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Supply chain flexibility in the special purpose vehicle industry.

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SUPPLY CHAIN FLEXIBILITY IN THE SPECIAL PURPOSE VEHICLE INDUSTRY

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Dipl.-Ing., Technical University of Munich, Oct. 2007

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ABSTRACT

SUPPLY CHAIN FLEXIBILITY IN THE SPECIAL PURPOSE VEHICLE
INDUSTRY

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Supply chains of the Special Purpose Vehicle (SPV) industry are
complex and with many constraints. Since the SPV industry is a special field
of operation, there is no classical supply chain strategy which is appropriate. It
is possible to apply concepts of industries with similar requirements but there
is a high loss of time and money because these classical concepts do not fit
to the SPV industry. Even strategies of the conventional automobile industry
cannot be transferred. Therefore, there is the need to develop a supply chain
concept for companies of the SPV industry. As a first step, basic knowledge
about supply chain management is provided. Based on this, special supply
chain characteristics of the SPV industry are analyzed in detail. A profound
research shows that the focus of the developed supply chain should be on
flexibility. High supply chain flexibility addresses the specific difficulties related
to the SPV industry. These are for example individual customer requirements
and uncertain demand. Therefore appropriate flexibility methods are derived

which are called variant, volume and time flexibility. For the implementation, several formulas and strategies are derived. This supply chain concept is a basic concept. It can be adapted to the environment of different SPV companies. For the application of the derived formulas, MATLAB codes are provided. These MATLAB scripts and functions are also used for a performance evaluation. Therefore, economic parameters, which are same important for all companies, are used. Thus, all improvements and strategies in this research are evaluated mathematically.

A performance evaluation with realistic input values shows that the following savings are expected for the three flexibility types:

- volume flexibility: 47%

- variant flexibility: 42%

- time flexibility: 42%

A comprehensive example with all the flexibility types shows that overall savings of about 18% can be realized. This comprehensive example includes further new approaches like an asymmetrical flexibility and a method to order the optimal quantity at the posterior point of time which is explained and introduced.

The savings due to the individual flexibility types, which are mentioned above, are related to costs and thus very high at first glance. Furthermore, these results depend on input variables, which reflect realistic examples. Thus, these values can be different in other example. They are however appropriate indicators to show that the new supply chain strategy for the SPV

industry is profitable, reliable, stable and flexible. Thus, the new approach is a research contribution, which leads to clear benefits in reality.

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH MOTIVATION

The Special Purpose Vehicle (SPV) industry is a small part of the automobile industry. This field of industry produces special vehicles, which do not benefit from large sales markets, such as military vehicles or special construction vehicles. But not only the vehicles of the SPV industry are special. Also the supply chain characteristics are very special and cannot be compared to the conventional automobile industry. Manufacturers of special vehicles as well as of conventional vehicles are part of the automobile industry. However, both company types are fundamentally different, because the environmental conditions, the goals and the methods are opposed. Companies of the SPV industry, such as military vehicle manufacturers, only produce small quantities compared to the conventional vehicle manufacturers. Therefore, they are relatively small and not as good organized as companies of the conventional automotive industry. There are several reasons for this. One is the fact that companies, which are part of the Supply Chain (SC) in the

automobile industry, have to be certified according to automotive standards, such as ISO/TS 16949. A lot of money and effort has to be invested to get these certificates. The daily rate for a certification company is about 1000 Euros (Cassel, M., 2007, p. 2). The costs in the USA for a QS-9000 certificate or the replacement ISO/TS 16949, which is also absolutely mandatory for all companies of the automotive industry, were about $ 118.100 in 1997 (Cassel, M., 2007, p. 3). Small companies of the SPV industry, which have a much lower turnover, cannot afford this money. Therefore, they are not forced to improve their SC in such a way. Another reason for the differences between the automotive and the SPV industry is the historical development of these two branches. The automotive industry has always been in the forefront of SC optimization, in contrast to the SPV industry. The automotive industry has started its evolution over 120 years ago. For the conventional automotive industry, a lot of research was done, to answer the questions of what to make, how much to make, and when to make it. Also the associated issues of acquiring raw materials, choosing and adjusting the production methods, and planning the material flow were investigated in detail. However, most of it is not appropriate for the SPV industry, although both produce vehicles. For example already Henry Ford's introduction of a moving assembly line in 1913 was a big step for the automotive industry. But even this basic improvement was not feasible for smaller companies, such as SPV companies due to the high investment, which is necessary for assembly lines. Later, Lean Production, which is based on the findings of the automotive industry, was presented by Womack, Jones, and Roos (1990). One aspect of this SC concept is using rigorous standardization to reduce variation and to create

flexibility and predictable outcomes. However in SPV industry, standardization is only possible to a very limited extent, because the produced vehicles are often too different. Thus, the gap between the conventional automobile industry and the SPV industry was widening over time and the scientific focus is still on big companies of the automotive industry. It becomes obvious, that it is not possible for companies of the SPV industry to find detailed and scientifically sound literature, as it is available for companies of the conventional automobile industry.

It is possible to identify the differences between the SPV and the conventional automotive industry more detailed. This is done in the following to develop strategies that allow manufacturers of SPV vehicles to better design, structure and operate an appropriate supply chain. The new SC concept will also yield increased competitive advantages for winning new business and delivering good operating results. This is the motivation to explore the characteristics of SPV manufacturers and to generate a supply chain which is tailored to these special conditions. This well designed supply chain strategy, which will be based on high flexibility, is supposed to yield financial, operational and strategic results which create real value, when applied in SPV industry.

1.2 DIFFERENCES OF SPV SUPPLY CHAINS TO SUPPLY CHAINS OF OTHER INDUSTRIES

Later in this thesis a SC will be designed which is tailored to the SPV industry. For a better understanding the differences to other industries are discussed in this chapter. This knowledge will not only highlight the importance of this research, but will also help to understand the most important characteristics of the SPV industry. These characteristics are for example specific flexibility types, which will be implemented in the SC concept later in the thesis.

It is the goal to develop a SC concept for companies of the SPV industry. Therefore the abbreviation SPV will be used very often in the following. To avoid misunderstandings it should be now defined which types of vehicles are called SPV in this work, because everyone has a different understanding of what a special vehicle is. Special military vehicles were already mentioned as one example. Other examples could be construction vehicles, snow groomer, airport vehicles or fire-fighting trucks, as shown on the pictures below. All these vehicles have in common that only low quantities are produced, that they are for a small group of potential customers and that they are technically very complex.

Figure1: Examples for SPVs

Currently, SPV manufacturers normally use methods of the conventional automobile industry for the sake of simplicity. These methods are appropriate for the conventional automobile industry such as BMW, Ford or GM. Both kinds of companies produce vehicles. However, their environment, restrictions and requirements are completely different, which is why the methods of the conventional automobile industry do not fit very well for SPV manufacturers. As already implied, supply chain strategies need to be tailored to meet the specific needs and constraints of a branch of industry.

Compared to the conventional automobile industry, manufacturers of SPVs or military vehicles have their own conditions. Some of these needs and constraints, which are new or typical for the military vehicle industry, are listed below. These points have to be considered when developing the SC:

1. different customer wishes which lead to high flexibility
2. low volume
3. high demand uncertainty
4. high supply uncertainty
5. lots of different individual parts, subassemblies and complete assemblies, integrated in vehicles
6. high profit margins
7. long-term supply contracts only for individual customer orders
8. limited supply sources
9. a lot of different suppliers due to many different parts lead to higher risks
10. multistage supply chain
11. long lead time of some parts (6 months; in exceptional cases more than 6 months)
12. some same parts in different vehicles → heterogeneous demand of these same parts
13. homogenous demand of parts belonging to the same vehicle (except same parts)

14. difficult planning circumstances due to heterogeneous costs for too high and too low order quantities (these costs are also affected by same parts)

15. growing business competition

16. offset regulations with countries of foreign customers

17. modular production design

18. standardization, where possible

19. globalization

20. environmental consciousness

21. regulatory requirements concerning environmental protection

22. rapidly changing threat scenarios (affecting the market of military vehicles)

23. increasing technical complexity

24. no normal distribution of the demand (explanation follows later in the thesis)

As already mentioned, the SPV industry is very different to the automotive industry, although both of them produce vehicles. This becomes even obvious through commercial topics. For example suppliers of the conventional automobile industry can close mid- and long-term contracts which provide stability and predictability for a long time in the future. In automobile industry it is common that suppliers must quote binding prices to an Original Equipment Manufacturer (OEM) more than 3 years prior to Start of Production (SOP). However OEMs of SPVs do not have such a strong position toward their suppliers, since their purchasing volume is much lower.

Such binding commitments of automotive industry suppliers are closely connected with high risks. The margin of suppliers in the SPV industry is usually too low to compensate such high risks. While OEMs of the automobile industry can only focus on bottom line prices, the OEMs of SPV vehicles have to struggle with a further uncertainty. This disadvantage has to be handled by the OEMs and is another reason for the necessity of an appropriate and thought-out supply chain planning.

Automobile supply chains in general are very complicated, because of its special industrial characteristics, such as special norms and specifications, which differ from other supply chains. One special and very famous specification of the automobile industry is for example the ISO/TS16949 (Cassel, M., 2007). This specification helps to reduce variation and waste in the supply chain. But even more specific features are associated with supply chains for the SPV industry. These individual constraints are discussed in the following.

Also the production quantity of SPV manufacturers is often very different to the production quantity of the automobile industry and other industries. VW for example sold more than eight million cars in 2011 (Stern.de, 2012). Compared to this, an SPV manufacturer like Krauss-Maffei Wegmann sold about 300 vehicles in 2011. These figures show the big difference between the production quantities. In addition, SPVs are higher customized than conventional vehicles.

Another big difference is the planning. Conventional automobile industries are forecast driven. SPV manufacturers however do not have the

possibility to get accurate forecasts. The reasons for this are explained in section 3.2. Since forecasts of the SPV industry are very inaccurate, other characteristics are more important, such as flexibility.

Another difference is stockkeeping. A lot of parts, which are needed by SPV manufacturers are usually rarely needed due to the low production quantities. Thus, stockkeeping is necessary to ensure short production times and to meet unexpected orders, since delivery times for some parts are very long. In contrast to this, OEMs of the conventional automobile industry work with just in time production. Due to reliable planning possibilities, it is possible for them to get the parts when they are needed. Thus, stock levels of raw materials, components and Work in Progress (WIP) can be kept to a minimum. For example, such a company would order the right number and type of brakes for one day's production. After that, the supplier would deliver them to the correct location within a very narrow time slot. A supply chain of the SPV industry could never work like this, since the quantities are very low and the parts often have to be produced for every single order. Brakes for example are no mass product for the SPV industry and have very long lead times.

But SPV industries are not only different to the conventional industry, but also to all other industry types. Additionally to the above mentioned characteristics of the SPV industry, there are many others. One characteristic is the high complexity of the SC. A vehicle consists of many thousands of parts. These parts are very different, since there are for example metal parts, plastic parts, machining, assemblies, coating and different services needed. A

lot of parts have to be specially designed, tested and produced for one specific vehicle. All this has to be handled by the SC.

In conclusion, there is no supply chain concept, which is applicable for the SPV industry.

1.3 SIGNIFICANCE AND GOALS

One branch of industry, which belongs to the SPV industry are manufacturers of military vehicles. For demonstration, the military vehicle industry is used in this work as a representative example of the SPV industry. Some other companies of the SPV industry have different restrictions than the military industry. However, manufacturers of military vehicles are a typical example of the SPV industry and are therefore used as demonstration in the following. Most other SPV manufacturers are confronted with similar difficulties.

With all the factors of section 1.2, supply chain management is of fundamental importance for SPV manufacturers. This is not the case up till now. A proper supply chain strategy provides financial returns. Correctively designing and effectively evaluating the supply chain as well as improving the supply chain structure dynamically over time, will become the key methods for SPV manufacturer to survive and succeed in the new, volatile environment. However, this is very difficult for companies of the SPV industry. Compared to companies of the conventional automobile industry, they are very small with low turnover. Thus, they do not have the necessary capacity to conduct

extensive research activities in the area of SC management. This is one main reason why research in the area of SPVs is either very limited, or does not exist. Therefore, a lot of companies tend to adopt methods from the conventional automotive industry, even if they are not completely adequate. This is the easiest approach and can lead to advantages, but it usually does not take into account all the needs of the SPV industry. A loss of profit is inevitable. Thus, there is still big space to improve the supply chains of SPV manufacturers. The aim of this work is the optimization of SCs of the SPV industry and to support the attainment of professional standards, which are already standard in the conventional automotive industry. Thereby, the focus is on flexibility. The improvement will be measured with specially developed performance evaluation (PE) methods in this thesis.

As already seen, the supply chain management organization (SCMO) of SPV manufacturers is confronted with managing the design of a world wide supply chains while dealing with unknown or unpredictable events. Therefore, a supply chain strategy with initiatives and innovations is needed. SPV manufacturers need to pursue strategies with a responsive supply chain rather than focusing on accurate forecasting. They have to improve their company's benefit as well as the benefit of the overall supply chain participators, by designing a proper supply chain and dynamically evaluate the supply chain performance, which furthermore leads to a Continuous Improvement of Process (CIP) of the supply chain. This is supported by this thesis, which describes the development of a supply chain in the SPV industry from the viewpoint of a Vehicle Manufacturer (VM). Thereby, the focus will be

on flexibility. The reasons why flexibility is the most important influence on the SC for SPV manufacturers are derived later in this work.

The significance of this work will become also obvious in Section 2.4. Literature about related research will be mentioned there and it is shown how far it can be used for this thesis. However there is no comparable research about supply chains of companies such as of SPV manufacturers. Thus, this thesis will be suitable as basis for further research. A lot of literature exists on different aspects and problems to supply chains. There is for example literature on supply chains for low volume, high mix and long lead time industries. But as it can be seen later in the thesis, these companies are very different to companies of the SPV industry. Therefore it is not possible to work with these SC concepts. For example the apparel industry often has similar requirements, such as high mix and long lead times. Nevertheless, it is obvious that such a SC strategy cannot meet the needs of the SPV industry. This becomes even more obvious in the course of this thesis. Numerous efforts were made to optimization models, dynamic characteristics, evaluation models, supply chain management and so on. Especially within the automotive industry, plenty of research has been done, since the automotive industry is almost the largest industry today. However, also the automotive industry is very different to the SPV industry, as described in section 1.2. It is always possible to apply SC concepts of industries with similar requirements, but there will be always high losses, because these concepts do not fit to the SPV industry. A detailed description about literature on industries with similarities to the SPV industry is given in section 2.4. Summing up, the

findings of existing literature are not applicable for supply chains of the SPV industry.

There is now the question, what part of the SC has to be improved through this thesis, since the field of SC is huge. In section 2.1 different definitions for SC are mentioned and the subareas of SC management are listed. However, it can be already anticipated, that this thesis will focus mainly on topics such as material flow, supply chain performance measurement, buyer-supplier relationships and supply chain controlling. Less important for this thesis are topics such as outsourcing, order processing and SC management concerning services and information. These topics are not considered in detail, because they are not as relevant as the other topics and can be improved separately, without the developed strategy of this thesis since there is no direct connection.

The overall goal of this research is to find a way for supply chain optimization by OEMs in the SPV industry. This will be done by the integration of the right type and right amount of flexibility in the SC. Therefore some special constraints have to be considered. These constraints are for example very unreliable demand forecasts or long lead times of buy parts, among many others - see section 1.2. A supply chain scenario will be analyzed, evaluated, and improved step by step with the aim of getting a profitable, reliable, stable and flexible supply chain in the end. The result of the new SC concept will be compared to the results of SC methods that are typical for the current state of the art. Therefore it will be necessary to measure the performance of the SC concept. This can be carried out by doing a

performance evaluation. Since all improvements and strategies in this research are expressed mathematically, the mentioned goals can be measured numerically.

The most important performance measures will be profit and costs. They can be not only used to measure the overall supply chain performance, but also to evaluate the flexibility characteristics of a SC. Hence, these performance measures are frequently used in this work to evaluate the intermediate steps. But in the end, it will also help to compare two different scenarios. One scenario will show the costs for the combination of all developed flexibility types. The other one will derive the costs for the case if none of the flexibility types is considered. These two performance measures will be compared with each other to demonstrate the effectiveness of this work. The performance measures will have an important role, because they affect the strategic and tactical step-by-step approach when developing the SC.

The thesis will help to set up an improved supply chain by:

- determining a flexibility strategy for SPV manufacturers

- recommending follow-up actions

- determining mathematical models which can be used in the real world

- providing instructions for risk analysis

To be more specific, the SC of the SPV industry will be mathematically depicted as far as possible and as far as necessary. Essential will be

calculations for the expected demand, for the expected costs and for the expected profit. Also order quantities have to be considered very closely. This will result in a lot more useful factors and equations. The calculations will consider different SC strategies and different flexibility levels. In the end of every consideration or development step, there will be always a formula to calculate the costs, since low costs or high profit are the main goals of a company. To get realistic results, the developed formulas will include at least the following variables:

- overage costs

- underage costs

- reservation costs

- order prices

- order quantities

- capacity

Also statistical models, such as the probability distribution of demand will be considered and included in the research. Furthermore a time scale has to be defined, to implement time as one of the main influencing factors of SCs. All these calculations and methods have to be adapted to SCs of the SPV industry.

On that basis, it will be possible to see relationships, such as between costs and time. Also some time relationships can be derived, which show for example profit changes over time and will be used as performance indicators.

The present work will demonstrate that a proper supply chain strategy for SPVs provides financial returns. This will be done because the above

mentioned goals are all related to costs and profit. An appropriate and innovative SC can for example help to minimize costs for shortages or it reduces costs caused by waste, the so-called muda. The developed supply chain will be designed in a way that an OEM of the SPV industry allows itself and other supply chain partners to benefit from the new supply chain concept. Therefore, the new SC concept will be set up with regard to the maximum potential savings, the potential profit, the potential loss or the opportunity costs. The overall supply chain performance will be improved.

All in all, this work is intended to make unique and significant contribution to theory and practice. It will be important because it helps companies, which are similar to companies of the SPV industry, to improve a supply chain. This thesis will give instructions for optimizing supply chains or for building up supply chains. Furthermore it can give though-provoking impulses to companies which want to break away from old thought patterns.

1.4 ROADMAP

Figure 8 gives a rough overview of this research, which is segmented into several parts.

```
┌─────────────────────┐
│ theoretical         │
│ background of       │
│ flexibility         │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│ detection of        │
│ requirements on the │
│ supply chain of SPV │
│ industries          │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│ detection of        │
│ important flexibility│
│ types               │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│ integration of      │
│ important flexibility│
│ types in the SC     │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│ validation and      │
│ verification        │
└─────────────────────┘
```
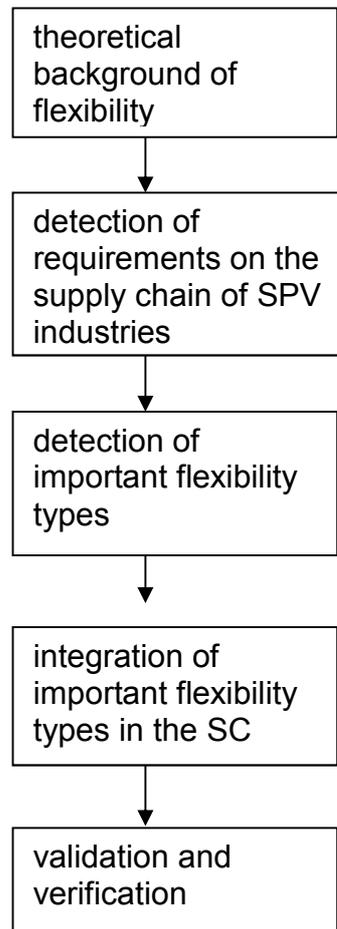
Figure 2: Research design of this thesis

According to this structure, the dissertation is organized as follows: After an introduction, a literature review is executed in Chapter 2. First, basic literature and the state of the arts to supply chains are mentioned. Then, a literature review to forecasting and flexibility is executed, because these are fundamental topics of this work. Afterwards, literature on research with parallels to the SPV industry has been carried out. The last subchapter gives

a short summary and explains the relevance of the found literature to the present research.

Also Chapter 3 is a comprehensive collection of theoretical information. It will serve as an excellent basis for the further approach where the SC concept is translated into a mathematical model. Therefore, supply chains of SPV manufacturers are discussed in detail with current trends and corresponding challenges of the SPV manufacturers. Based on this problem identification, characteristics of the SPV industry as well as forecasting methods and flexibility requirements of SPV manufacturers are derived. After some general information about supply chains, a thorough overview on definitions and traditional forecasting methods is provided. Section 3.3 is about flexibility. This second part is built on the previous explanations about forecasting, since forecasting has a wide influence on the flexibility of SPV industries. As it is very important for SPV manufacturers to have a good understanding of forecasting and flexibility, these two topics, which are partly related, are investigated consecutively in this chapter and lead to the problem that will be the subject matter of this thesis. The first tactical plans to reach the goal are defined. After that, the research background is explained in detail by providing general information about supply chain optimizations in the SPV industry. Also very important for SCs are build-to-order vs. build-to-stock decisions. Thus, this topic is discussed at next. All this information is used in the following to derive a new perspective on SPV supply chains. The following information is about SC performance evaluation. Since there is no general applicable method for performance evaluations, this will be also a big

challenge for this research. To start with the modeling of the supply chain, the probability distribution of the demand in the SPV industry has to be determined. As a basis for further calculations, the probability distribution is found out in section 3.9.

In the next step, these requirements are used to model an adequate supply chain. Therefore, the course of action which was presented in Chapter 3 is realized in Chapter 4. A stepwise approach is carried out until a realistic supply chain is build up.

Chapter 5 summarizes and evaluates the characteristics of the developed SC. Thereafter a performance evaluation is performed, which fits to the developed supply chain. This performance evaluation is not only done for illustration, but also for validation and verification of the new SC strategy. It will also show the feasibility and effectiveness of the model. All this will not only be practiced as an end in itself but more as an instruction for similar industries.

Chapter 6 is a preliminary conclusion of the thesis and shows the expected results of the thesis to be finished. In this context, the research contributions are delineated. Finally, recommendations for other researchers are given, to enhance the usefulness of this work.

CHAPTER 2

LITERATURE REVIEW

The goal of the thesis is the supply-chain optimization by OEMs of the SPV industry. Therefore, section 2.1 starts with a short summary of the literature and state of knowledge on supply chains. This context leads very quickly to the process of forecasting. It is known, that forecasting is one of the main influences in SC management. Thus, forecasting is described in section 2.2. In this section it will become obvious that SPV manufacturers cannot rely on their forecasting results. To compensate for this, the focus of this work will be on flexibility to improve this special SC. For this reason, section 2.3 will give more information about flexibility. Different types of flexibility are presented and it will become apparent, which types of flexibility are most important for SPV manufacturers. Calculations in the following sections will refer to these types of flexibility. For the sake of completeness, literature about industries with similar characteristics is reviewed in section 2.4. At next, subchapter 2.5 gives a short overview and shows the relevance to SPV supply chains.

2.1 LITERATURE AND STATE OF KNOWLEDGE ON SUPPLY CHAINS

In 1982 the term "supply chain management" was popularized by the two consultants Oliver and Webber who pointed out that business could potentially derive benefits from integrating the internal business functions of purchasing, manufacturing, sales, and distribution (Harland, 1996). Today this term is one of the main catchwords in academic research and industry business. It can be said that the popularity of Supply Chain Management (SCM) has risen to even higher levels by now. However the field of SCM is very huge, so that the claim that SCM is in some individual areas still in its infancy does not seem too farfetched or unrealistic.

The buzz words "supply chain" has plenty of definitions. Generally a supply chain is a network of companies, which act as suppliers, manufacturers, distributors and retailers, through which raw materials are required, transformed, produced and delivered to end customers (Ahn, Lee, & Park, 2003). But not only the flow of raw materials and products is involved, but also services, information and money are transferred through the complex hierarchies of the participating companies.

SCM is a very comprehensive field of activity. It means that a lot of knowledge from different kind of fields is necessary and has to be connected. Thus, SCM is a multidisciplinary area that asks for a lot of background knowledge, which can be assigned to many different bodies of research. Table 1 gives a short overview of some important subareas which are

fundamentally for research in SCM or which can be even contributed to the field of SCM.

Table 1: Background knowledge of SCM

Subareas of SCM	Sample source
Supply chain performance measurement	Gunasekaran, A., Patel, C. and McGaughey, R. E., 2004
Bullwhip effect	Disney, S., 2009
Buyer-supplier relationship	Terpend, R., Tyler, B. B., Krause, D. R. and Handheld R. B., 2008
Outsourcing	Bustinza, O. F., Molina, L. M. and Gutierrez-Gutierrez, L. J., 2010
Order processing related to supply chains	Wagenitz, A., 2007
Supply chain controlling	Winkler, C., 2008
Relationship between efficient SCM and firm innovation	Mabert, S. B. and Modi, V. A., 2010
Logistics and SCM	Christopher, M., 2005

After thinking about the structure of supply chains and its background, the question comes up as to what the objective of SCM is. For Tan (2006) the objective of supply chain management is to increase profits and profitability. Christopher and Jüttner (2000) defined SCM as the improvement of cooperation. For Christopher (2005) SCM means the controlling of upstream and downstream relationships with suppliers and customers to deliver superior customer values at less costs. For Davis (1993) the goal of SCM is the improvement of customer satisfaction while reducing overall costs. For Monczka, Handfield and Giunipero (2008), the emphasis of SCM is on four

areas: First, the cost and availability of information resources between entities in the SC. Second, the responsiveness and flexibility of organizations. Third, the fulfillment of customer expectations and requirements. Fourth, a rapid response of the SC to major disruptions in supply and downstream activities.

Most of the objectives mentioned above are related to a certain extent. But there are a lot of different formulations. However, the bottom line is always the same. If for example the cooperation in the supply chain is improved, the profit and profitability increases. The profit is related with the customer satisfaction. And the customer satisfaction in turn depends on the degree on how much the customer desires and expectations were met. The desires and expectations of the customers are met if for example the number of stockouts is improved or if the delivery time is minimized. The number of stockouts and the delivery time are again influenced by the SCM. It can be seen that there is always a connection between the different formulations and approaches of the different scientific investigations. However, all objectives described so far might contribute to achieving customer satisfaction since this is a superior point and at the same time the guiding principle of almost all companies.

But still all objectives are not independent of each other. As they are correlated, achieving one objective helps to attain another. Thus, by improving the supply chain, several different goals can be achieved if only one of the above mentioned objectives is pursued.

Another important point in SCM is the organizational effectiveness which can be measured by the degree to which an organization achieves its

goal. If for example, the objective is an increased customer satisfaction, it can be achieved by an improved supply chain. The customer satisfaction would be an indicator for the organizational effectiveness (Díaz, 2006).

2.2 LITERATURE AND STATE OF KNOWLEDGE ON FORECASTING

It is often said that there is a relationship between flexibility of a supply chain and forecasts. It is known that the degree of flexibility has to be higher if the used forecasting methods are inadequate (Armstrong, 2001). Thus, appropriate forecasts could be mandatory for a sound supply chain. This indicates that the flexibility of a SC becomes important if the quality of forecasts is low. Especially demand forecasts of OEMs are important, as they affect the whole SC. The demand forecast predicts the demand for the final product and determines the demand for sub-components and individual parts. Therefore forecasting methods are examined in this subchapter. To begin with, a common understanding for forecasting is needed. Armstrong (2001) simply defined forecasting as estimating in unknown situations. He states that forecasting is commonly used when discussing time series. This is also how forecasting is seen in this work.

Following is a brief overview of traditional forecasting methods and the reasons why they are not appropriate for the SPV industry:

- Time Series Forecasting:

This is one of the simplest forecasting methods. It is based on the assumption that the past is a predictor of the future. It can be for example realized with the method of moving average (Wheelwright, & Makridakis, 1985). This means, that a set of observed values is taken. The average of these values is the forecast to predict future demand (Yu, 2003). Unfortunately, this method would present very unreliable values to OEMs of the SPV industry, because the spread of the observed values is much too wide. In addition, apart from historical data, there are a lot more drivers which affect customer demand. For a good forecast it is for example necessary to place more emphasis on supply chain management and customer behavior to generate more accurate estimates of future demand. It is not sufficient to make predictions, only reflecting past business results. Information such as industry trends, new products and new competitors should be considered, because it might have significant impact on future demand. This can be for example gathered by carrying out marketing research.

- Genius Forecasting:

The genius forecasting is based on intuition, insight and luck. There is a high probability of wrong forecasting. It is impossible to recognize a good forecast until the forecast has come to pass. There is another weakness for some companies, because this method is not computer generated. It would be not possible for large companies to use the forecast for thousands of items each month. Especially this forecasting method is largely considered as an art that requires professional judgment. Unfortunately, the forecast depends on the knowledge of the forecaster. Thus, the result depends to a large extent on the person who does the forecast.

• Causal Forecasting:

This forecasting method develops a cause-and-effect model between demand and other influential variables (Gilliland, & Prince, 2001). Thus, the demand forecast is calculated as a result of a function of independent variables (Yu, 2003). These values do not have to be historical values such as in time series forecasting. These can be for example the demand related to the number of potential customers. Another well-known causal forecasting method is regression. A simple mathematical representation would be for example the linear regression, where the random variable Y is related to x by the following straight-line relationship:

$$E(Y|x) = \beta_0 + \beta_1 x \tag{2.1}$$

The intercept β_0 and the slope β_1 are unknown regression coefficients. In a demand forecast, Y would be the demand and x a factor that affects the outcome of the demand. The example above has only one independent variable or regressor x. Similar to this are multiple regression models for demand forecasts. Multiple regression models have more than one regressor that were identified as important factors to the demand. These regression models can be also a line of mean values. This means that there is for example a distribution of the demand Y at each x and that the variance of this distribution is the same at each x (Montgomery, & Runger, 2010).
For companies of the SPV industry, this method is not used, because it is very complex and costly to implement (Lapide, 1999). Additionally, the identification of the important factors x is very subjective.

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• Collaborative Forecasting:

Collaborative forecasting means that information is shared beyond the organization boundary, instead of using the information within a company. Therefore it is necessary to develop a communication infrastructure that enables collaboration among partners in the SC (Yu, 2003). One way of the collaborative forecasting is the online based forecasting. Supply chain partners often use the same online tool to share information very quickly (Roos, 2002). This information is usually a preliminary forecast of a downstream company. Afterwards, this forecast is passed on to the upstream companies for comments and suggestions. Based on this, a forecast can be made. Such online tools make it even possible for companies along the chain to get quick access to information on what's on order at all points along the chain (Truss, Wu, Saroop, & Sehgal, 2006). A big amount of information can be shared in short time. Relations along the SC can be visualized and should make a clearly defined and understood forecast process possible. Unfortunately, this forecasting technique is not sufficient for companies of the SPV industry. If the information from the end customer and the OEM, which are at the beginning of the information flow, are only very vague, a quick information flow does not help much. The bad information would only trace all the way back to the upstream companies. Military vehicle industry is a very exceptional field of operation, with a lot of unforeseeable events and circumstances. Especially for military vehicle manufacturers, it is not uncommon that main customers keep important information confidentially. A lot of wrong and belated information would be shared. Even a bullwhip effect would be unavoidable. Therefore, this forecasting method cannot be a

solution for an efficient SC in the SPV industry. Only if there is reliable information from the end customer, this forecasting technique can be used in the SPV industry. However this is done without software support, because the efforts would be far too extensive, because of the large number of suppliers in the SPV industry.

There may be other forecasting methods. However all forecasting methods usually imply the above mentioned information and techniques. This information and the explained procedures are important for guiding and influencing future decision-making and in most cases this is sufficient to predict the future demand very accurately. However, in SPV industry it would lead to wrong forecasts. Following are some general reasons why forecasting methods are not reliable, especially not in the SPV industry:

1. Important information is ignored, e. g. only historical data are considered.

2. The forecasting method uses the wrong weighting for the implied data.

3. It is not possible to automate the forecasting method for a multiplicity of different articles (e.g. „Genius Forecasting").

4. Continuing calculations for the supply chain planning, which are based on forecasts, cannot be executed because the forecasting method doesn't provide numeric results.

5. Forecasting methods depend on the person who does the forecast. Thus, the forecast is not reproducible and not reliable. As a result there are different forecasts for parts which are combined in the end. Thus, a

cross-company plan which matches these forecasts of different people is not possible.

6. Different influences cannot be combined in a proper way. All influences have to be expressed quantitatively. There is often no flexible mathematical equation to combine all these values.

It becomes even more obvious, that especially companies of the SPV industry cannot rely on forecasting.

In addition to all the forecasting methods above, it has to be mentioned, that there is another possible approach. Thereby, different forecasting methods are combined. There are already concepts of forming linear combinations of various forecasts with respect to particular objectives or of multi-objectives (Leung, Daouk, & Chen, 2001). However, this means that the workload is increasing dramatically, because all the applied forecasting methods have to be executed. This is a big disadvantage for companies of the SPV industry, because they usually do not have a lot of capacity. Furthermore, a bad result of only one of the applied forecasting methods would influence the complete result. Such a bad result would be unavoidable, as explained above.

Summing up, flexibility is needed to compensate these unreliable forecasts of the SPV industry and makes flexibility even more important. Therefore flexibility is discussed in the following section.

2.3 LITERATURE AND STATE OF KNOWLEDGE ON FLEXIBILITY

Based on relevant literature, the important elements of Supply Chain Flexibility (SCF) are discussed in this section. Thereby the focus is on OEMs. Later this knowledge is considered when appropriate flexibility methods are implemented in supply chains of the SPV industry.

There are a lot of different definitions of flexibility in literature. Shewchuk and Moodie (1998) calculated more than 70 different definitions of flexibility.

According to general understanding, flexibility reflects the ability of a system to properly and rapidly respond to changes, coming from inside as well as outside the system. Following are two definitions for flexibility, which are exemplary examples:

Li and Qi (2008) defined flexibility as the robust ability of supply chain network to restructure their operations, align their strategies, and share the responsibility to respond rapidly to the uncertainty of internal and external environment, to produce a variety of products in the quantities, costs, and qualities that customers expect, while still maintaining high performance.

Zhang, Vonderembse and Lim (2003) defined flexibility as the ability of the organization to manage production resource and uncertainty to meet various customer requests.

These are very typical definitions of flexibility. There may be slightly different definitions. It can be however stated, that SC flexibility usually deals with the following topics (Vickery, Calantone, & Droge, 1999; Viswanadham & Srinivasa Raghavan, 1997):

- launch

- product volume

- access

- target market

- volume

- routing

- delivery time

- new products

Flexibility is one of the major competitive advantages for OEMs in an increasingly competitive market. High supply chain flexibility (SCF) is essential for a company's business performance because supply chain operations are always subject to a variety of uncertainties like customer demand, supplier capacity, supplier lead time and product quality (Giannoccaro, Pontrantrandolfo, & Scozzi, 2003). Thus, in context of supply chain optimization, flexibility is an important issue which has to be discussed precisely and systematically.

Following are some properties of the SPV industry, which are the main reasons why flexibility is an important issue for SPV manufacturers:

- uncertain demand

- uncertain supplier capacity

- uncertain supplier lead time

- uncertain product quality

- short product life cycle

- large product portfolio

- short delivery times to the customer

- individual customer wishes

The developed supply chain must allow the management to continuously make decisions, often without the adequate informative support. Such decisions are necessary to accommodate the uncertainties and variations that characterize the product demand process. These uncertainties and variations could be for example a result of process quality problems or of reduced demand. In order to counteract arising problems such as demand peaks or low supplier capacity, supply chain management organizations (SCMOs) have to respond rapidly to changes. It is the goal of SCMOs to respond to changes in a faster and/or less costly manner than its competitors. Thus, SCF is important to SC performance.

However, it has to be taken into consideration that flexibility is not only an issue for OEMs. It is an underlying assumption that not only OEMs, but also suppliers through the whole SC are willing to accommodate the uncertainties and variations in each other's businesses. In order to ensure flexibility, also the robustness of the buyer supplier relationship under changing supply conditions has to be considered. It is helpful, that in modern supply chains, information technology and transportation networks are often

very developed. Thus, a good communication between buyers and suppliers and a cost effective movement of products in a short time are usually possible and helpful for the implementation of a sophisticated flexibility strategy.

Unfortunately, there are not many specific studies on the flexibility of supply chains in literature. Reason could be that the degree of flexibility and the type of flexibility have to be adapted to the specific SC. There is also no universal formula about how to evaluate the flexibility of supply chains. It is obvious that a company, which produces one single part at different locations, has different flexibility goals than an automobile manufacturer. Thus, an appropriate way has to be found to define the most important flexibility characteristics of SPV supply chains. The later development and evaluation of the SC will be based on these flexibility characteristics. Thus, it will be possible to develop the supply chain according to the specific needs of the SPV industry.

In academic literature on this subject, flexibility is often split up as follows (Tian, 2011):

- operational decision flexibility

- logistics flexibility

- information flexibility

- robust network and re-configuration flexibility

- market and supply flexibility/production flexibility

Table 2 goes some more into detail and explains the above mentioned subgroups and assigns a lot of common flexibility types to these subgroups. Additionally, Table 2 includes a variety of different flexibility terms, which are common in related literature.

