# A new method for improving decision-making in the supply chain risk management process. Supporting the learning project management organisation by applying advanced business modelling simulation techniques

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# A new method for improving decision-making in the supply chain risk management process. Supporting the learning project management organisation by applying advanced business modelling simulation techniques

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# DECLARATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

I declare the final word count of this thesis excluding abstract, table of content, overview on figures and tables and references accounts for 52.115 words.

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# ABSTRACT

The rise of importance of supply chain risk management both, in the scientific and business world, is essentially the result of solving an economical paradox. How can an organisation continuously increase its growth in revenue and increase its profit in a world in which the flow of goods and financial means is reaching a never seen complexity? This provides both, a threat and an opportunity to those organisations. The key is how to identify, manage and prevent operational risk. The following thesis aims at providing a new approach on the subject targeting project management organisations by bringing together three different disciplines, supply chain risk management, business modelling and simulation and the concept of the learning organisation.

The research is based on a literature review of the identified fields followed by an empirical assessment aiming to understand the main risks threatening a project's supply chain, the current state of supply chain risk management and application of business modelling and simulation in practice as well as gaining an understanding how the principles of the learning organisation are lived within a project management organisation. Furthermore, the thesis is providing an exemplary approach on how a simulation model could be built assessing identified supply chain risks.

The literature review, as well as the empirical assessment, conducted via the combination of questionnaire and interview, is clearly showing that, while the topic of supply chain risk management has become a constant part of the scientific discussion the real-world application, especially in the context of business modelling and simulation applying the principles of the learning organisation is still executed hesitantly. Furthermore, the thesis provides an example by which current state of the art simulation software is used to allow supply chain professionals to conduct each step of the supply chain risk management process in a virtual environment.

The relevancy of the work is founded in the combination of the three fields offering a new approach to complex project management organisations in further developing their supply chain risk management capabilities.

# ACKNOWLEDGEMENT

This thesis has been a long journey and would not have been possible without the endless support of my wife Salma and my family, who, during sickness and health, always supported me and showed me the way forward.

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# TABLE OF CONTENTS

# FIGURES

# TABLE

# NOTATIONS

## Abbreviations

| | |
|---|---|
| AEP | Annual Energy Production |
| BCP | Business Continuity Planner |
| CRM | Customer Relationship Management |
| DFIG | Double-Fed Inductance Generator |
| EM | Electrified Magnet |
| FMCG | Fast Moving Consumer Good |
| FMEA | Failure Mode and Effect Analysis |
| GVS | Global Value Sourcing |
| IEC | International Electrotechnical Commission |
| KPI | Key Performance Indicator |
| LC | Local Content |
| LCoE | Levelised Cost of Energy |
| MLS | Maximum Shop Load |
| MoB | Make or Buy |
| MPS | Master Production Schedule |
| MRP I | Material Requirement Planning |
| MRR II | Material Resource Planning |
| OEM | Original Equipment Manufacturer |
| PLM | Product Lifecycle Management |
| PM | Permanent Magnet |
| PPS | Product Planning and Steering |
| ROA | Return on Assets |
| ROI | Return on Investment |
| SA | Starvation Avoidance |
| SCM | Supply Chain Management |
| SCRM | Supply Chain Risk Management |
| SOP | Sales and Operations Planning |
| TLC | Total Landed Cost |

| | |
|---|---|
| TLC | Total Landed Cost |
| TOC | Total Cost of Ownership |
| TQM | Total Quality Management |
| V&V | Validation and Verification |
| VARI | Vacuum-Assisted Resign Infusion |
| VDI | Verband Deutscher Ingenieure |
| WoM | Word of Mouth |
| WR | Workload Regulating |

# Chapter 1

# Introduction

Risk is an ambiguous term. We all like to take risks for various different reasons. Some of us for the pure excitement, some of us for taking chances others won't. But while taking risks and accepting the fact that we are not fully in control of what is happing might bring us joy in our private life, the more frightened we are when we face risks in our professional life threatening the organisation, we are working in. A changing environment and the increased pressure of innovative development are forcing business organisations to take higher risks in order to survive on today's marketplaces. But not only the single risk for the organisation represents a threat, far more it is the high level of interconnections in modern business which leads to underestimated chain-reactions.

As a consequence, risk management became one of the mayor concerns in today's business environment, but how can one ensure that the action we decide to take today will lead to the desired effect in the future when it comes to risk management?

## 1.1. Supply chain risk in a project management organisation

Risk management, especially concerning the supply chain always existed in a shadowy way. This has changed dramatically.

The flow of material, information and financial assets from the raw material supply to the final customer covering the scope of a supply chain or network is facing an increased risk operating in today's business environment.

The reasons behind these threats are manifold and both, originated in- and outside the supply chain as a whole (Brindley, 2004).

One of the main reasons why supply chain risk in today's business organisation is such a focal point is, in fact, the concept of a supply chain itself.

According to Fawcett (Fawcett, Ellram, & Ogden, 2007) the desire of creating a comprehensive value chain from the supplier of raw material to the final customer and compete as a whole with another supply chains opened the door for a new perception of risk within the supply chain. The consequence of this development was, among others, that former business policies of pushing supply chain risks onto suppliers or other contractors no longer fitted to the concept of supply chain management as the overall performance of the supply chain has to be competitive.

The development of increased competition between whole supply chain networks does not take place due to purely intrinsic reasons. Christopher (Christopher, 2004, sq.28) identifies four main developments being responsible for these drastic changes in the macro-economic environment of a supply chain, emphasising even more the specific need of a comprehensive supply chain risk management.

- New rules of competition
- Downward pressure on price
- Globalisation of industry
- Customer taking control

All these factors create and promote an increase in either internal or external risks threatening not only a single company or organisation but the whole supply chain it is a part of. Prominent examples taken from a study conducted by the German BMI as well as other authors acknowledging the continuous change and development in today's supply chain networks, (Tukamuhabwa, Stevenson, Busby, & Zorzini, 2015), (Christopher, Mena, Khan, & Yurt, 2011), (Roberta Pereira, Christopher, & Lago Da Silva, 2014).

- Natural catastrophes
- Drastic price decreases
- Bottlenecks in capacity
- Dependencies on suppliers
- Quality issues in the supply chain

As a consequence of this in- and extrinsic development of supply chain risks, organisations have been and are in the need of finding appropriate answers. Supply chain risk management (SCRM) represents a structured framework supported by various tools by which organisations not only re-act but also preventively act towards risks threatening their supply chains and hence their customers.

Waters (Waters, 2007, p. 76) defines supply chain risk management (SCRM) as "[…] the process of systematically identifying, analysing and dealing with risks to the supply chain."
The generic SCRM process consists of a four-step framework which will be discussed in detail as part of the literature review in chapter 2. The generic steps are:

- Risk identification
- Risk assessment
- Risk mitigation
- Risk monitoring and management

In the same way as risks in the supply could be manifold, the type of supply and respectively the types of produced goods vary significantly. The single focus of this thesis is to analyse supply chain risk in a project management driven supply chain, whereby the term project directly relates to the commonly applicable definition that," projects are defined as work that happens one time only and has a clear beginning and end. This work may be contrasted with the on-going operations of an organisation that involves repetitive work – such as manufacturing or retail – with no defined end." (Verzuh, 2008, p. 11)
More tangible examples for modern project work are i.e., the erection of a bridge, or a power plant.

#### 1.1.1. Motivation for research

The entire research is following a concept of combining a triangle of three well-established research areas representing the foundation for the targeted contribution to knowledge. Figure 1.1.1-1 is illustrating this concept consisting of the areas **supply chain risk management**, **business modelling and simulation** and **organisational learning**. The frame which is surrounding this concept is the area of application in which all three concepts are being used, the **project management organisation.** The guidance provided by this concept is allowing the researcher to clearly identify the state of art knowledge in respect to the each of the fields individually, followed by identifying the contribution to knowledge in the intersection of all fields.

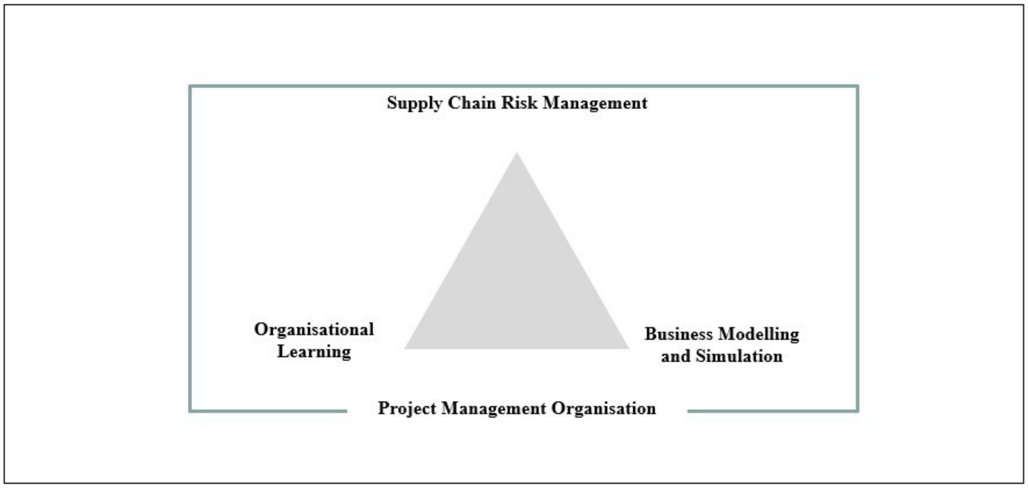


*Figure 1.1.1-1: Research triangle*

Starting with the process of **supply chain risk management** which comprises the elements of a generic problem-solving approach: Identification, assessment followed by managing and monitoring.

Within these steps an organisation faces various challenges; some of them connected to the environment they are acting in, some of these challenges arise due to the approach of how individuals behave when working with this complexity.

<u>Supply Chains – A complex environment</u>

Hakansson (Håkansson & Snehota, 1990) argues that contrary to the former view of a supply chain as a linear connection between always one supplier and a manufacturer delivering a good to a customer, today's supply chains represent a network structure including sometimes hundreds of players. Following Robinson (Robinson, 2004, p. 5) by adapting a system perspective to a supply chain network the critical factors characterising a supply chain are:

- Variability
- Interconnection
- Complexity

**Variability** describes the factor by which variables in a system change over time. The variability could follow a certain pattern (i.e., normal or seasonal distribution) or could be chaotic.

**Complexity** is expressed in two dimensions, dynamic and combinatorial complexity. Dynamic complexity arises from the interaction of components in a system over time (Sterman, 2000).

Robinson (Robinson, 2004, p. 5) concludes that combinatorial complexity is related to the number of components in a system or the number of combinations in the system that are possible.

The linkage between the various supply chains in a wider network and the intensity of their connections is represented by the level of **interconnection**.

In the context of supply chain risk management these characteristics are on the one hand a potential source of risk or in case an external risk threatens the supply chain hindering elements. One example is the lack of linear dependencies which ease the cause-and-effect evaluation in the process of risk management.

<u>The human factor in supply chain management</u>

The challenge for individuals working in supply chain risk management is now to take the described characteristics of variability, complexity and interconnection into account when dealing with supply chain risks.

By nature, the human mind is always looking for linear dependencies and direct cause-and-effect coherencies.

Various authors, for example Meadows, describe how human interaction within a complex system could cause contrary effects.

"The unexpected dynamics often lead to policy resistance, the tendency for interventions to be delayed, diluted, or defeated by the response to the system by the intervention itself." (Meadows, Richardson, & Bruckmann, 1982)

Furthermore, to this aspect it needs to be stated that supply chain performance is of course not depending on a single individual but on the collaboration of different partner spread out over the whole supply chain. This, combined with the factor of employee fluctuation, represents a major challenge for today's business organisations.

One approach of answering to this challenge according to Senge (Senge, 2006) is the implementation of organisational learning. Organizational learning describes the ability of an organization to adapt to a complex environment by for example carefully analysing cause-and-effect relationships within a business system.

As a consequence of the difficult environment risk management in the supply chain becomes more important than ever and at the same time more challenging than ever.

In a survey published by Mc Kinsey and Company in 2006 with a participation of 3.172 executives, the main finding has been, that:

- Almost 2/3 of the respondents say that the risk in their supply chains has increased of the last five years
- Nearly 1/4 say that their company does no formal risk assessment, and almost lack company-wide standards to help mitigate risk
- Executives say that they’re making surprisingly little use of some well-known tools and techniques that could help them to assess the business

A study conducted by the MIT Centre for Transportation and Logistics (MIT Center for Transportation and Logistics, 2010) in 2009 with 1.400 supply chain professionals in 70 countries recognise a certain development in the field of SCRM, however the study emphasises that major organisations […]”still lack the means to define the strategic picture of supply chain risk across the company and to communicate it effectively to the board. Nevertheless, work is under way on many fronts to develop best practices, define standard metrics, and create a standard vocabulary for managing supply chain risk.” (MIT Center for Transportation and Logistics, 2010, p. 4)

Besides the little utilisation of SCRM in the business world various authors indicate a lack of research on the topic of risk management for the supply chain.

In his article: “Logistic research: a 50 years’ march of ideas”, Klaus (Klaus, 2009) is reflecting on the results logistic research achieved so far, but in addition he is also providing an outlook which will be the critical research fields of the future. As part of this outlook SCRM is taking a central role.

Jütter (Jüttner, 2005) emphasises in her article that companies implement organization-specific risk management, but that there is little evidence of risk management at a supply chain level. This observation is slightly softened in her article from 2011 in which she constitutes that major events such as the global financial crisis has resulted in a stronger effort of corporate engagement in SCRM. (Jüttner & Maklan, 2011, p. 246)

In one of their essays published in Vahrenkamp and Anmann's work Mikus (Vahrenkamp & Amann, 2007) is stating that caused by the network-natured design of a Supply Chain a strong need for further research could be declared. They claim that the crucial issues of future research are:

- The analysis of the cause-and-effect chains and their coherences
- The development of management toolkit assessing and mitigating supply chain risk

Concluding on these observations it becomes evident that the topic of supply chain risk management in its overall variety concerning application, framework and applied tools offers a wide range of research opportunities which are not only relevant regarding a theoretical contribution but in addition are highly relevant for today's business organisations.

