify separators:	• Between $I_2R_4I_1$ and $I_1R_3R_4$ →R_4I_1 • Between $R_3R_1R_4$ and $U_2R_1R_4$ → R_1R_4 • Between $U_1R_1U_2$ and $U_2R_1R_4$ → R_1U_2 • Between $R_2R_4U_2$ and $U_2R_1R_4$ → R_4U_2 • Between $I_1R_3R_4$ and $R_3R_1R_4$ → R_3R_4

D. Discretization process

An effective approach to compute conditional probability densities of discrete and continuous variables in a BN model is to discretize the continuous variables (Jensen and Nielsen 2007). Because a hybrid BN was applied in this work, that contains both discrete and continuous variables, the dynamic discretization process is an exact computing solution. In the first step, it is required to recalculate the NPT approximations over the current discretized domains. Then the approximate marginal posterior probability density function of each node is calculated when propagating the discrete BN. And ultimately, intervals are merged until the whole model converges. The dynamic discretization produces a high number of intervals and allows many interval combinations which, in turn, result in a piecewise continuous function with no voids (Fenton and Neil 2012).

E. ASRIM relevant Probability Distribution (Montgomery and Runger 2010, Fenton and Neil 2012)

In practice, a few probability distributions dominate, two of the most important and used in the After Sales Risk Model (ASRIM) be presented shortly.

The Binomial Distribution

The binomial distribution is a discrete distribution based on the following principle. It is based on a random experiment that can have exactly two possible, mutually exclusive A and B results. For the probabilities applies:

$$P\,(A) = P \qquad (4.6)$$

$$P\,(\overline{A}) = 1 - P \qquad (4.7)$$

Such random experiment with two outputs is also called Bernoulli experiment. The experiment will performed n - times and the results of the iterations are independent of the previously carried out experiments. Of interest is the number x of n repetitions/deliveries by which the event A (Lacking time window capacity) occurs.

Example: Node: Lacking time window capacity per day in hour
Trial: total_capacity_time_window, Success: 0.01

That means when the transport received at central warehouse, it may happen that there is no free time window for discharge the truck.

Note: Deliveries are made daily and are therefore independent of each other.

If the result of the Random experiment is - with n repeats - a number between 0 and n and corresponds to the number of occurrences of A then the probability that A occurs exactly x times and is given by:

$$fx^{(x)} = \binom{n}{x} \cdot P^x \cdot (1-P)^{n-x} \qquad x = 0, 1, ..., n \qquad (4.8)$$

This type of probability function is called the binomial distribution. These distributions are determined by the two parameters n and P. We write for short B (n, p) distribution where numerical values are to be used for the parameters.

The following applies:

$$B(x|n,P) = fx^{(x)} = \binom{n}{x} \cdot P^x \cdot (1-P)^{n-x} \tag{4.9}$$

For binomial distributions generally applies:

$$E(x) = n \cdot P \tag{5.0}$$

and

$$VAR(x) = n \cdot P \cdot (1-P) \tag{5.1}$$

The distribution function is specified by summation:

$$F_X(X) = \sum_{k=0}^{X} \binom{n}{x} \cdot P^k \cdot (1-P)^{n-k} \quad x = 0, 1, ..., n \tag{5.2}$$

ASRIM Example (Lacking time window capacity):

The transport deliveries in the Warehouse are ruled by fixed time windows. If the truck are too late he will not unloaded and spare parts have lead time differences. We suppose 10 deliveries per week, what is the number of deliveries with lacking time window capacity. It is n = 10 and P = 0.5 and the probability that in one week 4 truckloads are not unloaded in time is:

$$B(4|10, 0.5) = \binom{10}{4} \cdot 0.5^x \cdot (1-0.5)^{n.x} = \frac{10!}{4! \cdot 6!} \cdot 0.5^{10} = 0.205 \tag{5.3}$$

The entire distribution (for n = 10 and P = 0.5) can be represented graphically as follows:

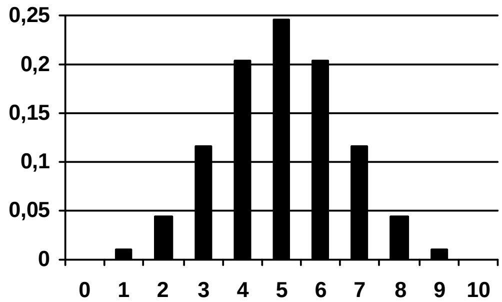


Figure 33 Appendix E: The symmetric Binominal Distribution

As expectation value is E(X) = 10 · 0,5 = 5 and the variance is VAR(X) = 10 · 0,5 · (1 - 0,5) = 2,5, then the symmetrical shape of the distribution in the sample arises from the fact that P = 0.5, that is if the probability of A and the event of $\overline{A}$ is similar.