Table 2: Overview of flexibility types (Li, & Qi, 2008; Schütz, & Tomasgard, 2011)

Flexibility Type	Explanation	Examples
Operational decision flexibility	- focused on flexibility in the supply chain operations - includes manufacturing flexibility (organizational abilities, advanced technology and automatic capability, product flexibility and technology flexibility) - includes resource flexibility (labor flexibility, financial flexibility and machine flexibility)	- assignment of jobs to machines is changed due to a breakdown - a different Bill of Material (BOM) has to be used to produce the finished product - labor force skills have to be aligned to the needs of the SC to meet customer requirements at each participating company of the SC
Logistics flexibility	- inventory flexibility (flexible warehouse space and stock strategy) - delivery flexibility (ability to handle demand as a flexible instead of a fixed entity; handled is both delivered amount and delivery date) - includes material handling flexibility - routing flexibility	- raw materials and finished products are transferred in a way to accommodate sudden peaks in demand or bottlenecks in production capacity - higher levels of stock to balance seasonal variations in supply and demand - higher levels of inventory of certain raw materials, products, modules or systems in times of cheap market prices for these items to reduce procurement

		costs
Information flexibility	- synchronization of information systems with supply chain partners - information sharing across internal business processes (appropriate information transmission speed, information transmission quality and information sharing depth) - information sharing across the supply chain (appropriate information transmission speed, information transmission quality and information sharing depth)	- reducing bullwhip effect (see Chapter 3)
Robust network and re-configuration flexibility	- focus is on existing relationships in response to changes in the business environment and the ability to reconfigure the supply chain - ease of changing supply chain partners in response to changes in the business environment - cultural flexibility (adaptation to different cultures at each node of the supply chain; helps to improve cooperation and communication across the SC)	- no monopolists as suppliers for critical parts
Market and supply flexibility and production flexibility	- focuses on the ability to respond to forecasts and the ability to change the supply of products - includes mix flexibility - includes volume flexibility - includes market flexibility (ability of response and introducing new products) - includes modification flexibility/variety flexibility (product variations and new products in order to meet the changing needs of customers or suppliers) - includes supply flexibility - includes changeover flexibility (ability to add new products to the portfolio) - includes rerouting flexibility (ability to react on defect production machines) - includes material flexibility (ability to replace materials)	- increasing or decreasing production volume according to demand - production of modified products according to customer wishes - change of market conditions and customer needs and wants - change of the supply chain plan in response to the changes in customers and downstream firms (consignment flexibility, order fulfillment rate and on-time delivery rate)

	- includes process flexibility (ability to react on unexpected disturbances and changes of the production environment)	

One challenge is to find the best level of flexibility, since additional flexibility has not only advantages but also disadvantages. Flexibility is always costly. If for example storage flexibility is used, costs for obsolescence occur. Additionally, storage flexibility is limited by a product's shelf life.

Figure 3 shows some more costs which most commonly occur due to flexibility.
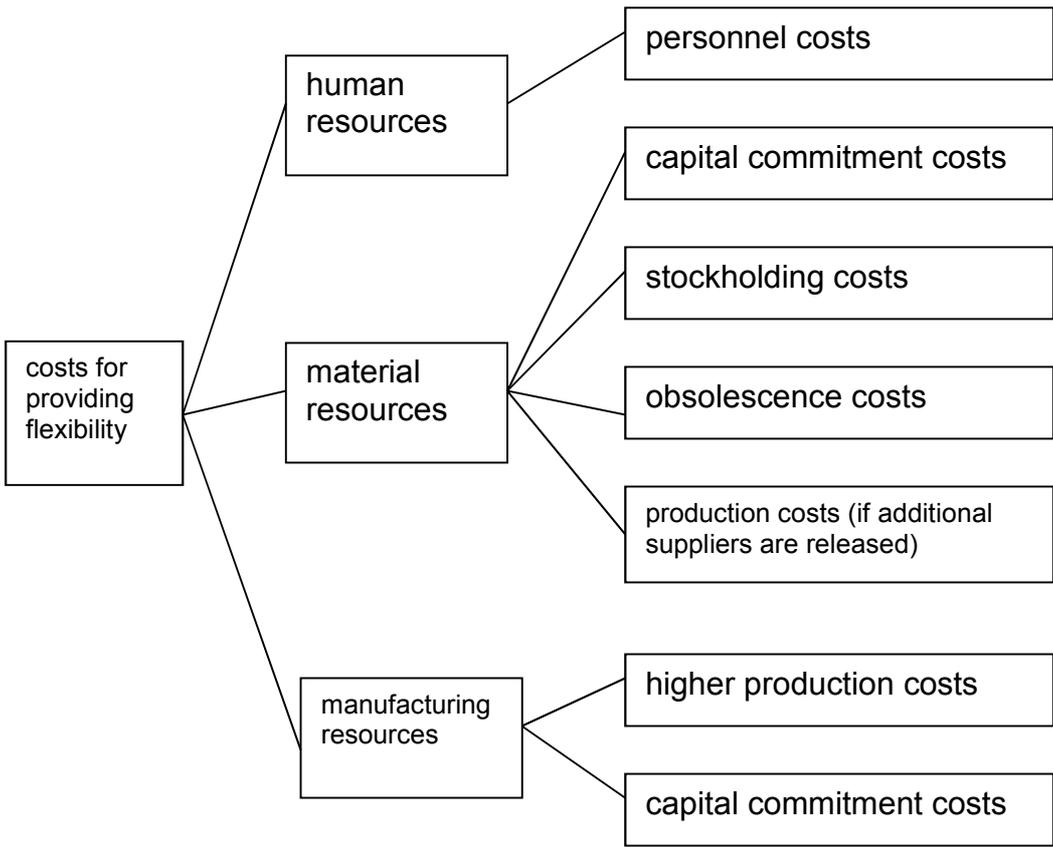
Figure 3: Examples for flexibility costs

It has to be considered that not only flexibility is costly but also inflexibility. The absence of flexibility leads to costs, such as contractual penalties. Due to a loss of flexibility there could be also lost orders, because customer wishes, for which flexibility would be necessary, cannot be realized. Compared to costs for flexibility, the costs for inflexibility are difficult to estimate.

However, as a general guideline it can be recommended that the SCF should balance out the environmental uncertainty (Merschmann, & Thonemann, 2011). This balance is shown in Figure 4. Thus, companies constantly have to assess how much flexibility they really need (Pujawan, 2004). The degree of flexibility should not be too high and not too low.
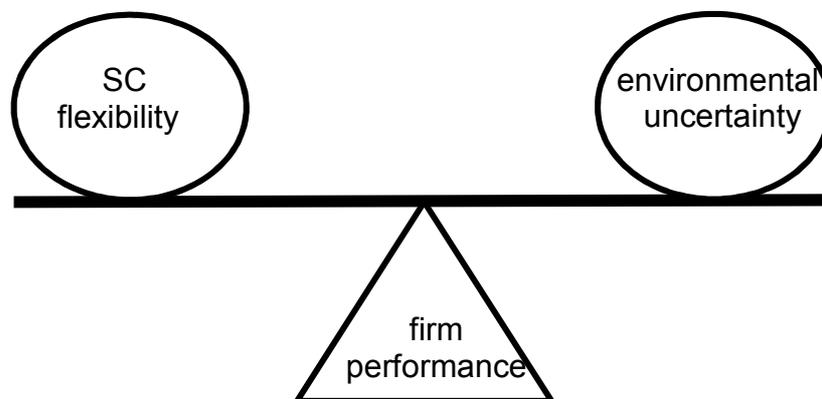
Figure 4: Balance between SCF and environmental uncertainty

It is very difficult to determine and measure the needed flexibility of companies. There is also no generally applicable model for this purpose. The problem of evaluating flexibility or of measuring the need for flexibility has to

be solved individually for each type of industry or company. Thus, it is also a challenge of this research, to handle this problem for OEMs of SPVs.

2.4 LITERATURE ON RESEARCH WITH PARALLELS TO THE SPV INDUSTRY

As it was already explained in section 1.2, supply chains of the SPV industry are very different to supply chains of other industries. Nevertheless, there could be some similarities to other industries, which are helpful in designing an appropriate SC for the SPV industry. Therefore especially literature about SCs of the automotive industry and literature of SCs for low volume, high mix and long lead times are reviewed in the following.

For example Tian (2011) gives a good overview of SCs in the automotive industry. Two different methods for a performance evaluation/PE are explained. A very effective method to evaluate the performance of a supply chain is developed. Also in the present research, a PE with a similar approach will be done, to evaluate the developed SC of this research in the end. In contrast to this research, the work of Tian (2011) is only focused on PE. This is not the purpose of this research. However, a PE will be needed in the end. Thus, it can serve as useful guidance. But there will be one big difference to the work of Tian (2011), because the primary measure of this research will be profit. In reality, costs or profit is always the final measure. Beside the execution of a PE, Tian (2011) also shows in his work, that all SC participators can benefit from a proper SC. He proves that an appropriate SC

design leads to a higher profitability. This is the main driver to develop an appropriate SC for companies of the SPV industry in this research.

Lee (2002) wrote about "Aligning supply chain strategies with product uncertainties". Lee (2002) tried to characterize a product. This characterization should help to find the right supply chain strategy. He introduces a method to distinguish between the two key uncertainties of products. The one is demand uncertainty and the other is supply uncertainty. The next two distinctions of Lee (2002) are between functional and innovative products and between stable and evolving supply processes. In the end, Lee (2002) found out, that this approach cannot be used to devise the right SC strategy. Later in this research, it is also shown, that a clear distinction is not possible for companies of the SPV industry and that this distinction would help to develop an appropriate SC. However, Lee (2002) also states, that the right SC strategy is mandatory for successful companies and that the strategy has to be tailored to meet the specific needs of the customers.

Another work about demand uncertainty was published by Fisher, Hammond, Obermeyer and Raman (1997). They pointed out, that reducing lead time enables a company to react more quickly to demand variability. Therefore, a method to realize this intention is explained. It helps to match supply with uncertain demand more easily. This approach is not explicitly considered in the present work. It is only a further approach to improve a SC, which is already standard for most companies. The approach of this work goes much more into detail and does not affect this basic method. Furthermore, this work pursues some more objectives. The only similarity is

the goal to reduce lead time. But the approach will be different in the present work.

A scientific paper of Minkyun Kim (2010) claims, that SC performance mainly depends on SC risks. If there is a high risk in a SC, the performance is low and if there is a low risk, the performance is high. It is shown that SC integration mitigates SC risk. SC integration is already a widely applied management practice in order to improve the SC performance. The focus is on collaboration between companies of the SC. However, as it was shown in section 2.2 (subject to Collaborative Forecasting), a better information flow does not help much to improve supply chains of the SPV industry. It creates a value for every company of the SC, but the effect on companies of the SPV industry is relatively low. Hence, the approach of Kim (2010) is appropriate for companies of other industries but leads to the wrong direction for companies of the SPV industry. Similar to the paper of Kim (2010) is a research of Kaijie Zhu (2004), in which the benefits of sharing information are modeled. But it is also not helpful for the present research, for the same reasons.

Another survey about information sharing was exhausted by Cachon and Fisher (2000). In contrast to the above mentioned papers, they have further differentiated between information technology and the flow of information itself. They have found out that a sound information technology for a fast and effective physical flow of goods through a SC is much more valuable than using information technology to expand the amount of information, which is passed on in the SC. For supply chains of the SPV industry both, the information technology and the information flow itself are of

secondary importance, because the information quality can be only improved to a very low limit.

Feitzinger and Lee (1996) write about mass customization of printers. There are many differences to the SPV industry, such as the customer market. However, Feitzinger and Lee (1996) address the predicament that customers are demanding that their orders are fulfilled in short time and at the same time they are demanding highly customized products and services. They introduce principles, which should be considered for an effective mass-customization. One is to design products so that they consist of independent modules. The next is to design manufacturing processes so that they consist of independent modules too. Another one is to improve logistical factors, such as the location of manufacturing and distribution facilities. Furthermore, for Feitzinger and Lee (1996) postponement of tasks is one of the key methods. Products for specific customers should be differentiated at the latest possible point in time. Postponement is a very good method to reduce lead times. Therefore this method can be also strongly recommended for SPV manufacturers. Later in this work, an additional method of postponement is derived, which is even much more effective for companies of the SPV industry. Instead of postponing the differentiation of products, a sophisticated method to postpone orders until the last possible moment is shown.

Milner and Kouvelis (2002) conducted an exhaustive survey, on the value of information, production flexibility and supplier flexibility. They have investigated companies, which have to struggle with uncertain forecasts, leading to a high demand uncertainty. The right balance between information

flow and flexibility should counteract this difficulty. For the specific case of this research, it was shown, that the greater the demand uncertainty, the greater the value of information relative to the value of flexibility, especially for companies with long lead times. Thus, SPV manufacturers will have to get the best possible results from flexibility methods, since they do not have the chance to get the desired reliable information. Therefore, the present thesis develops methods to enhance flexibility in supply chains of the SPV industry.

Obviously, flexibility will play an important role in this research. Also Gong (2008) has dealt with flexibility. He measured the flexibility for a supply chain with an uncertain environment. Therefore, he built some models with basic flexibility elements and measured their SC flexibility. The developed SC is different to supply chains of the SPV industry. The SC of Gong (2008) represents a network between suppliers, different manufacturers and a couple of distributors. But this is not important, because the focus is on evaluating the economic benefit of the SC flexibility. Flexibility measuring does not exactly address the goal of the present thesis. However, it can give some hints, because flexibility models will be also developed in this thesis and they will have to be economically evaluated too. Gong (2008) concludes that the performance of the entire SC can be improved by implementing flexibility components in the entire chain. This is also the overall idea of the present work. Additionally, Gong (2008) also uses costs as suitable measuring index for the economic evaluation of flexibility. The same approach will be used here. Instead, profit could be used as measurement index, which is almost the same, because minimum costs are equivalent to maximum profit.

Also Chuu (2011) proposes an algorithm for determining the degree of SC flexibility. Therefore, a fuzzy linguistic approach is used. For the evaluation of the SCF, five flexibility dimensions are used: operations systems flexibility, logistics process flexibility, supply network flexibility, organizational design flexibility, and information systems flexibility. Each dimension is assessed by four flexibility characteristics: efficiency, responsiveness, versatility, and robustness. A group of experts has to be formed, to assess these flexibility characteristics for all five flexibility dimensions. The experts use linguistic terms for this group decision-making model. Thus, the evaluation depends on subjective judgments and is very time-consuming and burdensome. For the development of the SC in the present work, it will be necessary to evaluate different SC methods on a quantitative basis to find the best strategy. It would be very circumstantially to convert the statements of experts to get reliable evaluations. Thus, the present work will assess the SC methods on the basis of mathematical derivations instead.

Also Merschmann and Thonemann (2011) have examined the match between flexibility and environmental uncertainty. They have presented evidence that there is a relationship between environmental uncertainty, SC flexibility and firm performance. It was also shown that companies that match SCF and uncertainty realize higher performance than companies that do not achieve such a match. For SC managers, this result is a matter of course. Also for the present research it is only a confirmation of the plan that SCF itself and the optimal degree of SCF are the right way to react on uncertainty. Unfortunately, the work of Merschmann and Thonemann (2011) does not

explain how to realize this goal. The present research will go one step further, because this realization for SCs in the SPV industry will be part of it.

Another work about supply chains with high uncertainty of demand and customer capacity was written by Hing Kai Chan and Felix Chan (2010). Center of interest are Make-to-Order (MTO) supply chains, with a material flow which is triggered by customer orders. They have investigated the effect of flexibility, adaptability to the system and variations in suppliers' capacity as independent variables. As a result, the simulation has shown that the flexibility approach and the proposed adaptive mechanism can reduce the total cost. Thus, the main contribution of this paper was to prove the usefulness of adding flexibility and adaptability to a SC. It was also explained, that an adaptive mechanism can improve the demand fill rate of a system. This result is not surprising, but it is a motivation to realize these advantages for supply chains of the SPV industry. Furthermore, a lot of variables are not considered in the research of H. Chan and F. Chan (2010), such as information sharing or postponement. The present research is different, because it will consider the SC of SPV manufacturers and it will be much more comprehensive, by including all essential influences. In addition, no agent-based simulation is employed. Instead of this computational simulation, the focus of this research will be on a pure mathematical simulation.

Das and Abdel-Malek (2003) also dealt with flexibility in supply chains. They developed a method to estimate the level of supply flexibility. Similar to the present research, the focus is on delivery lead-times and order quantities, because these are often the reason for supplier buyer grievance. Therefore,

the buyer supplier relationship plays an important role in the survey of Das and Abdel-Malek (2003).They made a connection between the annual procurement costs and SC flexibility. This is no problem for many companies, such as companies of the automotive industry. These companies produce very high quantities. Thus, all costs are exactly calculated by using cost accounting methods. All companies of the automotive industry are working with these methods. In this way, it is possible to draw a conclusion about the costs for flexibility. However companies of SPV industries produce only very low quantities. Thus, all the costs, which are not related to production costs, are very high compared to production costs. For example the inclusion of insurance costs can be very different between competitors and have a significant influence on price calculations. Hence, costs allow no conclusions to be drawn about flexibility in the SPV industry. As an additional complication, OEMs of the SPV industry usually do not have the possibility to check the calculations of their suppliers because the efforts would be far too extensive compared to the ordered quantities. In comparison, it is much easier for companies to screen prices of suppliers if millions of parts are bought every year. This is never the case for companies of the SPV industry. These companies are not as focused on the buyer-supplier relationship. As a consequence, the methods of Das and Abdel-Malek (2003) can be even not used partially in the SPV industry.

Das (2010) extended his work of him and Abdel-Malek (2003), mentioned above, and developed models to integrate different types of flexibility in a SC to address demand and supply uncertainty and to improve market responsiveness. The different types of flexibility had been supplier

flexibaity to overcome supply uncertainty, capacity flexibility to solve demand uncertainty, product mix flexibility to ensure market responsiveness and input flexibility as well as customer service level flexibility to improve the overall SC performance. For Das (2010) the combination of these five flexibility types is the best possibility to respond quickly to emerging business opportunities and to changing requirements for SCs. But all these flexibility types are integrated in typical SCs without taking into account the irregularities of SPV manufacturers, mentioned in section 1.2. Nevertheless, the research of Das (2010) has some very distant parallels, because it also tries to improve SCs by increasing flexibility. However, the environmental conditions of the considered SCs and the implemented flexibility types are different to the challenges in context with the SPV industry.

All the scientific studies and books mentioned above are related to the constraints and characteristics of the SPV industry. Nevertheless, it became obvious that the introduced results, methods and strategies are not sufficient and not completely appropriate for a SC in the SPV industry. There are still big gaps, which have to be filled.

2.5 SUMMARY AND RELEVANCE TO SPV SUPPLY CHAINS

In section 2.1 basic knowledge on SCs and an insight in the general understanding of SCM was provided. Afterwards, the objectives of SCM were discussed, which has led to the fact that an improved SC always results in higher profit and profitability. For this reason, a lot of industry sectors have already developed supply chain structures for their special needs. However the literature review has shown that there are still industry sectors which are unexplored. Also SCs for the SPV industry are a field of operation which is almost unexplored. Most companies of the SPV industry are very different to other companies. They have to handle a lot of constraints and conditions which are characteristic of this industry. This fact is very costly because supply chain strategies need to be tailored to meet specific needs and constraints Tian (2011). For example a product with a stable demand and a reliable source has to be managed in a different way as one with an unpredictable demand and an unreliable supply. The demand and supply characteristics are only two examples. Specific industries however need to fulfill a number of constraints. Hence research in supply chain improvement was already done for a lot of different industries. For example the apparel industry is already well explored, for example by Lee (2000), Ning (2006) and Ying (2010). However, there is no assistance or guideline for SPV manufacturers or similar companies which helps to set up an appropriate supply chain. Therefore these companies are not organized in a proper way. To start with SC optimizations, it is necessary to have a closer look on

demand forecasting and flexibility. There is a close relationship between SC performance and these two topics. Therefore literature about forecasting is reviewed in section 2.2 and about flexibility in section 2.3. When considering the different forecasting methods in section 2.2 it becomes already obvious that demand forecasting offers no potential for SPV manufacturers to improve their SC performance. Much more hope comes up when literature about flexibility is analyzed in section 2.3. All the relevant literature about flexibility makes clear that there are great possibilities to improve SCs of the SPV industry by developing an appropriate strategy for more flexibility. Unfortunately, there are two sides to every coin, because flexibility is associated with costs. Thus, the right balance between flexibility and environmental uncertainty has to be figured out. After the direction of the present research is now defined, parallels between the proposed course of action and the existing literature have to be found. These similarities, which were revealed in section 2.4, are considered in this research as far as possible. However big steps are still necessary to develop a new, innovative SC, which will be tailored to the needs of the SPV industry.

CHAPTER 3

BACKGROUND INFORMATION AND RESEARCH

DESIGN

SPV-manufacturers are challenged by matching supply and demand. Therefore these companies invest in forecasts that reflect the demand information over time. On the other hand, companies use flexibility in their sourcing practices to compensate volatile demand. Especially companies like SPV-manufacturers need to respond quickly on market demand, and should provide a high service level to their customers. Since these companies are in volatile market environments, investments in forecasting methods or flexibility are essential. As it was seen in Chapter 2, it is more reasonable to focus on flexibility in the SPV industry. Thus, high flexibility makes the companies more responsive to customer needs while controlling relevant costs. Hence, specific background information on these topics and on SCs of the SPV industry in general is given in the following.

3.1 SUPPLY CHAIN OF THE SPV INDUSTRY

Today's market is characterized by complexity, increasing speed and high information content. Therefore, the strategic focus of industry companies is undertaking a constant transformation. Especially the automotive manufacturing industry and its Automotive Supply Chain (ASC) are extremely competitive and have to be continuously adapted to the environment. This is also true for the SPV industry. These companies have recognized that the competition is now actually a competition of supply chains. Often a good supply chain management defines who will stay and who will leave the market (Guilherme, & Osmar, 2005). Most companies of the automotive industry are already focusing on their supply chain management to develop competitive advantages. However, it is obvious that SPV industries are very unprogressive in this field of research since the SPV industry is a border area of the automobile industry and needs a completely different supply chain concept. In general, the supply chains have to consider the involved material flow, information flow and financial flow to achieve an optimal situation and thus enhance the companies' competitiveness.

Figure 5 shows the environment of an OEM with all in- and outputs which is considered in this thesis. This rough structure of a SC from the viewpoint of an OEM is important, because the SC in this thesis will be developed from the viewpoint of an OEM, since this is the one who has normally the most influence on the SC.

```
                    ┌──────────────┐
                    │ Environmental │
                    │ Influences    │
                    └──────┬───────┘
                           │
                           ▼
Raw material
and assembly
groups                                        Vehicles

┌──────────┐         ┌──────────┐         ┌───────────┐
│ Suppliers │ ──────▶│   OEM    │ ──────▶ │ Customers │
└──────────┘         └──────────┘         └───────────┘
         ↘                ↑      ↑               ↙
           Random events              Uncertain
                                       demand
```
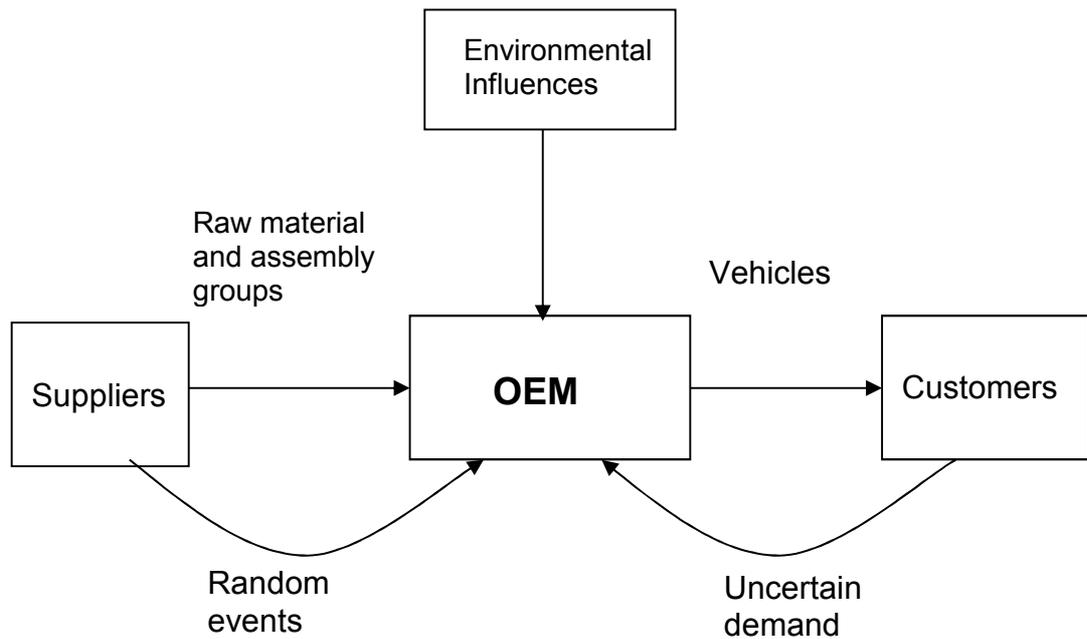
Figure 5: Supply chain from OEMs' view

An OEM of the SPV industry has about 2000 suppliers for only one

vehicle type. And these suppliers again have suppliers, too. Therefore, the SC

is very complex. A differentiation is needed because not all suppliers are to be

dealt with in the same way, are same important or have the same influence on

the supply chain. Obviously a kind of classification is needed. There are

already some methods to classify suppliers. One of these methods is for

example the Supplier Classification McKinsey. With this method, automotive

suppliers are classified into system developers, module assemblers,

component specialists and commodity suppliers (Tian, 2011). However, this

method is not appropriate for supplier divisions such as tier structures,

because such a division into groups is not relevant for the development of a

sound SC. Important information for the SC planning, as for example the material flow through the single steps of the SC, is ignored.

Another classification of products and hence their suppliers was done by Fisher (1997) and Lee (2002). They divide products into two different groups with totally different characteristics:

- functional products, such as windshield wiper

- innovative products, such as electronics

Parts which are purchased by OEMs of the SPV industry are often very different and should not be classified like this. The characteristics of functional and innovative products are shown in Table 3.

Table 3: Characteristics of functional and innovative parts

Functional	Innovative
Low obsolescence	High obsolescence
Low stockout costs	High stockout costs
Higher volume in stock	Low volume in stock
Low product variety	High product variety
Low profit margins	High profit margins
Low inventory cost	High inventory cost
Long product life	Short product life
Long/No selling season	Short selling season
Stable demand	Variable demand
Good predictable demand	Bad predictable demand

Regarding table 3 it becomes obvious that it would be very complicated and time-consuming to divide all parts into functional and innovative parts. Furthermore, a clear classification of every part will not be possible, because

some parts have characteristics of both types. For example tire inflation systems of special military vehicles can be characterized as parts with high volume in stock, low product variety, low inventory costs, long product life and without selling seasons. These are characteristics for functional parts. On the other side, tire inflation systems are subject to high obsolescence, high stockout costs, high profit margins, variable demand and bad predictable demand. Therefore there is the same number of reasons for tire inflation systems to be characterized as a functional part or as innovative part.

A more common classification than it was done by McKinsey or Fisher (1997) and Lee (2002) is the classification in tiers. In contrast to these two methods, this is a differentiation over the whole SC is the classification of suppliers in tiers. Thus, in automobile industry, the supply chain is normally organized in tiers (see Figure 6).

In this system, Tier 0 is the OEM which assembles the car.

The first tier manufactures and supplies modules or systems directly to the OEM. These modules or systems could be for example doors, dashboards or brake systems. First tier suppliers are usually experts for their modules of systems they provide. Therefore they often have to pass on their knowledge to OEMs and teach the lower tier companies as well.

Second tier manufacturers produce simpler individual components, which are included in a system of the first tier. Most companies of the automotive industry are component suppliers and thus part of Tier 2. They provide for example rear view mirrors or brake pads. Second tier and further tier suppliers are usually small and mid-sized companies.

Third tier and further tiers supply simple parts and raw materials. These

simple parts could be for example small injected parts or small machined

parts. The raw materials could be steel coils or blanks for further processing.

In recent times there is a trend that tier 3 suppliers process their raw materials

themselves. Reason is a high price pressure on raw material suppliers during

the last decade. Thereby 2nd and 3rd tier suppliers are now often combined to

one supplier.
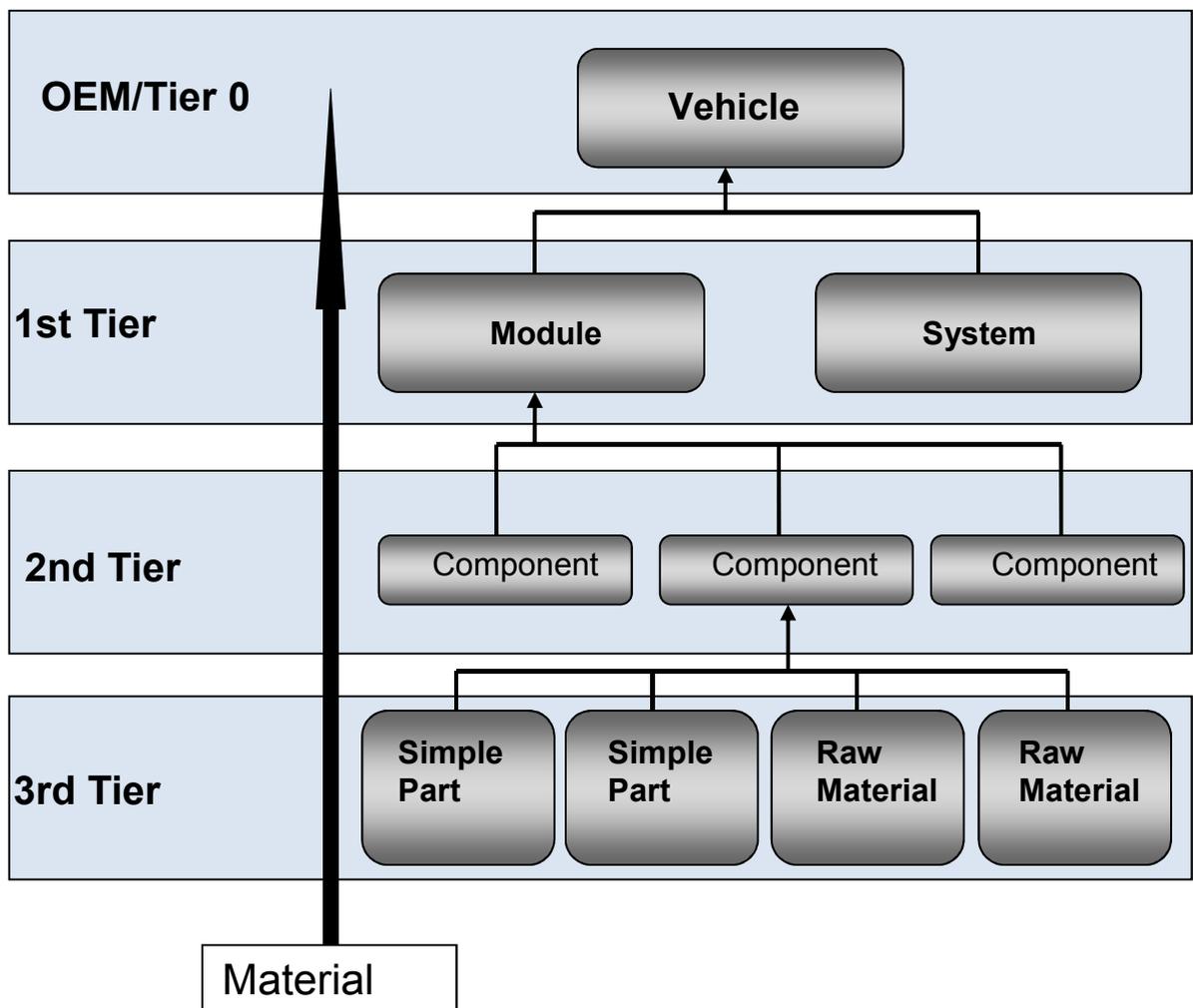
Figure 6: Example of a Tier System in the Automotive Industry

Most of the suppliers can be categorized into one of these tiers. However, there are some suppliers that do not fit into this system, e. g. suppliers which are mainly outsourced and offer services instead of concrete products. For this reason new methods were already found to categorize all suppliers (Tian, 2006). But since the Tier System is almost complete and the focus will be on Tier 0 in this thesis, the Tier System is absolutely sufficient for this research.

For the sake of completeness, it should be mentioned that the explanation above and Figure 6 show only a rough concept of the tier system. In reality it is often unavoidable that also components and simple parts are directly supplied to OEMs. However in history it was common that only components were supplied to the OEMs. Figure 423 a shows this conventional strategy of sourcing. As it was seen, OEMs have to handle a lot of suppliers and deliveries. Therefore, this strategy results in a great effort for the OEM. Today it is almost the opposite, because there are already OEMs in Europe, which do not buy components. They cooperate with few suppliers which sell several components to them. Reason is that it is beneficial to work with small companies as suppliers. OEMs often reduce the number of suppliers to minimize their efforts. Another common possibility is modular sourcing. The benefit for an OEM is higher if it is possible to cooperate with suppliers, which are specialized in producing certain modules. Figure 7 b shows that modular sourcing reduces effort for the OEM. The number of tier 1 suppliers is reduced since some components are preassembled by suppliers.