#### 1.1.2. Risk and uncertainty

A well-known fact within the business world is that specific terms are often used in an interchangeable way. The field of risk in a business context with all its various characteristics represents no exception.

According to Khan (Khan & Burnes, 2007) one key element of risk is its perception of being either objective or subjective, respectively exclusively threatening or to be seen partly as a chance.

The origin of the term risk in today's meaning goes back to mathematicians like Blair and Pascal, who were experimenting with the concept of gambling beginning the seventeenth century. (Frosdick, 1997)

During the eighteens century the term risk entered the business world following a pure negative and objective approach which is also reflected in most of today's relevant definitions. The Royal Society (The Royal Society, 1992) defines Risk as "[…] a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequence of the occurrence", and thereby queues up with other authors emphasising the two relevant dimensions of risk, probability and affect such as Lowrance (Lowrance, 1980), Rowe (Rowe, 1980) and Simon, Hillson and Newland (Simon, Hillson, & Newland, 1997).

After its application in business areas like insurance, finance and later on engineering, risk, respectively techniques of identifying and managing risks entered the field of supply chain management.

Due to its evolving importance Williamson (Williamson, 2008) argues that risk was originally used by assessing supplier relationships from a financial point rather than analysing complex network aspects which has changed dramatically.

Accompanying the concept of risk, the ideas of business uncertainty, vulnerability and resilience entered the discussion, describing various phenomena in supply chain management. Peck (Peck, 2005, p. 211) describes something to be vulnerable as "[…] likely to be lost or damaged," and resilience as "[…] the ability of a system to return to its original (or desired) state after being disturbed."

Following the common standpoint on the difference between risk and uncertainty the factor of knowing the probability of an event occurring has been the tipping point.

Referring to Knight's work (Knight, 1921), Frosdick states that "risk is something measurable in the sense that estimates can be made of the probabilities of the outcomes. On the other hand, uncertainty is not quantifiable and the possible outcomes are not known." (Frosdick, 1997, p. 200)

Contrary to this, Yates and Stone (Yates, 1992) argue in their article that risk can only exist when there is uncertainty about its occurrence. Otherwise, it would not be a risk.

This work is placed in the academic field of supply chain risk managing where risk is defined in alignment with the traditional position of the risk dimension probability and magnitude combined with a subjective reflection on current position and future expectations of the individual experiencing the risk.

A supply chain organisation suffers from external and internal risks, risks which are in and out of their immediate scope of control. Caused by the high-level connection between different partners in a supply chain regarding the exchange of physical goods, information or financial assets these risks, if not properly managed, materialise even more frequent and with a higher impact than ever before.

### 1.1.3. Supply chain risk management – from the back room to the front row

In early 2000 two of the world's leading mobile manufacturer, Ericsson and Nokia, faced similar fatalities in their supply chain. In both global supply chains, a fire destroyed a suppliers' warehouse holding a critical component for the assembly process.

The difference of both incidents was that Ericsson, in contrast to Nokia, did not possess a comprehensive supply chain risk management which would have been supportive in identifying, assessing and mitigating the risk proactively.

Nokia instead applied a risk alerted multi-sourcing strategy which allowed to company to continue the production process after quick ramp-up time for the already existing and qualified supplier. (Norman & Shimer, 1994)

This example illustrates how the objective of creating an even more efficient supply chain, by relying on a single-sourcing strategy without applying risk strategies, might lead to dramatic results.

The comparison of these two cases illustrates the importance of supply chain risk management in a highly interconnected business world. As indicated in the discussed survey conducted by McKinsey more and more supply chain partners are aware that supply chain risk management is becoming a major topic on their agenda.

The approach of an integrated risk management for the supply chain needs to be strictly separated from a supply chain risk management approach at a single corporate scope. As Juettner points out in her article on SCRM, "[…] however, a research gap still exists for investigating risk management with a systematic supply chain perspective and in identifying important issues of SCRM from a practitioner perspective." (Jüttner, 2005, p. 121)

The overview of the vast body of literature discussed in chapter 2 gives a clear statement that the topic of supply chain risk management made its way away from the backroom of supply chain risk management topics.

## 1.2. The supply chain risk management process in projects – decision making based on uncertainty

Focus of this thesis are organisations delivering customized products or service to their customer. One way to describe how these organisations are designed is the term project-management driven.

Every project has two essential characteristics which distinguishes it from a continuous and on-going operation. (Verzuh, 2008)

- Every project has a beginning and an end
- Every project produces a unique product

Transferred into a business organisation this might result in a matrix setup, where various projects make use of common resources. These resources comprehend the overall lifecycle of a project e.g., Sales, Project Planning, Manufacturing, Project Execution and Service.

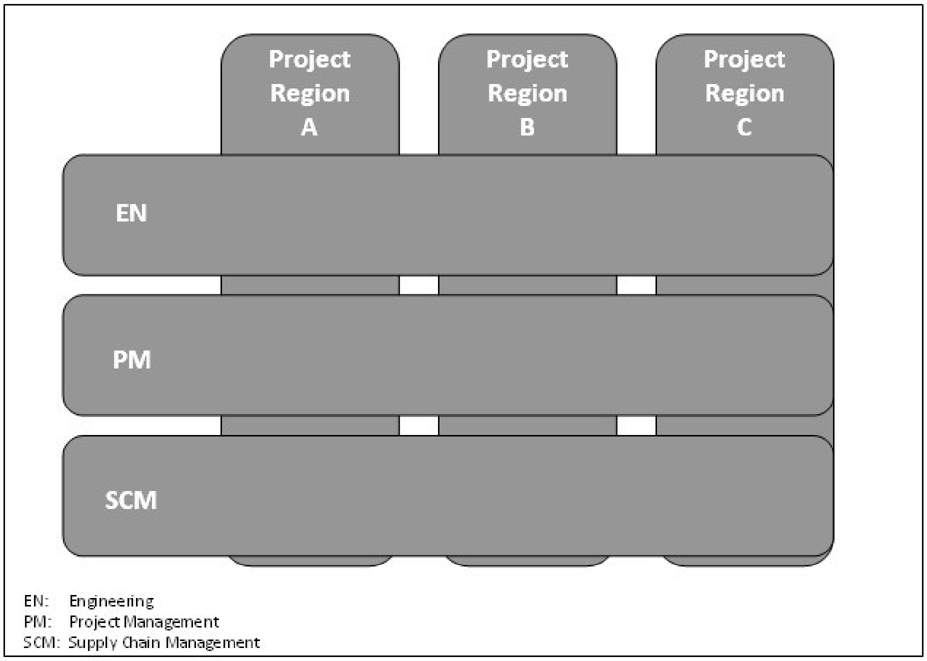


*Figure 1.2-1: Overview of Project Management Organisation*

However, the produced and sold good in the indicated region always has a unique character so the classification as a project is justified.

Supply chain risk management in the project management organisation combines the general characteristics of a supply chain environment with the concept of shared resources in a project environment.

During the process of identification, assessment and management of the internal and external risks threatening the supply chain organisation decisions concerning the risk mitigation need to be evaluated.

A profound decision is based on experience and/or a proof of successful application under comparable circumstances which in the case of SCRM represents a crucial factor as risk, closely connected to probability, and could not be used as a solid baseline.

## 1.3. Research question

The focus of the thesis is the process step of risk management and how supply chain organisations could verify their decision-making in an uncertain and dynamic environment.

In order to provide a comprehensive analysis of the area of SCRM management for the project organisation the thesis considers three different paths:

- How the process of SCRM is built up and what different types of analysis are usually used in order to successfully complete the relevant process step
- What tools and techniques can support the supply chain risk management organisation in managing the risk?
- How can an organisation ensure that the individuals managing the supply chain risk process are aware of the cause-and-effect loops within a complex system?

<u>The process of risk management for the supply chain</u>

In the process of selecting the right risk mitigation strategy towards a risk which either has already occurred or represents a potential threat to the supply chain organisation mainly qualitative and analytical tools are used. This selection is in that respect problematic as these tools often underestimate or disregard the main drivers of risk in the supply chain.

In a comprehensive overview Peck (Peck, 2003) discussed various examples of the applied tools are Delphi Forecasting, Brainstorming, Flowcharting for qualitative approaches and Business Process Re-engineering, Time based process mapping and statistical process control for the analytical ones.

The main drivers of risk in a supply chain are:

- Dynamic feedback loops
- Parallelism
- Influence of probability

As already argued are some of the effects occurring in a supply chain not intuitively easy to grasp for individuals especially as the perspective is often only limited to the own enterprise and not necessarily on the whole supply chain.

Applied tools in the risk management process

A well-established tool used in the business world when it comes to analysing dynamic and complex system is business modelling and simulation. Computer simulation offers, compared to the mentioned approaches, the possibility of incorporating the discussed risk drivers in the analysis as it follows a stochastic and not a deterministic approach.
By creating a virtual environment time delays between cause and effect, respectively stochastic distributions of material and information flow are considered in the analysis. Business modelling and simulation could be distinguished in three different paradigms, whereby each of them is used in a distinctive context depending on their view on reality.

- Discrete Event Modelling
- Continuous Modelling
- Agent Based Modelling

Examples of a successful application of the individual simulation paradigm in the context of risk management could be found among others in Sterman (Sterman, 2000), Tiehl (THIEL, 1996), Chang (Chang, 2001), Riane (Riane, 2002), Datta (Datta, 2007), Forget et al. (Forget, D'Amours, & Frayret, 2008), Chinbat et al. (Chinbat et al., 2009) and Schmitt et al. (Schmitt et al., 2009).

The Learning Organisation

When looking at a supply chain from an organisational science perspective it becomes obvious that one of the main characteristics is an increasing level of internal and external complexity that needs to be managed.
A key success factor for an organisation is the development towards a learning organisation. Senge (Senge, 2006) describes that a core element for an organisation in order to achieve sustainable success is the implementation of system thinking.
System thinking is closely linked to system dynamics describing how positive and negative feedback loop in a combination with time delay cause non-linear

dependencies between variables in a system. The challenge for a risk management organisation is now to implement the perspective of continual development and learning on supply chain's behaviour into a training enhancing individuals' perception.

The combination of these three paths defines the research question for this thesis following the main hypothesis **that in order to achieve sustainable learning in its' SCRM process of risk management and monitoring a project management driven organisation needs to apply business modelling and simulation as a virtual world environment.**

## 1.4. Research methodology and ethical considerations

### 1.4.1. Research methodology

**Research methodology** and the development of a comprehensive research strategy and approach are the result of an evolving process in familiarising oneself with the concept of research philosophies and its various dimensions. This process is not to be considered as a linear one but rather iterative, potentially involving multiple loops of evaluating the compatibility of the chosen approach and the research object and target. The basic understanding that using the suitable approach "[…] is the only guarantee that the knowledge obtained is valid, reliable and thus scientific" (Williams, May, & Wiggins, 1996, p. 15).

The way of how research is approached is defined in methodology. It follows a principle of cascading down various steps, starting from the researcher's believes and then gradually defining the generally chosen method and tools.

The research onion shown below in the figure 1.4-1 outlines the different cascades and therefore steps the researcher needs to take when conducting the research.

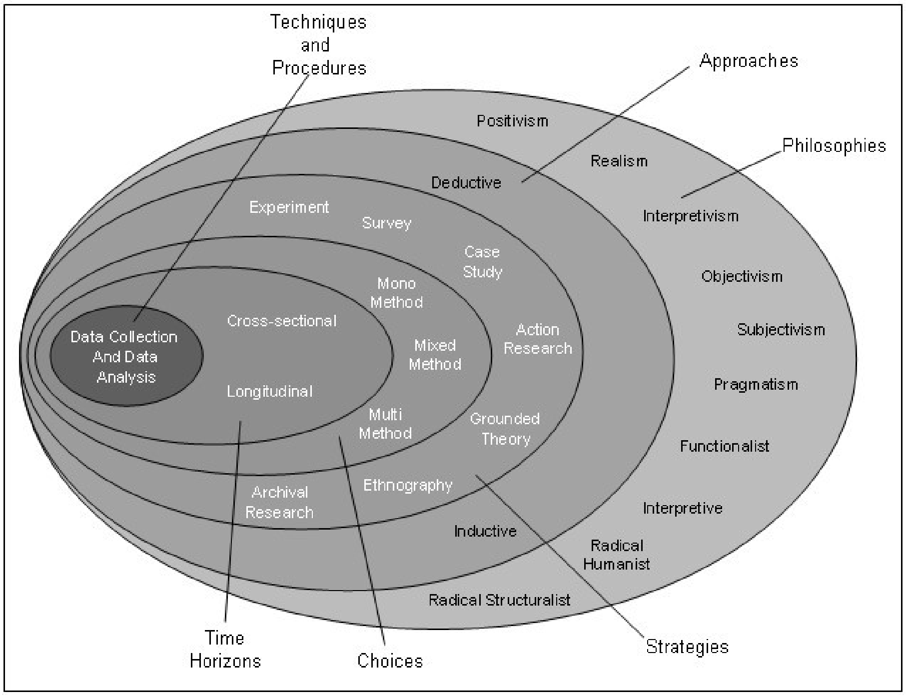


*Figure 1.4-1: From research philosophy to research methods*

The choices which are taken in every step are always chosen in dependency of the previous one. The different dimensions which need to be considered when choosing a research philosophy are:

- **Ontology**: The researcher's view of nature or reality of being
- **Epistemology**: The researcher's view regarding what constitutes acceptable knowledge
- **Axiology**: The researcher's view of values in the research

Smith describes in his contribution to Luciano's "The Blackwell Guide to the Philosophy of Computing and Information" that **ontology** seeks:" to provide a definitive and exhaustive classification of entities in all spheres of being. The classification should be definitive in the sense that it can serve as an answer to such questions as: What classes of entities are needed for a complete description and explanation of all the goings-on in the universe?" (B. Smith, 2004, p. 155). **Epistemology** has undergone an evolution in its philosophical depiction but in today's […] "much recent work in formal epistemology is an attempt to understand how our degrees of confidence are rationally constrained by our evidence, and much recent work […] an attempt to understand the ways in which interests affect our evidence, and affect our rational constraints more generally." (M. Steub & R. Neta, p. 1), whereas "[David] Hume's theory of knowledge (epistemology) is perhaps the best known example of philosophical doctrine known as "empiricism"" (Williams et al., 1996, p. 15).