For P = 0.25 (n = 10) following asymmetric distribution is obtained:

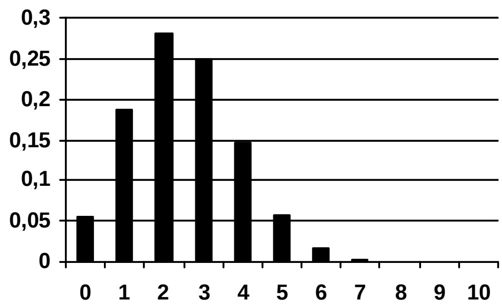


Figure 34 Appendix E: The asymmetric Binominal Distribution

The Normal Distribution

The normal distribution is the most important distribution at all. It occurs in many technical (e.g. manufacturing tolerances) and also in biological (e.g. body size) areas. It involves a continuous distribution with the following density function:

$$f_x(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (5.4)$$

The function contains two parameters μ and σ and describes a whole class of functions, also known as N (μ, σ^2) can be specified: The following applies:

$$E(x) = \mu \quad (5.5)$$

and

$$VAR(x) = \sigma^2 \quad (5.6)$$

The function is symmetric to the expected value μ and can be represented graphically as follows:

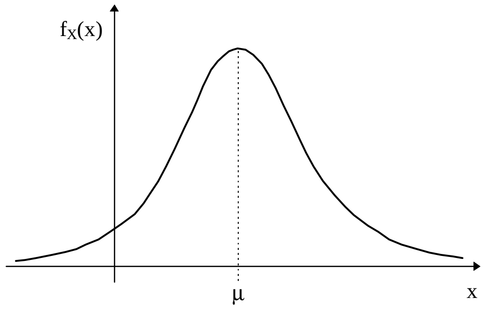


Figure 35 Appendix E: The Standard Normal Distribution

The distribution function cannot be expressed by other simple functions. Therefore, tables are used to looking for values. The standard normal distribution is equal to the N(0, 1) distribution, which is the normal distribution with mean 0 and variance 1.

F. Interaction matrix of AS risk interrelations

Supply chain	Supply chain risks	i \ j	E4	E3	E2	E1	2S5	2S4	2S3	2S2	2S1	2T2	2T1	1S5	1S4	1S3	1S2	1S1	1T2	1T1	C3	C2	C1
Focal company (central warehouse)	Stock availability	C1	A*	A*	A*	A*	A*	A*	A*	A*	O	O	A*	A*	V	A*	A*	A*	A*	A	A	A	X
	Delivery delay	C2	A*	A*	A*	A*	A*	A*	A*	A*	O	O	A*	A*	V	A*	A*	A*	A*	A	A	X	V
	Quality	C3	O	O	O	A*	A*	O	A*	A*	O	O	A*	O	X	O	A*	A*	A*	A	X	V	V
Trans-port	Delivery errors	1T1	X	A	O	A	O	O	O	O	O	O	O	O	V	O	O	A	X	X	V	V	V
	Means of transport	1T2	A	A	A	O	O	O	O	O	O	O	O	A	X	O	O	O	X	X	V*	V*	V*
1st-tier supplier	Packaging	1S1	V	A	A	A	O	O	O	O	O	O	O	A	V	O	O	X	O	V	V*	V*	V*
	Production problems	1S2	A*	A	A*	A	A	A*	A*	A*	A*	A*	A*	V	V	A	X	O	O	O	V*	V*	V*
	Procurement	1S3	A	A*	A	A	V	A*	A*	A	A*	A*	A	V	V	X	V	O	O	O	O	V*	V*
	Demand planning	1S4	X	A*	A	A	A	A*	A*	X*	A*	A	A	A	X	A	A	A	X	A	X	A	A
	Series priority	1S5	O	A*	A	A	O	A*	A*	A*	A*	A*	A	X	V	A	A	V	V	O	O	V*	V*
Trans-port	Delivery errors	2T1	X	A	O	A	O	O	O	O	A	X	X	V	V	V	V*	O	O	O	V*	V*	V*
	Means of transport	2T2	A	A	A	O	O	O	O	O	O	X	X	V*	V	V*	V*	O	O	O	O	O	O
2nd-tier supplier	Packaging	2S1	V	A	A	A	O	O	O	O	X	O	V	V*	V*	V*	V*	O	O	O	O	O	O
	Production problems	2S2	O	A*	A*	A	A*	A	A	X	O	O	O	V*	X*	V	V*	O	O	O	V*	V*	V*
	Resource capacity	2S3	O	A	A	A	A	O	X	V	O	O	O	V*	V*	V*	V*	O	O	O	V*	V*	V*
	Procurement	2S4	O	O	A	A	V	X	O	V	O	O	O	V*	V*	V*	V*	O	O	O	O	V*	V*
	Technological changes	2S5	O	O	O	A	X	A	V	V*	O	O	O	O	V	A	V	O	O	O	V*	V*	V*
External factors	Natural catastrophes	E1	V	V	V	X	V	V	V	V	V	O	V	V	V	V	V	V	O	V	V*	V*	V*
	Economic factors	E2	V	V	X	A	O	V	V	V*	V	V	O	V	V	V	V*	V	V	O	O	V*	V*
	Strikes	E3	V	X	A	A	O	O	V	V*	V	V	V	V*	V*	V*	V	V	V	V	O	V*	V*
	Import and export	E4	X	A	A	A	O	O	O	O	A	V	X	O	X	V	V*	A	V	X	O	V*	V*