The developed supply chain in the thesis will be built up on the sourcing

strategy of Figure 7 and the main focus will be on Tier 0.

```
                        ┌─────────┐
                        │ Vehicle │
                        └─────────┘
                             │
    ┌──────────┬──────────┬──┴───────┬──────────┐
┌───────────┐┌───────────┐┌───────────┐┌───────────┐┌───────────┐
│Component 1││Component 2││Component 3││Component 4││Component 5│
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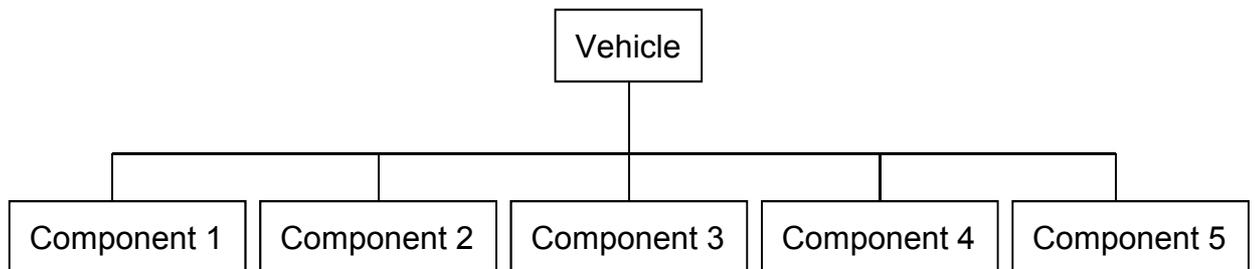
a) Conventional sourcing strategy

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                        ┌─────────┐
                        │ Vehicle │
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         ┌───────────────────┴───────────────────┐
    ┌──────────┐                            ┌──────────┐
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│Component 1││Component 2││Component 3││Component 4││Component 5│
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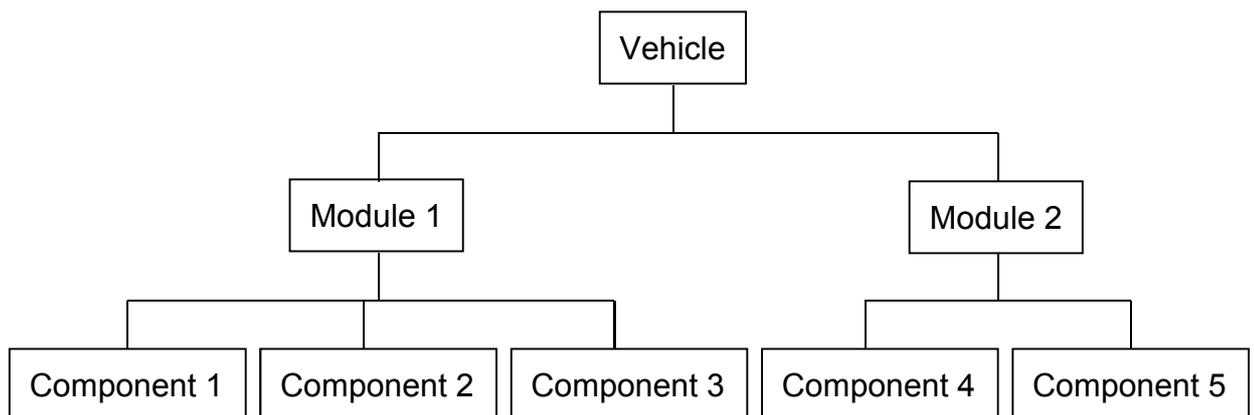
b) Preferred sourcing strategy

Figure 7: Sourcing strategies

Essential for modular sourcing is modular product design. Customers

of SPV vehicles expect cars which are designed to meet their requirements

and wishes. A modular design helps to design a variety of products with the

same modules of components called platforms.

An example offers the military vehicle industry. Since a couple of years, it is very common that military vehicles are available with a modular construction. There are vehicle families that are offered with a uniform drive module or platform and user specific deployment modules. Thus, the same drive module could be used for field ambulances, for personnel carriers, for standard transport vehicles, for communication vehicles, for radar jamming vehicles, NBC reconnaissance vehicle and so on. In simple terms, the vehicle consists of two parts. One is the chassis, which is always the same and the second is the specific upper body. But modules in vehicles can be also smaller and unremarkable for end customers, such as power train systems. Modularization is still developing and includes more complex modules or entire systems, which can be used in many fundamentally different vehicles. A declared objective is to group components of products in a module for practical production objectives. Thus, a wide range of options can be offered to the customer for an acceptable price.

Such modules are often completely supplied by tier 1 suppliers. By purchasing such modules, OEMs can save a lot of time and money because the final assembly work to preassembled modules is done by suppliers. The internal variety and complexity at OEMs can be decreased. This advantage for the OEMs is sometimes a disadvantage for suppliers. They have to compensate these costs and higher risks for the often complicated modules. For this reason, only relatively large suppliers which are specialized in their core competence can master these circumstances. Furthermore, the suppliers of modules usually produce parts for several OEMs. Thus, they have much more experience with these modules than the single OEMs. Brake

manufacturers would be one example. The number of brake manufacturers on the market is very limited. But for these companies, modularization can be also advantageous. A brake for commercial vehicles consists of more than 120 single parts. Thus modularizations can be also applied at the process level because it reduces complexity with administrative tasks. The production of modules makes an independently developing, designing and producing of the modules possible. Thus, core competences can be created and value adding activities become more transparent (Boutellier, & Wagner, 2003).

Thus, modular designs have a lot of advantages which affect the supply chain. Some of them are summarized below:

- outsourcing
- distinct family design savings
- lower costs for inventory and logistics
- lower life cycle costs through easy maintenance
- comparatively easy manufacturing
- module task specification
- increased number of product variants
- simple exchange of modules
- parallel manufacturing of modules
- fast assembly and relatively low production time due to specialization
- system reliability due to high production volume and learning curve of the supplier

Same important as modularization is standardization. Standardization means that common components are used. Thus one of the goals in optimizing a supply chain is standardization. However, the OEMs have to master a balancing act. On the one side they have to maintain product differentiation to satisfy the customers. On the other side, they have to standardize parts which are required for the entire model range.

But also a growing environmental consciousness is affecting SPV manufacturers. In the past, SPVs, such as fire fighting trucks or military vehicles were designed to meet its specific requirements. Environmentally friendly vehicles were of secondary importance. Today, also environmental consciousness affects the decisions of customers of SPV manufacturers. But not only the vehicles itself should be environmentally friendly. Also an environmentally friendly production in terms of energy and raw material is nowadays a must in most countries. For example, more and more companies of the automobile industry are audited and certified in accordance with ISO 14000, which is a family of standards related to environmental management.

Similar to the environmental protection was the development concerning safety protection. Also in this area rising regulatory requirements increased the pressure on SPV manufacturers and thus the SC.

Also new threat scenarios require OEMs of military vehicles to adapt their products. The task range of the vehicles had to be adapted to the deployment and tasks of modern army operations. In recent years, the SPV manufactures reacted with a massive expansion of their model range and equipment options.

The complexity of vehicles with many new models and product launches is one of the reasons for a changing environment of SPV manufacturers. This fact becomes even more serious in recent years. Additional to the high level of complexity, a significantly increasing electronic content in vehicles has to be managed. In the past suppliers were mostly focused on mechanical parts of the vehicle. Now electronic devices become more and more important.

Compared to the conventional automobile industry, OEMs of SPVs produce a small quantity of vehicles with a high variety. OEMs of SPVs are usually too small to keep a lot of know how in-house. Only core competencies which are important for competitiveness are kept as internal secret. Thus, these OEMs are demanding that suppliers produce a great proportion of each vehicle's systems. Some suppliers become a primary assembly arm for the OEMs. Therefore, suppliers are often forced to outsource portions of their own production to lower tiers and make the supply chain even more complex. It becomes difficult for a lot of OEMs to get their supply chain agile and flexible. It is often unavoidable and desired that such a complex SC system works globally and for a broad customer base. Thus, a certain level of precision is needed. It is often a difficult challenge for old structured OEMs of SPVs to handle this challenge.

As it was already stated, a company of the SPV industry has about 2000 suppliers. Therefore it is not surprising, that the proportion of purchased parts is very high in the SPV industry. Hence, more than 95% of all parts are usually purchased parts. Since most of the parts, which are integrated in a military vehicle, are sourced parts, only these parts are considered in this

thesis. Additionally, purchased parts are more relevant for the SC. However, the findings of this research are also valid for own-manufactured parts. There is no external supplier for own-manufactured parts. However, there is an internal supplier, for which the developed strategies are also valid. Only small adjustments need to be made to transfer this theory from sourced parts to own-manufactured parts. For example instead of purchasing prices, production costs have to be used for calculations.

There are even more specific characteristics of SPV manufacturers. For example manufacturers of military vehicles had to struggle with a changed market demand. Due to a changed international threat scenario in the last decade, there was a demand for a bigger variation and specialization of military vehicles. This change offers new opportunities. On the other side, the problems due to excessive inventory, unpredictable future, inappropriate processes, degraded customer service, growing costs, declining profits and a poor return of assets got more serious from year to year. Therefore, the established supply chain concepts, which were never adequate, became even less suitable.

However, the reason for demand changes was not only a new international threat scenario. Besides the demand quantity, also the military vehicles itself had to be adapted to new customer wishes. Also globalization was new for a lot of companies in the military industry. Even though it is commonly believed the world is fully globalized, it was never an important factor for the SPV industry and especially in military vehicle industry (Bonefeld, & Psychopedis, 2000). It was very uncommon to buy military

vehicles in foreign countries. But the advantages of globalization and the need for special vehicles in the short term caused another way of thinking. Today most manufacturers of military vehicles face a worldwide competition but also a worldwide market. The globalization of the SPV industry for military vehicles is not only a result of a general worldwide trend. It is also very often mandatory due to economic offset obligations. Offset agreements are legal trade practices in the military industry. It is an agreement between two parties, whereby a supplier agrees to buy products from the party to whom it is selling. In military industry the seller is in most cases a foreign company and the buyer is a government that stipulates that the seller must agree to buy products from companies within their country (Brauer, & Dunne, 2005). Unfortunately, these countries are often very unfavorable for purchasing goods. Low cost countries (LCCs) are usually not participated. This has often a negative influence on the supply chain. The aim of these economic offset obligations is often to even-up a country's balance of trade. This is a common part of international defense contracts. This means that a growing global customer market leads inevitably to a growing global supplier market because the OEMs of military vehicles have to buy products in the countries of their customers. Thus, globalization was never important for OEMs of SPVs. Now it is a new and serious influence on the supply chains of military vehicle manufacturers which should be taken into account while developing an appropriate supply chain. Every decision of a global acting company must be made with full consideration of the total supply chain in view of the cost and the need for efficiency and associated strategies. As a result, material management becomes more complex and these companies are entering into

unfamiliar environments where they need much more market insight and anticipation. E. g. cultural differences, geographic barriers, and variations in international business rules can make management of global operations extremely demanding. Some OEMs of military vehicles could even experience problems when trying to patent their advanced technology in foreign markets.

As it can be seen, SPVs and particularly military vehicles are a very special field. Therefore no ready-made strategy for supply chains of military vehicles exists. Additional, current literature about existing strategies is totally inapplicable, since a lot of constraints have to be considered, which are typical for SPV manufacturers. Furthermore, for setting up a very professional supply chain, very detailed examinations are necessary. Thus, things like heterogeneous demand of same parts, homogenous demand of parts belonging to the same vehicles or heterogeneous costs for too high and too low order quantities have to be considered.

After discussing all the topics above, the overall questions arise now: What are the typical challenges SPV manufacturers are confronted with? How important are these characteristics and how should they be considered when developing the SC? How should the modeling be organized? What are the critical questions? All these questions will be answered in the following.

3.2 **FORECASTING**

Section 3.1 was investigating the problems related to SCs of SPV manufacturers. This section goes into detail about forecasting and explains the relationship between forecasting and the SC in the SPV industry. Based on this, the further development of the SC and especially the development of a sound flexibility strategy can be aligned. In scientific publications, forecasting and flexibility are usually discussed in another context than it is in this work. However, forecasting and flexibility are closely related to each other and to supply chain performance. Flexibility is often defined as the possibility to react on uncertain future environmental demand. The uncertainty of demand depends to a great extent on the forecasting methods and their quality. Thus, there is a connection between forecasting and flexibility. If for example the forecasting methods of a company are very bad, there is a higher demand for flexibility. For this reason, forecasting and flexibility for OEMs of the SPV industry are discussed together in this thesis.

As shown in section 2.2, one of the main points in forecasting, and especially in collaborative forecasting is communication. Therefore, information flow through the supply chain is fundamental in SCM and forecasting. To go more into detail, Figure 6 illustrates the typical information flow in a supply chain of the SPV industry.

Information Flow

Tier 2
Suppliers

Tier 1
Suppliers

OEM

Customers
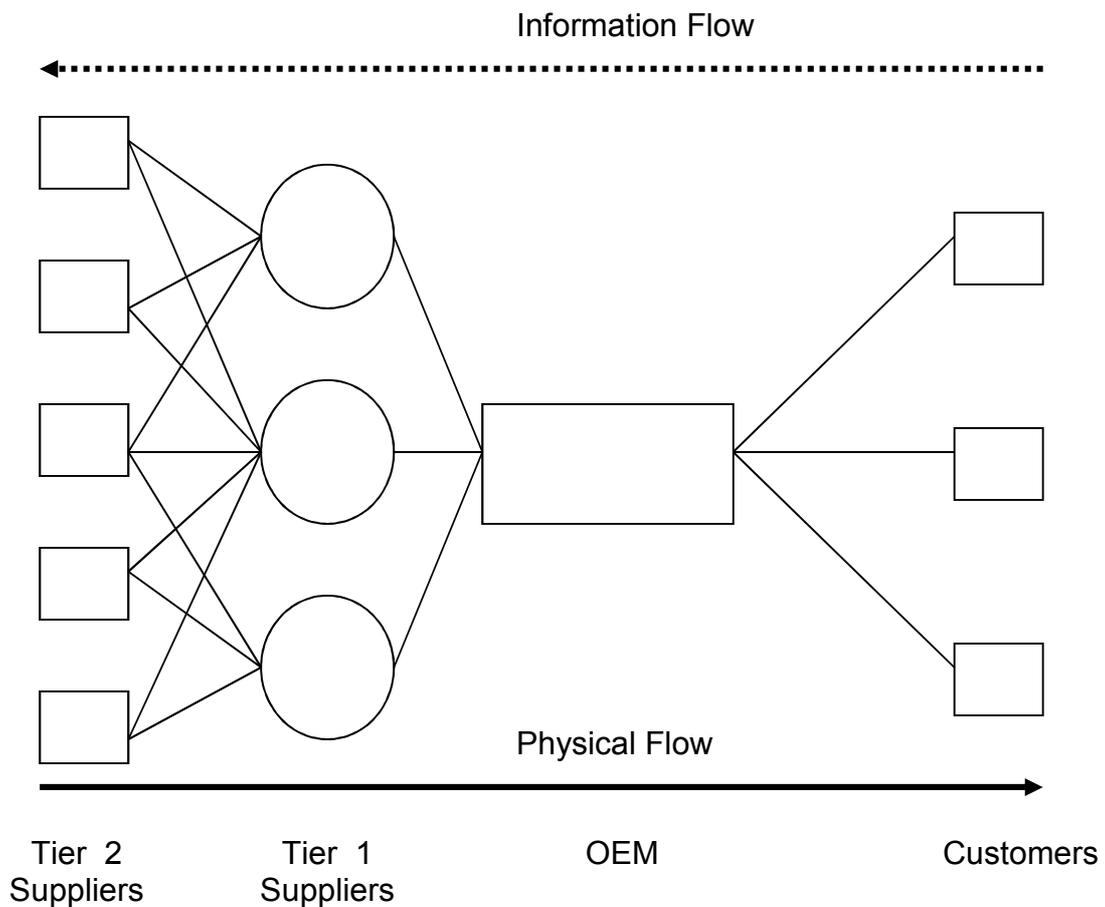
Physical Flow

Figure 8: Physical flow and information flow in a supply chain
(Tian, Y., 2011)

As it can be seen in Figure 8, the physical flow goes from upstream to downstream. Contrary to this, the information flow goes the opposite way around and has its source at the customer and goes upstream through the supply chain. Reason is that usually only the OEM has direct contact to the end customer and passes it's information on to the next tier and so on. Accordingly, the demand is provided by each chain member step by step from

the customer to the supplier. Thus, the transmitted information often gets

distorted. This effect is called bullwhip effect (Askin, & Goldberg, 2005).

Sometimes it is also called whiplash or whipsaw effect. Figure 9 shows the

bullwhip effect in the surrounding of SPV manufacturers. As it can be seen,

small changes at the customer are progressively amplified further back in the

chain.
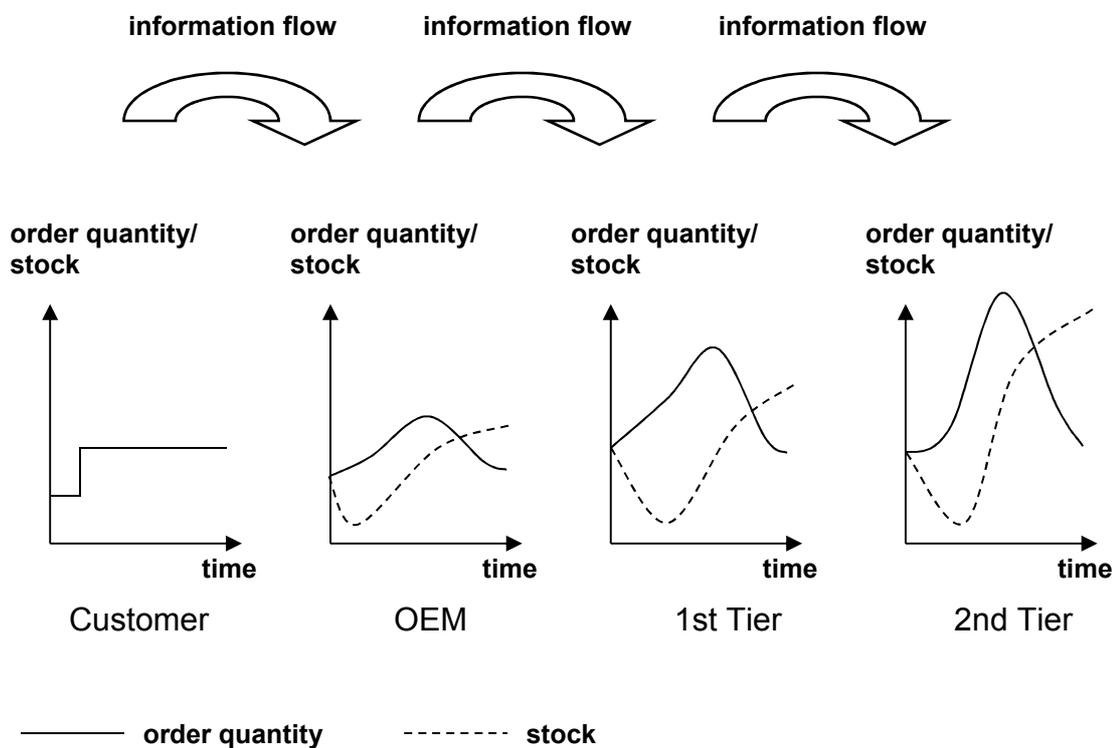
Figure 9: Bullwhip effect in the surrounding of SPV manufacturers

As shown above, the bullwhip effect is a phenomenon, where a small

variation in consumer demand can cause wild swings in orders and inventory

upstream. The reaction of the chain members get bigger as farer they are

away from the end customer. This is due to the fact that SC members carry

out their own forecast by including the demand input from the immediate downstream member. The next supplier of the SC relies on the forecast of the customer again. As a result, every shift of the actual demand goes through the whole SC. This is a typical effect how forecasts, which rely on customer information, go wrong. These forecast errors are one of the main reasons why companies carry on inventory buffer. Thus, the stock is also increasing up the SC, as it can be seen in Figure 9. Each SC member has a greater observed variation in demand and thus greater need for safety stock (Buchmeister, Pavlinjek, Palcic, & Polajnar, 2008). In plain words, suppliers need safety stock for the increased safety stock of their customers.

Following are the three main reasons for the bullwhip effect (Lee, Padmanabhan, & Whang, 1997):

1. Demand forecasting: A supplier often doesn't know the real demand. Every company in the chain does forecasting based on the information it gets. Thus, as already mentioned, forecasting is often based on the order history from a company's immediate customer. If a company places an order, the upstream company takes this information as a signal about future demand since the supplier supposes the customer's order to be the real demand. Based on this signal a demand forecast is updated and a higher safety stock is planned. Consequently a bigger order is placed at the next tier. The next upstream company will do the same and will cause even bigger swings.

2. Order batching: Usually a company does not immediately place an order as soon as it gets an order from it's customers. Often demands are batched before an order is placed, because of logistical or financial related reasons. These shifts lead to a high variability. Based on the wrong information of the

bullwhip effect, decisions concerning production scheduling, capacity

planning, inventory control and material requirements planning are made.

3. Forward buying: Companies often buy products before they are needed for

a specific demand. Reasons could be price discounts or quantity discounts.

Since these orders do not reflect the actual needs, it is very difficult for

companies to foresee this demand with a forecast method. To compensate

this additional inventory, a customer reduces it's order quantities in other

times. Thus, the variations of the ordering quantities increase along the SC.

There have been already efforts to eliminate the bullwhip effect.

However it is only possible to reduce this error, not to eliminate it. One

attempt to reduce the bullwhip effect would be to make demand data from the

downstream site available to the complete SC. Methods like a Vendor-

Managed Inventory (VMI) or Continuous Replenishment Program (CRP) are

helpful for this purpose.

The bullwhip effect negatively influences customer service, production

schedules, inventory, reliability, costs and other key factors for business

success. As mentioned above, a complete elimination is not possible. It is

however very important to realize that the demand forecast is one of the main

reasons for the bullwhip effect and that it is important to understand the

bullwhip effect when developing a SC.

Especially for OEMs of military vehicles, reliable forecasts would be

important, since these OEMs are directly connected with the end user. Bad

forecasts of the OEM can cause a bullwhip effect. There is often no retailer or

wholesaler between the OEM and the end user. But the OEM is not only in

contact with the end user, he has also the possibility to control and influence the whole supply chain. Thus, OEMs generally hold control dominance over the supplier network, which would make good forecasting methods even more important. Therefore they must be as familiar as possible with the structure and processes of the network. Some companies managed to reduce their inventory by up to 50% and stockout rates down to almost zero as a result of improved forecasts and a low bullwhip effect (Lee, 2002). This is one reason more why good forecasts, especially of OEMs, would be absolutely essential. Unfortunately, these good forecasts are not possible for OEMs of the SPV industry, as described above. SPV manufacturers have no forecasting method which provides reliable information. Every company of the SC has to struggle with unreliable forecasts and bullwhip effects. But in general, a better response would be possible by being more resourceful in using demand indicators or by instituting a system for tracking forecasting errors. However, as it was seen, the environment of SPV manufacturers is very volatile and complex. Hence, by improving the forecasting methods, it is not possibility to significantly improve the supply chain of SPV manufacturers.

Some companies organize their supply chain through inventory control models. This is also a way to influence the forecasting results. In these models, the supplier makes use of the customers' inventory status in deciding his order placement time. However, customers of SPV-manufacturers usually do not have inventories which should be replenished. They are also not responsible for maintaining appropriate inventory levels of the customers. Additionally, there are no retailers between the OEMs and customers, which have inventories to replenish. Thus, common JIT delivery policies (Kim et al.,

2005) are not applicable for SPV-manufacturers and the customers' inventory gives no additional information to help OEMs to build up an appropriate supply chain.

There is also another big difference between SPV-manufacturers and other companies, because most supply chains concentrate on warehouses, distributors, customers, orders and transportation. For SPV-manufacturers however it is not possible to rely on this information to control the flow of products and information through the network.

As already mentioned, the product demand of SPVs, such as military vehicles, is very unstable. In practice it would be advantageous for OEMs of SPVs to provide their suppliers with exact demand forecasts. Since this is not possible for these companies, suppliers have no chance to carry out a precise planning. Moreover, it is unavoidable that the different suppliers for the same vehicle have a different planning for their capacities and different lead times. Consequently, there are always suppliers, which are responsible for shortages as well as suppliers, which suffer overcapacities. It is not possible for the suppliers to avoid this problem, since the produced parts require different expenditures. If possible, arising costs are usually passed on by the suppliers to the customers, for example by adding them to the unit price. Additionally, the supply shortages lead to a delayed production of the OEMs itself. These are all serious problems of SPV manufacturers, which should be solved.

Conventional automobile manufacturers have the possibility to get very accurate demand forecasts. However, as explained above, SPV

manufacturers do not have the possibility to determine reliable forecasts. Therefore it became normal that parts were not bought in sets according to the number of vehicles which should be produced. Instead, employees of the purchasing departments are ordering according to prices, availability and lead times. Basis for decision-making is often only the gut feeling of every single purchaser. The orders of the different parts of the same vehicles are not related to each other and not optimally harmonized. It would be a stroke of luck if all parts and modules arrive exactly at the time, when they are needed. Currently, SPV manufacturers are far away from coordinating this.

It becomes obvious that under the unfavorable conditions of the SPV industry, it is not possible to implement an appropriate forecasting method. Also statistically sophisticated and complex methods do not necessarily result in more accurate forecasts. It is not possible to develop a completely new forecasting method which is a reliable basis for a flexible supply chain. This fact has to be taken into account when developing an appropriate supply chain for the SPV industry. Another possibility for achieving the goals of SPV manufacturers is necessary. Thus, it became obvious, that the focus will be on flexibility when developing the SC.

3.3 FLEXIBILITY

As it was shown in section 2.3, SCF is very important for companies. Taking a closer look, it becomes obvious that for OEMs of SPVs flexibility is even more important than for most other companies.

Following are the main reasons:

First, SCF helps to meet individual customer requirements and allows companies to produce products for specific customers. This is absolutely mandatory for SPV manufacturers.

Second reason is uncertain demand, with which especially SPV manufacturers have to struggle. As seen in section 3.2, it is not possible for SPV manufacturers to overcome this problem by applying forecast methods. Thus, it is even more important to tackle this problem with SCF. It is well known that uncertainty is even one of the main reasons to enhance SCF. Particularly the SPV industry, requires upside and downside flexibility. This means that a company has the possibility to rapidly increase or decrease production to a new unplanned level.

Third, forecasting is only reliable as long as no unforeseeable event occurs. If there is for example an unexpected customer order, SC flexibility becomes important again.

Finally, the SPV industry faces an ever changing environment. SCF helps to rapidly introduce new products, to quickly respond to customer requirements and to enable a fast turn-around on customer orders.

In section 2.3 it was also shown, that the requirements concerning flexibility are very different. They depend for example on the type of company, the field of industry and the position in the tier system. Thus, the focus in this subchapter is especially on the needs of OEMs of the SPV industry since a SC for these companies will be developed in this thesis. However as far as supplier flexibility is concerned, it is possible to extend the below considerations to a certain extent.

It is very difficult or even not possible to transfer all the findings in section 2.3 on supply chains for SPV manufacturers. Supply chain optimization and especially flexibility is a very complex and versatile field of research. Reasons are the different flexibility types and the difficulty to measure flexibility. Unfortunately a lot of literature only defines the term flexibility. But a useful procedure to handle the different flexibility types and variables is often only based on assumptions or is completely missing. Furthermore, there are also a lot of different and incompatible terms that are related to SCF. Up to now SPV manufacturers are working in a strongly improvised manner to cope with these problems. This way of working is often called chaotic flexibility. For a company's business performance it is however necessary to implement a well organized SCF system. This planned flexibility includes rules and defined procedures, which can be systematically improved. Compared to this, a chaotic flexibility cannot be strategically enhanced in terms of CIP. Thus, it is advantageous or crucial for a company to develop a supply chain that enables a planned flexibility (Thonemann et al., 2003). The developed SC in this thesis will make it possible for OEMs of the SPV industry to imply planned flexibility.

To develop an appropriate SC for OEMs of the SPV industry it is not only necessary to analyze the different types of flexibility, in order to evaluate their impact on the whole system. Additionally, the optimal degree of flexibility has to be found to attain the highest degree of success.

In section 2.3 the different types of flexibility were analyzed. It is shown that there are three types of flexibility, which are very important for the SPV

industry. Thus, when developing the SC, the main focus will be on volume flexibility, variant flexibility and time flexibility. The reasons for choosing these flexibility types become obvious, if the main areas, causing the difficulties in SCM of the SPV industry are reviewed. Following, the chosen flexibility types and its connection to the characteristics of the SPV SC is shown:

- Volume flexibility: The demand in the SC of the SPV industry is usually unknown. Thus, the possible production or order quantity should be flexible. This can be achieved with volume flexibility.

- Variant flexibility: One of the main problems of SPV manufacturers is the low order or production quantity. However, by considering the parts across all vehicle types, additional risk-pooling effects can be used for same parts. Hence, the advantages of same parts have to be taken. Therefore, variant flexibility is an important parameter, which is always considered in further calculations.

- Time flexibility: As it was explained in section 3.1, SPV manufacturers always work against a deadline. As soon as there is a new order, which was not foreseeable, the time pressure is very high. It is even more frustrating, that the time pressure of the different parts and modules is very different. Thus, a way has to be found, to synchronize the different time constraints, to reduce time pressure, and to shorten lead times. This will be done by time flexibility. For this reason, time flexibility is an important goal for the optimization of the SC.

To avoid misunderstandings, it has to be said, that the terms volume flexibility and variant flexibility are often used in literature. However, in other scientific papers these terms are used in a different context. In the SPV industry, the reasons for variant flexibility are for example different to the reasons for variant flexibility of other types of industry. It is possible for some companies to create variant flexibility by using the same production capacity for different products. Compared to these companies, OEMs of the automotive industry cannot use this type of flexibility since most of the suppliers produce only one part and low quantities. Thus, it is not possible to switch the production capacity of a supplier from one part to another. And if different parts are supplied by one company, these parts are usually not produced with the same machines or tools. Thus it is not possible for a customer or OEM just to skip the order of one part and get other parts from the suppliers instead. It is not possible to shift resources from the production of one part to the production of another part. Hence, this type of flexibility is not possible for OEMs of the SPV industry. But since the demand for flexibility is very high, another way to create variant flexibility was found and described above. The SPV industry can realize this type of flexibility by using synergies from different vehicle types. This possibility to create variant flexibility should be considered when developing the supply chain.

There are even more examples where these terms for flexibility are used in a different way or where the reasons for these types of flexibility are different. To avoid confusion, the developed variant flexibility of this thesis should not be compared with variant flexibility of other scientific papers, since

it is not the same. In analogy, other types of flexibility should be compared with caution.

While the SC of SPVs is improved in the following, it is important to realize, that flexibility is related to costs. Higher flexibility leads to higher costs. On the other side, different types of flexibility, such as volume, variant and time flexibility help to reduce costs, if a company is confronted with high merchandising risks and unreliable forecasts. These costs can be obsolescence, caused by excess capacity or opportunity costs caused by shortages. Therefore, flexibility and merchandising risks have to be balanced out, as already described in subchapter 2.3.

3.4 BASICS FOR AN IMPROVED SUPPLY CHAIN

The focus of this thesis is a higher flexibility for an improved SC. Therefore, some initiative and innovative methods will be developed in this work. Apart from these main topics, which are related to flexibility, there are a lot of basics which are mentioned in the following. These basics do not interact with the developed measures of this thesis and are thus mentioned separately. For the sake of completeness, a short overview is mentioned here, because these points are also mandatory for a sound SC. Thus, the following principles should be essential for SPV manufacturers:

- **Waste/Muda**: Non-value added activities should be eliminated.

- **Controlled processes through the whole SC:** Not only OEMs have to push and apply flexibility. It is an underlying assumption of a good SC that OEMs and suppliers through the whole SC are willing to accommodate the uncertainties and variations in each other's business.

- **Economies of scale**: Economies of scale should be pursued.

- **Information flow**: Information linkages should be established to ensure the most efficient, accurate and cost-effective transmission of information across the supply chain. If demand, inventory and capacity information are made transparent throughout the supply chain, production and distribution schedules can be improved. Thus, buyer and supplier should have a relationship whereby the buyer provides the supplier with needed information at fixed intervals and vice versa. Especially the information linkage between the OEM and the first tier suppliers is important. OEMs should give all relevant information frequently to the first tier suppliers. Thus, Tier 1 suppliers are able to proactively advise of problems and can avoid bottlenecks. But also for the rest of the supply chain, the information flow is absolutely necessary to improve the utilization of resources and to ensure supply security. A good information flow enables a collaborative demand and capacity planning process. Some companies use the internet to enable a tight and easy information integration. This way of information sharing is explained separately in the next point.

- **Communication by internet technologies:** Some companies link multiple tiers of suppliers via Internet. One of these systems, which is very popular in the automotive industry, is the International Material Data System

(IMDS). Such systems help to coordinate supply and demand across the supply chain. It enables to identify potential supply and demand problems at an early stage. After proper warning is given to everyone who is concerned with, resolution actions can be taken. Nevertheless this option is not appropriate for the SPV industry. Due to small production quantities of SPV manufacturers, the effort is too high compared to the advantages. It is a tradeoff between the costs incurred and the cost savings that can be achieved by sharing information. Also the suppliers of SPV manufacturers would face a great challenge to keep this system running. Hence, most of these suppliers would even refuse the installation of such a system.

- **Stock sharing**: If there are alternative supply sources available for a part, a higher near-term availability could be achieved if companies share their stock for this critical part. By sharing the safety stock with other companies or competitors, that also need this part, the stock could be increased because the costs for maintaining this safety stock can be shared, too. Manufacturers of SPVs do not purchase a lot of components which are suitable for this strategy. However a military vehicle consists of up to 20,000 parts. Some of them are key components or critical parts with a long lead time which can be vulnerable to the supply chain. For these parts this strategy could make sense. Especially under the background of a high demand uncertainty of the SPV industry, inventory pools can be most effective, because these inventory stocking points decouple the supply chain. Thus, inventory uncertainties of supply can be shielded.

Again inventory sharing is very important for this strategy. Information transparency among the members of the supply chain that are sharing the

inventory makes the system more efficient (Lee, 2002). However in real life there are only a few companies which want to cooperate with their competitors in such a way.

- **CIP and Kaizen**: Continuous improvement of processes/CIP over the whole supply chain helps to make a supply chain more flexible. Another buzzword in this context is Kaizen. Kaizen refers to the philosophy or practices that focus on continuous improvement of processes in manufacturing, engineering, development, business management, purchasing and logistics.

- **Adjustment to the environment**: A supply chain should be continuously adjusted to a changing environment. For example compliance regulations emerging from customer requirements and mandates need constant attention.

- **Total quality management**: To reduce supply chain disruptions.

- **Effective logistics system:** For the supply chain in the SPV industry it could be advantageous if products can be directly shipped from the manufacturer to the OEM. It should be checked if it is possible to deliver products without going through distribution centers. To eliminate such additional steps saves time. Especially for manufacturers of SPVs, time has often a higher priority than costs. Thus, the possibility of eliminating steps is worth to prove.

- **Supplier contracts:** Supply contracts are key documents to define the parameters which are necessary for parties to work together. As it is a legally

binding document it should always consider changes in future. Usually contracts are negotiated at the start of new projects or at the start of new relationships. But a contract should always be flexible enough to be applicable and appropriate in all expected demand-supply scenarios. The development or realization of a good supply chain strategy should be never hindered by an unfavorable contract. Thus, a flexible supply chain relationship must be still possible.

- **Supplier performance:** A common method to improve supplier performance is the evaluation of suppliers. Based on this, good performance can be rewarded and helps to motivate suppliers. Furthermore local sourcing can help to shorten lead times.

- **Stockkeeping:** Some of the parts which are included in SPVs have a very long lead time compared to the mean lead time. If there is no other possibility which is more economic, these parts should be stockpiled so that the order fulfillment process will not be disrupted due to part shortages. This "risk-hedging" decouples the supply chain of these critical parts. Hewlett-Packard, for example, revealed that about 60% of its inventory is used to hedge against demand uncertainty (Davis, 1993). The possibility of stockkeeping is also discussed later in this work.

- **Lean manufacturing:** To make SCs more efficient, it is often possible to introduce self-managed work teams, to shorten cycle times, to reduce setups and to remove bottlenecks.

- **Customer satisfaction:** The design of supply chains should be focused on one of the main goals of a company, which is customer satisfaction. However, customer satisfaction is often a painful objective, since market preferences shift more rapidly than ever, quality demand grows more strident and profit margins becomes thinner. Thus, OEMs and suppliers need to compete by producing high quality products, while reducing the cost of quality and lowering their fixed costs.

- **Quality:** In a competitive, global market, quality must be a "given" through the whole SC. An OEM or supplier, that delivers poor quality, is unlikely to survive if there are competitors.

- **Multiple suppliers:** Generally monopolists are unfavorable for the supply chain. Especially for critical parts it is essential to develop multiple suppliers if possible. To manage multiple suppliers can be more cost intensive. However, there are many advantages. For example the risk of supply outages can be reduced.

3.5 BUILD-TO-ORDER VS. BUILD-TO-STOCK

There are another two production strategies which have to be considered for the development of a supply chain of the SPV industry. These two strategies have a very strong influence on the supply chain. Especially the production strategy of OEMs of the SPV industry affects the whole supply chain. Thus, the characteristics of these two strategies have to be discussed.

The first production strategy is Build-to-Order (BTO) or sometimes referred to as Make-to-Order and the second is Build-to-Stock (BTS) which is also known as Build-to-Forecast (BTF). If a business is organized so that production only starts after receiving an order it is called BTO. If a company produces parts for stock and to carry enough finished inventory to fulfill orders as they come in, it is called BTS.

BTO has relatively long production time requirements after the order as well as low inventory requirements. It is the favored strategy of the automotive industry in the 21st century. BMW for example is an example of a BTO manufacturer. BMWs are very individual products. No two BMWs that are produced are the same. But about one week before the cars get assembled, the customer can change the specification of his car. Therefore a very efficient supply chain and distribution network is necessary. This is very typical for large companies, because it is easier for them to handle this additional effort. It can be already seen that there is a conflict for SPV manufacturers. On the one hand the SPV industry has to handle small quantities and on the other hand customized products are sold.

BTS has a short lead time to the customer because finished products are produced and assembled before the order is placed. It is the traditional production system. Theoretically, parts can be delivered as soon as transport can be arranged. Unfortunately the inventory of finished goods is large. High costs for materials, warehousing and labor accrue before a final purchaser is identified.

Whether to build to orders or to stock is one of the first logistics decisions. The trade-off in these two strategies is shown in Table 4.

Table 4: Trade-off between BTO and BTS

	BTO	BTS
Customer waiting time	long	short
Inventory level/Costs	low	high

There is already a lot of literature about the advantages and disadvantages of BTO and BTS (Brauer, & Seidel, 2008).

Related approaches to BTO and BTS are ETO (Engineering-to-Order), where development work is done after receiving an order, or Assemble-to-Order (ATO), where assembly work is done after receiving an order.

The above mentioned advantages and disadvantages of BTO and BTS are all relevant for SPV manufacturers. Depending on the specific parts, time or costs are more important. For this reason both production strategies are pursued in this thesis. There will be no strict separation between BTO and BTS. The focus will be on BTO, but also BTS is advantageous for some parts. It is very unusual to consider both approaches. However it still seems reasonable since the SPV industry itself is very unusual.

A possible approach would be to start the production of a certain number of vehicles and to interrupt it at some stage. After such kind of preassembly it could be still possible to finish the vehicle after receiving an

order for these vehicles. Before the vehicles are delivered to the customer, they could be modified according to customer wishes. Likewise expensive or large parts which have a short lead time could be implemented after receiving an order. This approach will be pursued along this thesis. Up to now BTO is the most common production strategy of SPV manufacturers. However, by taking a combined approach, where some items of the vehicles are BTS and others are BTO, the advantages of both strategies can be used.

3.6 NEW PERSPECTIVE ON SPV SUPPLY CHAINS

The SPV industry is a special area, which is very different to all other branches of industry (see section 1.2). Therefore, there are no methods which can be adopted directly. For the development of an appropriate SC, all the conditions and constraints of the SPV industry have to be taken into account. SPV industries for example usually complete their vehicles only after receiving binding customer orders. However, after receiving a customer order, the time pressure on the OEMs is usually very high. A high flexibility is needed and the long lead times of numerous parts and modules have to be considered. This conflict is a big challenge for the SPV industry, which has to be kept in mind.

Figure 10 provides an overview of different influences on the Supply Chain of SPV manufacturers. It is also shown that supply chains of SPV manufacturers are directly affected by the different influences. If there is for example a change of the customer behavior, such as an unexpected demand,

the supply chain has to react on this change rapidly, since the supply chain is directly affected. Such a reaction on short notice allows only a small scope of action. To be better prepared, these influences should be centralized and modeled or expressed by the improved SC concept in a mathematical way as shown in Figure 11. This means that all relevant information should be gathered and used to control the supply chain.
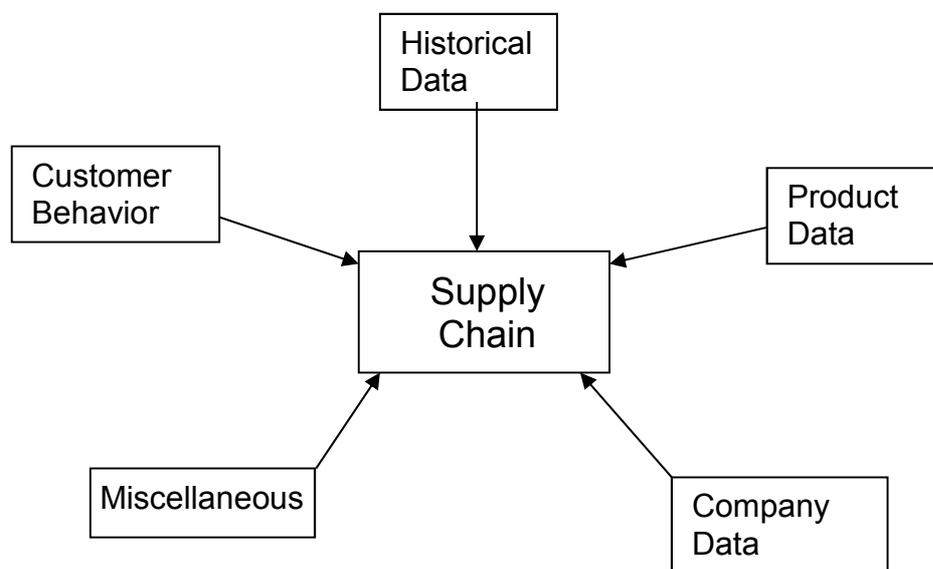
Figure 10: Factors influencing the supply chain