Furthermore, a decision regarding the research approach needs to be taken. The two methods which are used are either deductive or inductive. Working **deductively** means to consult the theoretic background of the topic, followed by setting initial hypothesis which are then tested and either could be proofed or disproved. In order to proof or disprove the hypothesis, **empirical data** needs to be collected.
When the **inductive** approach is chosen, when several observations indicate a certain pattern leading to a tentative hypothesis upon which a theory is built. Toepfer (Töpfer, 2010) argues that, when considering the reality in which the researcher acts, only a combined approach will lead to the desired result.

As mentioned, empirical data is required in the process of hypothesis testing. The way this data is collected could either be in a **qualitative** or **quantitative** way. Qualitative research uses tools like interviews and questionnaires to collect data from individuals, which if collected in the right amount achieve statistical significance. Quantitative research is based in the natural sciences, where every phenomenon is measurable. Applied to the field of economical science this means quantitative measures are numbers from stock markets, orders or number of customers.

How the qualitative or quantitative data is collected is decided in the research strategy. Some of the alternatives are, conducting a survey, action research, operational research or a case study.

Following Thornhill et. al (Lewis & Thornhill, 2010) the four philosophies applied in the context of management research are **positivism**, **realism**, **interpretivism** and **pragmatism**.

Positivism

Ryan argues in her article “Introduction to positivism, interpretivism and critical theory” that “[…] positivism is considered a form of or a progression of empiricism” (Ryan & Sfar-Gandoura, 2018, p. 42) and following Bryman (Bryman, 2008) should comprehend four important characteristics:

- Phenomenalism – only knowledge confirmed by the science is genuine knowledge
- Deductivism - theory generates hypothesis that can be tested for provable laws
- Objectivity – science must be value free
- Inductivism – knowledge is gained by gathering facts that provide the basis for laws

Interpretivism

In contrast to positivism interpretivism argues that “[…] truth and knowledge are subjective, as well as culturally and historically situation, based on people’s experiences and their understanding of them” (Ryan & Sfar-Gandoura, 2018, p. 43).

Realism and Pragmatism

Seeking for an adequate representation of real-world systems, both realism and pragmatism, are taking an objective approach when referring to their interpretation of ontology and epistemology, however using the individual human context (Lewis & Thornhill, 2010, p. 119).

While the above describes the various aspects of research philosophy and approach in general authors like Kotzab (Kotzab, 2005) are putting the general discussion into the context of supply chain management. In his edited compilation of essays Kotzab is summarizing the state of the art in regards to surveys, case studies, action research and modelling of supply chains.

Golicic et al. (Susan L. Golicic, Donna F. Davis, Teresa M. McCarthy, 2005) identify one of the main ambivalent characteristics of supply chain management research. The basis of logistical and manufactural movement is clearly to be observed under a positivistic paradigm, however, as supply chain management is more and more considered as a key strategic variable the qualitative side of understanding ones rational in setting up those systems becomes more and more relevant. This fact strongly suggests to open the research towards interpretivism. Findings like those encourage researchers like Golicic et al. in referring to Dunn (Dunn, Seaker, Stenger, & Young, 1994) to argue "[…] that logistics and supply chain researchers appreciate and encourage methodological diversity in their research programs in order to thoroughly understand the critical issues facing the discipline" (Susan L. Golicic, Donna F. Davis, Teresa M. McCarthy, 2005, p. 23). The essay follows to name Ellram as another strong advocate for the application of mixed or balanced methods applying quantitative and qualitative approaches throughout several publications (Ellram, 1991), (Ellram, 2002).

However, this dilemma is not easy to be solved when approaching the target research of this thesis.

Assessing the various alternatives of collecting primary data as part of the research strategy in the discussed research onion has as well been subject of multiple discussions in the research community. Van Donk and Van der Vaart (Dirk Pieter van Donk, Taco van der Vaart, 2005) point out that for example both strategies on the qualitative side, surveys as well as case studies have their pitfalls, i.e. that the length of a questionnaire suffers an opposing effect of amount of information with theoretically could be obtained versus the motivation of participants to conduct the entire work or, in respect of the case study that the selection of the assessed case is predetermined by the chances of success.

However, when conducted thoroughly they are well suited for scientific enquiry in the field of supply chain management.

While authors like Yin (Yin, 1994) and Stake (Stake, 1999) are describing and arguing for the case study as part of a general approach of a research strategy which will be further discussed in thesis prior to the actual application in the thesis, Seuring (Stefan Seuring, 2005) provides in his article:" Case Study Research in Supply Chains – An Outline and Three Examples" three examples which outline the two core question that are to be answered in an supply chain management application of a case study:

- How can a suitable supply chain which can serve as a case be identified?
- How can access be gained to the different stages of the supply chain to allow data collection at some or all relevant stages?

When discussing the choices leading up to a decision on how the actual research is conducted Lewis and Thornhill (Lewis & Thornhill, 2010) distinguish between **mono method, mixed method** and **multi method**. In his article "Supply Chain Management Research Methodology Using Quantitative Models Based on Empirical Data" (Gerald Reiner, 2005) Reiner is providing a solid foundation for the utilisation of modelling as part of mixed method concept. By referring to Krajewski (Krajewski, 2002), Rocco et al. (Rocco, Bliss, Gallagher, & Perez-Prado, 2003) and Voss et al. (Voss, Tsikriktsis, & Frohlich, 2002) Reiner is outlining that not only researchers should make an active effort to adjust previously hold reservations against mixed methods in order to satisfy today's challenges in the scientific community but also to specifically answer to the questions raised in the area of supply chain management and the described interface between a "[…]dominant positivist epistemology" (Gerald Reiner, 2005, p. 440) based its quantitative heritage and newer approaches such as strategy and customer relationship management.

Provided the assessed framework following breaking down the scientific approach from philosophy to application with the special focus on its application in the field of supply chain management, the thesis will follow a mix of phenomenological and positivistic philosophies, as the main target is to analyse human behaviour within a complex system triggered by clear heuristic rules.
In a first step a comprehensive literature review on the topics of SCRM, application of business simulation in the context of risk management and organisational learning sets the foundation.
A deductive approach will be pursued, applying a "top-down" taxonomy leading from theory to hypothesis to observation to a final confirmation, which will then be verified by an indicative exemplary case study.
The input for the exemplary case study will be based on the structure of a real-world application providing scalable and measurable input for a simulation model.

### 1.4.2. Ethical consideration

Considering the fact that the thesis is partially based on qualitative research conducted in form of semi-structured interviews, a firm understanding of the ethical implications surrounding interviews and the way how qualitative research is conducted is crucial.

Lewis and Thornhill (Lewis & Thornhill, 2010) describe that within the area of business management two ethical considerations widely considered. The deontological and the teleological view.

Israel and Hay (Israel & Hay, 2006) are using the terminology of consequentialist when describing the teleological approach and non-consequentialist when referring to the deontological approach.

The opposing character of both approaches is, that the teleological view ultimately justifies the practice of unethical research with the ultimate result to be archived, while the deontological approach generally rejects an unethical method regardless of the targeted result (Lewis & Thornhill, 2010, p. 184).

The underlying philosophical approach of the non-consequentialist, deontological approach is strongly linked to the work of Immanuel Kant and the categorial imperative dictating the logical process of determine if behaviour is to be considered ethical (Israel & Hay, 2006, p. 15).

While the philosophical concept seems abstract the actual consequences and implications on business management research are fairly tangible. In their article:" Business Research Ethics: Participant Observer Perspectives" Wallace and Sheldon are specifically assessing the ethical risk associated with low-risk business research conducted as part of a doctoral thesis in the context of the Australian National Health and Medical Research Council providing a frame work for social research in general (Wallace & Sheldon, 2015). According to the authors:"[…] it may be argued that much business and management research is informed by social science principles and methods, and no research is entirely value free or exists in a completely risk-free context" (Wallace & Sheldon, 2015, p. 267).

Figure 1.4-2 illustrates an adapted view of the various challenges which, according to Lewis and Thornhill (Lewis & Thornhill, 2010, p. 188), are to be addressed in each stage of the research.

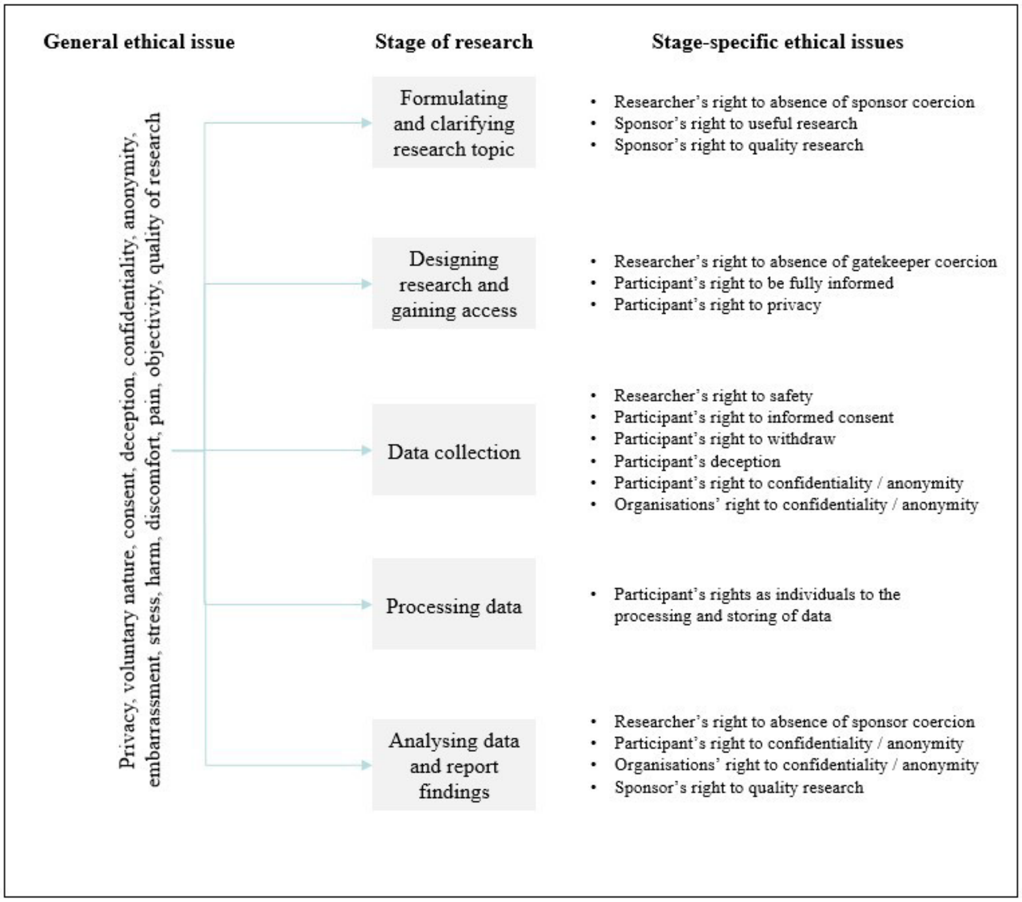


*Figure 1.4-2: Ethical issues at different stages of research*

When assessing the various examples, it becomes obvious, that conducting ethical research mainly refers to a compliant relationship among the involved stakeholders, namely the researcher, the participants and if applicable any organisations or sponsors as well as the observance to quality standards.

In the context of this thesis the aspects the most relevant aspects are linked to the relationship and agreements between participants and researcher in addition to the data processing and storage.

The overall objective of conducting compliant research has been achieved by taking the following steps in line with the theoretical framework.

- None of the selected participants in the semi-structured interview is considered vulnerable due to either age, personal background or relationship with the interviewer
- The discussed content is not of a private or confidential matter
- All participants have been informed and provided consent to being voice recorded during the interview as well as to the utilization of the answers and data provided
- All participants have been anonymised
- All data relating to the conducted interviews is stored in a password protected cloud data storage

Ethical clearance for the research project has been granted by the University's ethics commission.

## 1.5. Existing approaches and their shortcomings

A large body of literature exists on the topic of supply chain risk management describing the need for further development of the field itself. Since the topic has become a focus point within the academic and industrial world around the year 2000 a lot of progress has been made in defining and further developing the concept. However when assessing the stringent view of the scientific community the consistent need for a comprehensive approach covering methodology, process, approach and tools remains evident as expressed by Svensson (Svensson, 2002), Riddalls and Bennett (Riddalls & Bennett, 2002), Ivanov and Sokolov (Ivanov & Sokolov, 2010), Peck (Peck, 2003), Kamalahmadi and Parast (Kamalahmadi & Parast, 2017), Ho et al. (Ho, Zheng, Yildiz, & Talluri, 2015), Rajagopal et al. (Rajagopal, Prasanna Venkatesan, & Goh, 2017) and Elleuch et al. (Elleuch, Dafaoui, Elmhamedi, & Chabchoub, 2016).

As discussed, mainly analytical and qualitative tools are used in the process of risk identification, assessment and managing/monitoring, resulting in the uncertain situation for supply chain managers identifying potential effects caused by decisions made related to a complex system. Authors taking this line of argumentation are among others North and Macal (North & Macal, 2007), Robinson (Robinson, 2004), Kelton et al. (Kelton, Sadowski, & Sturrock, 2007), Sterman (Sterman, 2000) and Thierry et al. (Thierry, Thomas, & Bel, 2008).

Computer simulation, as mentioned, seems to be a promising addition to support the mentioned decision taking / evaluating process. Existing approaches of the application of business simulation and modelling to the field of supply chain risk management indicate a supporting function in the decision-taking process, however they are either limited to a single entity of the supply chain or they are limited to a single simulation paradigm which therefore limits the supporting scope.

Manny of the published articles on the topic either focuses on a single point of application, meaning for example the OEM shop floor or excluding parts of the holistic supply chain system, e.g., the planning part and purely focussing on the material flow. For the individual purpose of the respective publication this of course is sufficient but leaves a gap concerning the overall supply chain perspective.