G. Reachability matrix of AS risk interrelations

i \ j	C1	C2	C3	1T1	1T2	1S1	1S2	1S3	1S4	1S5	2T1	2T2	2S1	2S2	2S3	2S4	2S5	E1	E2	E3	E4	Driving power
C1	1	0	0	0	0*	0*	0*	0*	1	0*	0*	0	0	0*	0*	0*	0*	0*	0*	0*	0*	**2**
C2	1	1	0	0	0*	0*	0*	0*	1	0*	0*	0	0	0*	0*	0*	0*	0*	0*	0*	0*	**3**
C3	1	1	1	0	0*	0*	0*	0	1	0	0*	0	0	0*	0*	0	0*	0*	0	0	0	**4**
1T1	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	**7**
1T2	1*	1*	1*	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**6**
1S1	1*	1*	1*	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	**7**
1S2	1*	1*	1*	0	0	0	1	0	1	1	0*	0*	0*	0*	0*	0*	0	0	0*	0	0*	**6**
1S3	1*	1*	0	0	0	0	1	1	1	1	0	0*	0*	0	0*	0*	1	0	0	0*	0	**7**
1S4	0	0	1	0	1	0	0	0	1	0	0	0	0*	1*	0*	0*	0	0	0	0*	1	**5**
1S5	1*	1*	0	0	1	1	0	0	1	1	0	0*	0*	0*	0*	0*	0	0	0	0*	0	**6**
2T1	1*	1*	1*	0	0	0	1*	1	1	1	1	1	0	0	0	0	0	0	0	0	1	**10**
2T2	0	0	0	0	0	0	1*	1*	1	1*	1	1	0	0	0	0	0	0	0	0	0	**6**
2S1	0	0	0	0	0	0	1*	1*	1*	1*	1	0	1	0	0	0	0	0	0	0	1	**7**
2S2	1*	1*	1*	0	0	0	1*	1	1*	1*	0	0	0	1	0	0	0*	0	0*	0*	0	**8**
2S3	1*	1*	1*	0	0	0	1*	1*	1*	1*	0	0	0	1	1	0	0	0	0	0	0	**9**
2S4	1*	1*	0	0	0	0	1*	1*	1*	1*	0	0	0	1	0	1	1	0	0	0	0	**9**
2S5	1*	1*	1*	0	0	0	1	0	1	0	0	0	0	1*	1	0	1	0	0	0	0	**8**
E1	1*	1*	1*	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	**19**
E2	1*	1*	0	0	1	1	1*	1	1	1	0	1	1	1*	1	1	0	0	1	1	1	**16**
E3	1*	1*	0	1	1	1	1	1*	1*	1*	1	1	1	1*	1	0	0	0	0	1	1	**16**
E4	1*	1*	0	1	1	0	1*	1	1	0	1	1	0	0	0	0	0	0	0	0	1	**10**
Dependence power	**18**	**17**	**11**	**6**	**7**	**5**	**13**	**11**	**21**	**12**	**6**	**5**	**4**	**8**	**5**	**3**	**4**	**1**	**2**	**3**	**9**	