```
          ┌──────────┐
          │Historical│
          │Data      │
          └──────────┘
┌─────────┐     │
│Customer │     │
│Behavior │     ▼
└─────────┘  ┌──────────────┐        ┌──────────────┐
      ╲      │New SC        │        │Supply Chain  │
       ╲     │Concept       │───────▶│Management    │
┌────────┐   │(Mathematical │        └──────────────┘
│Product │──▶│Relationship) │
│Data    │   └──────────────┘
└────────┘      ▲      ▲
        ╱       │
┌────────┐      │
│Company │      │
│Data    │   ┌─────────────┐
└────────┘   │Miscellaneous│
             └─────────────┘
```
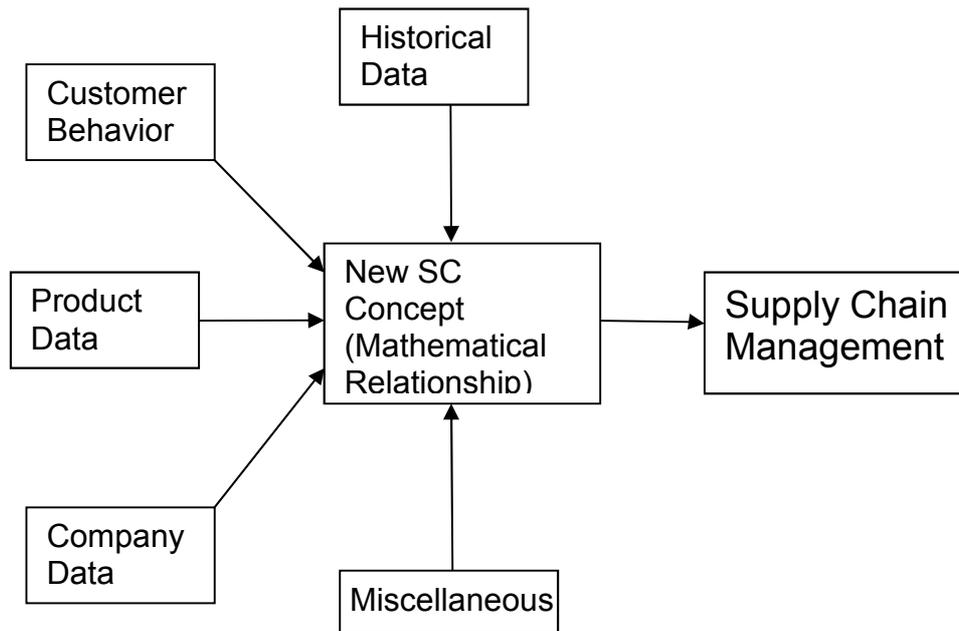
Figure 11: Improved supply chain controlling

In Figure 10 and Figure 11 miscellaneous effects are mentioned. Miscellaneous effects are infrequent, not as important or not foreseeable. Events which are not foreseeable are very common in SPV industry. For example manufacturers of military vehicles can be affected by sudden changes of political situations.

These influences have to be taken into account by finding an appropriate way of flexibility. The question of how to describe the influences on the supply chain in a mathematical way to enable a high flexibility has to be answered now.

So far SPV manufacturers usually work with a single period system. They use methods which are very similar to the conventional automobile industry. Thus, planning is mainly based on forecasts of demand. The

problem is that the demand uncertainty should be incorporated into their

planning system. Thus, the used methods, which are taken over from the

conventional automobile industry, are unfavorable. Contrary to the automobile

industry, some other industries use two different order, production or planning

points to control their supply chain. One point of time can be called prior point

of time t_0 and the other one can be called posterior point of time t_1. Until now

this approach is only common in industries that trade with short life-cycle

products and unreliable forecasts such as fashion footware, women's apparel

and fashion items (Milner,& Rosenblatt, 2001). This approach is a kind of

postponement strategy. Van Hoek (2001) defined postponement as the

delaying of supply chain activities until customer orders are received. This

strategy is not completely new for SPV manufacturers. Maybe it was

sometimes done unintentionally. However, there should be a way to use it

intentionally, strategically effective, standardized and consistent over all parts

and modules.

There are different reasons for companies to use postponement. One

is that differentiation in the manufacturing process is delayed, which leads to

reduced inventory, obsolescence and other logistics costs (Rabinovich, &

Evers, 2003). Additionally postponement gives a higher flexibility to

compensate high uncertainties (Boone, Craighead, & Hanna, 2007). Lee

(2002) stated that agile supply chains should work with postponement

strategies. Agile supply chains are classified as shown in Figure 12. SPV

manufacturers have to struggle with high demand uncertainty and high supply

uncertainty. Thus, it is clear that SPV manufacturers need agile supply chains that work with postponement.

	Low Demand Uncertainty ⟷ High Demand Uncertainty	
Low Supply Uncertainty	Efficient Supply Chains	Responsive Supply Chains
High Supply Uncertainty	Risk-Hedging Supply Chains	Agile Supply Chains
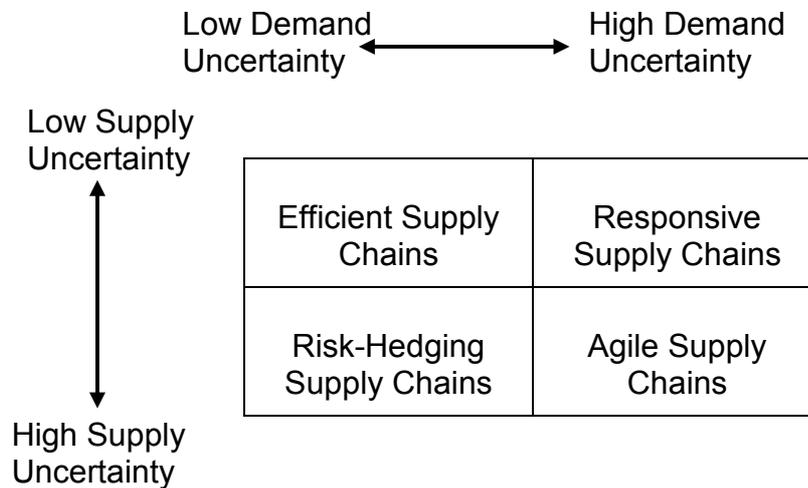
Figure 12: Supply chain classification (Lee, 2002)

Such postponement strategies are also used in production. This strategy is for example used by Dell for it's build-to-order online store. Also companies of the SPV industry could use such a postponement strategy. It helps to incorporate individual customer wishes as late as possible (assembly postponement). A differentiation and adjustment to customer wishes can be postponed until time t_1. Until then or until orders are received, standardized products or modules can be produced, based on demand forecasts (push system). After receiving specific orders, the standardized products can be supplemented to receive the customized and different versions (pull system). The transition from the customer unspecific production to the customer specific production is called decoupling point, order penetration point, or freeze point. With the example of a military vehicle manufacturer, such

individual customer wishes could be additional armor plating or a specific painting.

Also another type of postponement, the so called purchasing postponement should be used. It means that purchasing of expensive and non-ageing resistant materials will be delayed. Other postponement strategies, such as time postponement, where finished products are kept in central locations until they are distributed, are not favorable for the SPV industry, because the vehicles are too customized.

Usually, postponement strategies are used by companies which produce short life-cycle products. But the intended strategy in this work can have a great effect on the flexibility which is absolutely essential for SPV manufacturers. Thus, a postponement strategy with two different planning points could be very favorable for OEMs of SPVs. Additionally the following advantages can be maintained by delaying some supply chain activities until customer demand is revealed:

- reduced transportation costs
- reduced inventory costs
- reduced obsolescence
- improved competitiveness by quickly offering customized products

At the prior point of time, only very inaccurate demand forecasts are available, since customer orders are received a relatively long time afterwards. Due to the resulting planning risks at time t_0, only a minimum

order quantity is fixed. Contrary, at the posterior point of time a lot more information is available. A much lower risk is involved at this point of time. Thus at time t_1, an additional order quantity is added to the minimum order quantity of t_0. This additional order quantity can be realized by using a reactive capacity, which was fixed at t_0.

Especially companies of the automobile industry need a lot of different parts and modules for the assembly of the final product. The needed parts differ for example in demand quantities, prices, costs and constraints, that are determined by suppliers. The characteristics of these parts are very different. Almost every possible situation and value could arise. Even different forecasting results for all the parts have to be considered when developing the SC. It is also very important that the prior and posterior point of time is optimally adapted to the characteristics of the different parts. Currently, the SCs of the SPV manufacturers do not consider this difficult task. Also existing research papers exclude this requirement. However, especially for SPV manufacturers it is very important because they are confronted with a lot of different parts.

Also important for creating a supply chain is the attitude towards stockkeeping, which should be aligned to the processes of a SC. In the SPV industry, some process strategies are taken over from the conventional automobile industry, where stockkeeping is completely avoided in terms of Lean Management. However, practice shows that for SPV manufacturers stockkeeping is essential. Since OEMs of SPVs have to struggle with high supply risks and demand uncertainties, it will be not possible for them to

completely eliminate stockkeeping. Thus, when developing a SC in this work, the goal is to reduce stockkeeping and the related costs to a minimum. From experience it is known, that a lot of unnecessary costs for stockkeeping arise due to an unfavorable SCM. Considerable savings are possible in this field.

It becomes obvious again that SPV supply chains are very exceptional compared to others. Within these supply chains a lot of decisions have to be made, based on a very complex and extensive environment. All the above mentioned circumstances should be taken into account by the developed SC.

As it was seen, a postponement strategy could provide a lot of advantages to SPV supply chains. The objective is to adapt such a strategy for the SPV industry. At the same time, all other constraints and conditions should be considered.

3.7 SUPPLY CHAIN PERFORMANCE EVALUATION

If a supply chain is developed, it is important to know, how a supply chain can be evaluated. Therefore, it is an increasingly important topic, which is regarded in the following.

Before starting with a Performance Evaluation (PE), the evaluation criteria have to be chosen. Following is a selection of evaluation criteria:

- demand management
- cycle time
- risk management

- quality

- transportation aspects

- delivery aspects

- resources

- profitability

- costs (total cost; production cost; inventory cost; logistic cost; guarantee cost)

- added value

- turnover rates (cash turnover time; inventory turnover time; capital turnover)

- sales revenue

- on time delivery to customer

- respond time to customer

- order fulfillment rate

- lead time

- supply reliability

- process reliability

- order fulfillment rate

- cost control

- customer service

As it was already shown in section 3.3, flexibility is most important for supply chains of the SPV industry. Thus, flexibility evaluation will be the most important criteria for the supply chain, which has to be developed in this thesis.

A lot of research was already done on a lot of very different PE methods. One of these methods is the Expert Evaluation Method, in which expert opinions are used. It is a very simple system. Unfortunately there is no repeatability, because it is not only based on objective, but also on subjective perceptions. A lot of other objective methods are based on mathematical statistics. These methods avoid human influences. However, they are designed for specific supply chains.

For this reason, a special PE method will be developed, which is appropriate for the supply chain of this thesis.

3.8 PROBABILITY DISTRIBUTION OF DEMAND IN THE SPV INDUSTRY

Undoubtedly, the most widely used probability function for the distribution of demand is a normal distribution (Chen, H., 2011; Hu, & Munson, 2011). Reason is that a forecast can be seen as a random experiment. Generally, a normal distribution is the most widely used model for the distribution of a random variable. The random variable that equals the result over the replicates tends to have a normal distribution as the number of replicates becomes large (Montgomery, & Runger, 2010). It can be assumed that each forecast value results from a replicate of a random experiment. Thus the normal distribution is often used to make approximate conclusions about this uncertainty. Additionally, there are also empirical experiences,

which show that a normal distribution is the most appropriate probability distribution for forecasting values (Fischer, M. L., 2007).

However, there is one big disadvantage. A normal distribution has a relatively high probability of generating a negative demand when the mean is small. Additionally, the expected demand for SPVs is very low. Thus, this probability distribution is not appropriate for modeling the demand in this thesis. This relationship is often expressed with the coefficient of variation (CV), which is calculated by $\frac{\sigma}{\mu}$. When this coefficient is large, the normal distribution is not appropriate, because it assigns a significant probability to negative demand. Also the Poisson distribution would be inappropriate due to this large coefficient (Halkos, & Ilias, 2011).

To avoid the occurrence of negative demand values, a probability distribution has to be found, which is appropriate. From experience it is known, that a typical demand of the SPV industry has the following characteristics:

- no negative demand

- low demand quantities occur with a low probability

- for a low mean demand the probability is fast increasing when the low demand quantities become higher

- relatively smooth decrease of the probability after the peak if the mean demand is low (positive skewed probability density function (pdf) to the right)

Comparing these characteristics with different probability distributions, it can be seen, that all this can be modeled with a lognormal distribution. A

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lognormal distribution is a continuous probability distribution of a random

variable, such as the demand of SPVs, whose logarithm is normally

distributed (Montgomery, & Runger, 2010). The lognormal distribution is often

used if the coefficient of variation is small (Halkos, & Ilias, 2011). If D is the

demand, the pdf of a lognormal random variable D is shown in Equation 3.1.

$$f(D) = \frac{1}{D\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2}\right] \qquad 0 < D < \infty \qquad (3.1)$$

The mean and variance of the Demand D are

$$E(D) = e^{\mu + \frac{\sigma^2}{2}} \qquad\qquad (3.2)$$

$$V(D) = e^{2\mu + \sigma^2}\left(e^{\sigma^2} - 1\right) \qquad\qquad (3.3)$$

The parameters of the lognormal distribution are μ (location) and σ^2

(scale). These parameters have to be defined in a way that the distribution fits

to the forecast of the SPV manufacturer. Figure 14 illustrates some lognormal

pdfs with selected values of μ and selected values of σ^2.
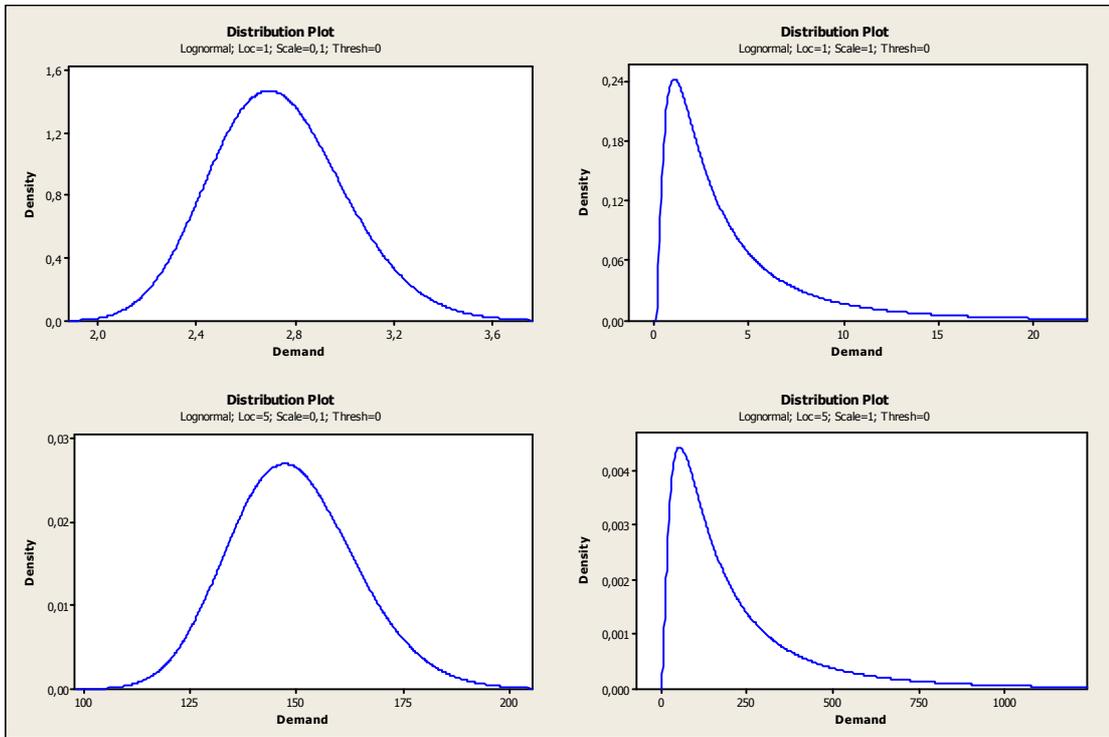
Figure 13: lognormal pdfs with selected values of μ and selected values of σ^2

CHAPTER 4

MODELING SUPPLY CHAINS OF SPV MANUFACTURERS

As shown, flexibility will be a very important characteristic of the SC. Therefore implementation of appropriate flexibility strategies is important. Therefore, the aim is to integrate the three most important types of flexibility for SPVs - volume, variant and time flexibility. It will be also necessary to find out the influencing variables on the SC. These variables will be examined in detail, to find out how they should be handled in real life. The goal is to develop an innovative and appropriate SC for this specific but important application.

To ensure maximum flexibility, a procedure is needed which is different to common methods of the SPV industry. As it was already explained in Chapter 3, a postponement strategy could help to take up this challenge. Postponement strategies maximize the possible benefit and minimize risk by delaying further investment into a product or service, until the last possible moment (Van Hoek, 2001). These goals are also important for SPV

manufacturers and should be realized in the following. Therefore, the strategy of this thesis with two times of planning will be also called postponement strategy. This must not hide the fact that the developed strategy in this thesis should fulfill much more requirements than a typical postponement strategy. Hence, a strategy will be developed which is based on two different times of planning. In other areas, e. g. fashion industry, such strategies were already successfully implemented. Fisher and Raman (1996), Eppen and Iyer (1997a and b), and Iyer and Bergen (1997) present order quantity models for such a two-period setting. Iyer and Bergen present a way to use the first period for collection of information on early demand indicators without a production commitment in the first period. With these early demand indicators, the demand distribution forecast is updated and an order is placed. In this thesis, these two times of planning should be used differently. However, the split in two different time periods for a better planning is remarkable. This approach can be seen as suggestion for this thesis and will be continued to pursue. But it has to be defined how these two times of planning should be used best. This means what has to be done when, and how to benefit from it.

It should be possible to balance supply and demand on periodically basis, which defines the first point of time. This helps to ensure that the right parts are available at the right time in order to satisfy demand. The second point in time is defined by the planning horizon which can be four weeks (see Figure 14). The planning for the production and material flow, which is for example four weeks in advance, depends on the forecast. Decisions will be

based on rolling schedules. This means that these planning periods are continuously repeated.

The two times of planning are called prior and posterior point of time and will be explained in more detail below.
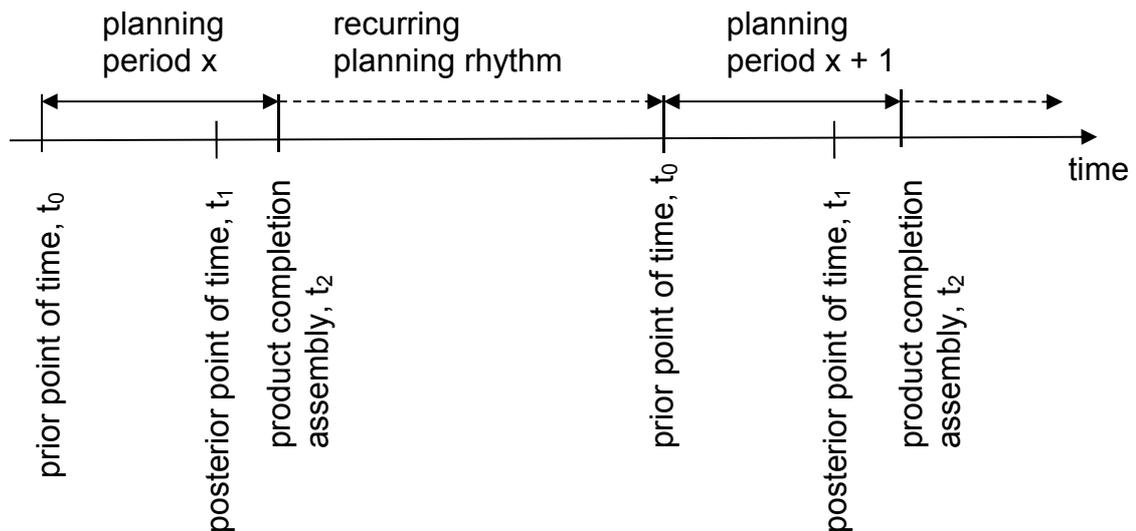
Figure 14: Approach with two times of planning

The two planning periods of Figure 14 are shown one after another to make it clearer and easier to understand. However, in reality, these planning periods could overlap. A certain time period after t_0, another prior point of time would be fixed to plan for some weeks in advance again. The same time period after the second prior point of time, a third t_0 would be fixed to start the third planning period and so on.

The following list shows the necessary actions of OEMs in the SPV industry at the prior point of time:

- Planning activities at the prior point of time are based on forecasts.

- This first step at time t_0 is the determination of the minimum production quantity. The minimum production quantity is definitely planned and ordered at the prior point of time and thus fixed.

- Also determined is the reactive capacity. The reactive capacity defines a range for ordering an additional quantity at the posterior point of time.

- Prior points of time should be carried out on a recurring basis. The time between these points of time have to be short enough to enable an appropriate internal planning. The prior points of time should help OEMs to give important information to the suppliers and to enable an appropriate information flow through the supply chain. With this information it is also possible for suppliers to reserve capacity.

- At the prior point of time, there could be the option for OEMs to buy capacities by paying for upcoming costs, such as fixed costs, in advance. However, this is dependent on the customer supplier relationship or the own production possibilities. The additional degree of freedom leads to volume flexibility. For companies of the SPV industry it could be very helpful, since shortages due to late deliveries or bad planning are very costly. Only one missing part could stop the completion of a vehicle.

Analysis at the posterior point of time:

- Planning activities at the posterior point of time are based on concrete orders or on a reliable state of knowledge.

- This step is the determination of the actual production/order quantity as well as the related time planning.

- Posterior points of time are also carried out on a recurring basis, because they are related to the associated prior point of time.

- The posterior point of time is the time of the sale minus the lead time if parts are ordered or minus the time for production if parts are produced internally plus the time for internal processing. Later production or ordering times would lead to missing parts or even to backlogs.

As already shown, a postponement strategy should be developed for the SPV industry. A long-term planning at the prior point results in the advantage of being able to plan at an early stage if necessary. By separating in a long-term and short-term, i. e. posterior and prior point of time, an improved planning is possible and parts can be ordered at the right time in the right quantities. OEMs of the SPV industry have to struggle with very different lead times as well as parts with long lead times of several months. In addition, they are confronted with unreliable forecasts and low demand. Having two times of planning is the best way to tackle this problem.

A lot of studies for different types of industry assume that the demand rate is either high or low (Milner, & Kouvelis, 2002). Such is often the case for the fashion industry where two scenarios are likely and once this source of uncertainty is resolved, good forecasts may be obtained.

To have a clear and structured methodical approach, the development of the supply chain for the SPV industry will go on stepwise in the following.

Therefore, the complexity of the modeled supply chain increases with every section. Thus, section 4.1 starts with a supply chain that only considers single parts or components. At next, in section 4.2, the supply chain is amended by all parts that are included in one vehicle type. Realistic homogenous forecasting errors and homogenous sales figures are used. Finally, in section 4.3, supply chains for all parts and several vehicle types are set up. This type of supply chain is presumed to be most realistic in real life. Different forecasting errors and heterogeneous sales figures have to be considered, because the demand of different vehicle types is included. By considering the parts across all vehicle types, additional risk-pooling effects result from an additional variant flexibility. For an appropriate SC, all these effects have to be considered when creating the model.

To create such a temporal division in prior and posterior points of time, the forecasting and planning has to be executed periodically. One planning period could start after a certain period of time or when required, if for example a new customer Request for Quotation (RFQ) exists. This means that the planning periods with the prior and posterior point of time have to be repeated over and over again (see Figure 14). Based on experience with SCs for military vehicles, a rhythm of 3 months could be appropriate. An adjustment to given circumstances by shortening or extending the time period is always possible without fundamental changes.

There are companies which are forced to align their SC to such temporal divisions. Manufacturers of seasonal products, as for example some companies of the fashion industry, are forced to do it. The fashion industry

often has to align its SC to summer and winter season. Companies of the SPV industry should implement such a strategy artificially to benefit from numerous advantages. One of these benefits is the possibility to determine the variables for SC calculations periodically after certain time periods. For example, the regular sales prices p, the reduced sales prices p_r and variable purchase order prices c can be determined for each new period in the planning horizon. To do this planning every period is perfectly sufficient for the SPV industry since the determination of variables, which are needed for the planning and adjustment of the SC, is subject to a certain degree of uncertainty. It is also not possible to find the exact values of the variables for a certain point in time. Thus, the best possible forecasts of the needed values, which are valid for a certain time period, are sufficient and adapted to reality. If it is possible to get more precise data, shorter intervals between the planning periods and thus a more precise planning is possible. As a very general rule of thumb, the better the forecasts of the conditions (e. g. prices, costs, demand), the shorter the time periods, because the planning becomes more accurate.

In literature, there are no investigations to companies that are related to companies of the SPV industry. Thus, most of the elementary methods as well as the detailed propositions, which are used in the following, will have to be set up new. The other methods, calculations and propositions will be based on a variety of existing SC theories for other types of industries. All these useful theories will be combined and adapted to the needs of SPV manufacturers. All of the considerations, data and steps later in this chapter are from a practical point of view, realistic, applicable and appropriate.

4.1 MODELING ELEMENTARY SUPPLY CHAINS FOR INDIVIDUAL COMPONENTS

This subchapter starts with a supply chain that only considers single parts or components.

4.1.1 AT THE PRIOR POINT OF TIME T_0

Obviously there is a forecast value μ_0 or an expected demand at the prior point of time t_0. The expected demand can be seen as expected value for the quantity of sales D at the particular point of time t_2. In practice, this forecast value μ_0 can be determined by forecasting methods as explained in section 2.2. The demand D is assumed to be the quantity of sales and should be same high as the production volume.

It is well known that risk and flexibility planning is subject to uncertainties of forecasting results. As it was shown in section 3.9, these uncertainties should be modeled with a lognormal distribution. Thus, the demand quantity of a particular article at a certain point of time can be described as a lognormal distribution with an expected value μ_0 and the standard deviation σ_0 at the prior point of time. The expected value or mean is a measure for the center or middle of the probability distribution. The variance is a measure of the dispersion or variability in the distribution.

For the realization of the desired volume flexibility, the fixed order quantity X_0 has to be implemented. The quantity X_0 is a fixed inflexible order quantity, which is expected to be the minimum demand and is already ordered

at the time t_0. The fixed order quantity X_0 is determined by forecasts and customer orders. The way of getting X_0 mathematically, is shown in section 5.2.1. A adjustment of X_0 after the prior point of time is not possible.

At time t_0, a mean capacity option should be fixed additionally. Therefore R_m is defined, which is the initial point for the flexibility range. This capacity option defines the volume flexibility. The capacity option makes it possible, to take decisions about the ordered or produced quantity of a product when the improved forecast value for the mean at time t_1 is available. The range of the capacity is

$$X_0 + R_m \pm \Delta R$$

The flexibility range is expressed with the equation above, because this symmetrical value range could be changed to an unsymmetrical value range very easily. Such a flexible range can be useful for different underage and overage costs and is derived later.

The size of this symmetrical range is

$$R_0 = 2 \Delta R$$

In concrete terms, the ordered/produced quantity at time t_1 is in the following range:

$$X_0 \leq x_1 \leq X_0 + R_0$$

The amount of the mean capacity option has to be agreed with the suppliers for every single part. Only parts which can be always supplied quickly and in a sufficient amount are excluded.

If a company pursues a multi-supplier strategy and therefore has multiple suppliers for the same part, the capacities of the single suppliers have to be added. Relevant for the SC planning is the overall capacity.

The order quantity X_0 has to be communicated by the OEM to the supplier at time t_0. The mean capacity option R_m and ΔR is not determined by the OEM. It has to be agreed jointly. It is possible, that a reservation price c_R [Monetary Unit (MU)/Quantity Unit (QU)] for the capacity option has to be negotiated with the suppliers of each individual article. Suppliers often have additional costs for reserving a certain amount of capacity. Thus, the resulting variability leads to additional costs c_R.

If a volume depending sliding-scale price for an article is agreed with a supplier, it has to be considered additionally. Later these variables will be used for generating the SC concept.

The determination of the variables c and c_R are only the first step concerning financial aspects. For further considerations, profit and cost accounting has to be included. At this point, the newsvendor model has to be mentioned, since it is certainly the most important model. Despite its rather specific name, the newsvendor model is applied in a wide variety of areas. It is for example used as basis of many multiperiod dynamic inventory, capacity-planning, and contract-design problems (Agrawal, & Seshadri, 2000). However, for the following reasons, the newsvendor model is not completely appropriate for the SPV industry:

- The newsvendor model is used for seasonal items, e. g. clothing, snow blowers or newspaper.

- The newsvendor model assumes that after some time, the demand and thus the sales prices decreases.

On the one side, there are the above mentioned reasons, why the newsvendor model is not appropriate for the SPV industry. On the other side, it is still possible to use this model. Military vehicles for example are no seasonal products. However, as described above, a split into time periods has to be done, to make a better planning possible. Every single-period can be seen as a stochastic demand inventory problem and thus as a news vendor problem. Compared to typical seasonal products, the time periods have no characteristic, periodical changes. Nevertheless, certain trends can be modeled. But similar to the newsvendor problem, the SCM has to decide the quantity of the goods to purchase prior to the single period. Also in the SPV industry, the procurement lead-time tends to be quite long relative to the selling season. Furthermore it is also common that there is no opportunity to replenish inventory once the season has begun.

Thus, the newsvendor model can help to make profit and cost accounting decisions. For such decisions, the relevant decision criterion could be minimization of the probability of loss or maximization of the probability of profit.

Also in each case, the decision-maker must carefully decide how much to order before demand for vehicles is known. Reason is that extra items

result in additional storage costs and in obsolescence of stock. On the other side, shortages result in a loss of potential profit. The loss results from missed milestones in production or even from withdrawal from sale contracts. Thus, there is a tradeoff between the cost of disposing extra inventory and the loss in profit from shortages.

For the reasons mentioned above, it seems as if the newsvendor model is crucial for further considerations. Therefore the newsvendor model is explained and adapted to the conditions of the SPV industry in the following (Askin, & Goldberg, 2005).

The classical newsvendor model includes the following considerations of prices and costs:

- unit selling price in the regarded time period p [MU/QU]
- purchase or production costs of each item c [MU/QU]
- salvage value of each unsold item c_s [MU/QU]

To avoid trivialities it is assumed that $p > c > c_s$

Essential for feasible results of the newsvendor model is a realistic estimation of the salvage values. In this work it is assumed that input variables are correct. There is already a lot of literature about finding correct values such as the salvage value (Cachon, & Kök, 2007).

The following theory of the newsvendor model should support further planning:

The objective in the newsvendor model is to choose an order quantity to

maximize expected profit. If for example a production or order quantity x_0 is planned which is lower than the forecasted value μ_0, there is a high risk for shortages $(x_2 - x_0)^+$, where x_2 is the actually needed quantity at time t_2. On the other side, there is a low risk for excess quantities $(x_0 - x_2)^+$. It is the opposite if the production quantity x_0 is planned higher than the forecasted value μ_0. The higher the production quantity x_0, the smaller is the risk for shortages, but the higher is the risk for excess capacity. Diruf (2007) has shown that the expected shortages and the expected excess capacity can be calculated as follows for a normal demand distribution

$$E_{\text{shortages}} = \sigma_0 \cdot \varphi \left(\frac{x_0 - \mu_0}{\sigma_0} \right) = \sigma_0 \cdot \varphi(z_0) \tag{4.1}$$

$$E_{\text{excess capa}} = \sigma_0 \cdot \varphi \left(-\frac{x_0 - \mu_0}{\sigma_0} \right) = \sigma_0 \cdot \varphi(-z_0) \tag{4.2}$$

where $z_0 = \frac{x_0 - \mu_0}{\sigma_0}$ is the standard normal random variable.

$\varphi(z_0)$ is the standard normal random variable for the order quantity x_0.

Transferred to the lognormal distributed demand with the mean Θ_0 and the variance ω^2, equation (4.3) and (4.4) can be written as follows:

$$E_{\text{shortages}} = E(s) = \omega_0 \cdot \Phi \left(\frac{\ln x_0 - \theta_0}{\omega_0} \right) = \omega_0 \cdot \Phi(z_0) \tag{4.3}$$

$$E_{\text{excess capa}} = E(e) = \omega_0 \cdot \Phi \left(-\frac{\ln x_0 - \theta_0}{\omega_0} \right) = \omega_0 \cdot \Phi(-z_0) \tag{4.4}$$

where

$$z_0 = \frac{\ln x_0 - \theta_0}{\omega_0} \qquad (4.5)$$

With equation (4.5) and (4.6) the negative part of the profit accounting could

be calculated. However, it is very difficult to understand and evaluate

equations 4.5 and 4.6. To avoid mistakes, it is better to derive the equations

for the calculation of the expected shortages and the expected excess

capacity logically. Therefore it is assumed now that the order quantity is equal

to the mean. In this case, there is excess capacity, if the actual demand D is

smaller than the mean Θ_0. With the integral of D multiplied with the probability

for D, the expected excess capacity can be calculated. For this probability, the

probability density function f(D) is used. To consider the range, where the

demand D is smaller than the mean, the integral is used from 0 to Θ_0. Similar

to this, the expected shortages are calculated. Therefore the integral is taken

from Θ_0 to infinity. Only these equations are used in the thesis, instead of

equation 4.1. and 4.2.

$$E_{\text{shortages}} = \int_{D=0}^{\theta_0} [\Theta_0 - D] \cdot f(D) dD \qquad (4.6)$$

$$E_{\text{excess capa}} = \int_{D=\theta_0}^{\infty} [D - \Theta_0] \cdot f(D) dD \qquad (4.7)$$

As expected, $E_{\text{excess capa}}$ of equation (4.6) increases with a decreasing