A further shortcoming of existing approaches is the lack of educational use a simulation tool offers. A simulation offers the possibility of evaluating the cause-and-effect dependencies of a complex system in a virtual world environment. The identified lack is the incorporation of the principles of the organisational learning into the concept of supply chain risk management.

## 1.6. Business modelling and simulation for the learning supply chain risk management organisation for projects

"An organisation's ability to learn, and translate that learning into action rapidly, is the ultimate competitive advantage."[1]

Based on the pure statement it is difficult to assess in which context Jack Welch was considering organisational learning when making it, but in the end, it does not matter as the concept itself represents entirety. The competitive advantage is given whether the action is triggered to influence a positive or negative event with either re-enforcing or minimizing it. Organisational learning is a structured framework, when combined

[1] http://www.brainyquote.com/quotes/quotes/j/jackwelch173305.html (Aug. 24th, 2.52pm)

with the appropriate approach such as business modelling, representing an adequate answer when facing risks in a complex supply chain network.
By its design, the general approach how organisational learning is tackling problem solving and aiming at improvement via i.e., the five disciplines by Senge (Senge, 2006) which are to be discussed in detail in chapter 2.3, seem to fit in a very complementary way to the risk characteristics of today's supply chains. Especially the aspect of system thinking directly creates a connection between the way how an organization improves over time and the key critical aspects of dynamic feedback loops, parallelism and influence of probability which have been established earlier.
In combination with the technical abilities provided by today's powerful business model and simulation tools and environments the rare opportunity of combining and therefore creating a new framework of managing supply chain risks sustainably in an organisation, could be created.

## 1.7. Contribution to knowledge

The contribution to knowledge of the PhD thesis is a literature review on current methods facilitating the decision-making process with SCRM with the main focus on the application of business modelling and organisational learning in a project management environment.
An empirical research of SCRM decision-making structures and policies evaluated in a multiple simulation approach

A development of a generic simulation model designed towards the needs of a learning SCRM organisation.

- The example model will be able to represent the most relevant kinds of supply chain risks according to the respective supply chain type
- The example model will be able to show the supply chains' behaviour after introducing SCRM measures
- The example model will be valid enough to describe these effects, but at the same time simple enough to be used and validated by non-simulation experts like supply chain managers

# Chapter 2

# Literature Review

This chapter sets the baseline for all following analysis and inquiries conducted in the thesis. The process of establishing the current state of the art is following the concept of the triangle introduced in the beginning of the thesis. Aim is to provide an overview on the existing research body connecting the triangular of supply chain risk management, business modelling and the learning organisation.

The paragraph 2.1. supply chain management and risk will primarily describe the development of supply chain management deriving from logistical concepts. In a next step this concept will be put in the context of risk management and the existing state of the art on research on the topic.

Paragraph 2.2. introduces the concept of business modelling and simulation to the area of supply chain risk as a potential management tool and framework and describes the state of the art of applying discrete-event based, continuous and agent-based simulation to the area of research.

Concluding on the mentioned triangle of supply chain risk management, business modelling and organisational learning paragraph 2.3. describes the published knowledge in applying simulation techniques to the area of supply chain risk management.

The body of literature that has been analysed and consulted for this thesis is generally following the previously introduced triangle with the main emphasise of supply chain risk management, business modelling and simulation and organisational learning.

Aiming at the adequate balance between well-established sources and, i.e., text books, and journals or conference proceedings which are continuously discussed in the scientific community the thesis is supported by the split shown in in figure 2.0-1.

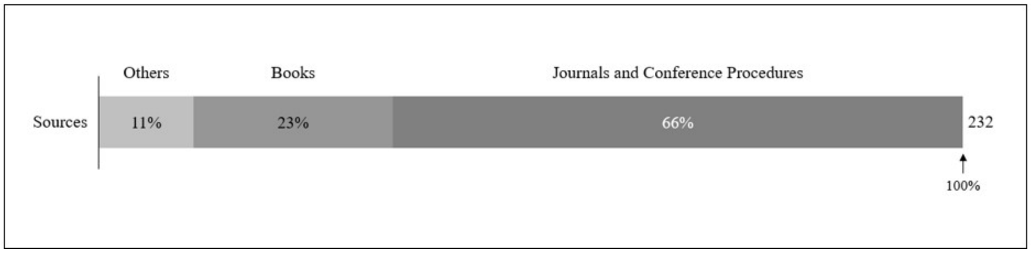


*Figure 2.0-1: Overview of literature sources per type of publication*

The vast majority of the overall 232 sources, 66% is either taken from journals or conference proceedings, whereas 23% of the consulted literature are text books. The remaining 11% are mostly referring to internet documents and publications.
Within the group of scientific journals, it is to be mentioned that in particular the publications in the Journal of Physical Distribution & Logistics Management. Figure 2.0-2 illustrate the journals mostly cited in the thesis.

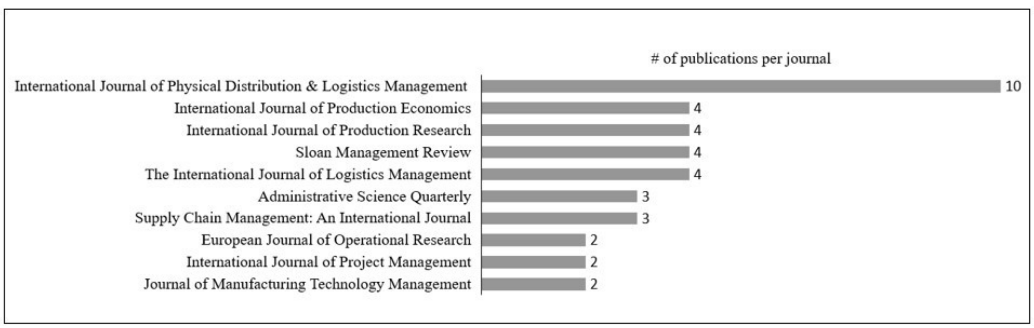


*Figure 2.0-2: Ranking of mostly quoted journals*

In order to manage and allocate sources more efficiently in respect to the different focus areas in the thesis a structure covering ten categories has been developed separating the 232 references. As shown in figure 2.0-3 the three core themes of the applied research triangle are occupying the majority of sources with 50 references in the area of supply chain risk management, 48 in organisational learning and 44 in business modelling and computer simulation.

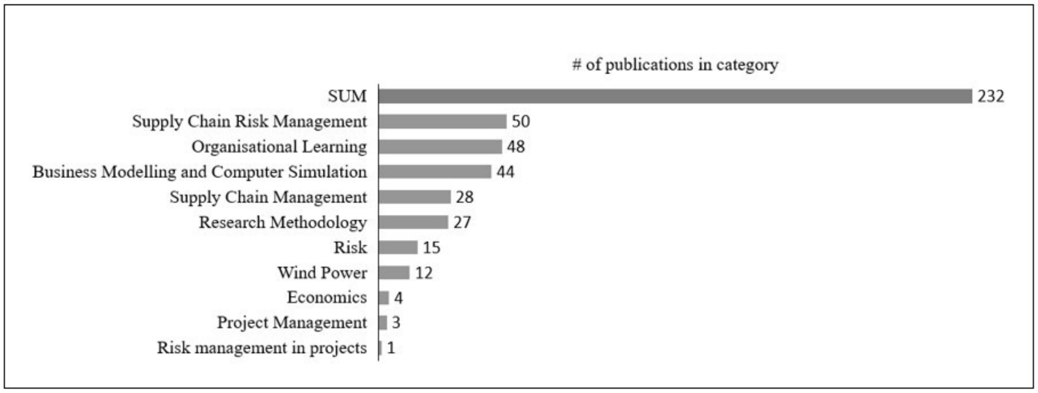


*Figure 2.0-3: Overview of literature sources per research category*

The purpose of the remaining categories is to further support and substantiate the discussion of the main research areas.

Considering the actuality of sources consulted for the thesis figure 2.0-4 provides an overview the considered timeframe.

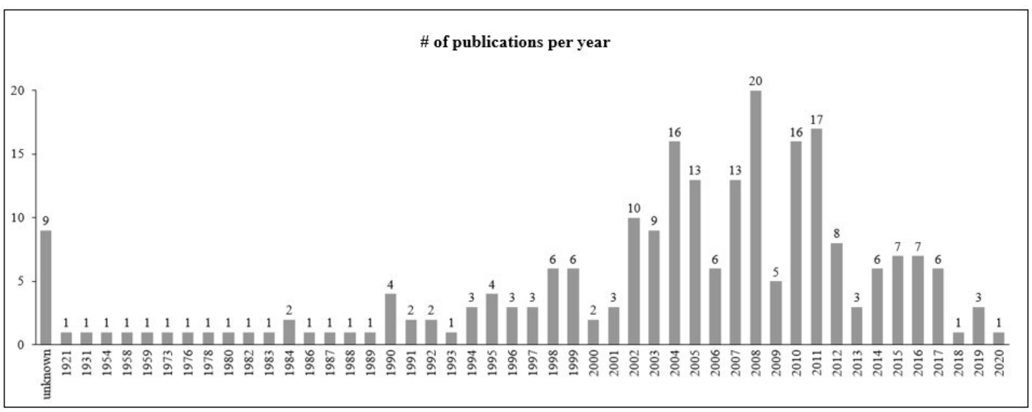


*Figure 2.0-4: Overview on main sources consulted for thesis displayed per year of publication*

Notably, the main publications covering supply chain risk have been published around the turn of the millennium, following another peak around the financial crisis around following 2008 with a continuous relevance in the years to follow indicating that the supply chain risk management became a well-established subject in the research community.

## 2.1. Supply chain management, logistics and risk

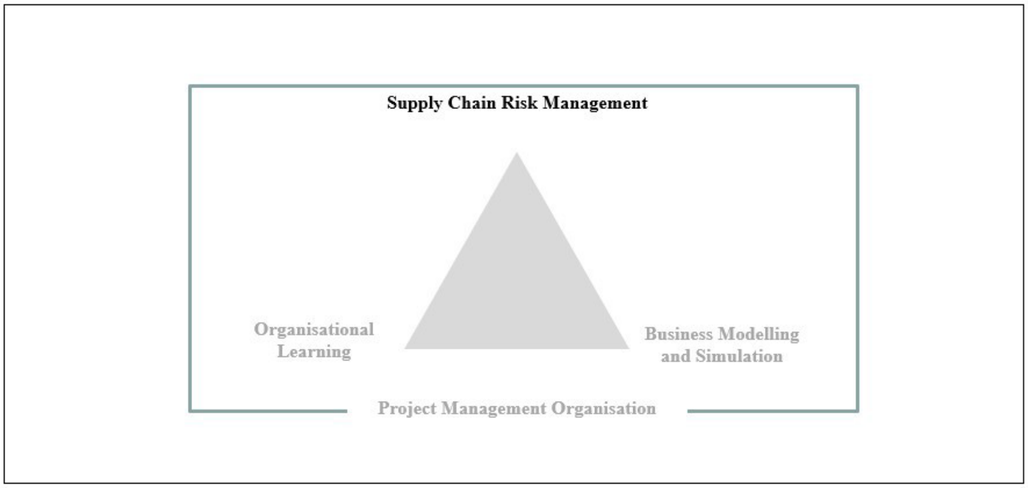


*Figure 2.1-1: Supply Chain Risk Management as part of the research triangle*

If the concept of logistics defines the transport, transhipment and storage of goods it reaches back to the 13th century when merchants all over Europe organised trading routes and developed the concept of, first domestic and finally international markets. (Gudehus, 2010)

The historical background of the word logistics is based in the military and defined a process of delivering supplies to the troops. In today's understanding logistics is "[…] the process of strategically managing procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organisation and its marketing channels in such a way that current and future profitability is maximised through the cost-effective fulfilment of orders." (Christopher, 2004, p. 4)

This definition already indicates the main differences between the two concepts logistics and supply chain management. Logistics, in contrary to supply chain management, focusses on the internal organisation of a single enterprise and thereby represents the origin of modern supply chain management which overcomes these boundaries by considering the full value chain from raw material to final customer.

Harland (Harland, 2008) refers to Oliver and Webber as one of the first times when the term supply chain management was used in the context of having a positive impact on business performance by integrating functions like procurement, manufacturing into sales and distribution.

Since then, an impressive diversification of the term and has happened both in the academic world and the practical application of the concept.

In his dissertation, Ziegenbein (Ziegenbein & Schönsleben, 2007) comprehensively summarises some of the major movements in categorising supply chain management, referring to the main authors of the respective trend, Blackstone and Cox (Blackstone & Cox, 2005), Christopher (Christopher, 2004, p. 4), Harrington (Harrington, 1995, p. 30) and Ellram (Ellram, 1991, p. 17).

**Definition of supply chain management**

| Research focus | Definition |
|---|---|
| **Functional Chain Awareness**<br>Supply chain as a sequence of functional areas (e.g. procurement, manufacturing) with a continuous flow of material | **APICS Dictionary**<br>"The design, planning, execution, control and monitoring of supply chain activities with the objective of creating net value, building a complete infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally." |
| **Linkage/Logistics**<br>Connections (Relationships) of functional areas via the flow of material with a special focus on logistics and transport | **Christopher, M.**<br>"The management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole." |
| **Information**<br>Focus on the flow of information between the different partners in the supply chain | **Harrington, L.**<br>"Product and information flow encompassing all parties beginning with the supplier's supplier and ending with customers or consumer/end user." |
| **Integration/Process**<br>Supply chain as chain of connected processes and as a holistic system | **Ellram, L.**<br>"[...] an integrative approach to using information to manage the materials flow from suppliers to end-user to achieve improved customer service at reduced overall costs, SCM represents a network of firms interacting to deliver a product or service to the end customer." |

*Figure 2.1-2: Overview of Supply Chain Focus*

A general distinction that is made when characterising a research focus by which a supply chain is analysed is the separation in qualitative and quantitative consideration of the topic.

While many authors like Christopher and Harrington emphasise that, besides the technical integration of various functions in the supply the aspect of knowledge sharing represents a critical success factors other authors like Hopp (Hopp, 2011) and Hopp and Spearman (Hopp & Spearman, 2001) take a rather technical position towards the supply chain and analyse the concept from a system perspective.