H. ASRIM Supply Chain Risk Scenarios

						Scenario 1 Raw material scarcity		Scenario 2 New parts		Scenario 3 Demand increase	
SC level node	**Synthetic node 1**	**Synthetic node 2**	**Synthetic node 3**	**Event node**	**Baseline**	**Evidence**	**Risk probability**	**Evidence**	**Risk probability**	**Evidence**	**Risk probability**
Delivery at focal company	-	-	-	Stock value in Mio EUR	**1,044,900**		1,251,800		1,254,700		1,187,300
	-	-	-	Behind schedule delivery in days	**13.7**		16.4		16.4		15.5
	-	Transportation delay to focal company in hours	Transport-related delay per day in hour	Total time window capacity per day in hour	**6.8**		6.8		6.8		6.8
				Lacking time window capacity per day in hour	**0.9**		0.9		0.9		0.9
				Total forwarder capacity per day in hour	**6.9**		6.9		6.9		6.9
				Lacking forwarder capacity per day in hour	**0.9**		0.9		0.9		0.9
				Transit-time related delay per day in hour	**4.8**		4.8		4.8		5.0
					6.6		6.6		6.6		6.7
					7.7		7.7		7.7	High: 55.0*	9.3
	-	-	-	1st-tier supply	**27.2**		32.8		32.1		31.7
1st-tier supply problems	After-sales specific risks	-	-	Series priority	**45.2**	High: 80.0*	76.8	High: 80.0*	85.0	High:80.0*	77.3
		-	-	Change Management	**40.0**	High: 70.0*	60.9	High: 60.0*	50.0		40.0
		-	-	AS concept	**50.6**		70.3	High: 70.0*	85.2		70.9
		-	Demand planning	Volatile order quantity	**70.0**		70.8		71.2	High: 90.0*	95.6
				System failure	**10.0**		11.0	High: 60,0*	16.3		11.1
				Communication problems	**30.0**		32.1	High: 60.0*	42.6		32.2
					39.0		50.0		58.0		52.2
					37.3		58.2		60.1		49.9
	External risks	-	-	Natural catastrophes	**5.0**		5.0		5.0		5.0
		-	-	Bancruptcy 1st-tier	**15.0**		15.0	High: 55.0*	17.7		15.0
		-	-	Strikes	**20.0**		20.0		20.0		20.0
					18.0		18.0		18.2		18.0
	Internal risks	Production risk	Production capacity	Man power capacity risk	**60.0**		60.0		60.0		67.4
				Tool set-up time risk	**60.0**		60.0		60.0		62.1
				Focal company machinery	**30.0**		30.0		30.0		34.6
					57.9		57.9		57.9	30*-50*-20*	76.6
			Product-related risk	Product complexity	**80.0**		80.0	30* - 60* - 10*	95.4		80.0
				Product variants	**80.0**		80.0	35* - 60* - 5.0*	97.6	35*-55*-10*	95.1
					80.9		80.9		90.5		84.0
					71.5		71.5		75.3		78.9
		Procurement bottleneck at 1st-tier	Transportation delay	Sea freight	**90.0**		90.0		90.0		90.4
				Air freight	**90.0**		90.0		90.0		90.8
					88.8		88.8		88.8		90.2
			Raw material scarcity	Plastics	**10.0**		10.0		10.0		12.0
				Metals	**10.0**		10.0		10.0		12.0
				Minerals and non-metalics	**10.0**		100.0		10.0		12.0
				Other	**10.0**		10.0		10.0		12.0
					34.4		100.0		34.4		41.4
			2nd-tier supply	*cp. 2nd-tier*	**54.8**		59.9		54.8		63.9
					61.5		84.0		61.5	High: 75.0*	82.7
					49.2		56.3		50.6		59.3
					27.2		32.8		32.1		31.7
2nd-tier supply problems	Internal risk	Production risk	Production capacity	Man power capacity risk	**90.0**		90.0		90.0		90.2
				Tool set-up time risk	**40.0**		40.0		40.0		40.1
				Multiple-machine operation	**90.0**		90.0		90.0		90.2
					93.7		93.7		93.7		94.0
			Product-related risk	Product complexity	**30.0**	Low: 100.0*	0.0		30.0		30.5
				Product variants	**30.0**		30.0		30.0		30.3
					39.9		22.8		39.9		40.8
					76.4		71.7		76.4		77.9
		-	Raw material scarcity	Plastics	**10.0**		10.0		10.0		12.0
				Metals	**10.0**		10.0		10.0		12.0
				Minerals and non-metalics	**10.0**	Yes: 100.0*	100.0		10.0		12.0
				Other	**10.0**		10.0		10.0		12.0
					34.4		100.0		34.4		41.4
					51.5		60.8		51.5		57.7
	External risks	-	-	Natural catastrophes	**25.0**		29.0		25.0		25.5
		-	-	Bancruptcy 2nd-tier	**32.5**	High: 60.0*	41.9		32.5		33.1
		-	-	Strikes	**10.0**		10.0		10.0		10.3
					28.6		30.53		28.6		31.3
					54.8		61.1		54.8		63.9