demand D and increases with a decreasing demand. It is the exact opposite

for $E_{\text{shortages}}$, which already shows the plausibility of these equations.

Together with the costs for excess capacity and the costs for shortages, a cost assessment for the developed SC will be done.

In this thesis the demand is assumed to be lognormal distributed as it was already derived in this chapter. However, the distribution could be also for example normal, uniform, gamma, or exponential. It was numerically shown by Naddor (1978) and Fortuin (1980) that different distributions do not always lead to different results, if the mean and the variance are specified. Thus, the lognormal distribution is a good assumption which can be replaced by another distribution if necessary. The effect of this probability distribution compared to others, will be shown later. If some companies of the SPV industry have difficulties to completely characterize the demand distribution, Perakis and Roels (2007) show up modified newsvendor models as solution.

For rational decisions, equations (4.6) and (4.7) have to be supplemented by additional variables for considering costs. Using the specific underage costs per unit c_s and the specific overage cost per unit c_e, cost analysis is possible. The expected costs for shortages and the expected costs for excess capacity can be calculated. Shortages means, that not all parts are available, which are needed to assemble vehicles. In contrast, excess capacity is the existence of parts which are not needed to satisfy customer wishes. In this way, it is possible to get an indicator for making further decisions. The criterion for making a decision could be the expected costs for merchandising risks $E_{costs, time\, t_0}$. The expected costs $E_{costs, time\, t_0}$ are the sum of the expected costs for excess capacity and the expected costs for shortages:

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$$E_{costs,time\ t_0} = E_{costs,excess} + E_{costs,shortages} \tag{4.8}$$

$$E_{costs,time\ t_0} = c_e E_{excess\ capa} + c_s E_{shortages} \tag{4.9}$$

With equation 4.8 and 4.9, the expected costs can be calculated as follows:

$$E_{costs,time\ t_0} = c_e \cdot \left(\int_{D=0}^{\Theta_0} [\Theta_0 - D] \cdot f(D) dD \right) + c_s \tag{4.10}$$
$$\cdot \left(\int_{D=\Theta_0}^{\infty} [D - \Theta_0] \cdot f(D) dD \right)$$

$E_{costs,time\ t_0}$ plotted against the demand has a u-shaped curve.

For further considerations, a model for expected profit could be used. The risk-free expected profit can be calculated with the following equation, where b is the profit and n is the number of sold parts.

$$E_{risk\ free\ profit} = b \cdot n \tag{4.11}$$

For the profit b a realistic value has to be taken for every single article. However there is no exact value b for every part, since the single parts are assembled and sold together as a vehicle. However, it is okay to find good approximations.

Realistic assessments of expected profits $E_{\text{risk free profit}}$ can be obtained from the newsvendor model by subtracting the sales risk costs from the risk-free expected profit.

Similarly, the maximum expected profit E^*_{profit,t_0} can be calculated, using the optimal production quantity x_0^*:

$$E^*_{\text{profit},t_0} = b \cdot n - E^*_{\text{costs},t_0} \tag{4.12}$$

However, equation 4.12 has no variable which is important for the further SC planning and optimization. Therefore, it will be sufficient to calculate the expected costs in later calculations without calculating the expected profit. **AT THE POSTERIOR POINT OF TIME T$_1$**

At the posterior point of time t_1 more information about the demand at t_2 is available than at the prior point of time t_0. This additional information at time t_1 can help to make better forecasts. This means that at the posterior point of time, a revised forecast value ω_1 is available. Thus, compared to ω_0, the forecast value ω_1 is usually more accurate. The change of standard deviation can be described with a forecast optimization factor α.

With the standard deviation ω_0 at time t_0 and the standard deviation ω_1 at time t_1, the forecast optimization factor is defined as follows:

$$\alpha = \frac{\omega_1}{\omega_0}$$

However, θ_1 and ω_1 are still subject to variations and are therefore random variables which can be expressed as a lognormal distribution.

Usually the factor α is lying in the following range

$0 \leq \alpha \leq 1$

and is an indicator for the optimization. A small α value close to 0 means that the forecasted demand is much more accurate at time t_1 than at time t_0. If however α is close to 1, there was no significant information growth and if α is higher than 1, the forecast became even worse. Normally this is not the case, because the closer to time 2, the more information available and the better is the forecast. Hence, variability at the prior point of time is usually higher than at time the posterior point of time.

But there is not only an expected change of the standard deviation. Also the mean could change, for example because an expected customer order comes true or is definitely cancelled between time t_0 and time t_1. Furthermore, an unexpected order could be received during this period. All this would primarily affect the mean demand at time t_1. Therefore, a second optimization factor β has to be defined. The optimization factor β should describe the changes of the mean. The forecast optimization factor β is calculated similar to the calculation of α:

$$\beta = \frac{\theta_1}{\theta_0}$$

Expressed in stochastic terms, it can be summarized that something similar like a two-stage random drawing process accrued:

$\Theta_0, \omega_0 \rightarrow \Theta_1, \omega_1 \rightarrow D$

The optimization factors α and β will be relevant for the development and evaluation of the time flexibility in Chapter 5.

4.2 MODELING SUPPLY CHAINS FOR ALL PARTS OF A SINGLE VEHICLE TYPE

The considerations of the supply chain in section 4.1 are only about one single product. In this chapter the supply chain should include all parts, which are integrated in one vehicle type.

The following variables of section 4.1 are going to be taken over and the corresponding calculations and theories will be extended:

- Θ_0, Θ_1
- ω_0, ω_1
- α
- β
- X_0
- R
- c_R

4.2.1 AT THE PRIOR POINT OF TIME T_0

The assumptions of section 4.1 will be adapted to the relevant characteristics and relationships between all parts i of a vehicle type.

So it is estimated, that there is a forecast value Θ_{0i} at the prior point of time t_0 for every article i (i = 1, …, m) of a vehicle type. It is also assumed that the standard deviation ω_{0i} describes the deviations of the demand for every article i at the prior point of time.

Similar to the considerations for one single part at the time t_0, a fixed order quantity X_{0i} and a capacity option R_i has to be determined for every article of one vehicle type. The capacities of different suppliers have to be added up too, if these suppliers provide the same parts.

Furthermore, the regular purchasing costs c_i and the reservation prices c_{Ri} [MU/QU] have to be known.

4.2.2 AT THE POSTERIOR POINT OF TIME T_1

When studying the articles i of one vehicle type at the posterior point of time t_1, a lot more information is available than at the prior point of time t_0. This growth in information makes an improved forecast for the demand of all articles at time t_2 possible. Hence, there is a revised forecast value Θ_{1i} for every single article i at the posterior point of time. The forecast values Θ_{1i} and Θ_{0i} behave like the upper mentioned forecast values Θ_1 und Θ_0. Similar to section 4.1, the change of the normal distribution of Θ_{0i} to Θ_{1i} can be described with the forecast optimization factor α_i. From a prior point of view, the demand has a lognormal distribution with an improved expected value Θ_{1i} and an improved forecast optimization factor

$\alpha = \omega_{1i}/\omega_{0i}$

As already mentioned, a flexible order capacity R_i is fixed at time t_0 in addition to the order quantity X_{0i}. Thus, at the posterior point of time, there is the following requirement for the order quantity x_{1i}:

$X0i \leq x1i \leq X0i + R0i$

4.3 MODELING SUPPLY CHAINS FOR ALL PARTS AND SEVERAL VEHICLE TYPES

The considerations of the supply chain in section 4.1 are about one single product and in section 4.2 about all parts of one vehicle type. In this section the supply chain should include all parts which are integrated in all vehicle types, i. e. the whole product portfolio of a company. Thus, in the following risk-pooling effects will be considered to benefit from variant flexibility.

The following variables of section 4.1 and 4.2 are going to be taken over and the corresponding calculations and theories will be extended:

- Θ_{0i}, Θ_{1i}
- ω_{0i}, ω_{1i}
- α_i
- β_i
- X_{0i}
- R_i
- c_{Ri}

Supply chain planning becomes much more complex, if not only parts of one vehicle type are considered, but all parts of a complete product range. It can be seen, that synergy effects only occur for parts which are the same across all vehicle types. Hence, only these parts are pursued further. In contrast to this, parts which are only integrated in one vehicle type do not offer

advantages resulting from variant flexibility. Thus, these parts are considered separately. The approach for these parts was explained in section 4.2.

The demand for parts, which are same parts across all vehicle types, results from forecasts of every single article of the different vehicle types. To combine the same parts has advantages, such as reduced warehousing and production/ordering costs. Even more important is the reduction of uncertainties concerning production quantities. The better planning reliability results from risk-pooling effects. A higher variant flexibility leads to the following advantages:

• For a fixed volume flexibility (capacity option), the sales risk costs (costs for excess capacity and shortages) can be reduced.

• If sales risk costs are fixed or planned in advance, the volume flexibility per supplier can be reduced.

4.3.1 AT THE PRIOR POINT OF TIME T_0

The variant flexibility leads to two actions at the prior point of time:

• The minimum production quantity X_{0ij} for every article i and every vehicle type j has to be defined at the prior point of time.

• The overall volume of reactive capacities has to be fixed for all parts. In contrast to this, the reactive capacity of parts which are no same parts across some vehicle types, have to be treated as stand-alone parts.

Since different lognormal probability distributions have to be combined, it seems obvious that the Central Limit Theorem has to be applied. The

central limit theorem states that the sampling distribution of the mean of a sufficiently large number of independent random variables, each with a well-defined mean and well-defined variance, will be approximately normally distributed, regardless of the underlying distribution (Montgomery, 2010).

For the variant flexibility it is important to know how the different probability distributions interact. With the Central Limit Theorem these interactions of the sample sum can be calculated. Given a random sample X_1, ..., X_n with mean µ and variance σ^2, it can be expressed as follows:

$$S = \sum_{i=1}^{n} X_i \tag{4.13}$$

$$E(S) = n\mu \tag{4.14}$$

$$Var(S) = n\sigma^2 \tag{4.15}$$

Therefore the standardized version for the lognormal probability is

$$P(S \leq s) = \Phi(\frac{\ln(S) - n\mu}{\sigma\sqrt{n}}) \tag{4.16}$$

However, these equations cannot be applied to the scenario of the variant flexibility, because in reality, the lognormal distributions for the demand is available for every single vehicle type and thus for every single part and assembly group. In order to make use of the variant flexibility, the

demand for same parts has to be added up, too. Also the standard deviation changes as explained later.

The average demand for every part and vehicle type can be only added up:

$$\theta_{0i,\Sigma} = \sum_j \theta_{0i,j} \qquad (4.17)$$

The standard deviation for same parts has to be calculated differently. In order to do this, it is necessary to clarify, if the random variables are stochastically dependent or stochastically independent.

If there is a positive or negative correlation between the random variables, the overall standard deviation should be calculated as follows:

$$\omega_{0i,\Sigma 1} = \sum_j \omega_{0ij} \qquad (4.18)$$

If there is no correlation between the random variables, the overall standard deviation should be calculated with the following formula in the case of variant flexibility:

$$\omega_{0i,\Sigma 2} = \sqrt{\Sigma_j \, \omega_{0ij}^2}$$

Since $\omega_{0i,\Sigma 2}$ is smaller than $\omega_{0i,\Sigma 1}$, it is obvious, that only for stochastic independent random variables, risk pooling effects accrue, which can be used

for economic purposes. In reality this means, that the different vehicle types are independent and that no customer is accepting an offer because he refused another offer for another vehicle. This is usually the case for the industry of special purpose vehicles, such as the military vehicle industry. Usually a customer is only asking for an RFQ for only one vehicle type, since the vehicle types are very different. Hence, it can be assumed that demand values are stochastically independent in reality.

Therefore, in case of variant flexibility, the probability for the demand can be calculated as follows:

$$P(D \leq d) = \Phi(\frac{\ln d - \sum_j \theta_{0i,j}}{\sqrt{\sum_j \omega_{0ij}^2}}) \tag{4.19}$$

Figure 15 shows the effect of variant flexibility. In this example it is assumed that there are two vehicle types. Vehicle one has a mean of 100 and a standard deviation of 5. Vehicle 2 has a mean of 80 and a standard deviation of 3. With variant flexibility, the mean and the standard deviation can be calculated as follows:

$$\theta_{1+2} = \sum_j \theta_j = \theta_1 + \theta_2 = 180$$

$$\omega_{1+2} = \sqrt{\sum_j \omega_j^2} = \sqrt{\omega_1^2 + \omega_2^2} = 5.83$$
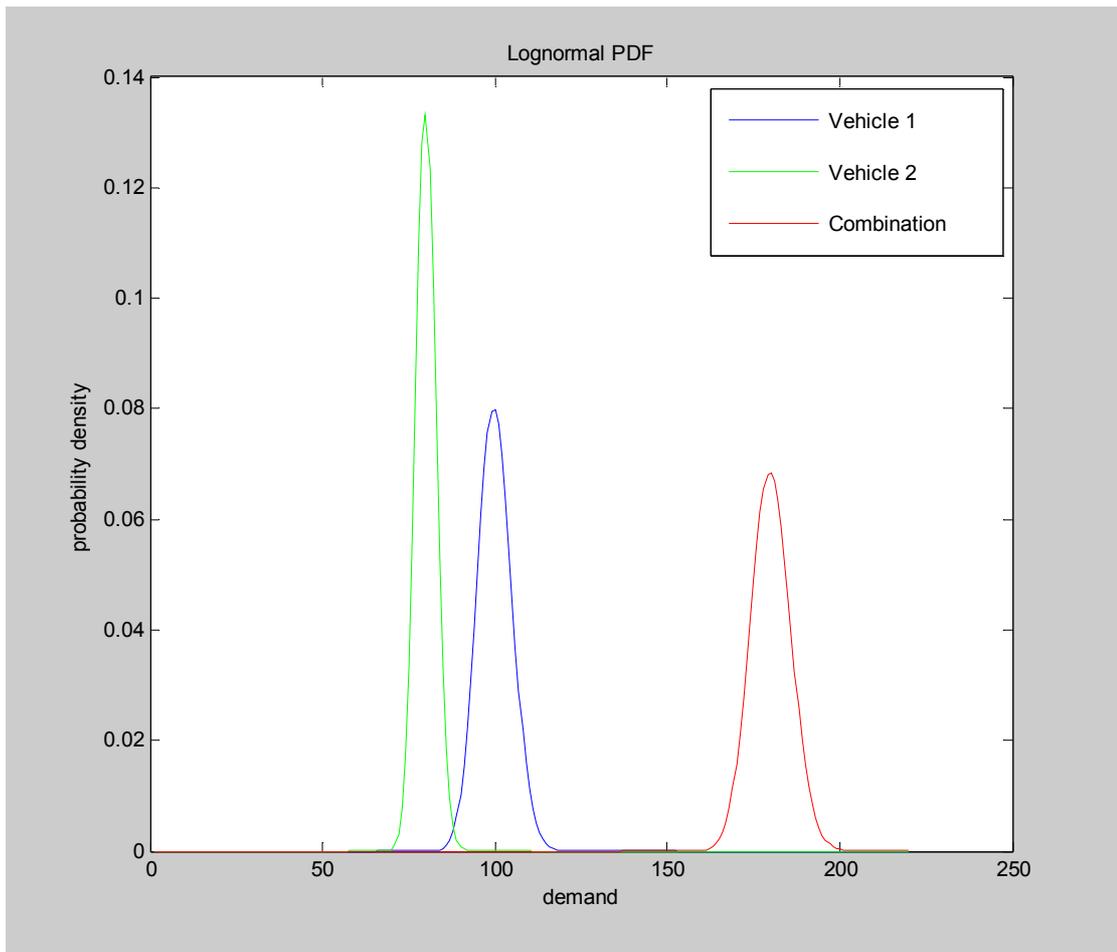
Figure 15: pdf with and without variant flexibility (Appendix A)

In Figure 15 the red line shows the probability distribution, if the forecasted demand of vehicle 1 (blue line) and vehicle 2 (green line) are combined. It is already obvious, that it is advantageous to do the SCM on the basis of the red distribution instead of considering both, the blue and the green distribution. However, for a better comparison, an imaginary probability distribution can be calculated with the following mean and standard deviation for the case without variant flexibility:

$$\theta_{1+2} = \sum_j \theta_j = \theta_1 + \theta_2 = 180$$

$\omega_{1+2} = 8$

With these values, the pdf without variant flexibility is shown in Figure 16 (black line). Furthermore the pdf for the case with variant flexibility is displayed in the same Figure (red line). The red probability distribution has a lower standard deviation than the black distribution. This direct comparison illustrates the smaller risk and the lower costs due to variant flexibility.
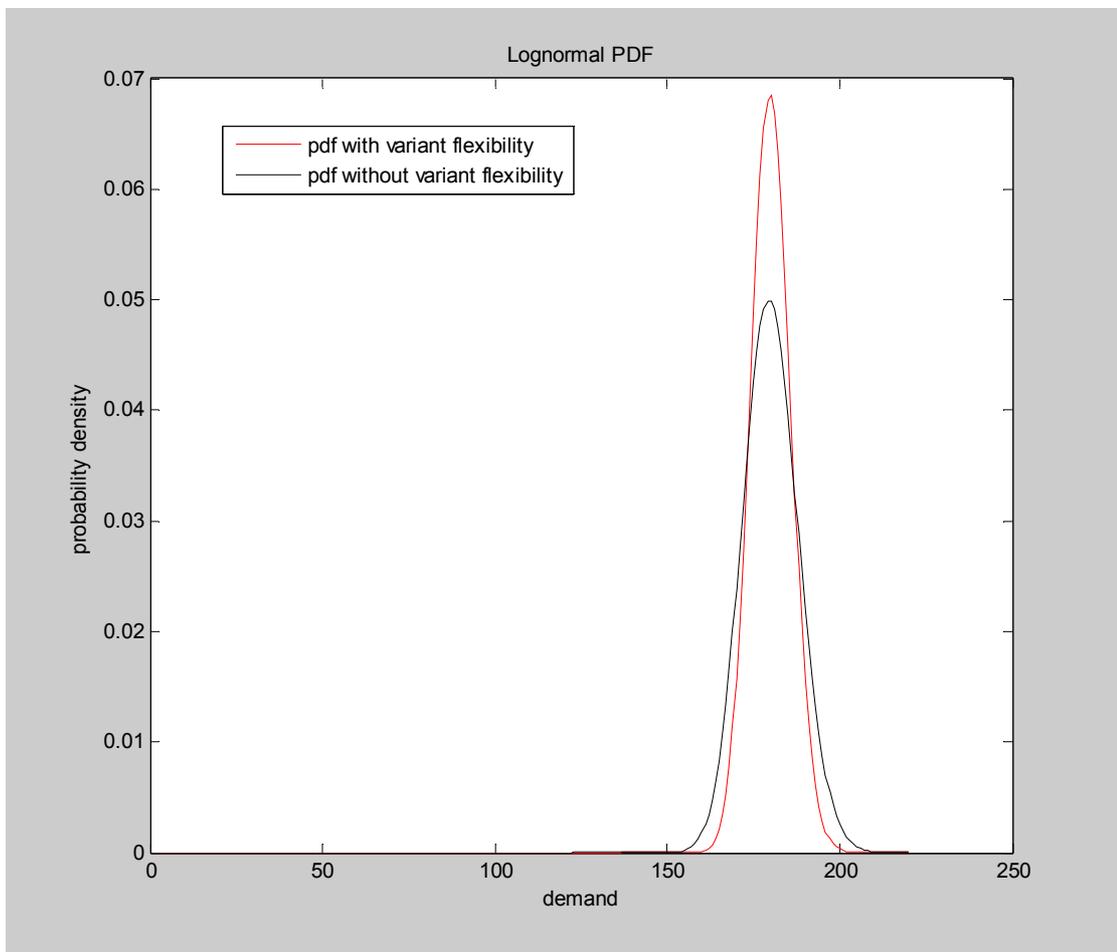
Figure 16: Effect of variant flexibility (Appendix B)

4.3.2 AT THE POSTERIOR POINT OF TIME T$_1$

At the posterior point of time, the decisions of the prior point of time are already fixed as explained in the sections before. Thus, a minimum order quantity X_{0ij} [QU] is already predetermined for all parts i of all vehicles j in a certain period of time. Additional, the upper and lower limit of a capacity option R_i [QU] are already fixed, which can be used in this range at the posterior point of time. Similarly to section 4.2, forecast values Θ_{1ij} are available. The values Θ_{1ij} are determined for all parts i of a vehicle j at the posterior point of time and are more accurate than the values Θ_{0ij}. Moreover, the overall forecast optimization factor $\alpha_{i,\Sigma} \bullet \omega_{0i,\Sigma}$ can be calculated.

In the case being considered - with same parts across different vehicle types - the order quantities x_{1ij} have to be still defined for all parts of every vehicle type. As explained above, the quantities are added up, before placing an order:

$$\sum_{j=1}^{n} x_{1ij}$$

On the contrary, the volume flexibility of the same parts or the standard deviation respectively, is not added up, as it was shown in section 4.3.1. Reason is that the risks for these parts of every vehicle type can compensate each other to a certain extent.

The order quantity at the posterior point of time has to be in the following range:

$$X_{0i} \leq \sum_{j=1}^{n} x_{1ij} \leq X_{01} + R_i \quad \text{for all i} \tag{4.20}$$

It becomes obvious that the consideration of same parts across the whole product portfolio leads to a higher flexibility and/or lower costs. But it is essential that this concept is supported by the used supply chain concept of a company. Therefore, the above mentioned strategy has to be considered in the following when the supply chain is set up. It is desirable, that advantage is taken out of as many same parts as possible. In general, the more same parts the better. Important positive effects can be achieved, such as commercial purchasing advantages. In practice, these positive effects are usually not used. One reason for this are conflicts of interests between purchasing and development departments, because of which the development of same parts is often not carried out. If however, variant flexibility is an overall goal in a company to realize a beneficial supply chain, a higher flexibility and a lot more advantages can be used.

At this point, the indices for the order or production quantities are listed for a better understanding:

$x_{tij,}$ where   t is time (prior or posterior)

                             i is the article number

                             j is the vehicle type, in which the article should be
                             integrated

At the posterior point of time, the optimal quantity x^*_{1ij} of every article i should be ordered or produced in line with the newsvendor model. Therefore, the sum of every article i, $\sum_{j=1}^{n} x^*_{1ij}$, across all vehicle types j has to fulfill the double equation (4.20). In this case, the expected costs at the posterior point of time are minimized. If however the single demand values θ_{1ij} are so high

that the sum of the mean order quantities $\sum_{j=1}^{n} \theta_{1ij}$ is higher than the

maximum capacity $X_{0i} + R_i$, some individual x_{1ij} values have to be reduced in

a way that the overall costs are as low as possible, compared to the optimal

solution. The corresponding procedure is carried out in the opposite case, if

the minimum order quantity X_{0i} is lower than the sum of the optimal order

quantity $\sum_{j=1}^{n} \theta_{1ij}$. In this case, the order quantities x'_{1ij} have to be inflated to

the lower limit $\sum_{j=1}^{n} x_{1ij} = X_{0i}$. To follow this approach, a strategy for optimally

increasing or decreasing the order quantity will be in subchapter 5.2.

CHAPTER 5

CHARACTERISTICS OF THE DEVELOPED

SUPPLY CHAIN STRATEGY

In Chapter 4, a supply chain concept was developed step by step. Following the most important characteristics of this supply chain are examined. Very important will be the impact of the main characteristics on the most important performance indicator of a company, which is the profit. Therefore, as indicator for a good supply chain, the maximum expected profit $E^*_{\text{profit,time } t_0}$ can be used. Instead of the potential or maximum profit, it would be possible to use the potential savings, the potential loss or the opportunity costs as indicator. No matter which indicator is used, it is important to be always focused on the selected indicator.

To get detailed information about the developed supply chain concept, the following scenarios will be examined:

- with and without variant flexibility

  (see section 5.1)

- with and without symmetrical volume flexibility ($R_m \pm \Delta R$)

(see section 5.2.1)

- with and without asymmetrical volume flexibility ($R_m - R_L$ and $R_m + R_H$)

(see section 5.2.2)

- reliable forecast ($\alpha = 0$)

(see section 5.3)

- unreliable forecast ($\alpha \neq 0$)

(see section 5.3)

- suboptimal order scenarios

(see section 5.4)

- order quantities at the posterior point of time with $X_1 = \theta_1$ and $X_1 \neq \theta_1$

(see section 5.5)

The comparisons under the above mentioned conditions should clarify the following questions:

• Which volume flexibility level should be fixed prior, to maximize expected profit?

• Which risk cost savings can be achieved with variant, volume and time flexibility?

• How are costs for sales risks quantitatively affected by the different types of flexibility?

• How are the different types of flexibility related to each other? Or how much

is it possible to decrease the level of one type of flexibility if the level of another type is increased?

5.1 BACKGROUND OF VARIANT FLEXIBILITY

There are a couple of variables, which influence variant flexibility. For example different standard deviations of same parts affect the levels of variant flexibility. Therefore, the influence of different standard deviations on the expected profit $E_{\text{profit,time } t_0}$ or on the expected costs $E_{\text{costs,time } t_0}$ is investigated in this chapter. It is also shown, if risk pooling effects by same parts are profitable.

In subchapter 4.3 the following formula for the overall standard deviation in the case of variant flexibility was found:

$$\omega_{0i,\Sigma 2} = \sqrt{\sum_j \omega_{0ij}^2}$$

The following section examines the influence of different standard deviations on the risk pooling effect or the expected profit $E_{\text{profit,time } t_0}$ respectively.

The following equation for the maximum expected profit was derived for individual components in section 4.1:

$$E_{\text{profit,time } t_0} = b \cdot \Theta_0 - E_{\text{costs,time } t_0}$$

The expected costs are the expected underage costs and the expected overage costs. Underage costs arise if the actual demand is higher than the order quantity, which is the mean θ_0. Therefore, shortages are calculated with the integral from the mean θ_0 to infinity. Overage costs arise, if the actual demand is lower than the order quantity. Thus, the shortages are calculated with the integral form 0 to the mean θ_0. The complete equation can be expressed as follows:

$$E_{\text{profit,time } t_0} = b \cdot \theta_0 - c_e \cdot \left(\int_{D=0}^{\theta_0} [\theta_0 - D] \cdot f(D) dD \right) - c_s \tag{5.1}$$
$$\cdot \left(\int_{D=\theta_0}^{\infty} [D - \theta_0] \cdot f(D) dD \right)$$

Following the focus is on expected costs, because the rest of the equation above is not influenced by standard deviations. Adapted to this section with different parts and different vehicles, the equation for the expected costs can be written as follows:

$$E_{\text{costs,time } t_0} = c_e \cdot \left(\int_{D=0}^{\theta_0} [\theta_0 - D] \cdot f(D) dD \right) + c_s \cdot \left(\int_{D=\theta_0}^{\infty} [D - \theta_0] \cdot f(D) dD \right) \tag{5.2}$$

It is assumed that the underage costs c_s and the overage costs c_e are the same for all parts and vehicle types. Otherwise some changes with c_{eij} and c_{sij} are necessary.

To calculate the overall standard deviation for variant flexibility, the following formulas were found in subchapter 4.3:

$$\theta_{0i,\Sigma} = \Sigma_j \, \theta_{0i,j}$$

$$\omega_{0i,\Sigma} = \sqrt{\sum_j \omega_{0i,j}^2}$$

In the equation above, $f(D)$ is the density function. For lognormal probability distributions, the density function can be expressed as follows (Montgomery, & Runger, 2010):

$$f(D) = \frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}} \tag{5.3}$$

If all this is implemented in the equation for the expected costs, it can be written as follows:

$$E_{costs,time\,t_0} = c_e \cdot \left(\int_{D=0}^{\Sigma_j \, \theta_{0i,j}} [\Sigma_j \, \theta_{0i,j} - D] \cdot \frac{1}{D \cdot \sqrt{\Sigma_j \, \sigma_{0i,j}^2} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \Sigma_j \, \mu_{0i,j})^2}{2\left(\sqrt{\Sigma_j \, \sigma_{0i,j}^2}\right)^2}} \, dD \right) + \tag{5.4}$$

$$c_s \cdot \left(\int_{D=\Sigma_j \, \theta_{0i,j}}^{\infty} [D - \Sigma_j \, \theta_{0i,j}] \cdot \frac{1}{D \cdot \sqrt{\Sigma_j \, \sigma_{0i,j}^2} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \Sigma_j \, \mu_{0i,j})^2}{2\left(\sqrt{\Sigma_j \, \sigma_{0i,j}^2}\right)^2}} \, dD \right)$$

The equation above is for the calculation of the costs over all vehicle types. Therefore, there is the sum of all vehicles j.

Variant flexibility leads to the effect, that the overall mean and the standard deviation for the demand of one article changes. In equation 22, these variables are in relation with the expected costs. Therefore, the expected costs depend on the mean and the standard deviation for the demand of several vehicle types. To get an impression of the behavior of equation 22, some examples with different scenarios are calculated. The results will be also used for the performance evaluation.

The following table shows some results for different $\omega_{0i,j}$. Three different cars with one same part are considered. Every example shown in Table 5 is about one part which is integrated in three different vehicles. In all five examples, the mean standard deviation is always 1. Every example shows the overall standard deviation for different standard deviations of the single vehicles.

Table 5: Overall standard deviation in different examples

	$\omega_{01,1}$	$\omega_{01,2}$	$\omega_{01,3}$	$\omega_{01,\Sigma} = \sqrt{\sum_j \omega_{01,j}^2}$
Example 1	1.0	1.0	1.0	1.73
Example 2	1.5	1.5	0	2.12
Example 3	1.9	1.0	0.1	2.15
Example 4	2.0	1.0	0	2.24
Example 5	3.0	0	0	3.00

In Table 5 it is shown with example 1, that the overall standard deviation is 1.73, if there is a risk pooling effect and if the average standard deviation is 1.0 for all vehicle types. It is obvious that the overall standard deviation $\omega_{0i,\Sigma}$ should be as small as possible to obtain a high expected profit.

Furthermore it can be seen that in the best case, the standard deviations should be equally distributed over all vehicle types. If the standard deviation is 0 for some vehicle types, only very little or no economic advantages of the risk pooling effect can be used. In the fifth example of Table 5 there is even no risk pooling effect. In reality a standard deviation of 0 means that the predicted demand will occur with 100% confidence. This is favourable, because there are no uncertainties concerning the demand of this single vehicle type. Therefore, the expected profit for this vehicle type is at a maximum. On the other hand, the risk pooling effect is very low or does not exist for the other vehicles, where $\omega_{0i,j} \neq 0$, so that the expected profit for these vehicles decreases. The effect of one vehicle type with a standard deviation unequal to 0 is equal to the effect of a full correlation.

To get a better feeling for the risk pooling effect of the variant flexibility, the following table shows the expected profit for the 5 examples of Table 5.

The following values are used for this exemplary calculation with equation 5.4:

$$\theta_{0,i,\Sigma} = \Sigma_j\, \theta_{0,i,j} = 30 \text{ [QU]}$$

$$c_s = 5 \text{ [MU/QU]}$$

$$c_e = 5 \text{ [MU/QU]}$$

For the calculation of the expected costs, it is important to convert the mean and the standard deviation of the lognormal distribution to the mean and the standard deviation of the normal distribution, since these values have to be inserted in equation 5.4. Thus θ und ω have to be converted to μ und σ.

There is the following correlation between the variables of the lognormal and the normal distribution (Montgomery, & Runger, 2010):

$$\theta = e^{\mu+\sigma^2/2}$$

$$\omega = e^{2\mu+\sigma^2}\left(e^{\sigma^2} - 1\right)$$

Conversely, μ and σ are found from θ und ω as follows:

$$\mu = 2\ln(\theta) - \frac{1}{2}\ln(\omega^2 + \theta^2)$$

$$\sigma = \sqrt{-2\ln(\theta) + \ln(\omega^2 + \theta^2)}$$

The following table shows the transferred values of Table 5.

Table 6: Transferred values

	$\omega_{01,\Sigma} = \sqrt{\sum_j \omega_{0,1,j}^2}$	θ	σ	μ
Example 1	1.73	30	0.0576	3.3996
Example 2	2.12	30	0.0706	3.3987
Example 3	2.15	30	0.0716	3.4038
Example 4	2.24	30	0.0746	3.3984
Example 5	3.00	30	0.0998	3.3962

Now, the expected costs can be calculated. The results are in Table 7.

Table 7: Expected costs in various examples

	$\omega_{0,1,1}$	$\omega_{0,1,2}$	$\omega_{0,1,3}$	$E^*_{costs,time_{t_0}}$[MU/QU]
Example 1	1.0	1.0	1.0	6.895
Example 2	1.5	1.5	0	8.4453
Example 3	1.9	1.0	0.1	8.5644
Example 4	2.0	1.0	0	8.9218
Example 5	3.0	0	0	11.9336

The costs of Table 7 were calculated with MATLAB (Appendix C). As expected, the calculated expected costs are the lowest in Example 1, because standard deviations of all three vehicle types are combined. The highest expected costs were calculated for Example 5, because vehicle one has a high standard deviation and variant flexibility has no effect, because vehicle two and three have no standard deviation.

For comparison, the expected profit is calculated for the case if there is no risk pooling effect at all and the standard deviation is 1.0 for every vehicle type, as in example 1, with $\theta = 10$ and $\omega = 1$:

$$E_{costs,time\ t_0} = 3 \cdot \left[c_e \cdot \left(\int_{D=0}^{\Theta_{0,i}} [\Sigma_j \Theta_{0,i} - D] \cdot \frac{1}{D \cdot \sqrt{\sigma_{0i}^2} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_{0i})^2}{2\left(\sqrt{\sigma_{0i}^2}\right)^2}} dD \right) + c_s \cdot \right.$$

$$\left(\int_{D=\Theta_{0,i}}^{\infty} [D - \Sigma_j \Theta_{0,i}] \cdot \frac{1}{D \cdot \sqrt{\sigma_{0i}^2} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_{0i})^2}{2\left(\sqrt{\sigma_{0i}^2}\right)^2}} dD \right) \right] = 3 \cdot \left[5 \cdot \left(\int_{D=0}^{10} [10 - D] \cdot \right. \right.$$

$$\frac{1}{D \cdot \sqrt{0.0998} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - 2.2976)^2}{2(\sqrt{0.0998})^2}} dD \right) + 5 \cdot$$

$$\left(\int_{D=10}^{\infty} [D - 10] \cdot \frac{1}{D \cdot \sqrt{0.0998} \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - 2.2976)^2}{2(\sqrt{0.0998})^2}} dD \right) \right] = 11.9336$$

The expected costs for this case, without variant flexibility, are 11.9336. Compared to example 1, there the costs decrease by about 42% due to variant flexibility. Thus, it is already demonstrated that variant flexibility is very favorable.

For comparison, the expected costs are now calculated for normal distributions instead of lognormal distributions. The results are shown in Table 8 (Appendix D). If there would be no variant flexibility and a normal demand distribution, the expected costs for example 1 would be 2.3937 (Appendix D). Thus, variant flexibility leads to savings of 58% in this example. These are very high savings, because they are only related to the expected costs. The savings are not in the complete context, because they do not consider all the related costs, as for example the purchasing costs. However, these results also show that risk pooling has a very high impact on the expected profit and is therefore very important.

Table 8: Expected costs in case of normal distributions

	$\omega_{01,1}$	$\omega_{01,2}$	$\omega_{01,3}$	$\omega_{01,\Sigma} = \sqrt{\sum_j \omega_{01,j}^2}$	$E^*_{costs,timet_0}[MU/QU]$
Example 1	1.0	1.0	1.0	1.73	1.3803
Example 2	1.5	1.5	0	2.12	1.6915
Example 3	1.9	1.0	0.1	2.15	1.7155
Example 4	2.0	1.0	0	2.24	1.7873
Example 5	3.0	0	0	3.00	2.3937

Table 7 and Table 8 do not only show that risk pooling effects are profitable. It becomes also obvious that even small quantities and only few different vehicle types are profitable with respect to variant flexibility. Also different standard deviations affect risk pooling. The examples illustrate that

the highest profits are achieved, if the standard deviations are low. Minimum costs accrue if standard deviations are equally distributed over all vehicle types, because risk pooling effects are optimally used.

Above, the risk pooling effect was calculated for time t_0. It would be also possible to calculate the risk pooling effect for time t_1. The only difference is that parameters of time t_1 have to be used:

$$E_{costs,time\ t_1} = c_e \cdot \left(\int_{D=0}^{\Sigma_j\,\theta_{1i,j}} \left[\Sigma_j\,\theta_{1i,j} - D \right] \cdot \frac{1}{D \cdot \sqrt{\Sigma_j\,\sigma_{1i,j}^2} \cdot \sqrt{2\pi}}\, e^{-\frac{(\ln D\, -\, \Sigma_j\,\mu_{1i,j})^2}{2\left(\sqrt{\Sigma_j\,\sigma_{1i,j}^2}\right)^2}}\, dD \right) + c_s \cdot$$

$$\left(\int_{D=\Sigma_j\,\theta_{1i,j}}^{\infty} \left[D - \Sigma_j\,\theta_{1i,j} \right] \cdot \frac{1}{D \cdot \sqrt{\Sigma_j\,\sigma_{1i,j}^2} \cdot \sqrt{2\pi}}\, e^{-\frac{(\ln D\, -\, \Sigma_j\,\mu_{1i,j})^2}{2\left(\sqrt{\Sigma_j\,\sigma_{1i,j}^2}\right)^2}}\, dD \right)$$

With the equation above, the expected profit $E_{profit,time\ t_1}^*$ can be determined. However, it is much more useful, to calculate $E_{profit,time\ t_0}^*$ at time t_0. The expected profit at time t_0 is important to define the volume flexibility, which is realized with the mean capacity option R_m and the capacity range R_0. The bigger the standard deviation of the demand is, the bigger the volume flexibility should be. Thus, if the standard deviation becomes smaller due to the risk pooling effect, the volume flexibility can become smaller, too.