The definition and perception of the term supply chain that is used in this thesis is a combined approach of Christopher (Christopher, 2004) and Hopp as both of them start their analysis at the overall aim of improving the customer value and subsume all downstream activities towards this goal.

Already in his introduction to the subject Hopp (Hopp, 2011, p. 1) emphasises that "the link between strategy and operations [supply chain management] lies in an organisation's value proposition. Firms that offer products or services compete on the basis of some combination of:

- Cost
- Quality
- Speed
- Service
- Variety

These, partly counteractive, factors need to be combined on different levels in the supply chain, namely on a single production step (i.e., a drilling machine), on a routing level (i.e., a full production line in car manufacturing) and a network (i.e., a supply and production network of engineering company manufacturing infrastructure projects).

The counteracting relationship is visualized in the graph 2.1-2 taken from Hopp (Hopp, 2011, p. 3) as a trade-off between efficiency frontiers.

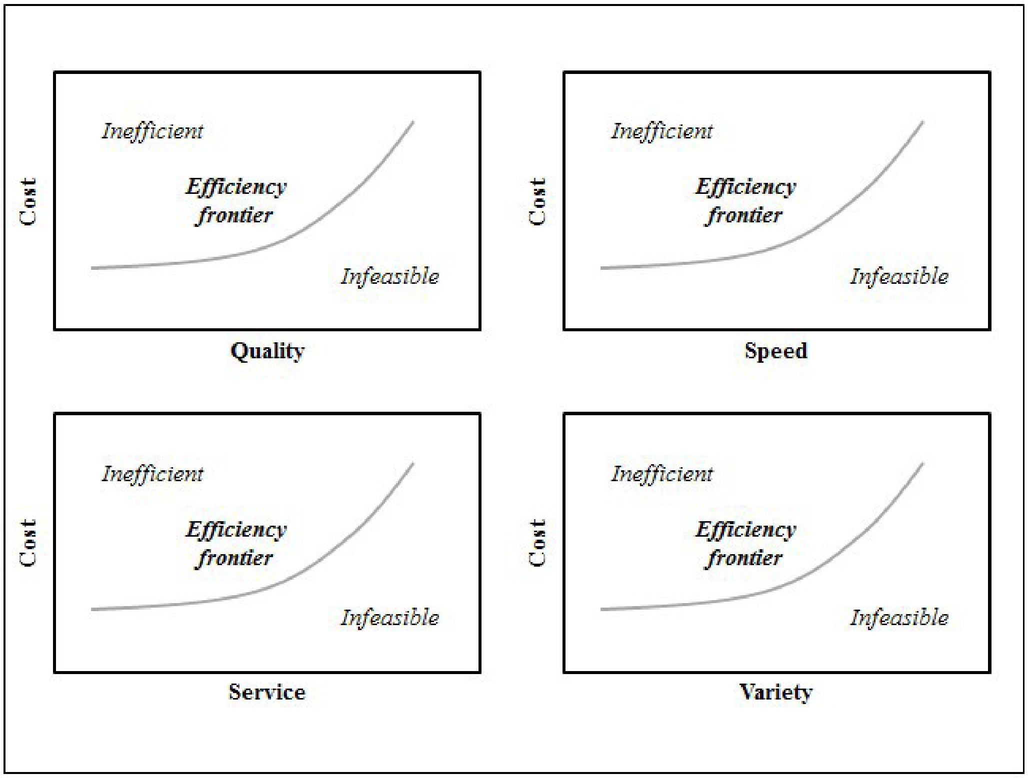


*Figure 2.1-3: Efficiency frontiers in supply chain management*

Christopher (Christopher, 2004, p. 46) defines the strategic customer value as the relationship between:

$$Customer\ \ Value\ = \frac{perceived\ \ value}{TOC}$$

The perceived value is directly linked to factors like quality, on-time delivery/flexibility, the Total Cost of Ownership (TOC) are mainly connected to the customers' invested capital and the dedicated time spend. From a customers' perspective the overall profitability is always connected to the Return on Investment (ROI)

$$ROI\ = \frac{profit}{investment}$$

Deriving from these target definitions of supply chain management every organisation, no matter in which industry it is active, needs to define a **supply chain strategy** developing a concrete model of target achievement under the consideration of marginal cost development.

### 2.1.1. Supply chain strategy

A supply chain strategy as does not exist as a stand-alone strategy in an organisation, it is always part of on an integrated framework serving an overall corporate strategy combining multiple targets.

Representative for the general opinion on strategy in the field of supply chain management, Chopra and Meindl (Chopra & Meindl, 2010) apply the following view.

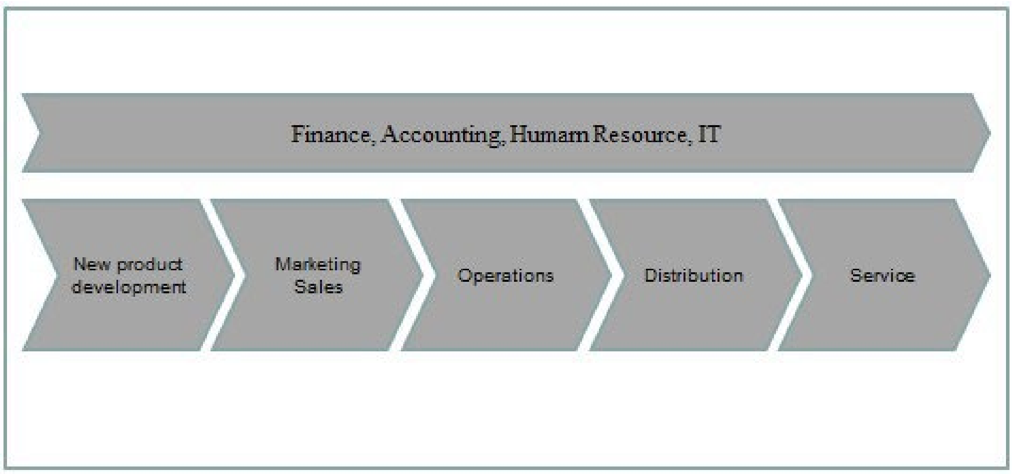


*Figure 2.1.1-1: Corporate strategy - functional subset*

Figure 2.1.1.-1 visualises the connection between the various functions in an organisation which together from a corporate strategy.

When approaching the strategy for the supply chain organisation Chopra and Meindl suggest a three-step model:

1. Understand customer and supply chain uncertainty
2. Understand supply chain capabilities
3. Merge dimensions

In order to understand the customer of a supply chain network needs to understand:

- The quantity of the product needed
- The response time that a customer is willing to tolerate
- The variety of a product needed
- The service level required

- The price of the product
- The desired rate of innovation in the product

Slack and Lewis (Slack & Lewis, 2008) define the operations or supply chain strategy as the result of inter-organisational and external influences. A top-down approach in the form of a corporate strategy verified by a bottom-up approach validating the supply chain capabilities combined with the external factors of capacity in the supplier network versus market requirements. In a consequent manner they describe the various decision areas as a result of a system equation as visualised in figure 2.1.1-2. (Slack & Lewis, 2008, p. 23)

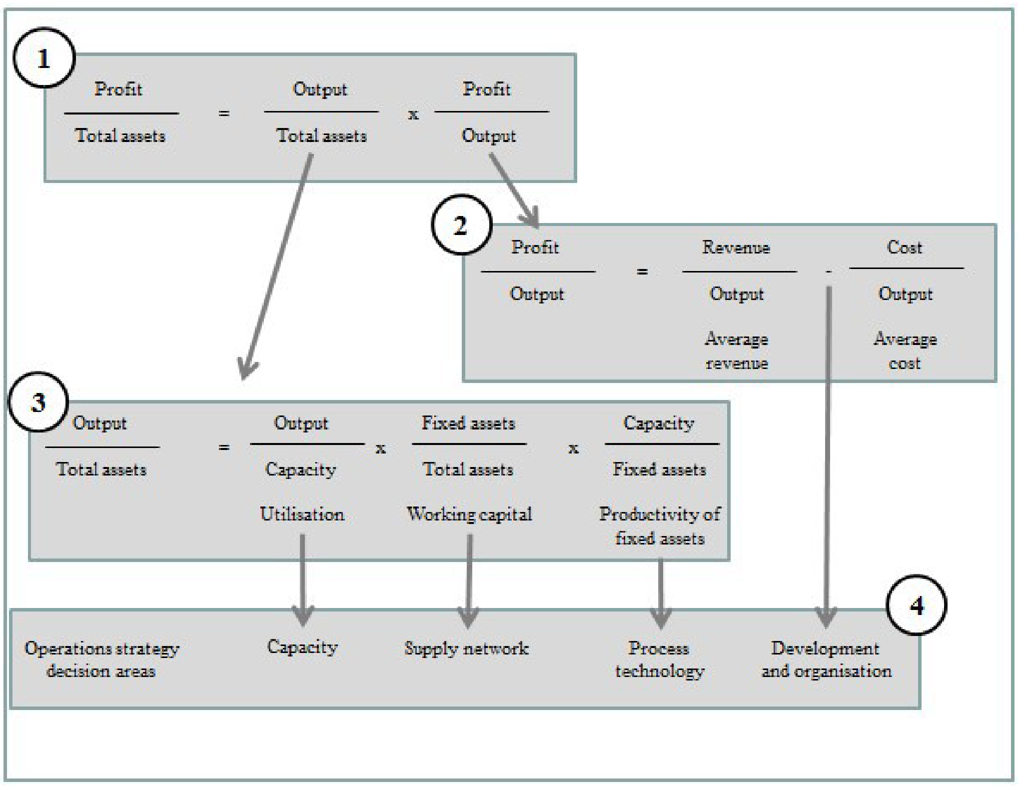


*Figure 2.1.1-2: Supply Chain Strategy Decision Factors*

The overall approach consists of an evaluation of the Return on Assets (ROA) as an internal key performance indicator (KPI), the equation by which the ROA is described is profit divided by total assets (1).

In comparison to the already discussed approach of measuring customer satisfaction by analysing the ROI, this view focusses stronger on the internal performance of the invested resources and goods.
The two ratios which are used to describe the relationship between performance and investment are **output divided by total assets** and **profit divided by output**.

The second equation monitors the average profit that is achieved by connecting investment with revenue and hence the customer.
It shows for example the positive impact of higher revenue due to e.g., increased quality and an under proportional increase in cost.

Output divided by total assets represents the produced value for the investment that being put into the operation. It consists of three main ratios influencing the following decision areas concerning supply chain strategy:

- Capacity
- Supply network
- Process technology

<u>Capacity:</u>
Defined by the equation of output / capacity it monitors the balance between demand towards i.e., production and the ability of a supply chain organisation to meet this demand. This KPI, also frequently referred to as utilisation, needs to be close to 1.
As part of his system perspective Hopp defines capacity as one of the major factors influencing performance of a supply chain system, namely **Throughput, Work in Process and Cycle Time**. He defines capacity as: "[…] the maximum average rate in which entities can flow through the system." (Hopp, 2011, p. 13)
As indicated by the used equation, the relevant is not only the capacity but also the frequency by which it is used, and then named utilisation.

Supply network:

Within the area of supply network, a supply chain organisation needs to apply decisions concerning on how the organisation is interconnected to the network of other operations from customer and supplier.

Process technology:

Process technology implies decisions on how an organisation plans and executes on its manufacturing facilities. Decision which are for example taken in this field are which production planning approach is used and how the internal flow of material, information and financials could be organised.

Concluding on the discussed perceptions towards defining a supply chain, respectively its strategy, the following figure 2.1.1-3 represents the applied approach for this thesis combining qualitative and quantitative aspects.

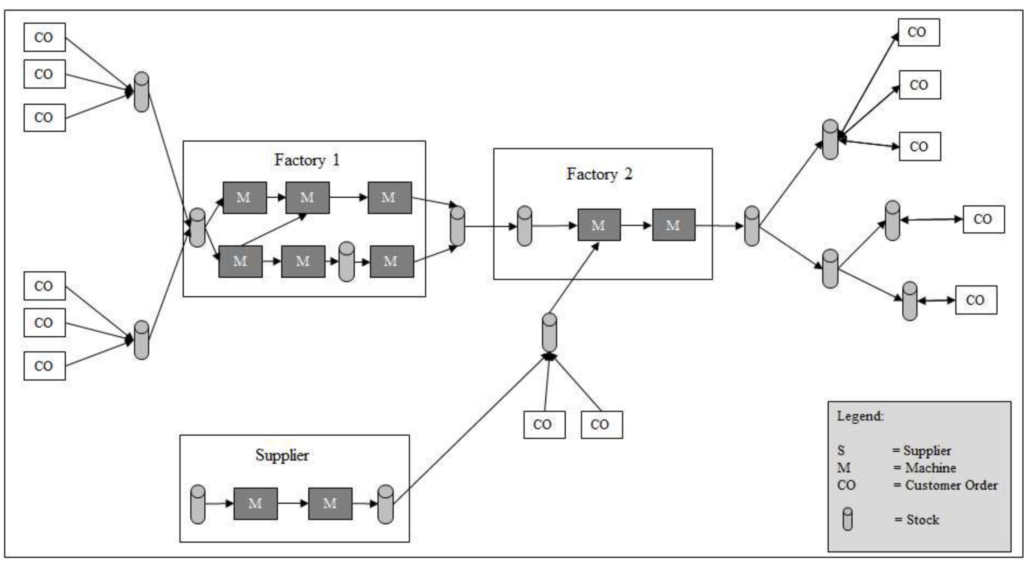


*Figure 2.1.1-3: Supply Chain Network*

The main factors which are defining the operational flow of goods, financials and information in a supply chain system are, as per self-conducted assessment with reference to Ziegenbein (Ziegenbein & Schönsleben, 2007):

- Focal company[2]
- Network
- Relationship

### 2.1.2. Supply chain operations

In contrast the supply chain strategy, the supply chain operation focusses on implementation. It covers the specific actions a supply chain organisation is taking to realize its strategic goals.

Concerning the current state of the art supply chain operations, although closely linked, could be distinguished into the tangible part of **goods and stocks** and the intangible part of **planning and steering.**

2.1.2.1 Goods and stocks

A first and crucial distinction that need to made when analysing the material flow and stock behaviour of a supply chain system, both in the academic world and the operational business, is the one into **planned** and **unplanned stock**.