I. List of Abbreviations

APO	Advanced Planning Optimizer
AS	After Sales
ASRIM	After Sales RIsk Model
BN	Bayesian Network
BOM	Bill Of Material
BSC	Balanced Score Card
DAG	Direct Acyclic Graph
DSR	Day of Stock Receipt
EDO	End of delivery obligation
EOP	End of production
EOS	End of service
FTA	Fault Tree Analysis
GIM	Global Inventory Management
IBM	International Business Machines Corporation
ISM	Interpretative structural modeling
JIS	Just in Sequence
JIT	Just in Time
LTD	Lead Time Differences
MIT	Massachusetts Institute of Technology
MRP	Manufacturing Resources Planning
MU	Monetary Units
NPT	Node Probability Table
OEM	Original Equipment Manufacturers
PG	Product Group
RM	Risk management
SAP	System Application Program
SC	Supply Chain
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCRM	Supply Chain Risk Management
SDT	Scheduled Delivery Time
SKU	Stock keeping unit
SOP	Start of production
SPAM	In this context: Pushing Advertising Mail
UCLA	University of California at Los Angeles
USD	United States Dollar

J. Notation

$Risk_n$	Total supply chain risk
$I_n(Loss_n)$	Significance n of the Loss n
$P_n(Loss_n)$	Probability n of the Loss n to arise
$Risk_{tier1}$	1st tier supplier risk
$Risk_{tier2}$	2nd tier supplier risk
$P_{tier1}(Loss_{tier1})$	Probability of Loss of 1st tier supplier
$I_{tier1}(Loss_{tier1})$	Impact of Loss of 2nd tier supplier
A, B	Event
$\overline{A}$	Complementary event to A
B(n, p)	Binomial Distribution
E(X)	Expected value of the random variable X
F_X	Distribution function of the random variable X
$f(x_i)$	Relative frequency of occurrence x_i
$F(x_i)$	Cumulative relative frequencies up to and including element x_i
$N(\mu,\sigma^2)$	Normal Distribution
P	Probability
P(A)	Probability for the occurrence of the event A
P(B)	Probability for the occurrence of the event B
P(B|A)	Probability for the occurrence of the event B under the condition that event A has already occurred
P(A|B)	Probability for the occurrence of the event A under the condition that event B has already occurred
VAR(X)	Variance of the random variable X
X, Y	Random variables
μ	Mean value
σ	Standard deviation
ω	Elementary event
Ω	Event space (safe event)
$A\cup B$	Composed event (union)
$A\cap B$	Average of events

$\varnothing$	Impossible event (empty set)
n	Sample size
N	The population size
S	Sample standard deviation
S^2	Sample variance
$\overline{X}$	Sample mean
σ	Standard deviation of a population
σ^2	Variance of a population
$\sigma^2_{\overline{X}}$	Variance of the sample means

CURRICULUM VITA

NAME:	Steffen Luksch	
ADDRESS:	Wacholderring 7 74629 Pfedelbach Germany	
DOB:	April 19, 1975 in Heilbronn - Neckargartach, Baden Württemberg, Germany	
EDUCATION:	2009 – 2014	Ph.D., Industrial Engineering University of Louisville J.B. Speed School of Engineering
	2006 – 2008	M. Eng., Technical Management Heilbronn University
	1998 – 2002	Dipl. Wirt. Ing (FH), Diplom Engineer Heilbronn University
PROFESSIONAL CAREER:	since 2006	Dr. Ing. h.c. F. Porsche AG After Sales Supply Chain Management Supplier Management
	2004 – 2006	Robert Bosch GmbH Division Automotive Electronics Ratio Planning
	2002 – 2004	Robert Bosch GmbH Division Automotive Electronics Plant Controlling