This leads to the next chapter, where the background of volume flexibility is examined in detail.

5.2 **BACKGROUND OF VOLUME FLEXIBILITY**

Section 5.1 was dealing with variant flexibility. The focus was only on this flexibility type. Other flexibility types were not included at all. Volume flexibility was completely excluded. In the calculations it was always assumed, that $x_{0i,\sum}$ can become every value at time t_1 and time t_2. In real life, there are restrictions such as capacity limits. Furthermore reservation costs for volume flexibility were not mentioned. Therefore, this section is about all these restrictions in context to volume flexibility. Especially the influence of the volume flexibility on the maximum expected profit is investigated to evaluate the effectiveness and to find the right degree of this flexibility type. To begin with, the next logical approach will be explained in subchapter 5.2.1, which is the symmetrical volume flexibility. In this chapter it will become obvious, that this strategy can be improved for the intended purpose. Therefore, an asymmetrical volume flexibility will be derived in subchapter 5.2.2.

But before doing this, a short overview of the so far determined approach is presented. This will help to keep track of the previous findings and the next steps.

First the demand is described mathematically at time t_0. This can be for example a lognormal distribution as follows:
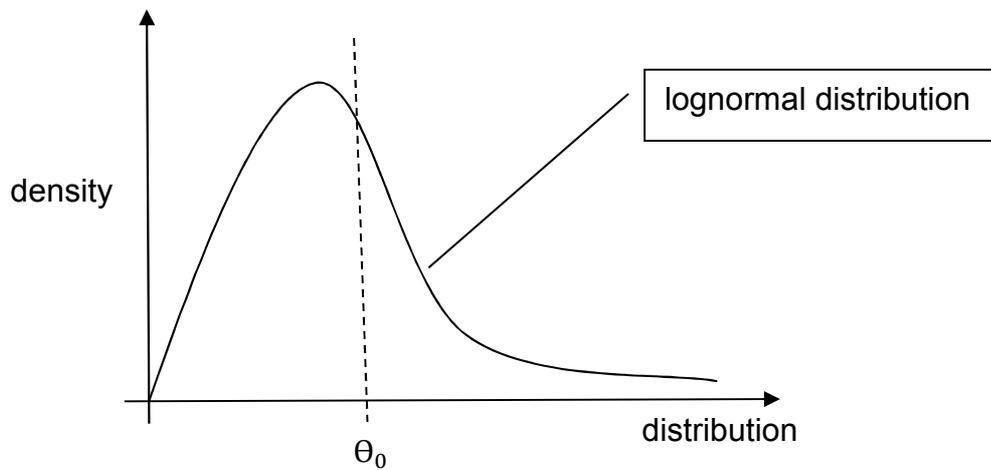

Figure 17: Lognormal distribution with mean Θ_0

After that the fixed order quantity X_0 is determined as well as the capacity range R_0 with $R_0 = 2 \cdot \Delta R$ for a symmetrical volume flexibility:
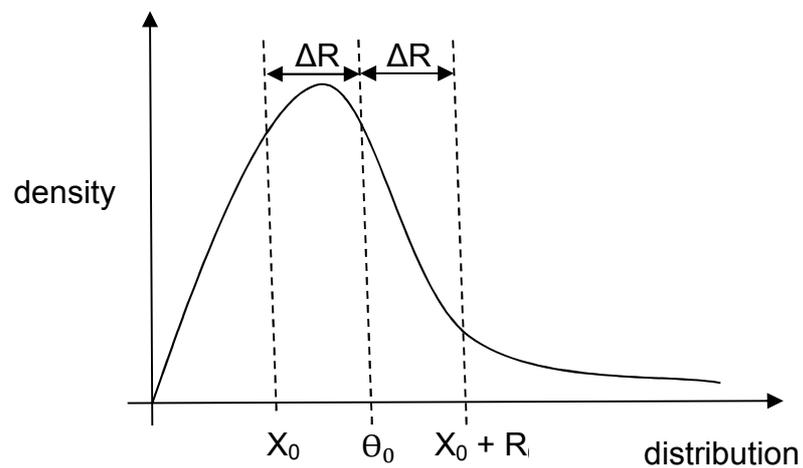
Figure 18: Lognormal distribution with symmetrical capacity range

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The approach for calculating the capacity range $2 \cdot \Delta R$ is shown in subchapter 5.2.1. The second possibility, for calculating the capacity range from $\theta_0 - R_L$ to $\theta_0 + R_H$ is explained in subchapter 5.2.2. This asymmetrical volume flexibility can be visualized as follows:
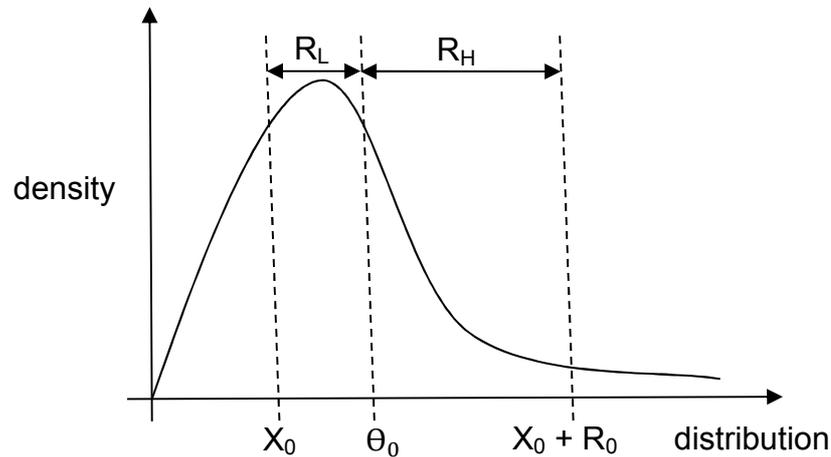
Figure 19: Lognormal distribution with asymmetrical capacity range

5.2.1 SYMMETRICAL VOLUME FLEXIBILITY

At time t_0 the flexibility range $R_m \pm \Delta R$ has to be fixed. This flexibility range makes the volume flexibility possible. Since ΔR is equal to both sides of R_m, this flexibility is called symmetrical in the following. In this section it should be explained how the flexibility range has to be determined.

The first value to determine is the expected mean flexibility R_m. This value is equal to the mean demand, which should be known from the demand forecast. The next, which has to be determined, is the size of the volume range. At first glance it seems obvious that the volume flexibility should be equal to both sides of R_m. This is the intention in this section. Hence, the

flexibility range is $R_m \pm \Delta R$ instead of $R_m - R_L$ and $R_m + R_H$ with different R_L and R_H.

In the work above, it was still not discussed, how the order quantity X_0 is determined. In Figure 19 and 20 it becomes obvious, that X_0 does not have to be calculated separately. It can be seen, that X_0 depends on R_m and ΔR for the symmetrical volume flexibility and R_m and R_L for the asymmetrical volume flexibility respectively. The capacity range ΔR and R_L are calculated, as it will be shown later. In the best case, the mean capacity R_m is always equal to the mean θ_0. Therefore, the order quantity X_0 is predetermined by the following equation:

$$X_0 = R_m - \Delta R$$

In reality, there could be exceptions, where X_0 is not equal to $R_m - \Delta R$. This is for example the case, if it is for any reason not possible for a company to order the quantity $R_m - \Delta R$ of an article at time t_0. Therefore, this case is called suboptimal scenario in the following. If this happens, slight changes have to be made to adapt the considerations of this work. A short overview will give subchapter 5.4.

Following, the optimal symmetrical flexibility range ΔR is determined. Therefore the maximum expected profit is calculated again. Thus, the costs for the capacity range have to be known. The costs, which may result from the capacity range, are the reservation costs for the capacity C_{res} as well as the expected underage and overage costs $E_{costs, time\ t_0}$. Therefore, the overage and

underage costs c_e and c_s are needed. To understand how these costs can be

calculated, it is helpful, to have a look on the following graph:
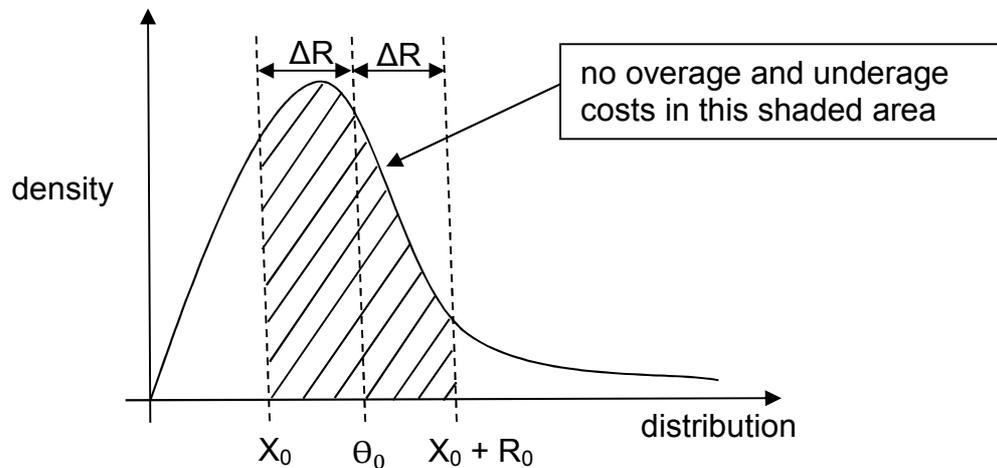
Figure 20: Visualization of areas with underage and overage costs

For the shaded areas in Figure 20 no overage and underage costs

accrue, because the actual demand in this area can be always met due to the

variant flexibility. Therefore, the probability of an actual demand outside of the

flexibility range $2 \cdot \Delta R$ has to be considered. Thus, the non-shaded areas will

lead to the expected underage and overage costs, whereas the shaded area

will lead to the reservation costs for the volume capacity. The costs for excess

capacity can be calculated by multiplying the costs for one excess unit with

the number of excess units and with the probability for this case. To consider

all these possible cases, the integral has to be taken from 0 to X_0. The

expected costs for shortages can be calculated similarly. Therefore, the

expected shortages and the expected excess capacity can be calculated as

follows:

$$E_{costs,excess} = c_e \cdot \int\limits_{D=0}^{\theta_0 - \Delta R} [(\theta_0 - \Delta R) - D] \cdot f(D)dD \tag{5.5}$$

$$E_{costs,shortages} = c_s \cdot \int\limits_{D=(\Delta R + \theta_0)}^{\infty} [D - (\theta_0 + \Delta R)] \cdot f(D)dD \tag{5.6}$$

With equation 5.5 and 5.6, the capacity range will lead to the following costs:

$$E_{costs} = C_R + E_{costs,excess} + E_{costs,shortages} \tag{5.7}$$

$$E_{costs,time\ t_0} = c_R \cdot 2\Delta R + c_e \cdot \int\limits_{D=0}^{\theta_0 - \Delta R} [(\theta_0 - \Delta R) - D] \cdot f(D)dD + c_s \\ \cdot \int\limits_{D=(\Delta R + \theta_0)}^{\infty} [D - (\theta_0 + \Delta R)] \cdot f(D)dD \tag{5.8}$$

In the equation above, $f(D)$ is expressed again as follows (Montgomery, & Runger, 2010):

$$f(D) = \frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}}$$

With the equation above, the expected costs can be calculated as follows:

$$E_{costs,time\ t_0} = \tag{5.9}$$
$$c_R \cdot 2\Delta R + c_e \cdot \int_{D=0}^{\theta_0 - \Delta R} [(\theta_0 - \Delta R) - D] \cdot \left(\frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}} \right) dD + c_s \cdot$$

$$\int_{D=(\Delta R+\theta_0)}^{\infty} [D - (\Theta_0 + \Delta R)] \cdot \left(\frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}} \right) dD$$

The first part of equation 5.9 shows the higher costs with a growing flexibility range ΔR. The second and third part of this equation show that the costs decline with a growing flexibility range ΔR. This relationship is shown in the graph below:
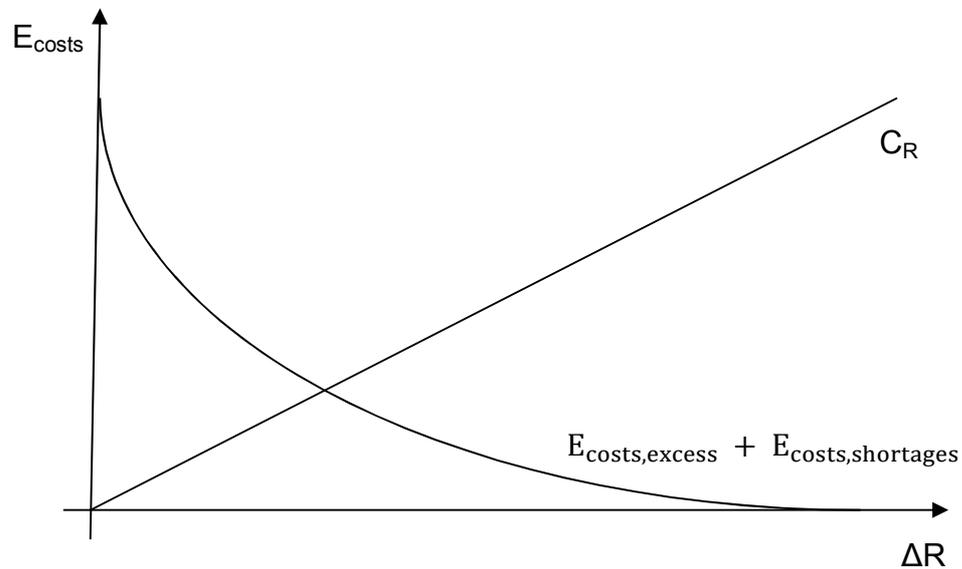
Figure 21: Elements of costs in relation to the flexibility range

It must be mentioned, that the graph for $E_{costs,excess} + E_{costs,shortages}$ could have a different shape, because $E_{costs,shortages}$ and $E_{costs,excess}$ can be very different, since both depend on the probability distribution of the demand.

The minimum value of $E_{costs,time\ t_0}$ in equation 5.9 leads to the optimal range of 2 ·ΔR.

Equation 5.9 does not contain R_0. Also the simple equation in the following, which shows the expected revenue at the prior point of time, does not mention R_0.

$$R_{re} = b \cdot X_0$$

For these reasons, R_0 is not considered in this section.

With equation 5.9 the capacity range ΔR can be calculated. The optimum value for the capacity range ΔR leads to the minimum costs. One way to find the best value for ΔR is an analytical calculation with MATLAB, which is shown in Appendix E. To get an impression of the calculations with equation 5.9, an example with realistic values is shown in the following. The MATLAB code, which is shown in the appendix, makes it possible for the user to enter own values for the standard deviation of the demand, for the overage costs, for the underage costs and for the reservation costs. The following variables were entered in the MATLAB program:

- mean of the demand: $\theta_0 = 100$
- standard deviation of the demand: $\omega_0 = 5$
- overage costs $c_e = 5$
- underage costs $c_s = 10$
- reservation costs $c_R = 1$

The MATLAB program, which was specially created for this purpose, provides the result for the minimum expected costs and the result for the optimal flexibility range. For the above defined variables, the following results have been received:

$$E_{\text{min costs,time } t_0} = 16.3475$$

$$\Delta R = 6$$

This means that the size of the symmetrical range is $R_0 = 2 \cdot \Delta R = 12$. Hence, it is most economical in this case if a flexibility of 12 parts is retained. This would be an expected demand at time t_1 of 6 parts more or 6 parts less than the expected demand at time t_0.

Additionally, the result for this example is visualized with Matlab:
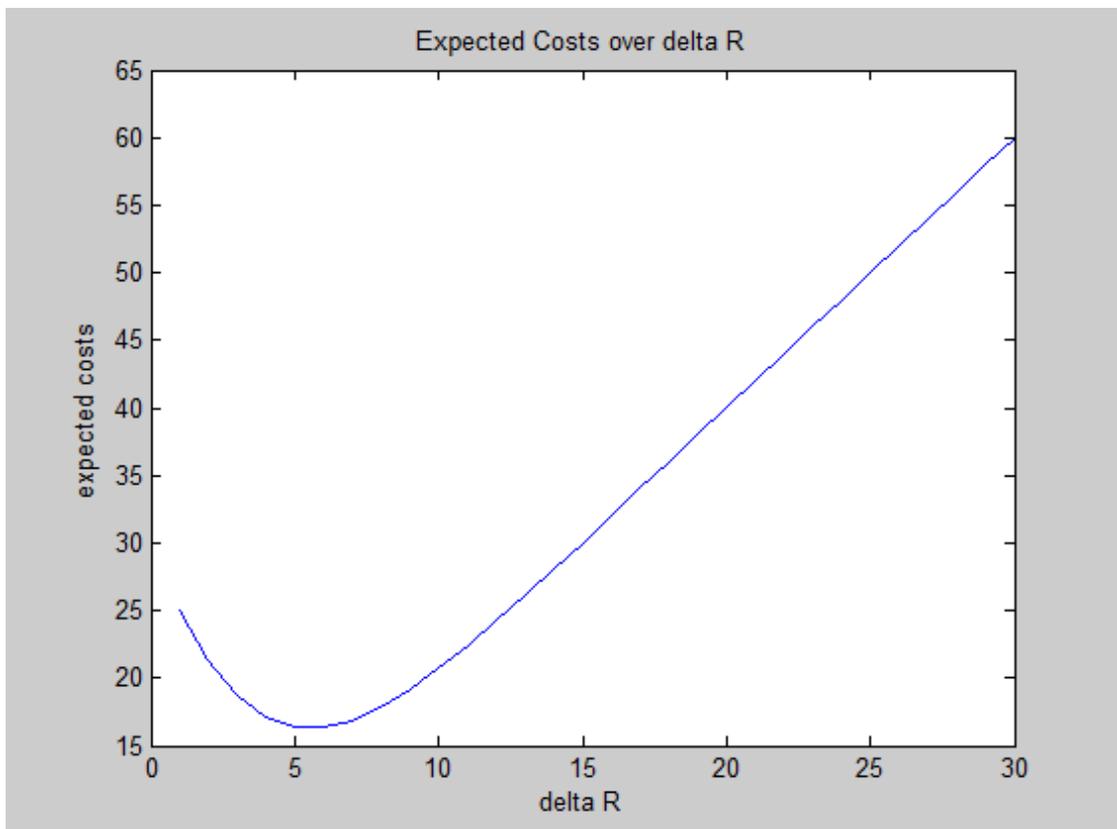
Figure 22: Relation between expected costs and ΔR

It can be seen that the expected costs depend on the following variables:

- the capacity range ΔR

- the standard deviation of the demand ω_0

- mean of the demand Θ_0

- the overage costs c_e

- the underage costs c_s

- the reservation costs c_R

Figure 22 shows the expected costs for ΔR from 0 to 30. It would be also possible to increase this range. However, this would mean more computational work, which is not necessary, because the result is already predictable. With a bigger range, the optimal value for ΔR will still be the same, because the expected price will increase due to higher reservation costs. Additionally, the probability of occurrence decreases with the distance of the mean. This becomes obvious, if the probability distribution of the demand is visualized for this example.
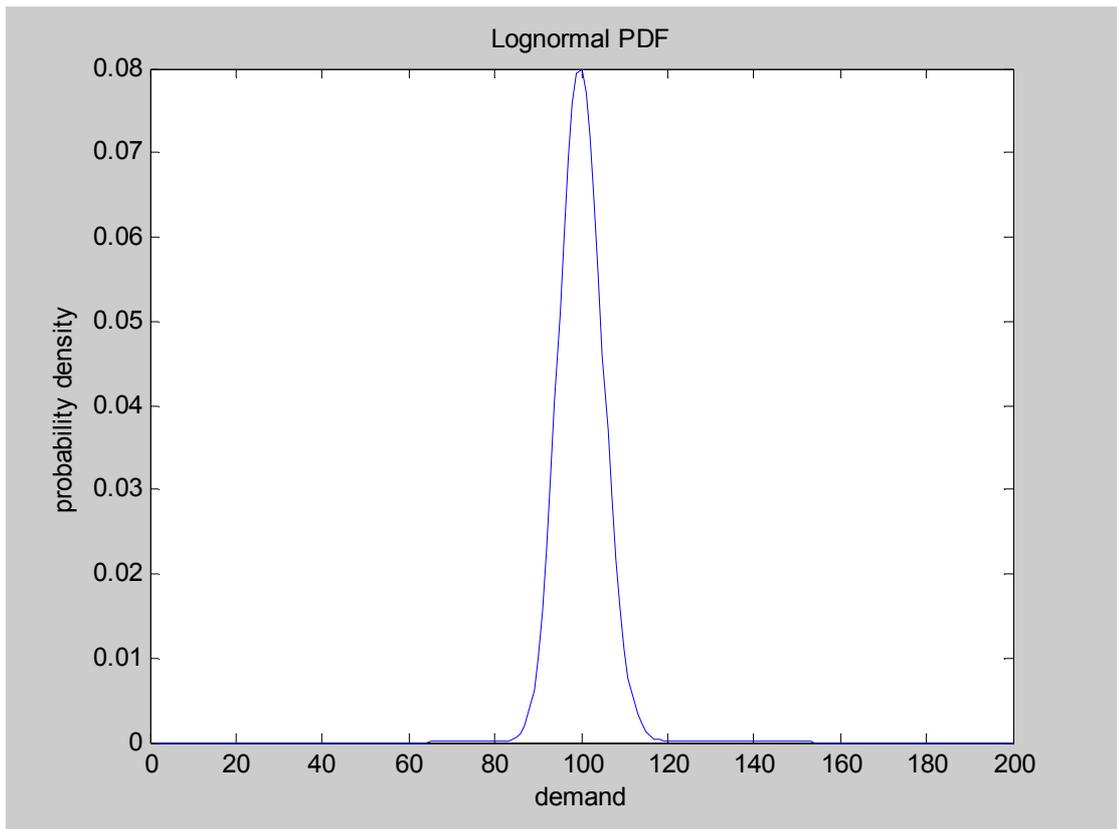
Figure 23: PDF for the demand (Appendix F)

The only variable, which can be influenced by 100% is the capacity range ΔR. In some special cases, another variable could be influenced to a certain extent such as the standard deviation of the demand ω_0, because this variable depends on the quality of the forecast. As it was already stated, OEMs in the SPV industry do not have the possibility to get sound demand forecasts. But it is worth to improve the demand forecast values and thus the standard deviation of the demand as good as possible. To improve forecasts is not the intention of this work, but the graph shows that a good forecast with a small standard deviation of the demand has also a great influence on the expected costs. Unfortunately, the standard deviation is not only affected by the quality of the demand forecast. There are also external factors, such as

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unforeseeable decisions of customers. Also variant flexibility would affect the

standard deviation. But this is not considered in this subchapter. The following

table illustrates the importance of the standard deviation by showing the

influence of the capacity range and the standard deviation on the costs. It is

very difficult to influence the standard deviation and it is only possible to

change the standard deviation to a very limited extent. Therefore Figure 24 is

just for information. The focus is still on variables, which can be changed by

the SCMO. For the following graph, the same input variables were taken as

for Figure 22. But it shows the effect of different standard deviations on the

expected costs.
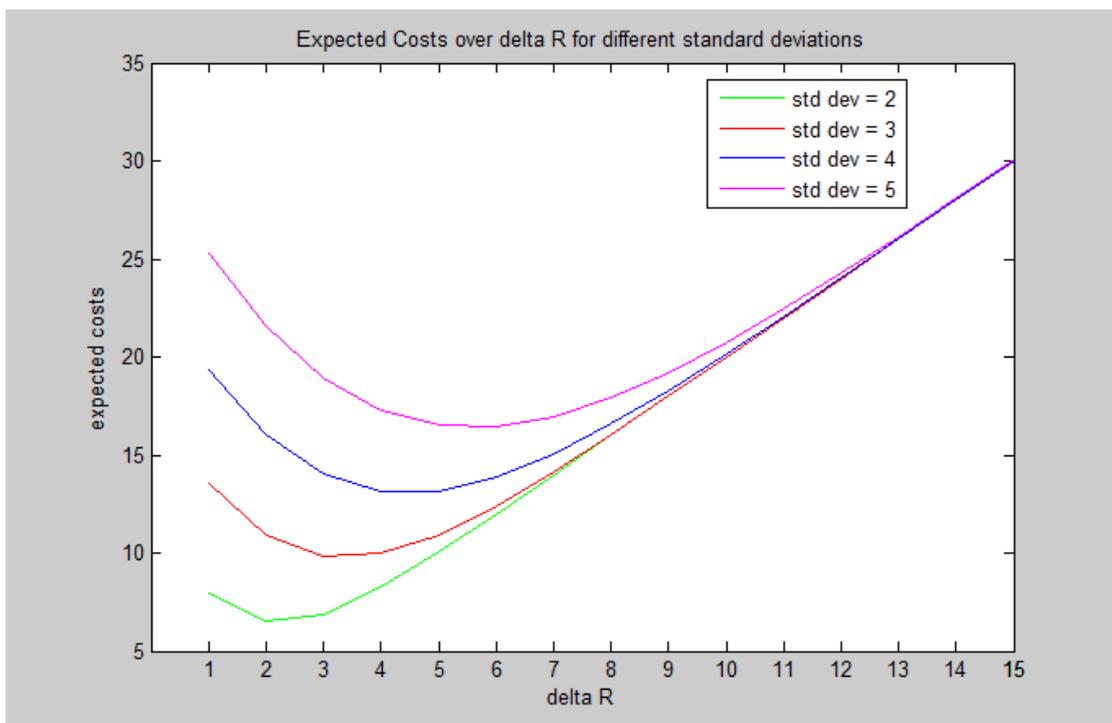
Figure 24: Expected costs for different standard deviations (Appendix

G)

5.2.2 ASYMMETRICAL VOLUME FLEXIBILITY

Also in this section, $X_0 + R_m$ is set equal to the mean θ_0. However, the flexibility range should not be $R_m \pm \Delta R$, but from $R_m - R_L$ to $R_m + R_H$ with different R_L and R_H. It was explained above, that this could be advantageous, if there is a significant difference between the overage and underage costs.

A small difference to the symmetrical volume flexibility is the calculation of the order quantity at time t_0, which can be now expressed as follows:

$$X_0 = R_m - R_L$$

Also for this flexibility type, the expected costs have to be calculated again. In section 4.1.1 the following equation for the expected costs was derived for time t_0:

$$E_{costs,time\ t_0} = c_e E(e) + c_s E(s)$$

Here the reservation cost is also considered:

$$E_{costs} = C_R + E_{costs,excess} + E_{costs,shortages}$$

Now the costs for the expected excess capacity and the costs for the expected shortages are expressed mathematically.

At next the expected costs for excess capacity $E_{costs,excess}$ can be derived. It is only possible to have excess capacity if the actual demand D will be between 0 and the minimum order quantity $(\theta_0 - R_L)$, as it can be seen below.
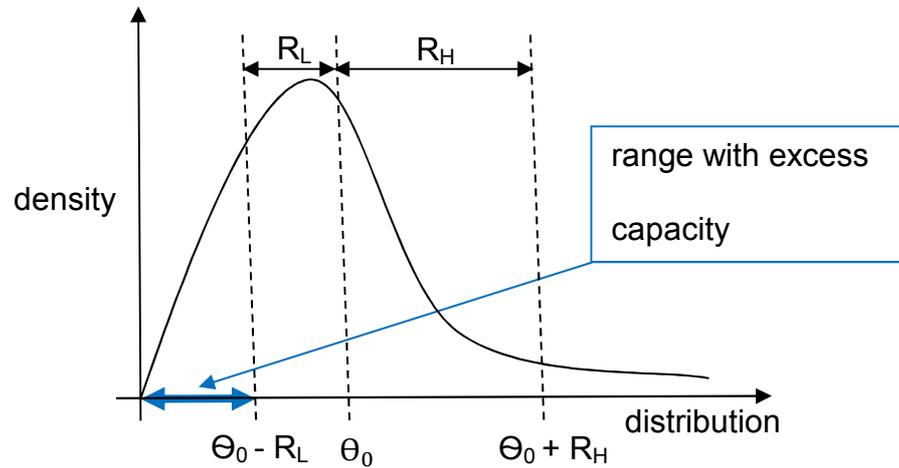
Figure 25: Range which leads to excess capacity after time t_0

To calculate the costs for the expected excess capacity, the cost for one excess unit c_e has to be multiplied with the probability for the occurring demand $f(D)$ and with the number of excess units, which is $(\Theta_0 - R_L - D)$. This has to be calculated for the range, which was shown in Figure 25. Therefore the integral from 0 to $(\theta_0 - R_L)$ is needed. This can be expressed mathematically as follows:

$$E_{costs,excess} = c_e \cdot \int_{D=0}^{\theta_0 - R_L} [(\Theta_0 - R_L) - D] \cdot f(D)dD \tag{5.10}$$

Equivalent to this, the expected costs for the shortages can be calculated as follows:

$$E_{costs,shortages} = c_s \cdot \int_{D=(R_H+\theta_0)}^{\infty} [D - (\Theta_0 + R_H)] \cdot f(D)dD \tag{5.11}$$

The reservation costs have to be calculated for the lower and the upper range:

$$C_R = c_R \cdot (R_L + R_H) \tag{5.12}$$

Thus, the expected costs at the prior point of time can be calculated as follows:

$$E_{costs,time\ t_0} = c_R \cdot (R_L + R_H) + c_e \cdot \int_{D=0}^{\theta_0 - R_L} [(\theta_0 - R_L) - D] \cdot f(D)dD + c_s \tag{5.13}$$

$$\cdot \int_{D=(R_H + \theta_0)}^{\infty} [D - (\theta_0 + R_H)] \cdot f(D)dD$$

In the equation above, $f(D)$ is again the density function for lognormal probability distributions. It is expressed as follows (Montgomery, & Runger, 2010):

$$f(D) = \frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}$$

Now, the equation for the expected costs can be rewritten to:

$$E_{costs,time\ t_0} = c_R \cdot (R_L + R_H) + c_e \cdot \int_{D=0}^{\theta_0 - R_L} [(\theta_0 - R_L) - D] \cdot \tag{5.14}$$

$$\left(\frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}} \right) dD + c_s \cdot$$

$$\int_{D=(R_H + \theta_0)}^{\infty} [D - (\theta_0 + R_H)] \cdot \left(\frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}} \right) dD$$

In equation 5.14, it is possible to equate Θ_0 with R_m. Due to this relationship and the findings above, it becomes obvious why it makes sense to use the variables R_m, R_0, ΔR, R_L and R_H to express the volume flexibility.

Equation 5.14 is a function with two variables R_L and R_H. To find the optimum values, the extreme values have to be calculated. For the calculation of the extreme values and to visualize the equation above, a MATLAB program was written (see Appendix H).

For demonstration, equation 5.14 is visualized for different R_L and R_H in Figure 26. Therefore, the following variables were entered:

- mean demand $\Theta_0 = 100$
- standard deviation of the demand: $\omega_0 = 5$
- overage costs $c_e = 5$
- underage costs $c_s = 10$
- reservation costs $c_R = 1$
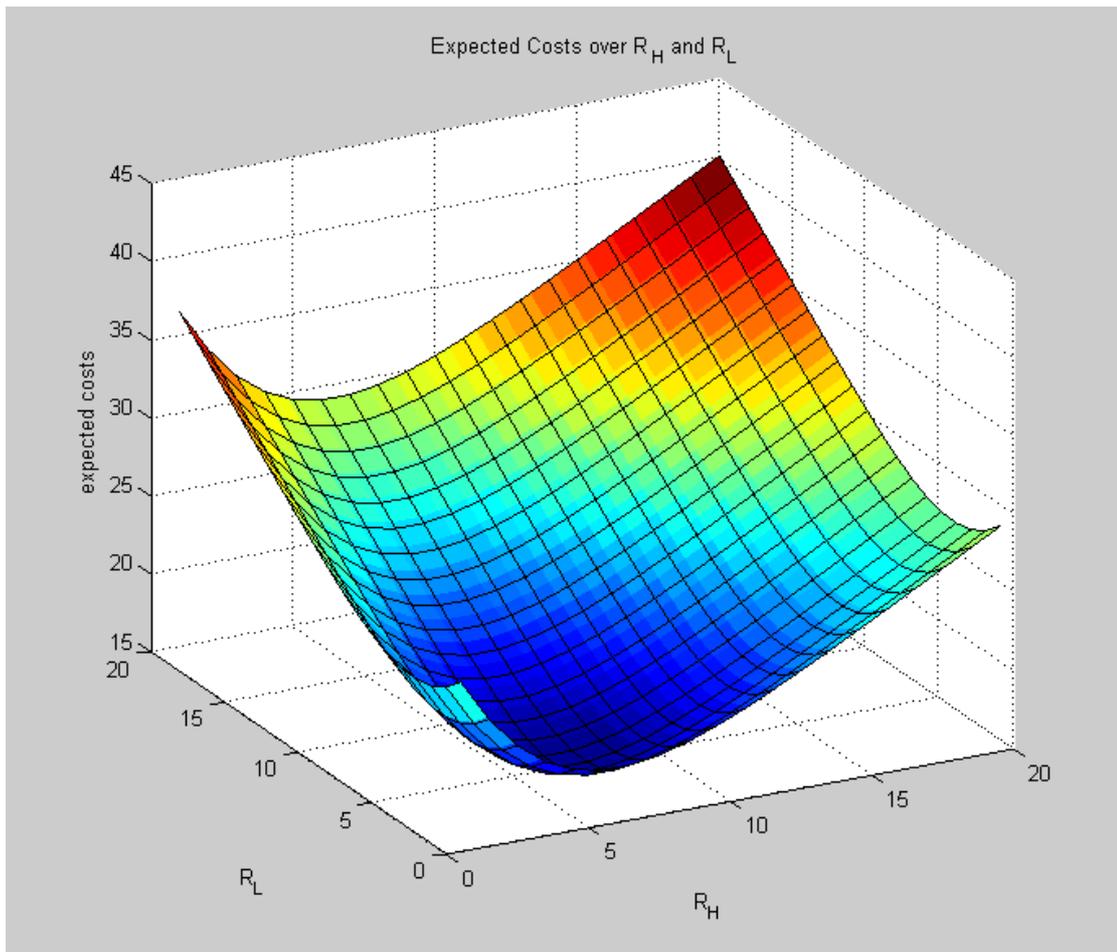
Figure 26: Expected costs over RL and RH

The following results were calculated with MATLAB:

- Optimal value for R_L = 4

- Optimal value for R_H = 6

- Minimum costs $E_{min\,costs,time\,t_0} = 15.95$

Figure 26 shows the expected costs for RL and RH from 0 to 20. It is not necessary to increase this range, because the result is already predictable. With a bigger range, the optimal values for R_L and R_H would be

still the same, because the expected price will increase due to higher reservation costs and the probability of occurrence decreases.

5.2.3 DIFFERENT SCENARIOS AT THE POSTERIOR POINT OF TIME

There are three different scenarios for the volume flexibility. These scenarios occur at both, the symmetrical and the asymmetrical volume flexibility. Following these scenarios are mentioned:

1. At time t_1 the optimal order quantity x_1^* is below the fixed flexibility range.

2. At time t_1 the optimal order quantity x_1^* is in the range of the volume flexibility, which can be used at time t_2.

3. At time t_1 the optimal order quantity x_1^* is higher than the maximum order quantity.

Following, these three scenarios are explained in detail.

Case 1:

In this case, the optimal order quantity at time t_1 is lower than the reserved capacity. Hence, the ordered quantity x_1 must be higher than the optimal order quantity x_1^*:

$$x_1 > x_1^*$$

Or in other terms, if variant flexibility is included:

$$x_{1i,\Sigma} > x_{1i,\Sigma}^*$$

To suffer the slightest damage, the ordered quantity at time t_1 should be at the lower limit over all vehicle types j, which was fixed prior:

$$x_{1i,\Sigma} = R_{m,i,\Sigma} - \Delta R_{i,\Sigma} = x_0 \qquad (5.15)$$

Or for the asymmetrical volume flexibility:

$$x_{1i,\Sigma} = R_{m,i,\Sigma} - R_{L,i,\Sigma} \qquad (5.16)$$

This means that the following excess capacity is expected at time t_1:

$$E_{\text{excess capa},t_1} = x_0 - x_1^* \qquad (5.17)$$

Thus, the expected costs for excess capacity can be calculated as follows:

$$E_{\text{costs,time } t_1} = E_{\text{excess capa},t_1} \cdot c_e = (x_0 - x_1^*) \cdot c_e \qquad (5.18)$$

Case 2:

Here the ordered quantity x_1 can be as high as the optimal order quantity x_1^*, since x_1^* is in the range of the volume flexibility:

$$R_{m,i,\Sigma} - \Delta R_{i,\Sigma} \le x_{1i,\Sigma} \le R_{m,i,\Sigma} + \Delta R_{i,\Sigma}$$

Or for the asymmetrical volume flexibility:

$$R_{m,i,\Sigma} - R_{L,i,\Sigma} \le x_{1i,\Sigma} \le R_{m,i,\Sigma} + R_{H,i,\Sigma}$$

This case is a little bit more complicated. Furthermore, it is not possible to calculate the expected costs yet. The optimal order quantity x_1^* is not always the mean demand at time t_1. For different overage and underage costs, it makes sense to adjust this order quantity accordingly. Thus, there is a separate subchapter 5.5 on finding the optimal order quantity x_1^* and to calculate the expected costs for case 2.

Case 3:

In this case, the optimal order quantity is higher than the maximum available capacity. Reversely to case 1, the ordered quantity x_1 must be lower than the optimal order quantity x_1^*.

$$x_{1i,\Sigma} > x_{1i,\Sigma}^*$$

Similar to case 1, the ordered quantity should be at the upper limit over all vehicle types j, which was fixed prior:

$$x_{1i,\Sigma} = R_{m,i,\Sigma} + \Delta R_{i,\Sigma} \tag{5.19}$$

Or for the asymmetrical volume flexibility:

$$x_{1i,\Sigma} = R_{m,i,\Sigma} + R_{H,i,\Sigma} \tag{5.20}$$

This means that at time t_1 shortages have to be expected at time t_2. The expected shortages are the optimal order quantity at time t_1 minus the maximum order quantity:

$$E_{shortages,t_1} = x_1^* - \left(R_{m,i,\Sigma} + \Delta R_{i,\Sigma} \right) \tag{5.21}$$

Thus, the expected costs for shortages can be calculated as follows:

$$E_{costs,time\ t_1} = E_{shortages,t_1} \cdot c_s = \left[x_1^* - \left(R_{m,i,\Sigma} + \Delta R_{i,\Sigma} \right) \right] \cdot c_s \tag{5.22}$$

Combination of case 1, case 2 and case 3:

In reality, only one of the above mentioned cases occurs, because the optimal order quantity x_1^* is known at time t_1. The quantity x_1^* is known from forecasts. This optimal order quantity is in one of the above mentioned ranges. Thus, only one of the three scenarios has to be calculated in reality.

5.3 BACKGROUND OF TIME FLEXIBILITY

As it was shown in section 3.3, there are three important flexibility types for OEMs in the SPV industry. Two of them were discussed in section 5.1 and 5.2. The third important flexibility type is time flexibility. The influence of time flexibility on the profit is discussed here.

Time flexibility is not only one of the three most important flexibility types in this work, it is also one of the most important SC performance measures of Chapter 6. Thus, time flexibility has to be considered in detail. One of the most important influences on time flexibility is the reliability of forecasts. In literature, it is usually enough to have one optimization factor to

express the reliability of forecasts. In this work it is not enough to have only one optimization factor, because two values of the probability distribution of the demand can change over time. One of these optimization factors is the mean θ and the other one is the standard deviation ω. The two optimization factors, which are related to time flexibility, were derived in subchapter 4.1.2. The change of the standard deviation ω is expressed with the forecast optimization factor α, whereas there are reliable forecasts at time t_1 where $\alpha = 0$ and unreliable forecasts with $\alpha \neq 0$. The change of the mean θ is expressed with the forecast optimization factor β. With regard to β, it is a reliable forecast if $\beta = 1$ and an unreliable forecast if $\beta \neq 1$. If a forecast is not reliable ($\alpha \neq 0$ or $\beta \neq 1$), there can be a very high time pressure on the SC organization and time flexibility becomes even more important.

To avoid a misunderstanding, it has to be mentioned that α and β are in fact only forecast optimization factors. This means that α and β describe the change of the lognormal distribution of ω_0 to ω_1 and of θ_0 to θ_1, as it was explained in section 4.1.2. If there is no change of the mean Θ and the standard deviation ω between t_0 and t_1, one can speak of a reliable forecast for this time period. Therefore, α and β are indicators for reliable and unreliable forecasts in this thesis. However, until time t_2 these factors do not show whether a forecast is absolutely reliable or unreliable, since the demand is not yet fixed at t_1. The forecast optimization factors describe the development between time t_0 and t_1. There could be still a change after time t_1. However, at t_1 the order quantities are fixed. Thus, the forecast is only relevant until time t_1. All changes after that time cannot be taken into account.

Considering the two optimization factors above, there are four different scenarios, which should be evaluated:

1. optimal case: $\alpha = 0$

2. suboptimal case: $\alpha \neq 0$

3. optimal case: $\beta = 1$

4. suboptimal case: $\beta \neq 1$

These four scenarios and the impact on the expected costs are discussed in the following:

1. Optimal case: $\alpha = 0$

The case of an absolutely reliable forecast at time t_1 is very rare, because there are too many uncertainties, as it was shown in section 3.2. Therefore it is of secondary importance to plan with this unlikely event in the SC optimization of the SPV industry. An optimization factor of $\alpha = 0$ is the best case. This means that there is no risk at the posterior point of time, because the forecast at this time is absolutely reliable. Much more realistic is the next case, where this forecast is not reliable.

2. Suboptimal case: $\alpha \neq 0$

To evaluate the development of the standard deviation, it would be for example possible, to calculate the 95% confidence interval for different cases. However, the focus of this work is on expected costs. Therefore, it is necessary to find out how the expected costs can be calculated at time t_1 for different developments of the standard deviation.

It was already explained, that α is usually between 0 and 1. The

optimization factor α is defined as ω_1 divided by ω_0. This is also the

relationship with time flexibility, because time flexibility affects ω_0 and ω_1. In

this work, time flexibility is realized by fixing two order points. It can be

assumed that the closer the order point is at time t_2, the smaller the standard

deviation of the demand forecast. There are two conclusions, resulting from

this fact: First, ω_1 is smaller than ω_0. Second, a long time period between ω_0

and ω_1 is favorable.

The following graphs give a good impression about the effect of a

changing standard deviation. Both curves have the same mean, but the

difference of the curves is very significant. The green curve has a standard

deviation of 1.6 and the blue curve has a standard deviation of 1.1.
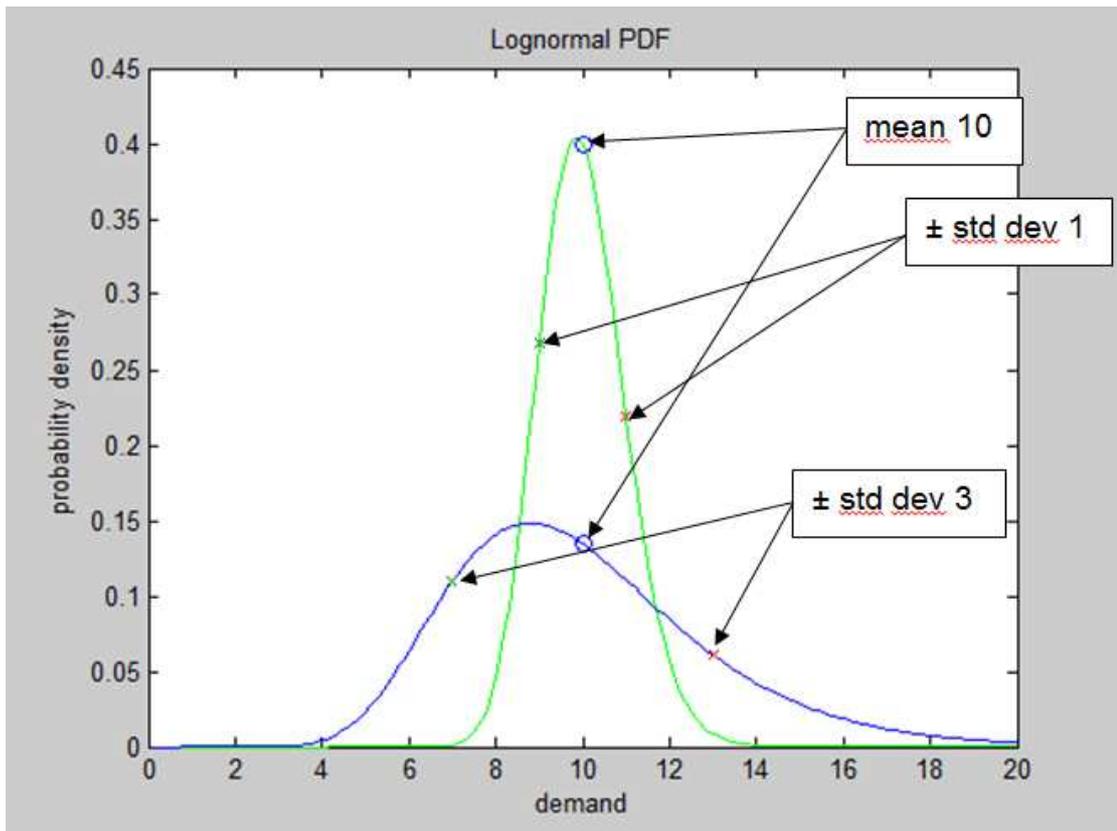
Figure 27: Lognormal distributions with different standard deviations (Appendix I)

The savings due to a smaller standard deviation in context of time flexibility can be expressed with the following simple equation:

$$E_{\text{savings,std dev}} = E_{\text{costs,time } t_0} - E_{\text{costs,time } t_1} \qquad (5.23)$$

The expected costs at time t_0, $E_{costs,time\ t_0}$ have to be calculated with the results of the forecast at time t_0. The expected costs at time t_1, $E_{\text{costs,time } t_1}$ have to be calculated with the results of the forecast at time t_1. Thus, the expected costs have to be calculated for these points of time, without

considering volume and time flexibility. A method to calculate the expected

costs without considering these two flexibility types is also necessary to

determine the optimal order quantity at the posterior point of time. A method

for this calculation is described in subchapter 5.5 and can be now used to

calculate $E_{costs,time\ t_0}$ and $E_{costs,time\ t_1}$. With the findings of subchapter 5.5, the

equation above can be written as follows:

$$E_{savings,std\ dev} = [c_e \cdot \int_{D=0}^{x_0}(x_0 - D)\frac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}}\ dD + c_s \cdot \tag{5.24}$$

$$\int_{D=x_0}^{\infty}(D - x_0)\frac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}}\ dD] - [\ c_e \cdot$$

$$\int_{D=0}^{x_1}(x_1 - D)\frac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}\ dD + c_s \cdot$$

$$\int_{D=x_1}^{\infty}(D - x_1)\frac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}\ dD]$$

This equation is very theoretical. It assumes that a certain quantity is

ordered at time t_1 instead of time t_0. However, the type of time flexibility, which

is derived in this work, is closely linked with volume flexibility. Therefore, the

order quantity is not shifted from time t_0 to time t_1. It is rather divided into an

order quantity for these two points of time. Nevertheless, if only time flexibility

is considered, there is a benefit correlated to the standard deviation, which

can be calculated with the equation above. The expected savings, if all other

flexibility types of this thesis are also included, are considered in subchapter

5.7.

3. Optimal case: $\beta = 1$

The optimization factor is calculated by $\frac{\theta_1}{\theta_0}$. If $\beta = 1$, the mean remains the same between t_0 and t_1. This case is very rare. If the optimization factor β is 1 and there is no change of the standard deviation, there is no benefit due to time flexibility. Therefore, the benefit or expected costs are not calculated for this case.

4. Suboptimal case: $\beta \neq 1$

In this case, a shift of the mean takes place. Thus, β can be every positive value. The closer β is at 1, the smaller the deviation of the mean. Furthermore, β indicates the position of θ_0 to θ_1. If β is smaller than 1, θ_1 is left of θ_0. If β is higher than 1, it is the other way around. The following graph shows an example, where the standard deviation is equal for both graphs. The obvious difference only results from the different mean of these distributions. The change of this mean is described with β.
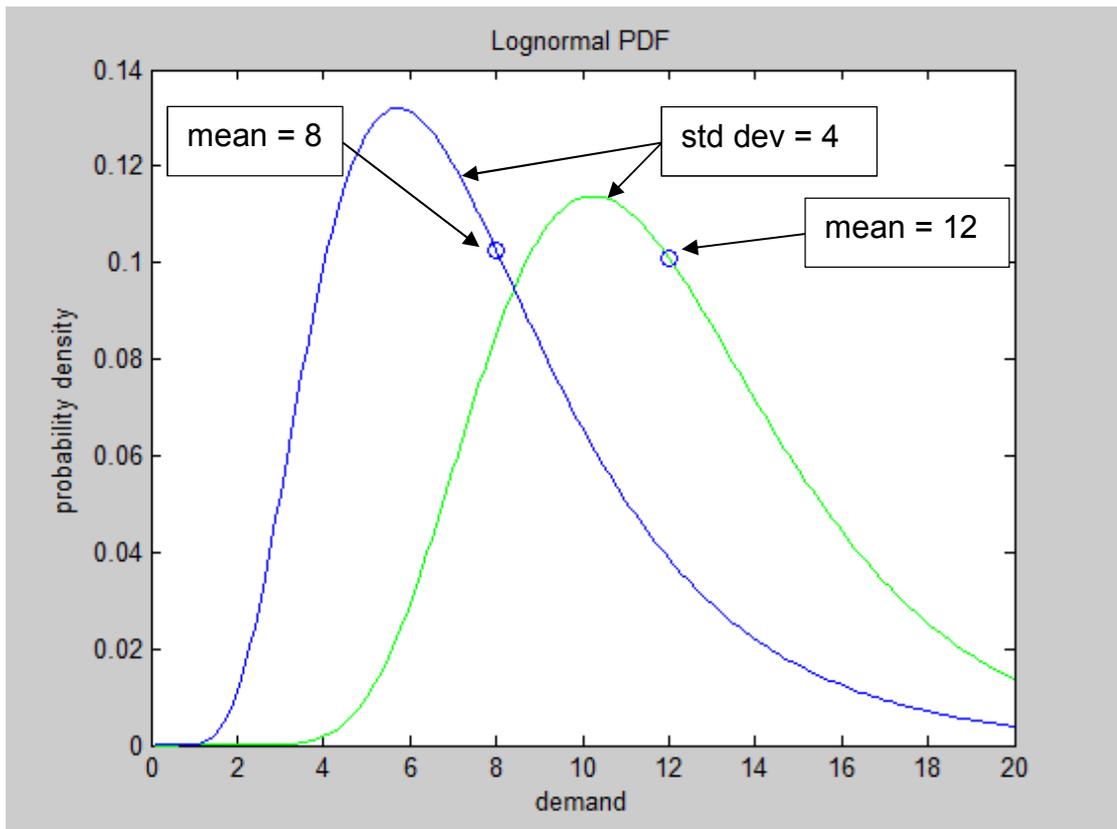
Figure 28: Lognormal distributions with different mean values (Appendix J)

Following, the savings due to time flexibility for the general case $\beta \neq 1$ are calculated. Here, this is done for the case with no variant and volume flexibility as well as no change of the standard deviation between time t_0 and time t_1. Therefore it is assumed that at time t_1, the actual demand is θ_1. In contrast to this, θ_0 is the wrong mean, which was derived at time t_0. The standard deviations ω_0 and ω_1 are identical. If θ_1 is smaller than θ_0, it is likely that too many parts are ordered at time t_1. Thus, this excess capacity has to be multiplied with the costs for excess capacity c_e:

$$E_{costs,excess} = c_e \cdot (\theta_0 - \theta_1) \tag{5.25}$$

If θ_1 is higher than θ_0, it is likely that too less parts are ordered at time t_1 and the expected costs can be calculated with the following equation:

$$E_{costs,shortages} = c_s(\theta_1 - \theta_0) \tag{5.26}$$

Summing up, the expected costs can be calculated as follows:

$$E_{costs,mean} = \begin{cases} c_e(\theta_0 - \theta_1) & \text{for } \theta_0 > \theta_1 \\ c_s(\theta_1 - \theta_0) & \text{for } \theta_0 < \theta_1 \end{cases} \tag{5.27}$$

These are the expected costs, if the wrong quantity is ordered. However, this can be also considered as savings, if the right quantity is ordered due to time flexibility. Therefore, the expected savings are calculated identically:

$$E_{savings,mean} = \begin{cases} c_e(\theta_0 - \theta_1) & \text{for } \theta_0 > \theta_1 \\ c_s(\theta_1 - \theta_0) & \text{for } \theta_0 < \theta_1 \end{cases} \tag{5.28}$$

Above, the four scenarios, which are influenced by time flexibility, were discussed. As a result, it is important to know how these variables can be influenced by time flexibility. There are two conditions, which lead to significant effects of time flexibility on the expected costs. First, the prior point of time should be fixed plausibly. The ordered quantity should be as high as possible, provided that the derived calculations of optimal order quantities had been considered. Second, the prior point of time should be as close to the

posterior point of time as possible. This way, the standard deviation is at a minimum and changes of the mean are unlikely after t_1.

5.4 SUBOPTIMAL ORDER SCENARIOS

Especially in the SPV industry it is often not possible to get the desired quantity of every article at the time when it is needed. As already explained, there could be for example exceptions, where X_0 is not equal to $R_m - \Delta R$ or $R_m - R_L$. This is for example the case, if it is for any reason not possible for a company to buy the quantity $R_m - \Delta R$ or $R_m - R_L$ of an article at time t_0. Therefore, this case is called suboptimal scenario in the following. Another suboptimal scenario would be the case where it is not possible to reserve the desired free capacity or to reserve only a reduced capacity for the posterior point of time.

Both cases do not affect the considerations of the variant flexibility directly. Apart from the indirect influence on variant flexibility, there is a big impact on volume and time flexibility. Here, the two mentioned cases have to be viewed separately.

In the first case, where it is not possible to order the optimal quantity at the prior point of time, it is likely that free capacity for the volume flexibility cannot be reserved, too. Therefore, volume and time flexibility has to be skipped completely in this unlikely event. The only reasonable thing is to order the maximum possible quantity, to get as close to the optimal scenario as possible.

In the second case, where it is not possible to reserve the optimal quantity ΔR or R_L and R_H, the goal is to reserve as much capacity as possible, to come close to the optimal capacity range. With some small changes, it is even still possible to calculate the expected costs with the derived formulas of this chapter. The main difference is only to adjust the mean capacity option R_m, because it is not possible to equate R_m with the mean demand Θ_0, as it was always done in this chapter.

Consequently, the derived methods of this thesis should be also considered for suboptimal order scenarios. Even if it is not possible to implement the three flexibility types in an optimum manner, the optimal planning and procedure of this thesis should be always used as guideline. If suboptimal order scenarios are sometimes unavoidable, it is still the goal to implement the derived methods as far as possible.

5.5 ORDER QUANTITY AT THE POSTERIOR POINT OF TIME

In section 5.2 the background of volume flexibility was discussed. It was mentioned that it can be advantageous to fix an asymmetrical volume flexibility at time t_0. This means that the flexibility range is defined by $R_m - R_L$ and $R_m + R_H$ instead of $R_m \pm \Delta R$. The main reasons for the asymmetrical range are different overage and underage costs. For the same reason, the order quantity at the posterior point of time t_1 should be also not same high as the expected demand θ_1. Following this will be discussed in detail.

Finally, at time t_1 it is necessary to determine the order quantity x_1. The most obvious thing is to analyze the lognormal demand distribution at time t_1 and to equate the mean θ_1 with the order quantity x_1. However, this can be disadvantageous if there are different underage and overage costs. Therefore it is necessary to find out how far the order quantity x_1 should be shifted away from the mean θ_1. However, it will be shown now that it can be better to have an order quantity different to θ_1. The volume flexibility could be for example allocated as follows:
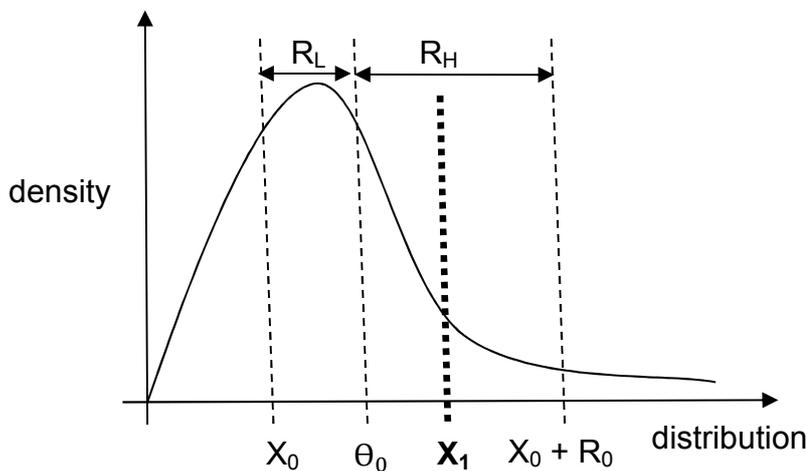
Figure 29: Lognormal distribution with order quantity X_1 at time t_1

There is also another reason, why it could be necessary that x_1 is not equal to θ_1. It is likely that the optimal order quantity x_1 cannot be ordered if x_1 is not in the flexibility range $R_m \pm \Delta R$ or $R_m - R_L$ and $R_m + R_H$. If the asymmetrical volume flexibility is used at time t_0, there is a higher risk that the expected demand at time t_1 is not in the flexibility range. Later it will be derived mathematically what the value x_1 should be instead and in which

direction and how far x_1 should be shifted away from θ_1. With the following

method, x_1 is shifted in the direction, where R_H or R_L is bigger, because both

calculations consider the overage and underage costs.

The idea of separating the order quantity x_1 from the mean θ_1 and how

this value is calculated will be explained in the following.

In section 4.1.1 the following equation for the expected costs was

derived for time t_0:

$$E_{costs, time\ t_0} = c_e E_{excess\ capa} + c_s E_{shortages}$$

Now the costs for the expected excess capacity and the costs for the

expected shortages are again expressed mathematically.

To calculate the costs for the expected excess capacity, the cost for

one excess unit c_e has to be multiplied with the probability for the occurring

demand f(D) and with the number of excess units $(x_1 - D)$. This has to be

calculated for every possible order quantity from D to x_1. Therefore the

integral from D to x_1 is needed. This logical approach can be expressed

mathematically as follows:

$$E_{costs, excess\ capa, t_1} = c_e \cdot \int_{D=0}^{x_1} (x_1 - D)f(D)dD \tag{5.29}$$

Equivalent to this, the expected costs for the shortages can be

calculated as follows:

$$E_{costs,shortages,t_1} = c_s \cdot \int_{D=x_1}^{\infty} (D - x_1)f(D)dD \qquad (5.30)$$

Thus, the expected costs for the excess capacity and the shortages can be added as follows:

$$E_{costs,time\ t_1} = c_e \cdot \int_{D=0}^{x_1} (x_1 - D)f(D)dD + c_s \cdot \int_{D=x_1}^{\infty} (D - x_1)f(D)dD \qquad (5.31)$$

In the equation above, $f(D)$ is again the density function. This distribution was already used in subchapter 5.2.2 and can be expressed as follows (Montgomery, & Runger, 2010):

$$f(D) = \frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}$$

Now, the equation for the expected costs can be rewritten to:

$$E_{costs,time\ t_1} = c_e \cdot \int_{D=0}^{x_1} (x_1 - D)\frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}} dD + c_s \qquad (5.32)$$
$$\cdot \int_{D=x_1}^{\infty} (D - x_1)\frac{1}{D \cdot \sigma_1 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}} dD$$

The above equation only reflects the costs, if no flexibility method is used. Therefore, it also does not include the reservation costs as in the equation of subchapter 5.2.1. This is exactly what should to be used at time t_1,

because at this point of time it is too late to use one of the three flexibility methods of this work again.

For demonstration, equation 5.32 is visualized in Figure 30. Therefore, the following variables were entered:

- mean demand $\theta_1 = 10$

- standard deviation of the demand: $\omega_1 = 3$

- overage costs $c_e = 1$

- underage costs $c_s = 10$

The overage costs are usually lower than the underage costs. Overage costs accrue, if too many parts are ordered, which leads mainly to increased inventory or salvage costs. Conversely, the underage costs are the costs of ordering too less. The consequence could be dissatisfied customers, which is much more expensive in the long term.

The MATLAB script for the graph below is attached in Appendix K.
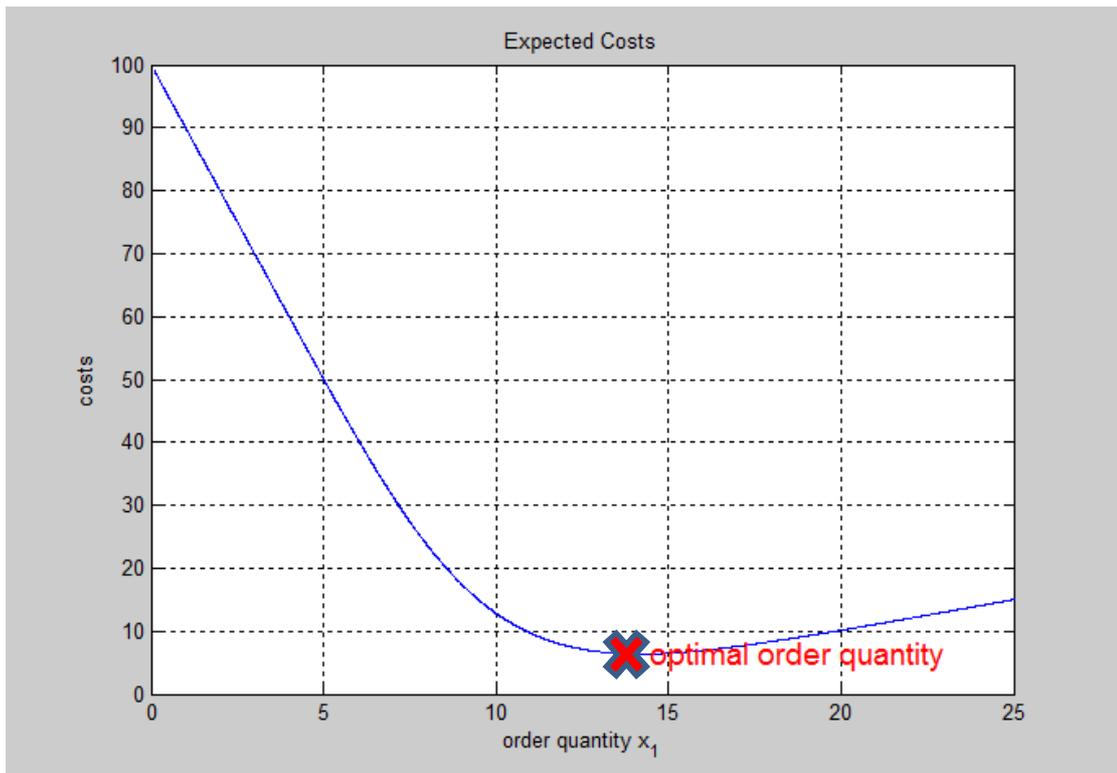
Figure 30: Expected costs at time t_1 for different order quantities x_1

Equation 5.34 shows a relationship between the expected costs, different overage and underage costs and the order quantity x_1.

Using this equation, the optimal order quantity x_0^* is set by the first derivative:

$$\frac{dE(C_1)}{dx_1} = 0 \qquad (5.33)$$

It would be very burdensome to calculate the first derivative of equation 5.32. Therefore, the optimal order quantity and the minimum costs are

calculated as shown in Appendix K. For the example above, with $\omega_1 = 3$, $c_e = 1$, $c_s = 10$ and $\Theta_1 = 10$ the following results were achieved by using Matlab:

- optimal order quantity $x_1^* = 14$

- minimum expected costs $E_{\min \text{costs,time } t_1} = 6.3741$

This means that although the mean is 10, it is more profitable to order 14 parts instead of 10 parts at time t_1 instead.

For the sake of completeness, the purchasing costs and the selling price have to be considered in equation 5.32, too. A higher order quantity leads to higher purchasing costs and to a higher sales volume or Return on Sales (ROS). These influences could affect the optimal order quantity.

5.6 PERFORMANCE EVALUATION OF EACH SIGNIFICANT FLEXIBILITY METHOD

In this subchapter, the performance evaluation is split up in the different flexibility methods. Afterwards, the benefits are shown, if all performance methods are considered.

5.6.1 PE OF VARIANT FLEXIBILITY

It was shown in this subchapter 5.1, that variant flexibility is very profitable. The expected costs for an example without variant flexibility were calculated and had been 11.93. The expected costs for the same example, but with variant flexibility had been 6.90. Thus, savings of about 42% were realized in this example. These savings are very high, because they are related to the expected costs. Compared to the overall costs, these savings would be lower. It is obvious that variant flexibility is very profitable.

5.6.2 PE OF VOLUME FLEXIBILITY

In chapter 5.2, two different types of volume flexibility were derived, which are the symmetrical and the asymmetrical volume flexibility. To get a better feeling for these flexibility types, realistic values have been used to calculate the expected costs for both cases. Theoretically, the flexibility range ΔR could be extremely high, if the reservation costs are very low. In this case, there would be almost no risk of overage and underage costs. In reality, this is not possible, because negative values could occur. Therefore, ΔR should be for example lower than θ_0 for a symmetrical flexibility range. Furthermore, the reservation costs would be too high in most cases.

For the calculation of a symmetrical flexibility range, the following variables were used in subchapter 5.2.1:

- mean of the demand: $\theta_0 = 100$

- standard deviation of the demand: $\omega_0 = 5$

- overage costs $c_e = 5$

- underage costs $c_s = 10$

- reservation costs $c_R = 1$

For these variables, the following expected costs were calculated:

$$E_{\text{costs,time } t_0} = 16.3475$$

For the calculation of an asymmetrical flexibility range, the same variables were used as for the symmetrical flexibility range.

- mean of the demand: $\theta_0 = 100$

- standard deviation of the demand: $\omega_0 = 5$

- overage costs $c_e = 5$

- underage costs $c_s = 10$

- reservation costs $c_R = 1$

For these variables, the following expected minimum costs were calculated:

$$E_{\text{min costs,time } t_0} = 15.9473$$

To get a value for comparison, the expected costs have to be calculated now, if no volume flexibility is used. In this case, there would be no flexibility range and no reserved capacity at the posterior point of time. Thus, it is only possible to order at the prior point of time under the conditions of the forecast at t_0. Thus, the equation for the expected costs can be expressed as follows:

$$E_{costs,time\ t_0} = c_e \cdot \int_{D=0}^{\theta_0} (\theta_0 - D) \frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}} dD + c_s \qquad (5.34)$$

$$\cdot \int_{D=\theta_0}^{\infty} (D - \theta_0) \frac{1}{D \cdot \sigma_0 \cdot \sqrt{2\pi}} e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}} dD$$

With MATLAB, the following result was calculated for the same variables, but without volume flexibility (Appendix L):

$$E_{costs,time\ t_0} = 29.8989$$

Now, three comparisons have to be made:

1. No volume flexibility vs. symmetrical flexibility

2. No volume flexibility vs. asymmetrical flexibility

3. Symmetrical flexibility vs. asymmetrical flexibility

For comparison, the calculated results have been used to calculate the improvements. The following table helps to evaluate the flexibility types.

Table 9: Comparison of flexibility types

	No volume flexibility	symmetrical flexibility	asymmetrical flexibility
expected costs	29.8989	16.3475	15.9473
saving compared to "no volume flexibility"	0	45%	47%

Looking at the table above, it becomes obvious that both, symmetrical and asymmetrical volume flexibility is very profitable. The flexibility types lead

to 45% and 47% savings in this example. It is necessary, to consider that these savings are again related to the expected costs, not to the overall costs. The overall costs are not part of the calculations, because the, mentioned savings are sufficient for the evaluation of this flexibility type. Furthermore, uncertain variables are avoided, such as the purchasing costs. These costs would have to be assumed and could distort the result unnecessarily. Thus, the results of Table 9 are appropriate. Unexpected are for example the savings of the symmetrical flexibility compared to the asymmetrical volume flexibility. The difference in this example is relatively low. The asymmetrical flexibility becomes more efficient compared to the symmetrical, if the overage costs c_e and the underage costs c_s differ more significantly. Nevertheless, the asymmetrical flexibility should be preferred, because the effort to implement this flexibility type is same high as to implement symmetrical flexibility.

Now, the following conclusions can be drawn:

1. For both cases, the benefit is very high. It is worth to implement volume flexibility.

2. It is better to implement the asymmetrical volume flexibility, instead of the symmetrical volume flexibility. The difference is not big, but still existing.

5.6.3 PE OF TIME FLEXIBILITY

In some special cases, there is no improvement of the demand forecast between t_0 and t_1. This means that there is no positive change of the standard deviation between t_0 and t_1 and that the mean remains the same. In this case,

there is no benefit due to time flexibility. Therefore it is possible to order at time t_0 under the same conditions as at time t_1. There could be even disadvantages due to time flexibility, because the provision of time flexibility could be associated with costs. Ordering at an early stage could make savings possible. However, this case is relatively rare, as it was already explained in subchapter 5.3. In reality, time flexibility is usually positive in terms of SC planning. In the following, the positive influence of time flexibility is evaluated. To get a feeling for the performance of time flexibility, a case is evaluated, where $\alpha \neq 0$ and $\beta \neq 1$. In subchapter 5.3 it was already explained, how expected savings can be calculated for both effects of time flexibility.

For the performance evaluation, the expected costs at time t_0 are calculated. After that, the expected costs at time t_1 are calculated. Furthermore, the additional costs due to the higher mean at time t_0 are calculated.

$$I_{performance} = \frac{E_{costs,std\ dev,1}}{E_{costs,std\ dev,0} + E_{costs,mean}} =$$

$$\frac{[c_e \cdot \int_{D=0}^{x_1}(x_1-D)\frac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}\ dD + c_s \cdot \int_{D=x_1}^{\infty}(D-x_1)\frac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_1)^2}{2\sigma_1^2}}\ dD]}{\left([c_e \cdot \int_{D=0}^{x_0}(x_0-D)\frac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}}\ dD + c_s \cdot \int_{D=x_0}^{\infty}(D-x_0)\frac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}}e^{-\frac{(\ln D - \mu_0)^2}{2\sigma_0^2}}\ dD]\right) + \left(\begin{cases} c_e(\theta_0-\theta_1) & \text{for } \theta_0>\theta_1 \\ c_s(\theta_1-\theta_0) & \text{for } \theta_0<\theta_1 \end{cases}\right)}$$

For this example, the following variables are used for the equation above:

$\theta_0 = x_0 = 100$; $\theta_1 = x_1 = 120$;

$\omega_0 = 7$; $\omega_1 = 5$;

$c_e = 5$; $c_s = 1.5$;

Thus, $\alpha = \frac{\omega_1}{\omega_0} = 0.71$ and $\beta = \frac{\theta_1}{\theta_0} = 1.2$

With MATLAB (Appendix M) a performance indicator of 42.19% was calculated. This means that due to time flexibility, the costs in this context and for this example decrease by 42.19%.

This result would be different for other input variables. In reality, the expected costs could be different to the result calculated above. If α ≠ 0 and β ≠ 1, there is a high risk that the order quantity x_1 is not in the range of the volume flexibility. If all flexibility types are used, the flexibility range has to be considered, too.

However, the result of 42.19% is representative for the savings if only time flexibility is considered. Therefore, it is possible to conclude that time flexibility is obviously cost-efficient.

5.6.4 PE AT THE POSTERIOR POINT OF TIME

There are two possibilities to define the order quantity at time t_1:

Method 1: The most obvious thing at time t_1 is to analyze the lognormal demand distribution and to equate the mean θ_1 with the order quantity x_1. However, this way would not consider different underage and overage costs.

Method 2: The second possibility, which was derived in subchapter 5.5, should be much better from an economic point of view. In this subchapter, the order quantity x_1 is shifted away from the mean θ_1.

For the performance evaluation of the method in subchapter 5.5, the expected costs for the two above mentioned order quantities have to be

compared. Therefore, realistic values are used again. For this comparison, the values of subchapter 5.5 are taken.

First of all, the expected costs for method 1 are calculated. Therefore, the order quantity x_1 is set equal to the mean θ_1. The expected costs at the posterior point of time $E_{time\ 1}$ were calculated with MATLAB (Appendix N):

$$E_{time\ 1}(C_1, x_1 = \theta_1) = 12.83$$

The costs for method 2 have been already calculated in subchapter 5.5:

$$E_{time1}(C_1, x_1^*) = 6.3741$$

Thus, there is a difference and financial benefit of:

$$E_{time\ 1} - E_{time\ 2} = 6.46$$

Hence, in this case method 2 is about 50% better compared to method 1. Such a high benefit was expected, because different underage and overage costs are considered in method two.

5.7 PERFORMANCE EVALUATION OF COMBINED FLEXIBILITY METHODS

In the previous sections, the three most important flexibility types were discussed in detail. Additionally a method to find the optimal order quantity at the posterior point of time was shown. In the following, all these methods are combined to enable a PE that demonstrates the overall profitability. For this

PE, all costs are compared for two different scenarios. One scenario is the implementation of all flexibility types. The other one deals with the expected profit if none of the flexibility types is considered.

To evaluate the combination of the flexibility methods, it is not possible to rely only on the results of chapter 5.6, where the performance of each method was investigated separately. It is necessary to consider the relations between the different methods. For example the effectiveness of time flexibility depends on the determination of the order quantity due to volume flexibility. Therefore all flexibility types are considered together in the following.

There is also another difference compared to the performance evaluations of the previous subchapters. By implementing all costs, it is now possible to evaluate the overall savings. In contrast to this, the evaluation of the single flexibility methods in the previous subchapters had been carried out by calculating the savings related to the expected cost and the reservation costs. Other influences have not been considered, because it was enough for the PE of the individual flexibility types. In this subchapter more influences are considered, to enable a comprehensive PE. Furthermore, all the costs from t_0 to t_1 are considered in the following. The time between t_1 and t_2 is not considered in both cases. Whether with or without flexibility methods it is not possible to adapt to influences caused by a changing demand in this time period.

For this PE, the following scenario is calculated:

- 3 different vehicle types

- mean demand at time 0 for vehicle 1: $\Theta_{0,1} = 50$

- mean demand at time 0 for vehicle 2: $\Theta_{0,2} = 100$

- mean demand at time 0 for vehicle 3: $\Theta_{0,3} = 150$

- mean demand at time 1 for vehicle 1: $\Theta_{1,1} = 60$

- mean demand at time 1 for vehicle 2: $\Theta_{1,2} = 110$

- mean demand at time 1 for vehicle 3: $\Theta_{1,3} = 160$

- standard deviation at time 0 for vehicle 1: $\omega_{0,1} = 2$

- standard deviation at time 0 for vehicle 2: $\omega_{0,2} = 4$

- standard deviation at time 0 for vehicle 3: $\omega_{0,3} = 6$

- standard deviation at time 1 for vehicle 1: $\omega_{1,1} = 1$

- standard deviation at time 1 for vehicle 2: $\omega_{1,2} = 2$

- standard deviation at time 1 for vehicle 3: $\omega_{1,3} = 3$

- overage costs $c_e = 5$

- underage costs $c_s = 3$

- reservation costs $c_R = 1$

- purchasing costs per part $p = 1$

As already mentioned, two scenarios are compared for the PE. First, the costs are added, if all flexibility types are implemented. These are the following costs:

- purchasing costs at time t_0, $C_{p,0}$

- reservation costs at timte t_0, C_{res}

- purchasing costs at time t_0, $C_{p,1}$

- expected costs at time t_1, $E_{costs, time\ t_1}$

Afterwards, the costs are added up for the case if no flexibility type is used:

- purchasing costs at time t_0, $C_{p,0}$

- expected costs at time t_0, $E_{costs, time\ t_0}$

- overage costs C_{ov} or underage costs C_{un}

These costs of scenario one and two are compared in the end.

To start with the first scenario, the optimal order quantity at time t_0 and the asymmetrical flexibility range have to be calculated. This is done according to subchapter 5.1 as follows:

Table 10: Overall standard deviation

	std dev for vehicle 1	std dev for vehicle 2	std dev for vehicle 3	$\sqrt{\sum_i \omega_{t,i}^2}$
time 0	2	4	6	7.4833
time 1	1	2	3	3.7417

Table 11: Overall mean

	mean for vehicle 1	mean for vehicle 2	mean for vehicle 3	$\sum_i \theta_{t,i}$
time 0	50	100	150	300
time 1	60	110	160	330

For the volume flexibility, the asymmetrical flexibility is used, because it was shown before, that this flexibility type is more profitable than the symmetrical flexibility. The flexibility range with R_L and R_H is now calculated according to subchapter 5.2.2:
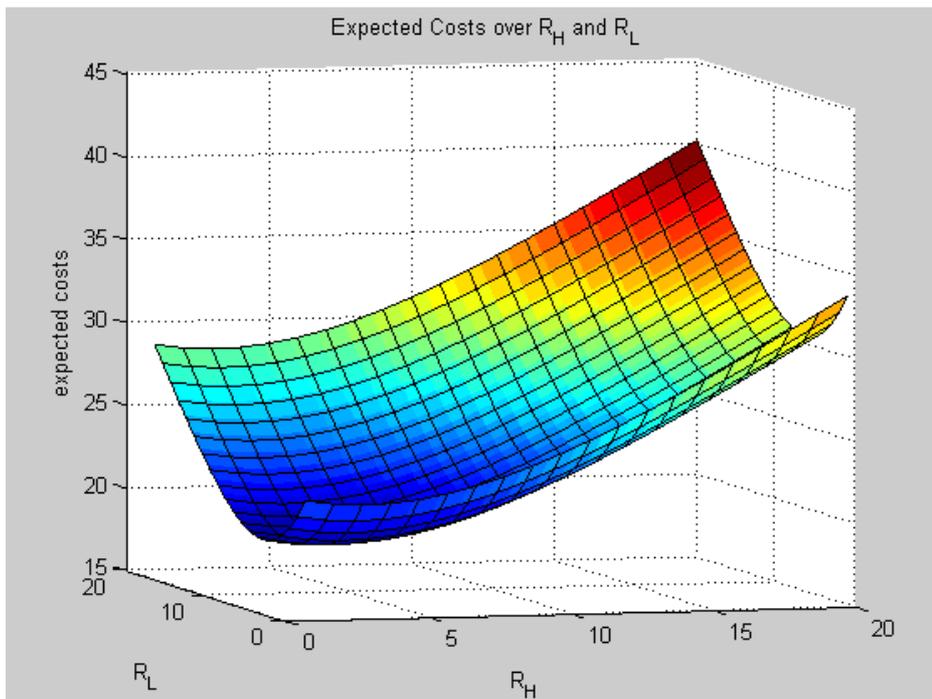
Figure 31: Optimal flexibility ranges (Appendix O)

- Optimal value for R_L = 6
- Optimal value for R_H = 3

Now, the reservation costs can be calculated:

$$C_{res} = c_R \cdot (R_L + R_H) = 9$$

The optimal order quantity at time t_0 is:

$$x_0^* = \left(\textstyle\sum_i \theta_{t,i}\right) - R_L = 294$$

The purchasing costs at time t_0 are:

$$C_{p,0} = p \cdot x_0^* = 294$$

The optimal order quantity at time t_1 is calculated according to subchapter 5.5 (Appendix P):

$$x_1^* = 329$$

The flexibility range is from 288 to 297. Thus, the complete ordered quantity at t_1, which is 329, is in the flexibility range. Therefore, no costs for being out of the asymmetrical flexibility range are expected.

Figure 32: Optimal order quantity at time t_1 (Appendix P)

Some parts had been already ordered at time t_0. Thus, the additional parts have to be ordered:

$$x^*_{1,additional} = x^*_1 - x^*_0 = 35$$

The purchasing costs at time t_1 are:

$$C_{p,1} = p \cdot x^*_{1,additional} = 35$$

The expected costs at time t_1 are calculated according to subchapter 5.5 and with the optimal order quantity x^*_1:

$$E_{costs,1} = 11.3478$$

If the above mentioned flexibility methods are used, the costs can be calculated as follows for this example:

$$C_{flex} = C_{res} + C_{p,0} + C_{p,1} + E_{costs,1} = 349$$

Now, the expected profit is derived for the case where none of the derived flexibility types is included. Therefore the expected costs are calculated for this inflexible case. This means that there is no volume flexibility, no variant flexibility and no time flexibility with the postponement strategy and thus all of the decisions have to be taken at time t_0. Furthermore, the optimal order quantity is not calculated at time t_0. Also, the difference between overage and underage costs at time t_1 is not considered here.

Now, every vehicle type is regarded individually. At time t_0, the mean demand of every vehicle type is ordered. In this scenario, there is no reservation capacity. Thus, it is not possible to implement more accurate

demand forecasts at a later point in time. Therefore, all the parts for t_2 have to be ordered based on the knowledge of t_0. Due to inaccurate forecasts, some more or less parts as expected are sometimes ordered. Since there is no logical approach, this decision is based on gut feelings and experience of the purchaser. In this example, the mean expected demand is ordered, since this is the most logical approach.

The prior point of time is the only order time. Thus, the expected costs at time t_0 for every vehicle type are as follows (Appendix Q):

$$E_{costs,0,1} = 6.3801$$

$$E_{costs,0,2} = 12.7602$$

$$E_{costs,0,3} = 19.1403$$

Also underage costs have to be considered, because we already know that there will be shortages of 30 units if strategy one is not used:

$$C_{un} = c_S * \left(\sum_i \theta_{1,i} - \sum_i \theta_{0,i} \right) = 90$$

The expected costs $C_{no\ flex}$ can be now calculated as follows:

$$C_{no\ flex} = p \cdot x_{0,1} + p \cdot x_{0,2} + p \cdot x_{0,3} + E_{costs,0,1} + E_{costs,0,2} + E_{costs,0,3} + C_{un}$$
$$= 428$$

If C_{flex} is compared with $C_{no\ flex}$, it can be seen that the costs for the approach without flexibility are about 79 higher. This means that the applied flexibility methods lead to savings of about 18%.

The calculated performance also depends on the probability distributions of the demands. The standard deviations for the demand could be much higher in reality. Furthermore, the implemented variables influence the calculated result. These facts and the calculated result of 18% show clearly that the derived flexibility methods are profitable and are highly recommended in supply chains of the SPV industry.

CHAPTER 6

SUMMARY AND OUTLOOK

6.1 CONCLUSIONS

In section 3.3 it was already shown that there are three main types of flexibility, which have to be considered and integrated when developing the supply chain for SPVs. These types of flexibility are: volume flexibility, variant flexibility and time flexibility. Additionally, a method was derived to calculate the optimal order quantity at time t_1. In Chapter 4, possibilities and methodical approaches were shown to integrate these types of flexibility in supply chains. For a better understanding, the following explanations demonstrate how the three flexibility types and the methodical approaches of Chapter 4 are correlated:

- Volume Flexibility: A capacity option R is fixed at the time t_0. This capacity option should be fixed for every single article. It is an order capacity, which can be used at the posterior point of time if necessary.

- Variant Flexibility: By considering the demand for the parts for all vehicles,

instead of focusing on only one vehicle type, synergy effects can be used, which lead to variant flexibility. This is possible with all same parts. The single quantities x_{1ij} for the same parts i of every vehicle j are added up:

$$\sum_{j=1}^{n} x_{1ij} \qquad \text{for all i}$$

Thus, volume flexibility can be used for parts of different vehicle types and the pooling effect leads to a higher flexibility - the variant flexibility.

- Time Flexibility: By introducing a new planning process with two planning times, namely the prior and posterior point of time, the forecast optimization factors α and β come up. These values describe the change of the demand forecast, which is more accurate at time t_1 than at t_0. Time flexibility helps to benefit form more accurate forecast values after t_0.

The performance evaluations of Chapter 5 have shown that there are some variables, which can be influenced by the SCM. These variables, which help to maximize the expected profit, are listed below:

- time between prior and posterior point of time or the forecast optimization factors α and β respectively
- the accuracy of forecast values at t_0 and t_1
- size of the capacity range R_0
- the order quantities x_0 and x_1
- the use of risk pooling effects

In this work several equations and formulas have been derived. Following are the resulting equations, which should be used to implement and evaluate the mentioned flexibility types:

Table 12: Most important equations of this work

application	equation
variant flexibility	$E_{costs,time\ t_0} =$ $c_e \cdot \left(\int_{D=0}^{\Sigma_j\,\theta_{0i,j}} [\Sigma_j\,\theta_{0i,j} - D] \cdot \dfrac{1}{D\cdot\sqrt{\Sigma_j\,\sigma_{0i,j}^2}\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\Sigma_j\,\mu_{0i,j})^2}{2\left(\sqrt{\Sigma_j\,\sigma_{0i,j}^2}\right)^2}}\, dD \right) + c_s \cdot$ $\left(\int_{D=\Sigma_j\,\theta_{0i,j}}^{\infty} [D - \Sigma_j\,\theta_{0i,j}] \cdot \dfrac{1}{D\cdot\sqrt{\Sigma_j\,\sigma_{0i,j}^2}\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\Sigma_j\,\mu_{0i,j})^2}{2\left(\sqrt{\Sigma_j\,\sigma_{0i,j}^2}\right)^2}}\, dD \right)$
symmetrical volume flexibility	$E_{costs,time\ t_0} = c_R \cdot 2\Delta R + c_e \cdot \int_{D=0}^{\theta_0 - \Delta R} [(\Theta_0 - \Delta R) - D] \cdot$ $\left(\dfrac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_0)^2}{2\sigma_0^2}} \right) dD + c_s \cdot \int_{D=(\Delta R + \theta_0)}^{\infty} [D - (\Theta_0 + \Delta R)] \cdot$ $\left(\dfrac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_0)^2}{2\sigma_0^2}} \right) dD$
asymmetrical volume flexibility	$E_{costs,time\ t_0} = c_R \cdot (R_L + R_H) + c_e \cdot \int_{D=0}^{\theta_0 - R_L} [(\Theta_0 - R_L) - D] \cdot$ $\left(\dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}} \right) dD + c_s \cdot \int_{D=(R_H + \theta_0)}^{\infty} [D - (\Theta_0 + R_H)] \cdot$ $\left(\dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}} \right) dD$
expected savings due to time flexibility	$E_{savings,std\ dev} = [c_e \cdot \int_{D=0}^{x_0} (x_0 - D) \dfrac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_0)^2}{2\sigma_0^2}}\, dD + c_s \cdot$ $\int_{D=x_0}^{\infty} (D - x_0) \dfrac{1}{D\cdot\sigma_0\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_0)^2}{2\sigma_0^2}}\, dD] - [\,c_e \cdot \int_{D=0}^{x_1} (x_1 -$ $D) \dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}}\, dD + c_s \cdot$ $\int_{D=x_1}^{\infty} (D - x_1) \dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}}\, dD] +$ $\begin{cases} c_e(\theta_0 - \theta_1) & \text{for } \theta_0 > \theta_1 \\ c_s(\theta_1 - \theta_0) & \text{for } \theta_0 < \theta_1 \end{cases}$
optimal order quantity at the posterior point of time	$E_{costs,time\ t_1} = c_e \cdot \int_{D=0}^{x_1} (x_1 - D) \dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}}\, dD + c_s \cdot$ $\int_{D=x_1}^{\infty} (D - x_1) \dfrac{1}{D\cdot\sigma_1\cdot\sqrt{2\pi}} e^{-\frac{(\ln D\,-\,\mu_1)^2}{2\sigma_1^2}}\, dD$
performance evaluation of combined flexibility methods	<u>costs with flexibility:</u> $C_{flex} = C_{res} + C_{p,0} + C_{p,1} + E_{costs,1}$ <u>costs without flexibility:</u> $C_{no\ flex} = p \cdot x_{0,1} + p \cdot x_{0,2} + p \cdot x_{0,3} + E_{costs,0,1} + E_{costs,0,2} +$ $E_{costs,0,3} + C_{un}$

To find the best approach for specific supply chains, some MATLAB scripts and functions have been modeled. These MATLAB codes help to use the derived formulas in real applications.

The MATLAB scripts and functions have been also used for the performance evaluation of the flexibility methods. A final and comprehensive evaluation was shown in chapter 5.7. This way it was possible to prove the high profitability of the derived flexibility methods.

6.2 RESEARCH CONTRIBUTIONS

It is not the goal of this work to develop a SC which can be incurred without modifications by all companies of the SPV industry. SCs of the SPV manufacturers are much too complex and extensive to develop an overall solution. For a SC optimization, it is important to analyze the complex structures of systems and processes. Therefore, this work can be seen as a red line which can be used as orientation guide if a direct transfer is not possible. A supply chain concept was generated, which is not only theoretically, but can be also used in reality. Companies of the SPV industry are able to set up their supply chain in the same way as it was shown in this thesis. Thus, the developed supply chain strategy of this thesis is a basic concept, which has to be adapted to the environment and continuously modified to guarantee an optimal, individual case suitable supply chain.

Therefore, decision makers should always draw emphasis on controlling the stability, reliability and flexibility of the SC.

The developed SC strategy is appropriate for the following three reasons:

1.   A SC is affected by a lot of factors. Especially SCs of the SPV industry are very complex and extensive. For this reason a certain degree of abstraction is necessary. This way it is possible to get the data as manageable as possible and to make the quantitative analyses controllable. Nevertheless, the assumptions of this work are close to reality and all relevant influences are considered.

2.   The biggest challenge when developing the SC for SPV manufacturers is the high demand for flexibility. Therefore an approach was shown in this thesis. It starts with background information of SPV industries, which helps to find the most appropriate flexibility methods. After that, strategies were developed to integrate these types of flexibility in the SC of SPVs. Finally, PEs were done to determine quantitatively the influence of these flexibility types on the performance of the SC.

3.   The supply chain strategy of this thesis is oriented to statistical estimators of flexibility as well as to potential savings, potential profit, potential loss or opportunity costs. Thus, it was possible to align the direction of the complete work to economic parameters which are same important for all companies. Hence, this work is consistent with the strategic goals of all Chief Executive Officers (CEOs).

The found strategy leads to the following properties of the supply chain:

1. time flexibility

2. volume flexibility

3. variant flexibility

4. fast reactivity

5. traceable

6. cost conscious

7. uniform and transparent along the value chain

There is also another outstanding characteristic of the developed supply chain strategy, because it is not only different to the conventional automotive industry and other industry types, but also to strategies which are used by SPV manufacturers up to now. There are no common strategies for SPV manufacturers known, which are based on two different times of planning as it is intended in this thesis. Even in literature no other practical strategy is available, which can be used by SPV manufactures.

Summing up, the goal of this thesis was SC optimization with focus on flexibility. Therefore a new SC strategy was set up, which is tailored to the special characteristics of the SPV manufacturers. The most important flexibility types have been worked out. The interaction of these flexibility types was investigated. The most important decisions when implementing the SC in the business environment will be x_0, x_1 as well as ΔR or R_L and R_H respectively. Formulas and MATLAB codes have been derived to calculate

the optimum values for these variables. In the end, the resulting strategy has been evaluated by calculating the minimum expected costs for different scenarios.

All this is a new approach for companies of the SPV industry and is a research contribution, which leads to clear benefits in reality.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

In this research it was assumed that the demand for the individual vehicle types is lognormal distributed. This was mainly assumed, because realistic demand scenarios can be modeled with this distribution. Furthermore, negative demand values are excluded. Since probability distributions of the demand are determined by forecasts, the developed approach of this thesis could be also adapted to different probability distributions. Therefore, further research could be based on different probability distributions.

However there are also other recommendations for future research, because in terms of CIP, a supply chain has to be continuously modified over time. This work already helps to develop a supply chain which is suitable for SPV manufacturers. But continuously improvement of a supply chain is a key method for companies to survive and succeed in the volatile and critical industrial environment of the SPV industry. Future research can help SPV manufacturers to go more into detail for a continuous improvement.

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APPENDIX A

EFFECT OF VARIANT FLEXIBILITY