Sterman (Sterman, 2000, p. 663) sees **three main reasons** causing the appearance of **unplanned stock** in supply chain network. The order volume is instable; it is subject of **oscillations**, which in a self-enforcing way are getting more and more severe throughout the supply chain, meaning they are affected by **amplification**. When a supply chain organisation is reacting towards these negative effects it could only do this with a certain reaction time causing a **phase lag**, which de-couples the linear link between cause and effect of an action.

The general target of a production system as described by Hopp (Hopp, 2011, pp. 1–36) is to deliver a high **Throughput (TH)** of products only keeping a minimal level of **Work in Process (WIP)** stock in the production system at the lowest possible **Cycle Time (CT)**.

[2] The term focal company defines the most prominent node in a supply chain e.g., the OEM in an automotive supply chain

The performance of the production system could be measured by assessing the **inventory turns,** whereby each of the applied variables is depend on several factors.

$$Inventory \quad turns = \frac{TH}{WIP}$$

In order to assess what different factors affect the above-mentioned equation, figure 2.1.2-1 illustrates a simplified production process.

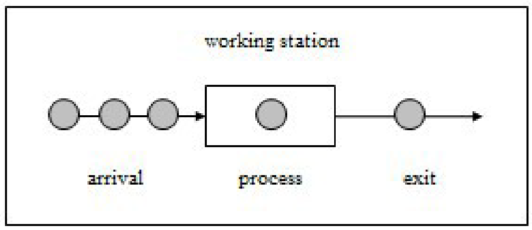


*Figure 2.1.2-1: Production Process - Station*

Customer orders arrive with a creation timely distribution at a work station where they are processed consuming production time. In important factor influencing this process is the already discussed **capacity**, respectively the applied **utilisation**. By analysing the utilisation rate of each production step in i.e., a manufacturing line the bottleneck could be identified. The bottleneck is the working station with the highest utilisation rate.

Applied in a production set up this means that: “The output of a system cannot equal or exceed its capacity”. (Hopp, 2011, p. 15)

The reason for this is **variability** or **oscillations** which causes, referring back to Sterman, an increase in unplanned stock.

If in a production system with a constant arrival time of customer orders the process time is disturbed and hence prolonged which has a negative impact on the capacity the WIP (the unplanned stock in the production system) will continuously grow.

In a system where the production rate equals the arrival rate of orders or products stocks will be built up over the long run, as the system won’t have any free capacity in order to compensate any previous disruption.

Connected to the utilisation rate could be stated that with every additional unit (WIP) the utilisation is peaking towards 100%, however, this is not linear but convex as probability of additional variance is in the system is increasing. Deriving from this observation is could be stated that the volume of WIP and hence the CT are increasing over proportionally compared to the achieved utilisation. In reality a utilisation rate of 100% will not be achieved as the increase asymptotic towards the capacity limit as shown in figure 2.1.2-2.

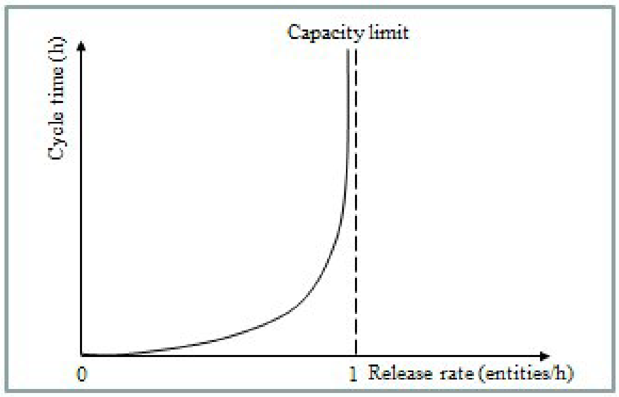


*Figure 2.1.2-2: Limits of Utilisation*

As a conclusion could be stated that first and foremost the variability of different elements (TH, WIP and CT), as part of a dependency on various factors (capacity and utilisation), are responsible for the existence of unplanned stock in a supply chain system.

In order to manage this variability properly it has to become measurable. One approach on this is the queuing theory.

The applied principle is the so called Little's Law referred to in Hopp (Hopp, 2011, p. 22), which says that: „Over the long-term, average Work in Process (WIP) and Cycle Time (CT), for any stable process are as follows:

$$WIP = TH \times CT$$

Variability as part of the cycle time could affect either the arrival time of the production entity or the production time. The magnitude of variability is measured by the combination of its arithmetic mean $\overline{x_i}$ and its standard deviation $\sigma$ called the coefficient of variation (CV).

$$CV = \frac{\sigma}{\overline{x_i}}$$

Hopp defines the boarders of a quantitative judgement on the variability as follows:

- CV $x \leq 0{,}75$ indicates little variation
- CV $0{,}75 \prec x \succ 1{,}33$ indicates medium variation
- CV $x \geq 1{,}33$ indicates high variation

The cycle time of every process combines **Waiting Time (WT)** and **Production Time (PT)**. Waiting time is influenced by mainly three different elements, a variability factor (V), an utilisation factor (U) the average process time for an entity of the station (T). (Hopp, 2011, p. 31)

The utilisation factor (U) is defined by the equation $U = \frac{UTIL}{1 - UTIL}$, whereby UTIL the utilisation is.

Relevant for the operational planning is the finding that high variability is most harmful in a working process with high utilisation.

Is the analysed production process affected by a high level of variation, is the only possibility of shortening waiting time to keep the utilisation factor low. Is the production process hardly affected by fluctuations it is possible to run the production process with a utilisation factor of close to 1.

In contrast to the negative effects of unplanned stocks due to waiting time problems, **planned stock** is not to be judged as purely negatively for the supply chain organisation.

Planned stock offers the organisation a higher level of flexibility when customer orders need to be satisfied on short request. The decision on the volume of stored goods always needs to be taking considering a full cost analysis including e.g., availability of production resources.

Consulting the current status of the art in field of stock planning and handling, most authors apply a simplified model of utilisation, order process and stock level. Representative for this approach the following framework, visualised in figure 2.1.2-3, is taken from Gudehus (Gudehus, 2010).

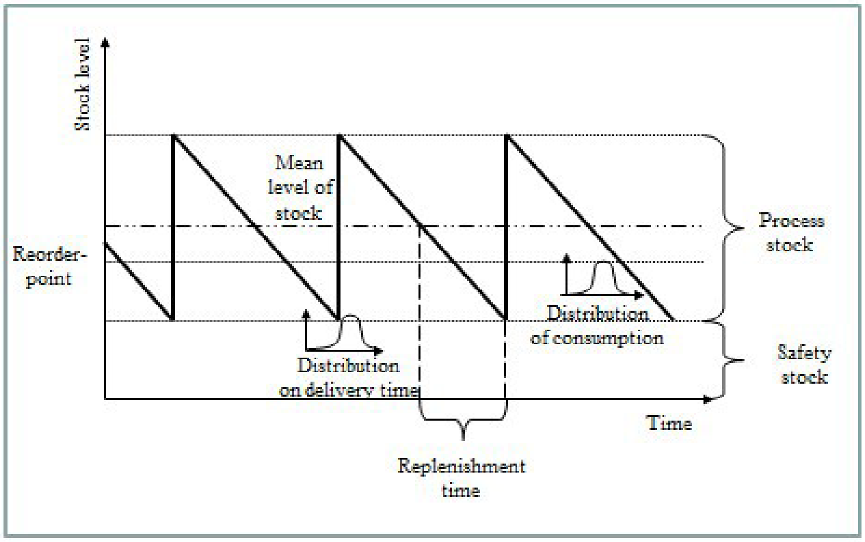


*Figure 2.1.2-3: Connection of re-ordering policy and material consumption*

As indicated in the graphic, the framework assumes that the volume of distributed goods stays constant over time. Furthermore, the model assumes that if an order is placed when the reorder point is reached the replenishment time is also to be considered as constant.

Under consideration of the stated assumptions, the average process stock is referred to as $m_N$ and equals the average supply volume. The average (overall) stock ( $m_B$ ) is the result of the following equation, whereby the average safety stock is referred to as $m_{sich}$.

$$m_B = m_{sich} + \frac{m_N}{2}$$

According to Gudehus (Gudehus, 2005, p. 371), the stock volume that is supplied to the customer is constantly deducted from the overall stock $m_B$ . Once the reordering point is reached, a pre-defined amount of goods is ordered. It is delivered after a constant replenishment time and added to the overall stock.

Following this description, the general rule is that the consumption of material may not exceed the remaining overall stock excluding the safety stock in order to avoid an idle system.

The level of material at which the reorder point is defined is now the dependent on the volume of the average safety stock and the consumption during the replenishment time

($n_{WBZn}*\square$), whereby $n_{WBZn}$ represents the average number of days for the replenishment time and $\square$ describes the average sales volume. As the reordering point is constantly changing according to these factors, the formula looks as following:

$$m_{MB}(t)=m_{sich}(t)+n_{WBZm}(t)*\square_m(t)$$

In this equation the safety stock is a freely defined buffer that ensures the ability to supply during the replenishment time and protects the supply chain system against stochastic oscillations. (Gudehus, 2005, p. 383)

The actual replenishment time varies by a certain dispersion around a mean. This dispersion is defined as:

$$s_{mWBZ}^{\;2}=n_{WBZ}*s_{\square}^{2}+\square_m^{2}*s_{WBZ}^{\;2}$$

In order to avoid a disruption of supply during the replenishment time, the safety stock needs to result from the product of a safety factor $f_s(n)$ and the mean dispersion of the material consumption during the replenishment time $s_{mWBZ}^{\;2}$

An approximation of the formula is:

$$f_s(n)=\frac{2n-1}{(1-n)^{0,2}}$$

Completing the product, the formula for the safety stock for a $n_{WBZn}\geq 50$ is:

$$m_{sich}=f_s(n_{WBZ})*s_{WBZ}^{\;2}$$

In contrary to the dynamical approach of calculating the required safety stock, this approach only accounts for the dependency of safety stock level on time frame between reordering activity till arrival of ordered material. Completely dynamic approaches also take the time spread before the reordering point. During this period the safety stock always accounts for 100% as the actual stock level is higher than the reordering level. According to Gudehus this offers a further potential of reducing stock level, this is taken into consideration for the dynamic safety stock calculation. (Gudehus, 2005, p. 383)

$$m_{sich}=f_s(\max(0,5;\min(n_{lief};1-(1-n_{lief})*m_N/(n_{WBZ}*\square_{VE}))))*s_{mWBZ}$$

#### 2.1.2.2 Planning and steering

Compared to a more historical and linear structure of a traditional supplier-vendor-customer relation today's network like supply chain structures require a rigid and comprehensive planning and steering approach of material, informational and financial flows in the system.

The additional complexity in the system is not only driven by the pure structure of the network, but also by the product which is produced and handled within the network. As already discussed, the two driving factors behind this complexity are the number of nodes and the amount of connection in a system.

This development is not intrinsically driven by the supply chain members, but a development of markets and customers.

Christopher describes four main reasons for this internal and external increase in complexity: (Christopher, 2004, p. 28)

The new rules of competition

In today's business world it is no longer about the competition between single companies or organisations; it is about the competition between whole supply chains. Due to a rising complexity in supply-, production- and distribution networks, the dependency of the single organisations linked to various partners, forces the supply chain as a whole to create and distribute customer value better than the competing supply chain. While in the past, passing on costs to the next linkage in the chain and therefore increasing the ultimate price the final customer has to pay seemed to be common practice, this attitude has changed by co-operatively optimising material-, financial-, and information flows through the system.

Globalisation of industry

A development which partly caused the previous one is the continuous globalisation of industries, which affects the overall supply chain in terms of dispensing supply- and distribution markets, as well as production facilities.

Downward pressure on price

The reason triggering this development is many folds. The deflation of prices is partly rooted in the strong tendency towards preferring commodity goods as well a rising competition from “low-cost” manufacturer.

The customers take control

Information as the main argument within the decision-making process of buying has shifted dramatically towards the customer. Due to new communication channels like the internet and the perception of transparency as a marketing feature the customer today is in the strongest position he has ever been.

These tendencies force supply chains to continuously aim at fulfilling these new customer expectations in order to survive on the market.

Concluding from this development for modern supply chain organisations it is crucial to plan and steer their resources properly and stay ahead of the competition. Chopra and Meindl point out that the advantage derived from a fast exchange and utilization of information represents today’s biggest lever that organisation have to outperform their competition. (Chopra & Meindl, 2007, p. 56)

Main reasoning supporting this statement is the fact that information could not only shorten the reaction time in a supply chain system dramatically but also, as shown in the previous paragraph on stocks, substitute physical stocks and hence investments.

It is also obvious that the improper handling of information in a complex supply chain system could lead to the opposite effect of higher cost and a decline in performance.

The most prominent example of this is the so-called bullwhip effect. The bullwhip effect was initially observed and described by Jay Forrester (Forrester, 2013) in his book Industrial Dynamics. According to Hopp and Spearman the bullwhip effect, “[…] refers to the amplification of demand fluctuations from the bottom of the supply chain to the top.” (Hopp & Spearman, 2001, p. 613)

In their article the bullwhip effect in supply chains Lee, Padmanabhan and Whang (Lee, 1997) assign the following causes to the phenomenon:

- Demand forecast updating
- Order batching
- Price fluctuation
- Rationing and shortage gaming

Overall is missing information and a desire for sub optimization combined with a underestimation of the time delay between cause and effect the reason for supply chain underperformance.

The topic on planning and steering a supply chain network will be primarily discussed by addressing forecasting methods followed by an introduction to production planning approaches.

As already discussed, every supply chain network generally consists of the level, planning, steering and disposition. In the context of this thesis the terms production-planning and steering (PPS) and Material and Resource Planning (MRP II) are used as synonyms.
According to Alicke (Alicke, 2005) PPS is a hierarchal planning concept, which is organised based on a top-down approach. Figure 2.1.2-4 visualised the six steps and the relation to the MRP II systematic.

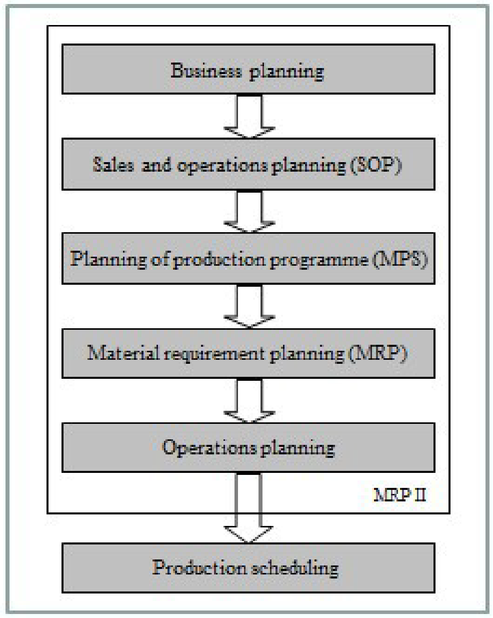


*Figure 2.1.2-4: Material Resource Planning Process*

The following paragraph will describe the individual steps of the PPS systematic; however, the applied tools and detailed approaches used are not subject of this thesis.[3]

- Business planning

Business planning represents the starting point of the production planning system and is closely linked to general corporate strategy and hence the supply chain strategy. The timely scope of the business planning covers at a minimum yearly rhythm, whereby the planning is update based on a rolling concept.

- Sales and operations planning (SOP)

Primary target of the sales and operations planning is the evaluation of the mid-term demand, capacity and production plan in order to determine in a next step the number of required resources, both material and human.

Basis of this mid-term evaluation is either contracted customer orders or a demand forecast. The demand forecast is based on an aggregated level, meaning that for example not every variant of a product line is individually represented in the forecast

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[3] If not mentioned otherwise the description of the PPS system is according to Thonemann, 2005, pp. 284–369.

volume. This inaccuracy and loss of information could be compensated by additional levers realised due to timely planning. Generally, a prognosis or a forecast is needed when future demands could not be assessed deterministically.
A forecast volume could be determined by either qualitative or quantitative approaches. Depending on the product, supply chain structure and customer behaviour a qualitative or quantitative proceeding is more suitable. Focus of this thesis is a quantitative approach.

- Qualitative forecasting

  Qualitative forecasting is used if none or comparatively little data is available as indication based on a small sample size might lead to wrong conclusions. Applied tools are customer surveys, expert or sales personnel interviews. The main benefit of qualitative forecasting is that knowledge from different internal and/or external sources is combined on a very detailed level. As a disadvantage could be marked that qualitative forecasting always implies a certain level of subjectiveness respectively lobbying by a certain group of stakeholders.

- Causal forecasting

  If a causal relation could be assumed between a known and the forecasted factor causal forecasting could be used. Via a regression analysis the future development of the targeted factor could be predicted. The mentioned relation between the two factors could either be linear or non-linear.
  A crucial requirement is the clearness of the causality and it should not be mixed with correlation indicating a common but not depending behaviour.

- Time series forecasting

  In case a supply chain organisation has a sufficient level of historical / empirical data and the organisation is convinced that the data available is also representative for future development, the application of a forecasting based on a time series is to be preferred. The mentioned judgment on the adequateness is crucial as for example the change of products or markets might jeopardise the application of the method.

The figure 2.1.2-5 describes the closed loop technique for developing a quantitative forecast. Starting point of the process is the collection of empirical data which then has to be analysed and split up from special effects. Reasoning of this step is to get a representative sample of data which does not include i.e., delivery peaks caused by a special sales activity. After obtaining a set of data, the respective forecasting method needs to be chosen. Is the factor for the forecast not connected to the historical data via a causal but a correlative dependency, a time series forecasting has to be applied. The parameterisation of the data set, obtained i.e., via a scatter analysis, provides the supply chain organisation a clearer picture which general trend is expected. Based on the combination of these input variables the forecast is compiled. The final check on the quality of the prognosis after comparing it to "real-world" data also indicated to the organisation whether the right tools have been used.

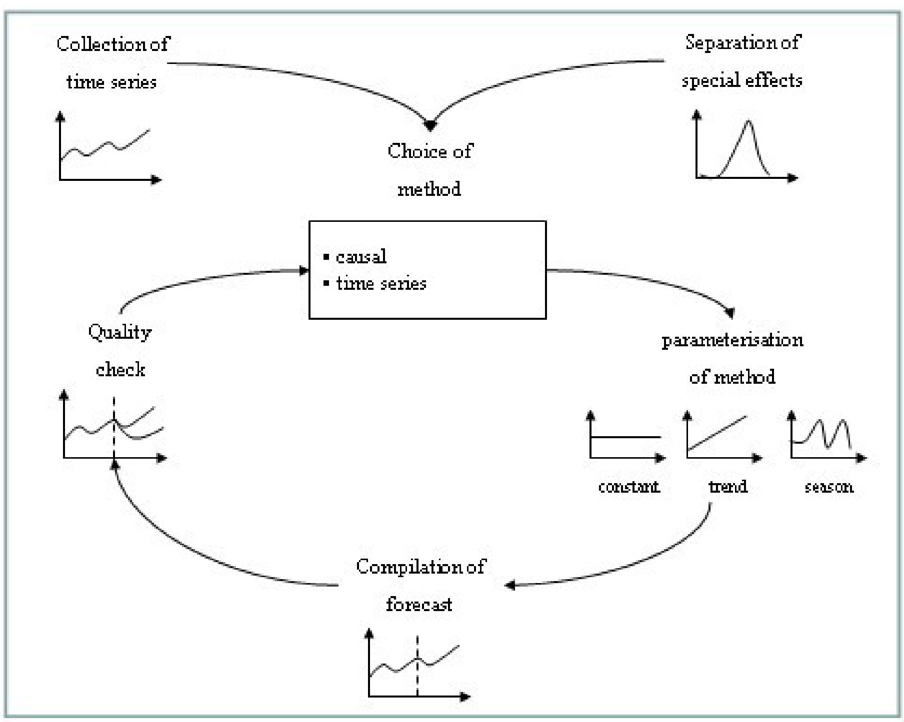


*Figure 2.1.2-5: Forecasting Cycle*

- Master Production Scheduling (MPS)

The MPS used the result of the customer order pipeline, respectively the forecast volume and translates this into the requirements for the production. According to Krischke (Krischke André, 2007, p. 69) the main intention of this management exercise is to align all stakeholders who are directly involved in the value chain process.

The necessity for this alignment arises due to the, sometimes counteracting, targets the various business functions have. For example, is the production management (operations) usually is measured against a balanced amount of coverage or a utilization rate of production assets while the sales organisation is measured on archived market shares or delivery reliability. Considering the various conflicts of targets the desired result of the MPS in form of a production plan feeds into the next planning step Material Requirement Planning (MRP I). As the specific production load is part of the production scheduling the current planning is based on an un-limited capacity assumption.

- Material Requirement Planning (MRP)

Part of the MRP are four steps visualised in figure 2.1.2-6. The overall target is to cascade the overall production volume downward to the shop floor and align the demand side with the current capacity available in the production system.

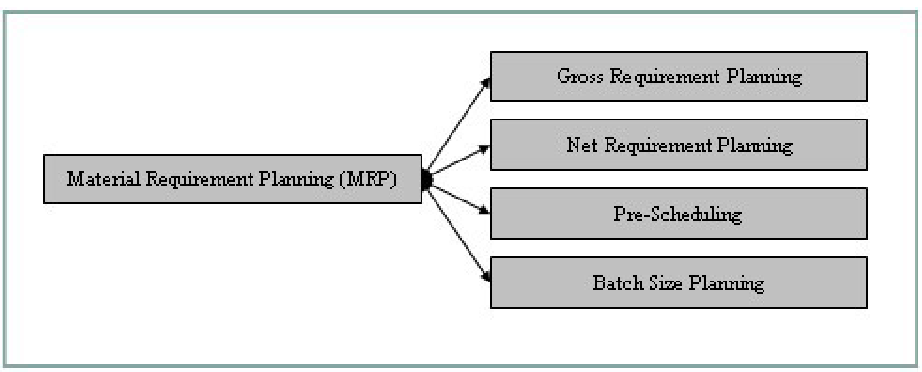


*Figure 2.1.2-6: Material Requirement Planning*

- Gross Requirement Planning

  As a starting point concerning the requirement planning in the production the final product, in combination with the planned volume need to be broken to component level in order assess with a Bill of Material (BOM) how many components need to be provided for the given planning period. The BOM could be built up using different approaches, either reflecting the structure of the product or the production process. Figure 2.1.2-7 visualizes the different approaches, whereby in both scenarios P represents the final product.

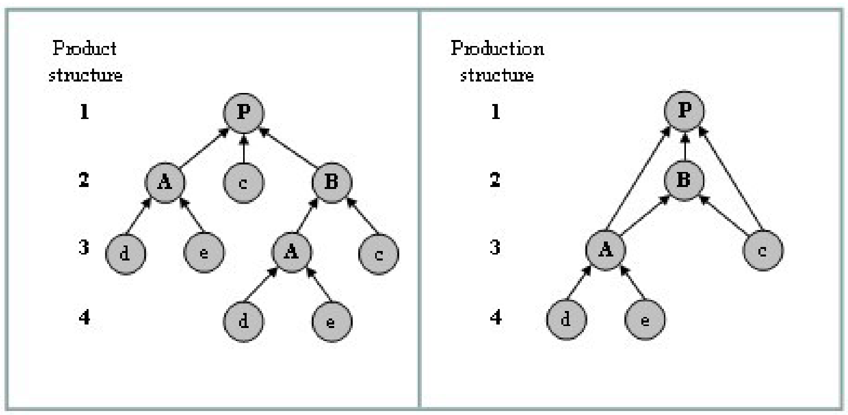


*Figure 2.1.2-7: Visualisation of Bill of Material*

The relationship between the different steps could either be linear, convergent or divergent which adds another level of complexity into the planning process. Alicke (Alicke, 2005, pp. 15–26) refers to the volume derived from the gross planning as primary demand; the volume derived from the BOM is to be referred as secondary demand.

The gross demand $(g_i)$ of a product $i$ is the sum of primary $(d_i^p)$ and secondary $(d_i^s)$ demand multiplied with a factor representing the level of production effectiveness. Is for example the rate of deficient goods 10% the level of utilisation accounts $(u)$ for 0.9.

Hence the gross demand is calculated as:

$$g_i = \left(d_i^p + d_i^s\right) * \left(1/u_i\right)$$

As part of the net demand calculation the gross demand is lowered by the level of stock $(I_i)$. In case a minimum stock policy $(t_i^{ti})$ is applied this needs to be taken into consideration when planning gross and net figures. The net demand $(n_i)$, in other words the production volume is derived by the following interval:

$$n_i = MAX(0;(g_i - I_i + I_i^{ti}))$$

Secondary demand $(d_i^s)$ is dependent on the net volume of successor products $(N_i)$ and the utilisation factor:

$$d_i^s = \sum_{j \in N_i} a_{i;j} * n_j$$

When solving this linear equation, a crucial remark is that primary demand is independent and secondary demand is dependent.

As a critical remark on the planning tool MRP I Alicke refers to the inobservance of lead time consumption by components and capacity restrictions of the production system. Other approaches in planning strive for batch size optimisation with a full-cost consideration, including set up times and cost and inventory cost. One example of this optimisation approach is the dynamic batch size optimisation according to Wagner and Within (Wagner & Within, 1958). In case a heuristically approach is chosen, the so called Andler formula could be applied:

$$x_{opt} = \sqrt{\frac{200 * m * b}{p * s}}$$

$x_{opt}$ represents the order volume, $s$ are the storage cost in percentage, $p$ refers to the price per unit, $b$ are the cost per order and $m$ refers to the yearly consumption.

The final step of the MRP II planning process is to establish a link to the shop floor production. Referring to Krischke (Krischke André, 2007, p. 112) the main task is to establish production dates and match those with the capacity available.

A key tool which is used in this context is the planning of production sequences. The positive effect of sequencing is illustrated in figure 2.1.2-8.

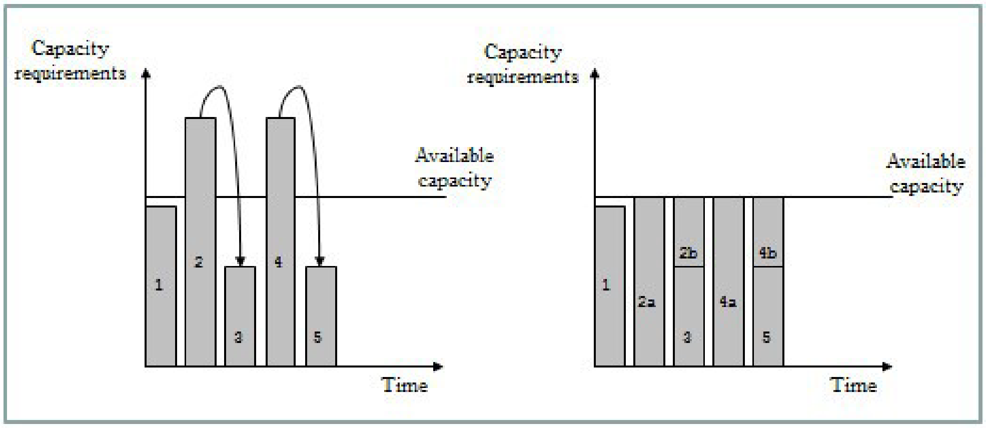


*Figure 2.1.2-8: Capacity Optimisation by Production Scheduling*

### 2.1.3. Risk and Supply Chain Management

"The dice and the roulette wheel, along with the stock market and the bond market are natural laboratories for the study of risk because they lend themselves so readily to quantification; their language is the language of numbers." (Bernstein, 1996, p. 132)

The following chapter will introduce the concept of risk and its management within the supply chain. In a first instance the term risk will be discussed and defined for the purpose of this thesis, followed by the introduction to risk management in the supply chain. This introduction will be described in a two-step approach, by laying out what specific risks are that are threatening the supply chain, especially in a project-management context, and by describing the process of supply chain risk management as an appropriate answer towards the various risks.