```matlab
clc;     %to clear the command window

clear;   %to clear all variables


th1 = (2*log(100))-(0.5*(log((5^2)+(100^2)))); %the mean of the
lognormal distribution convertet to the mean of the normal
distribution
w1 = sqrt( (-2*log(100)) + log(100^2 + 5^2) );  %the standard
deviation of the lognormal distribution converted to the standard
deviation of the normal distribution
D = (0:1:220);
fun1 =(exp((-((log(D)-th1).^2))/((2*(w1^2)))))./(w1*D*(sqrt(2*pi)));
plot (D, fun1)
hold on


xlabel('demand');
% Create xlabel
ylabel('probability density');
% Create ylabel
title('Lognormal PDF');
% Create title
```

```matlab
th2 = (2*log(80))-(0.5*(log((3^2)+(80^2))));   %the mean of the
lognormal distribution convertet to the mean of the normal
distribution
w2 = sqrt( (-2*log(80)) + log(80^2 + 3^2) );  %the standard deviation
of the lognormal distribution converted to the standard deviation of
the normal distribution
D = (0:1:220);
fun2 =(exp((-((log(D)-th2).^2))/((2*(w2^2))))).(w2*D*(sqrt(2*pi)));
plot (D, fun2, 'g')


th3 = (2*log(180))-(0.5*(log((5.83^2)+(180^2)))); %the mean of the
lognormal distribution convertet to the mean of the normal
distribution
w3 = sqrt( (-2*log(180)) + log(180^2 + 5.83^2) );  %the standard
deviation of the lognormal distribution converted to the standard
deviation of the normal distribution
D = (0:1:220);
fun3 =(exp((-((log(D)-th3).^2))/((2*(w3^2))))).(w3*D*(sqrt(2*pi)))
plot (D, fun3, 'r')
```

APPENDIX B

COMPARISON

```matlab
clc;      %to clear the command window
clear;    %to clear all variables


th1 = (2*log(180))-(0.5*(log((5.83^2)+(180^2)))); %the mean of the
lognormal distribution convertet to the mean of the normal
distribution
w1 = sqrt( (-2*log(180)) + log(180^2 + 5.83^2) );   %the standard
deviation of the lognormal distribution converted to the standard
deviation of the normal distribution
D = (0:1:220);
fun1 =(exp((-((log(D)-th1).^2))/((2*(w1^2))))) ./(w1*D*(sqrt(2*pi)));
plot (D, fun1, 'r')
hold on


xlabel('demand');
% Create xlabel
ylabel('probability density');
% Create ylabel
title('Lognormal PDF');
% Create title
```

```matlab
th2 = (2*log(180))-(0.5*(log((8^2)+(180^2)))); %the mean of the
lognormal distribution convertet to the mean of the normal
distribution
w2 = sqrt( (-2*log(180)) + log(180^2 + 8^2) );  %the standard
deviation of the lognormal distribution converted to the standard
deviation of the normal distribution
D = (0:1:220);
fun2 =(exp((-((log(D)-th2).^2))/((2*(w2^2)))))./(w2*D*(sqrt(2*pi)));
plot (D, fun2, 'k')
```

APPENDIX C

CALCULATION OF EXPECTED COSTS

```matlab
clc;      % to clear the command window

clear;    % to clear all variables


thlog = 30;           %mean of the demand

wlog = 3.00;              %standard deviation of the demand


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2)))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );


cE = 5;

cS = 5;


% calculation of t1, which is the first part of the cost function:

fun1 = @(D) ((thlog-D).*exp((-((log(D)-

th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

% calculation of t2, which is the second part of the cost function:

fun2 = @(D) ((D-thlog).*exp((-((log(D)-

th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

% the cost function:

E = (cE*(integral (fun1, 0, thlog)))+(cS*(integral (fun2, thlog,

Inf)))
```

APPENDIX D

CALCULATION OF THE EXPECTED COSTS FOR

NORMAL DISTRIBUTIONS

With variant flexibility:

```
clc;     % to clear the command window

clear;   % to clear all variables

w = 1.73;

th = 30;

cE = 5;

cS = 5;

% calculation of function 1, which is the first part of the cost
function:

fun1 = @(D) (th-D).*exp((-((D-
th).^2))/((2*(w^2)))./(w*(sqrt(2*pi)));


% calculation of function 2, which is the second part of the cost
function:

fun2 = @(D) (D-th).*exp((-((D-
th).^2))/((2*(w^2)))./(w*(sqrt(2*pi)));

% the cost function:

E = (((((integral (fun1, -inf, th)))+((integral (fun2, th, inf)))))
```

<u>Without variant flexibility:</u>

```matlab
clc;     % to clear the command window

clear;   % to clear all variables

w = 1;

th = 10;

cE = 5;

cS = 5;



% calculation of function 1, which is the first part of the cost
function:

fun1 = @(D) (th-D).*exp((-((D-
th).^2))/((2*(w^2)))).  /(w*(sqrt(2*pi)));

% calculation of function 2, which is the second part of the cost
function:

fun2 = @(D) (D-th).*exp((-((D-
th).^2))/((2*(w^2)))).  /(w*(sqrt(2*pi)));

% the cost function:

E = 3*((((integral (fun1, -inf, th)))+((integral (fun2, th, inf)))))
```

APPENDIX E

CALCULATIONS WITH MATLAB TO DETERMINE THE OPTIMAL CAPACITY RANGE ΔR AT TIME T_0

```
clc;      %to clear the command window

clear;    %to clear all variables


R = 1:1:100;        %this range for delta R should be regarded

cR = 1; % input for the reservation costs cR

cS = 10; % input for the underage costs cs

cE = 5; % input for the overage costs ce


mean = 100;         %mean of the demand

wlog = 5;           %standard deviation of the demand

th = (2*log(mean))-(0.5*(log((wlog^2)+(mean^2))));

w = sqrt( (-2*log(mean)) + log(mean^2 + wlog^2) );

syms D;             %to create the symbolic variable D

m = 100000000;      % high number as initial value


for k = 1:R(end)    %following R is substituted by k for the loop


fun1 = @(D) ((mean-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));

%function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-mean-k).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));
```

```matlab
%function 2 to calculate the first integral of the equation

E(k) = (cR*k*2) + (cE*(integral (fun1, 1, (mean-k)))) + (cS*(integral
(fun2, (k+mean), Inf)));
%to calculate the expected costs for different RL and RH

if E(k)<m

        m = E(k);           % store the minimum expected costs

        OptR = k;           % store the optimal low range

    end


end
plot(R, E) %to plot the graph


disp('optimal delta R:')
disp (OptR)                     %to display the optimum low range
disp('minimum expected costs:')
disp (m)                        %to display the minimum expected costs


xlabel('delta R');
% Create xlabel


ylabel('expected costs');
% Create ylabel


title('Expected Costs over delta R');
% Create title
```

APPENDIX F

PROBABILITY DENSITY FUNCTION

```matlab
clc;     %to clear the command window

clear;   %to clear all variables


mean = 100;          %mean of the demand

wlog = 5;            %standard deviation of the demand

th = (2*log(mean))-(0.5*(log((wlog^2)+(mean^2))));

w = sqrt( (-2*log(mean)) + log(mean^2 + wlog^2) );


D = (0:1:200);


fun =(exp((-((log(D)-th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));


plot (D, fun)


xlabel('demand');

% Create xlabel

ylabel('probability density');

% Create ylabel

title('Lognormal PDF');

% Create title
```

APPENDIX G

GRAPHS FOR DIFFERENT STANDARD

DEVIATIONS

```matlab
clc;     % to clear the command window

clear;   % to clear all variables

R = 1:1:15;        % this range for delta R is regarded

cR = 1; % reservation costs cR

cS = 10; % underage costs cs

cE = 5; % overage costs ce

thlog = 100;          % mean of the demand

wlog = 2;             %standard deviation of the demand

th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

syms D;               % to create the symbolic variable D


w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

for k = 1:R(end)    % following R is substituted by k for the loop

fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2))))./(w*D*(sqrt(2*pi)));

% function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-thlog-k).*exp((-((log(D)-
th).^2))/((2*(w^2))))./(w*D*(sqrt(2*pi)));

% function 2 to calculate the first integral of the equation

E(k) = (cR*k*2) + (cE*(integral (fun1, 1, (thlog-k)))) +
(cS*(integral (fun2, (k+thlog), Inf)));

% to calculate the expected costs

end

plot(R, E, 'g') % to plot the graph
```

```matlab
wlog = 3;

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

hold on

for k = 1:R(end)     % following R is substituted by k for the loop

fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));

% function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-thlog-k).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));

% function 2 to calculate the first integral of the equation

E(k) = (cR*k*2) + (cE*(integral (fun1, 1, (thlog-k)))) +
(cS*(integral (fun2, (k+thlog), Inf)));

% to calculate the expected costs

end

plot(R, E, 'r') % to plot the graph


wlog = 4;

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

hold on

for k = 1:R(end)     % following R is substituted by k for the loop

fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));

% function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-thlog-k).*exp((-((log(D)-
th).^2))/((2*(w^2))))).*/(w*D*(sqrt(2*pi)));

% function 2 to calculate the first integral of the equation

E(k) = (cR*k*2) + (cE*(integral (fun1, 1, (thlog-k)))) +
(cS*(integral (fun2, (k+thlog), Inf)));

% to calculate the expected costs
```

```matlab
end

plot(R, E, 'b') % to plot the graph


wlog = 5;

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

hold on

for k = 1:R(end)     % following R is substituted by k for the loop

fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

% function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-thlog-k).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

% function 2 to calculate the first integral of the equation

E(k) = (cR*k*2) + (cE*(integral (fun1, 1, (thlog-k)))) +
(cS*(integral (fun2, (k+thlog), Inf)));

% to calculate the expected costs

end

plot(R, E, 'm') % to plot the graph


xlabel('delta R'); % Create xlabel

ylabel('expected costs'); % Create ylabel

title('Expected Costs over delta R for different standard
deviations'); % Create title
```

APPENDIX H

OPTIMAL CAPACITY RANGES R_L AND R_H AT

TIME T_0

```
clc;     %to clear the command window

clear;   %to clear all variables


RL = 1:1:20;        %this range for the lower volume capacity should
be regarded

RH = 1:1:20;        %this range for the higher volume capacity should
be regarded

cE = 5;             %overage costs

cS = 10;             %underage costs

cR = 1;             %capacity reservation costs

thlog = 100;         %mean of the demand

wlog = 5;           %standard deviation of the demand


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));  %mean for the
normal distribution

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2));    %standard
devitation for the normal distribution


syms D;             %to create the symbolic variable D

m = 100000000;         % high number as initial value

E= zeros (RL(end), RH(end));   %definition of the matrix E with the
size of RL and RH


for k = 1:RL(end)    %following RL is substituted by k for the loop
```

```matlab
    for l = 1:RH(end)   %following RH is substituted by l for the loop



fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-

th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));

%function 1 to calculate the first integral of the equation



fun2 = @(D) ((D-thlog-l).*exp((-((log(D)-

th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));

%function 2 to calculate the first integral of the equation



E(k,l) = (cR*(k+l)) + (cE*(integral (fun1, 1, (thlog-k)))) +

(cS*(integral (fun2, (l+thlog), Inf)));

%to calculate the expected costs for different RL and RH



if E(k,l)<m

        m = E(k,l);              % store the minimum expected costs

        OptLowR = k;             % store the optimal low range

        OptHighR = l;            % store the optimal high range

    end



    end

end

[RL, RH] = meshgrid(RL, RH);     %to produce a grid represented by the

coordinate arrays RL and RH

mesh(RL, RH, E, 'EdgeLighting','flat', 'EdgeColor', 'black',

'FaceLighting','none', 'LineWidth',1, 'FaceColor','texturemap')

%to plot the graph/wireframe



disp('optimal low range:')
```

```matlab
disp (OptLowR)                    %to display the optimum low range

disp('optimal high range:')

disp (OptHighR)                   %to display the optimum high range

disp('minimum expected costs:')

disp (m)                          %to display the minimum expected costs


xlabel('R_H');

% Create xlabel


ylabel('R_L');

% Create ylabel


zlabel('expected costs');

% Create zlabel


title('Expected Costs over R_H and R_L');

% Create title
```

APPENDIX I

DISTRIBUTIONS WITH DIFFERENT STANDARD DEVIATIONS

```matlab
clc;      %to clear the command window
clear;    %to clear all variables
thlog = 10;
wlog = 1;


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));
w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );


D = (0:0.1:20);
fun =(exp((-((log(D)-th).^2))/((2*(w^2))))./(w*D*(sqrt(2*pi)));


D1 = thlog;       %for the marking of the mean
fun1 = (exp((-((log(D1)-th).^2))/((2*(w^2))))./(w*D1*(sqrt(2*pi)));
%for the marking of the mean
D2 = thlog-wlog;      %for the marking of the left standard deviation
fun2 = (exp((-((log(D2)-th).^2))/((2*(w^2))))./(w*D2*(sqrt(2*pi)));
%for the marking of the left standard deviation
D3 = thlog+wlog;       %for the marking of the right standard
deviation
fun3 = (exp((-((log(D3)-th).^2))/((2*(w^2))))./(w*D3*(sqrt(2*pi)));
%for the marking of the right standard deviation
plot (D, fun, 'g', D1, fun1, 'o', D2, fun2, 'x', D3, fun3, 'x')
hold on
```

```matlab
thlog = 10;

wlog = 3;

th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );


D = (0:0.1:20);

fun =(exp((-((log(D)-th).^2))/((2*(w^2))))./(w*D*(sqrt(2*pi)));

D4 = thlog;        %for the marking of the mean

fun4 = (exp((-((log(D4)-th).^2))/((2*(w^2))))./(w*D4*(sqrt(2*pi)));

%for the marking of the mean

D5 = thlog-wlog;       %for the marking of the left standard deviation

fun5 = (exp((-((log(D5)-th).^2))/((2*(w^2))))./(w*D5*(sqrt(2*pi)));

%for the marking of the left standard deviation

D6 = thlog+wlog;       %for the marking of the right standard

deviation

fun6 = (exp((-((log(D6)-th).^2))/((2*(w^2))))./(w*D6*(sqrt(2*pi)));

%for the marking of the right standard deviation


plot (D, fun, 'b', D4, fun4, 'o', D5, fun5, 'x', D6, fun6, 'x')


xlabel('demand');

% Create xlabel

ylabel('probability density');

% Create ylabel

title('Lognormal PDF');

% Create title
```

APPENDIX J

DISTRIBUTIONS WITH DIFFERENT MEAN VALUES

```matlab
clc;      %to clear the command window

clear;    %to clear all variables


thlog = 12;

wlog = 4;


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );


D = (0:0.1:20);

fun =(exp((-((log(D)-th).^2))/((2*(w^2))))./(w*D*(sqrt(2*pi)));


D1 = thlog;       %for the marking of the mean

fun1 = (exp((-((log(D1)-th).^2))/((2*(w^2))))./(w*D1*(sqrt(2*pi)));

%for the marking of the mean


plot (D, fun, 'g', D1, fun1, 'o')

hold on


thlog = 8;

wlog = 4;


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));
```

```matlab
w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );



D = (0:0.1:20);

fun =(exp((-((log(D)-th).^2))/((2*(w^2))))).  /(w*D*(sqrt(2*pi)));



D2 = thlog;        %for the marking of the mean

fun2 = (exp((-((log(D2)-th).^2))/((2*(w^2))))).  /(w*D2*(sqrt(2*pi)));

%for the marking of the mean



plot (D, fun, 'b', D2, fun2, 'o')



xlabel('demand');

% Create xlabel

ylabel('probability density');

% Create ylabel

title('Lognormal PDF');

% Create title
```

APPENDIX K

OPTIMAL ORDER QUANTITY X$_1$ AT TIME T$_1$

<u>MATLAB function:</u>

```matlab
function [ E ] = my_func( x )



thlog = 10;

wlog = 3;



th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );



cE = 1;

cS = 10;



% calculation of t1, which is the first part of the cost function:



fun1 = @(D) ((x-D).*exp((-((log(D)-

th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));



t1 = integral (fun1, 0, x);



% calculation of t2, which is the second part of the cost function:



fun2 = @(D) ((D-x).*exp((-((log(D)-

th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));
```

```matlab
    t2 = integral (fun2, x, Inf);


    % multiplying t1 and t2 with the costs and combining it to the
    equation for
    % the cost function:


    E = (cE*t1)+(cS*t2);


end
```

Matlabscript:

```matlab
clear                % clear all variables
clc                  % clear command window
m = 100000;          % high number as initial value
syms s order            % creation of symbiloc variables s and
order
for x = 0.1 : 0.01 : 20 % for loop to calculate the costs for
different order quantities
    sym s;           % to clear the value of the variable s
    s = my_func(x);      % calculation of the expected costs
    if s<m
        m = s;               % store the minimum expected costs
        order = x;           % store the optimal order quantity
    end
     plot (x, my_func(x), 'LineWidth',2)
    hold on
    title ('Expected Costs')
xlabel ('order quantity x_1')
```

```matlab
ylabel ('costs')

grid on

end

disp('optimal order quantity:')

round (order)    %rounds the value for the optimal order quantity to
the nearest integer

disp('minimum costs:')

s = my_func(round(order))        % calculates the expected costs for
the ROUNDED optimal order quantity

 text (round(order),m,['\color{red}  optimal order quantity at
minimum costs'], 'FontSize', 14)
```

APPENDIX L

EXPECTED COSTS WITHOUT VARIANT

FLEXIBILITY

```
clc;     % to clear the command window

clear;   % to clear all variables


thlog = 100;

wlog = 5;


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2)))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );


cE = 5;

cS = 10;


% calculation of function 1, which is the first part of the cost
function:


fun1 = @(D) ((thlog-D).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));


% calculation of function 2, which is the second part of the cost
function:
```

```matlab
fun2 = @(D) ((D-thlog).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

% cost function:

E = (cE*(integral (fun1, 0, thlog)))+(cS*(integral (fun2, thlog,
inf)))
```

APPENDIX M

EXPECTED COSTS WITHOUT VARIANT

FLEXIBILITY

```matlab
clc;     % to clear the command window

clear;   % to clear all variables


cS = 1.5; % definition of the underage costs cs

cE = 5;   % definition of the overage costs ce

thlog0 = 100;

wlog0 = 7;

th0 = (2*log(thlog0))-(0.5*(log((wlog0^2)+(thlog0^2)))));

w0 = sqrt( (-2*log(thlog0)) + log(thlog0^2 + wlog0^2) );

thlog1 = 120;

wlog1 = 5;

th1 = (2*log(thlog1))-(0.5*(log((wlog1^2)+(thlog1^2)))));

w1 = sqrt( (-2*log(thlog1)) + log(thlog1^2 + wlog1^2) );

x0 = 100;       % order quantity at time t0 as ln for the lognormal
distribution

x1 = 120;       % order quantity at time t1 as ln for the lognormal
distribution

syms D;               % to create the symbolic variable D


fun1 = @(D) ((x0-D).*exp((-((log(D)-
th0).^2))/((2*(w0^2)))))./(w0*D*(sqrt(2*pi)));
```

```matlab
%function 1 to calculate the first integral of the equation


fun2 = @(D) ((D-x0).*exp((-((log(D)-

th0).^2))/((2*(w0^2))))).  /(w0*D*(sqrt(2*pi)));

%function 2 to calculate the first integral of the equation


fun3 = @(D) ((x1-D).*exp((-((log(D)-

th1).^2))/((2*(w1^2))))).  /(w1*D*(sqrt(2*pi)));

%function 3 to calculate the third integral of the equation


fun4 = @(D) ((D-x1).*exp((-((log(D)-

th1).^2))/((2*(w1^2))))).  /(w1*D*(sqrt(2*pi)));

%function 4 to calculate the fourth integral of the equation


time0 = (cE*(integral (fun1, 0, x0))) + (cS*(integral (fun2, x0,

Inf)))

time1 = cE*(integral (fun3, 0, x1)) + (cS*(integral (fun4, x1, Inf)))

mean0 = cS*(x1 - x0)


I = time0 / (time1 + mean0)

%to calculate the performance indicator

disp('expected savings:')

I
```

APPENDIX N

EXPECTED SAVINGS DUE TO TIME

FLEXIBILITY

```matlab
clc;     % to clear the command window

clear;   % to clear all variables

cS = 10; % definition of the underage costs cs

cE = 1;   % definition of the overage costs ce

thlog = 10;          %mean of the demand

wlog = 3;            %standard deviation of the demand

th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2)))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

x = 10;        % order quantity as ln for the lognormal distribution

syms D;                % to create the symbolic variable D


fun1 = @(D) ((x-D).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

%function 1 to calculate the first integral of the equation

fun2 = @(D) ((D-x).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

%function 2 to calculate the first integral of the equation


E = (cE*(integral (fun1, 0, x))) + (cS*(integral (fun2, x, Inf)));


%to calculate the expected costs

disp('expected costs:')

E
```

APPENDIX O

OPTIMAL FLEXIBILITY RANGE

```matlab
clc;     %to clear the command window

clear;   %to clear all variables


RL = 1:1:20;            %this range for the lower volume capacity
should be regarded
RH = 1:1:20;            %this range for the higher volume capacity
should be regarded
cE = 5;                 %overage costs
cS = 3;                 %underage costs
cR = 1;                 %capacity reservation costs
thlog = 300;            %mean of the demand
wlog = 7.4833;          %standard deviation of the demand


th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));  %mean for the
normal distribution
w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2));    %standard
devitation for the normal distribution


syms D;                 %to create the symbolic variable D
m = 100000000;          % high number as initial value
E= zeros (RL(end), RH(end));   %definition of the matrix E with the
size of RL and RH


for k = 1:RL(end)       %following RL is substituted by k for the
loop
```

```matlab
    for l = 1:RH(end)    %following RH is substituted by l for the
loop


fun1 = @(D) ((thlog-k-D).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));
%function 1 to calculate the first integral of the equation


fun2 = @(D) ((D-thlog-l).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));
%function 2 to calculate the first integral of the equation


E(k,l) = (cR*(k+l)) + (cE*(integral (fun1, 1, (thlog-k)))) +
(cS*(integral (fun2, (l+thlog), Inf)));
%to calculate the expected costs for different RL and RH


if E(k,l)<m
        m = E(k,l);         % store the minimum expected costs
        OptLowR = k;        % store the optimal low range
        OptHighR = l;       % store the optimal high range
    end


    end
end
[RL, RH] = meshgrid(RL, RH);    %to produce a grid represented by the
coordinate arrays RL and RH
mesh(RL, RH, E, 'EdgeLighting','flat', 'EdgeColor', 'black',
'FaceLighting','none', 'LineWidth',1, 'FaceColor','texturemap')
%to plot the graph/wireframe
```

```matlab
disp('optimal low range:')

disp (OptLowR)                  %to display the optimum low range

disp('optimal high range:')

disp (OptHighR)                 %to display the optimum high range

disp('minimum expected costs:')

disp (m)                        %to display the minimum expected costs


xlabel('R_H');

% Create xlabel


ylabel('R_L');

% Create ylabel


zlabel('expected costs');

% Create zlabel


title('Expected Costs over R_H and R_L');

% Create title
```

APPENDIX P

OPTIMAL ORDER QUANTITY AT THE

POSTERIOR POINT OF TIME

MATLAB script:

```matlab
clear                   % clear all variables
clc                     % clear command window
m = 100000;             % high number as initial value
syms s order            % creation of symbiloc variables s and
order
for x = 250 : 1 : 400 % for loop to calculate the costs for different
order quantities
    sym s;              % to clear the value of the variable s
    s = my_func(x);     % calculation of the expected costs
    if s<m
        m = s;              % store the minimum expected costs
        order = x;          % store the optimal order quantity
    end
     plot (x, my_func(x), 'LineWidth',2)
    hold on
    title ('Expected Costs')
xlabel ('order quantity x_1')
ylabel ('costs')
grid on
end
```

```matlab
disp('optimal order quantity:')

round (order)    %rounds the value for the optimal order quantity to
the nearest integer

disp('minimum costs:')

s = my_func(round(order))         % calculates the expected costs for
the ROUNDED optimal order quantity

 text (round(order),m,['\color{red}  optimal order quantity'],
'FontSize', 14)
```

MATLAB function:

```matlab
function [ E ] = my_func( x )

thlog = 330;

wlog = 3.7417;

th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

cE = 5;

cS = 3;

% calculation of t1, which is the first part of the cost function:

fun1 = @(D) ((x-D).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));


t1 = integral (fun1, 0, x);

% calculation of t2, which is the second part of the cost function:

fun2 = @(D) ((D-x).*exp((-((log(D)-
th).^2))/((2*(w^2)))))./(w*D*(sqrt(2*pi)));

t2 = integral (fun2, x, Inf);

% multiplying t1 and t2 with the costs and combining it to the
equation for

% the cost function:

E = (cE*t1)+(cS*t2);


end
```

APPENDIX Q

EXPECTED COSTS AT TIME T_0

```
clc;     % to clear the command window

clear;   % to clear all variables

thlog =150;          %mean of the demand

wlog = 6;            %standard deviation of the demand

th = (2*log(thlog))-(0.5*(log((wlog^2)+(thlog^2))));

w = sqrt( (-2*log(thlog)) + log(thlog^2 + wlog^2) );

cE = 5;

cS = 3;



% calculation of t1, which is the first part of the cost function:

fun1 = @(D) ((thlog-D).*exp((-((log(D)-
th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));



% calculation of t2, which is the second part of the cost function:

fun2 = @(D) ((D-thlog).*exp((-((log(D)-
th).^2))/((2*(w^2))))).(w*D*(sqrt(2*pi)));



% the cost function:

E = (cE*(integral (fun1, 0, thlog)))+(cS*(integral (fun2, thlog,
Inf)))
```

APPENDIX R

ABBREVIATIONS

ASC	Automotive Supply Chain
ATO	Assemble-to-Order
BOM	Bill of Material
BTF	Build-to-Forecast
BTO	Build-to-Order
BTS	Build-to-Stock
CEO	Chief Executive Officer
CIP	Continuous Improvement of Process
CRP	Continuous Replenishment Program
CV	Coefficient of Variation
ETO	Engineering-to-Order
IMDS	International Material Data System
LCC	Low Cost Country
MTO	Make-to-Order
MU	Monetary Unit
OEM	Original Equipment Manufacturer
pdf	probability density function
PE	Performance Evaluation
QU	Quantity Unit
RFQ	Request for Quotation
ROS	Return on Sales

SC	Supply Chain
SCF	Supply Chain Flexibility
SCM	Supply Chain Management
SCMO	Supply Chain Management Organization
SOP	Start of Production
SPV	Special Purpose Vehicle
VM	Vehicle Manufacturer/OEM
VMI	Vendor Managed Inventory
WIP	Work in Progress

APPENDIX S

SYMBOLS

b	profit
c	variable purchase order prices
C_{res}	reservation costs
cR	reservation price
c_s	costs for shortages
c_e	costs for excess capacity
D	demand
E_{costs}	expected costs
$E_{excesscapa}$	expected excess capacity
E_{profit}	expected profit
$E_{shortages}$	expected shortages
P	profit
P_{rf}	risk free expected profit
m	number of vehicle types, a part is integrated
p	regular sales prices
p_r	reduced sales prices
p_s	$c_s + c_e$
R	capacity option
t_0	prior point of time
t_1	posterior point of time

t_2	product completion/assembly time
X_0	fixed order quantity
$x_0{}^*$	optimal order quantity
α	forecast optimization factor in terms of standard deviation
β	forecast optimization factor in terms of the mean
σ	standard deviation of the normal distribution
Θ	mean of a lognormal distribution
μ	mean of a standard deviation
ϑ	cost relationship
ω	standard deviation of a lognormal distribution

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