2.1.3.1 What risk is and what it is not

Risk is a term which is not only used in different manners in the professional and scientific world, but also within the very definition, meaning and interpretations differ to a great extent.

Bernstein (Bernstein, 1996) describes the origin of risk respectively risk management as it is known today in the scientific and professional world is tightly linked to the development of mathematics. By analysing the concept of probability and setting it into the context of gambling Blaise Pascal and Pierre de Fermat set to foundation to a numerical approach of risk management or risk judgement. The change of paradigm was, that compared to the former approach of foreseeing the future by applying "fortune-telling" like methods, the past was analysed by identifying certain patterns which might indicate future development. The judgment on risk has been pulled out of the corner of superstition to the corner of natural science.

In 1730 Abraham de Moivre introduced the concept of the normal distribution and the standard deviation to the field, leading to the law of averages[4].

A milestone in applying risk management in the field of economics has been the development of the portfolio analysis by Markowitz (Markowitz, 1959) in 1952. Markowitz discovered that by applying a mean-variance model, a specific portfolio of investment alternatives could be identified that has an optimal split between given rate of return and risk.

By applying this risk management knowledge into the business world, the door was pushed open to adapt similar concepts in various business areas like sales and operations.

When approaching the term risk and its special peculiarities one overall consideration needs to be done. Pfohl, Gallus and Thomas (Pfohl, Gallus, & Thomas, 2011) argue that Risk in general could be seen in two different dimensions, it could be related to a **cause** of a decision that has been taken or to the **consequence, respectively the effect** that a decision has.

In order to structure the discussion and hence the definition of risk for the purpose of thesis, the different approaches to risk are visualised in figure 2.1.3-1.

[4] The law of averages refers to the hypothesis that within a small sample size the result of random events will be evened out.

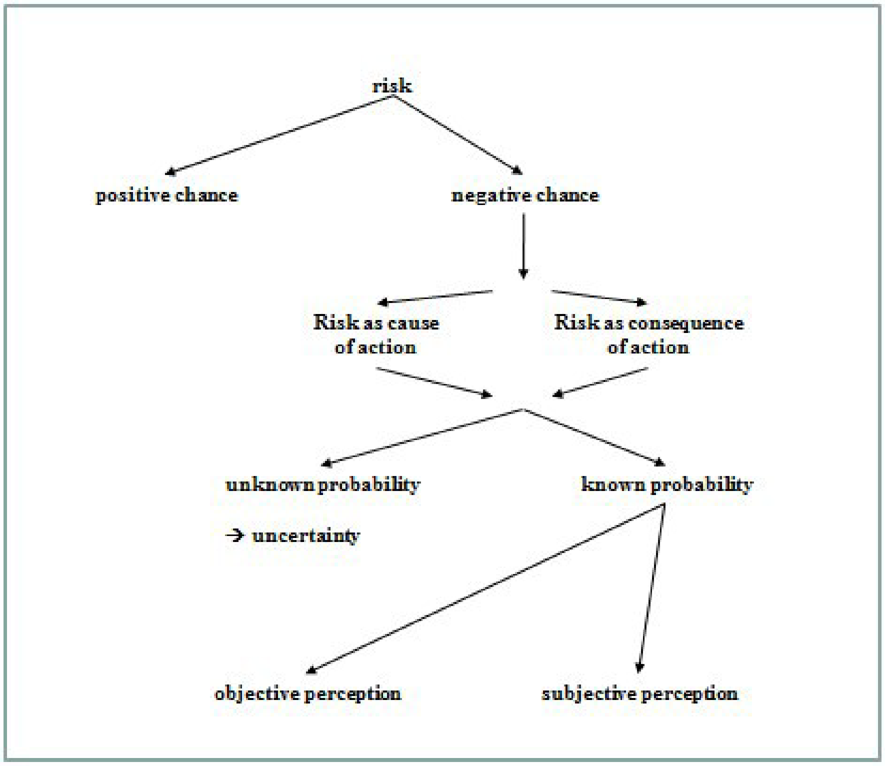


*Figure 2.1.3-1: Structural Map of Risk*

Based on the ground that risk is connected and expressed via probability is obvious that the phenomenon is not strictly connected to a negative state. The example of gambling emphasises this by setting the probabilities for an expected win or respectively loss. However, in a business context, the term risk has been mainly used by expressing an undesirable state which is also reflected in the most of the commonly known definitions, by the Royal Society or the British Standard. The first institution refers to risk as:" […] the probability that a particular adverse event occurs during a stated period of time, or result from a particular challenge." (The Royal Society, 1992, p. 2)

While the British Standards Institutions considers risk as:" […] a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence." (British Standards Institutions, 1991, p. 3)

Despite the overall consensus that risk is connected to probability the scientific community is arguing whether this probability could be seen as objective or subjective.

According to Holton (Holton, 2004), who in his article Defining Risk is mainly analysing Knight's work on risk (Knight, 1921), is referring to subjective and objective interpretation of probability in the following way:" According to objective interpretations, probabilities are real. We may discover them by logic or estimate them through statistical analysis. According to subjective interpretations, probabilities are human beliefs. They are not intrinsic to nature. Individuals specify them to characterize their own uncertainty." (Holton, 2004, p. 19)

Further authors proclaiming subjective probability are e.g. Ramsey (Ramsey, 1931), de Finetti (Finetti, 1964) or Savage (Savange, 1954).

Knight (Holton, 2004, p. 20), proclaiming objective movement, distinguishes between probabilities obtained in two manners:

- A priori probabilities are derived from inherent symmetries, as in the throw of a die
- Statistical probabilities are obtained through analysis of homogenous data

Hansson (Hansson, 2012) assigns five specialised uses and means to the terms risk:

- Risk is an unwanted event which may occur or not occur
- Risk is the probability of an unwanted event which may or may not occur
- Risk is the statistical expected volume of an unwanted event that may or may not occur
- Risk is the fact that a decision is made under conditions of known possibilities

In his book misperception of risk Aven (Aven, 2009) summarises various positions to what risk is, respectively how it could be characterised and approached in a numerical way. His argumentation is in line with the previously mentioned authors who also argue that risk as connected to probability implies a certain dilemma between discussed objective and subjective standpoint, respectively the interpretation of objectivism.

Within his book he refers to the various statistical possibilities of interpreting the subject, i.e., risk as a simple distribution of probability, or risk determination by historical data.

The present PhD thesis applies the objective perception of probability when defining risk.

Transferring the theoretical concept of risk to the concept of supply chain management Hopp defines risk as the "[…] exposure to negative consequence of uncertain events," and continuing he states that a "[…] supply chain system face risk from event beyond normal levels of variability. Hurricanes, political disruptions, act of terrorism, currency crisis, technological breakthrough and many other unpredictable events [that] can have a sustainable influence on supply chains." (Hopp, 2011, p. 145)

Already in the rather short definition of the term risk in connection to supply chain management it becomes obvious that risk could negatively influence the supply from various directions.

#### 2.1.3.2 Risk in the supply chain

While in a first step the abstract concept of uncertainty and risk has been introduced, this paragraph elaborates on the state of the art of applied categorizations for specific risks affecting the supply chain organisation. Taking into account the project management focus of this thesis the presented frameworks are to be used for all product or project type of supply chains.

Following Ziegenbein and Schönsleben (Ziegenbein & Schönsleben, 2007, p. 23) supply chain risks could be either categorized related to their cause or by their effect in the supply chain organisation.

Most authors relate in their categorisation to one of the three following approaches:

- Supply chain structure

  The supply chain structure is mainly defined by the supply, process & control and demand. Authors who apply this categorisation are e.g. Manuj (Manuj & Mentzer, 2008), Towhill, Manson-Jones et al. (Towill & Mason-Jones, 1998), the figure 2.1.3-2 is taken from Juettner (Jüttner, 2005, pp. 122–123) and visualises the categorisation. Another terminology that is used in this context reflects the different steps of the supply chain SCOR model, namely plan, source, make, deliver and return by i.e. Zeigenbein und Schoensleben

(Ziegenbein & Schönsleben, 2007) or Tang and Nurmaya Musa (Tang & Nurmaya Musa, 2011).

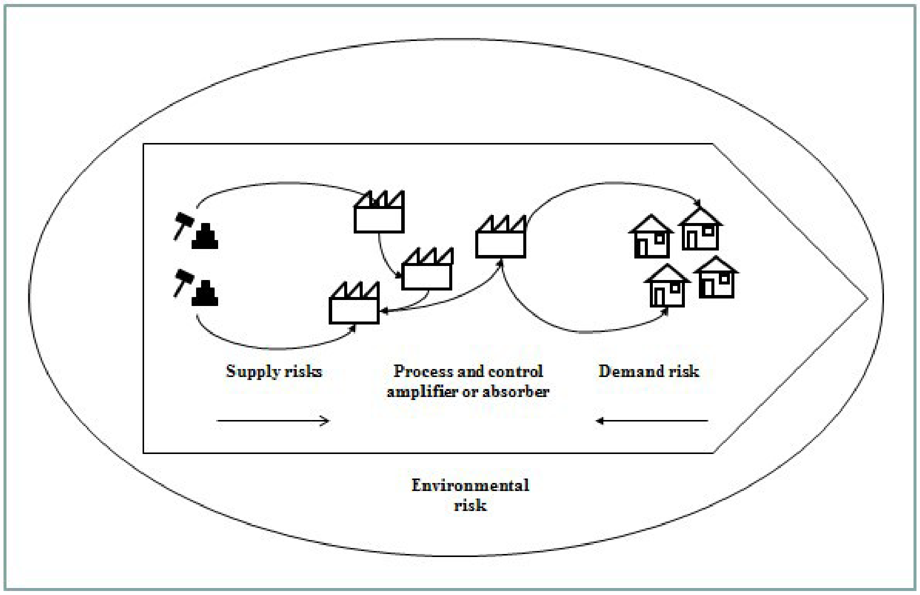


*Figure 2.1.3-2: Categorisation of Supply Chain Risks I*

- Supply chain borders

  The more mature a supply chain in terms of connecting and aligning material, informational and financial flows is, the more it might be considered as a closed loop environment. In this context authors simply refer to internal or external risks threatening the supply chain, i.e., Olsen and Wu (Olson & Wu, 2010) or Ritchie and Zsidisin (Ritchie & Zsidisin, 2008).

- Supply chain functions

  A categorisation into functions is not necessarily implying a risk perspective on the supply chain as a whole, as some of the examples stated in the literature are more likely to be applicable for a single company than for a whole supply chain organisation.

  Examples on the nature of different risks which could be found are: strategic, operational, competitive, financial, delay, informational or regulatory.

  In this context a problematic context might arise due to the fact that specific categories could interfere which each other, i.e., could a delay risk negatively affect operations, customer relationships or the financial situation of a company. Examples for the described categorisation are among others: Tummala and Schoenherr (Tummala & Schoenherr, 2011), Harland, Brenchley and Walker (Harland, Brenchley, & Walker, 2003), Cavinato (Cavinato, 2004), Giannakis and Papadopoulos (Giannakis & Papadopoulos, 2016), Rajagopal et al. (Rajagopal et al., 2017) and Arntzen (ARNTZEN, 2010).

The approach applied in the given thesis is partly combining the discussed categorisations adapted from Norman and Lindroth (Norrman & Lindroth, 2004).

The figure 2.1.3-3 shows the framework for assessing and positioning supply chain risks by analysing three dimensions. The **logistics unit of analysis** addresses the level of complexity / the organisational body which affected by the risk. A possible range spans from a single logistical operation in a supply chain partner's factory to the whole supply chain network as most complex construct. The **type of risk and uncertainty** provides an indication of the magnitude. The third dimension, **risk and business continuity management** already switch to the solution and mitigation of the risk by indicating which scale of reaction is appropriate considering the specific situation.

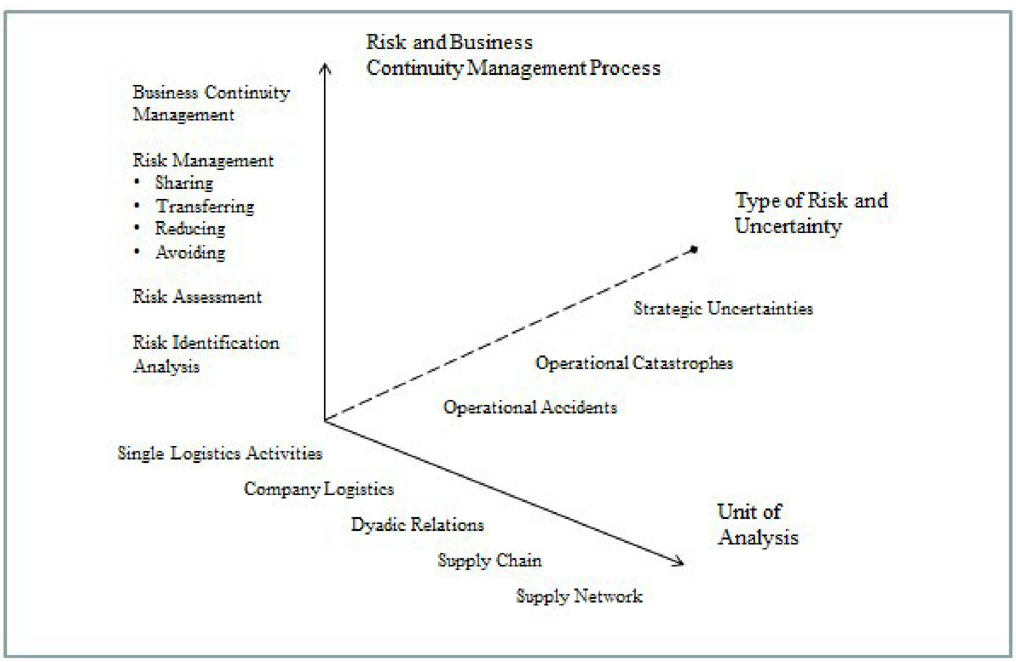


*Figure 2.1.3-3: Categorisation of Supply Chain Risks II*

In order to put the discussed approaches on categorising supply chain risk into a practical context, the main findings an empirical analysis conducted by Pfohl (Pfohl, 2004) are visualised in figure 2.1.3-4.

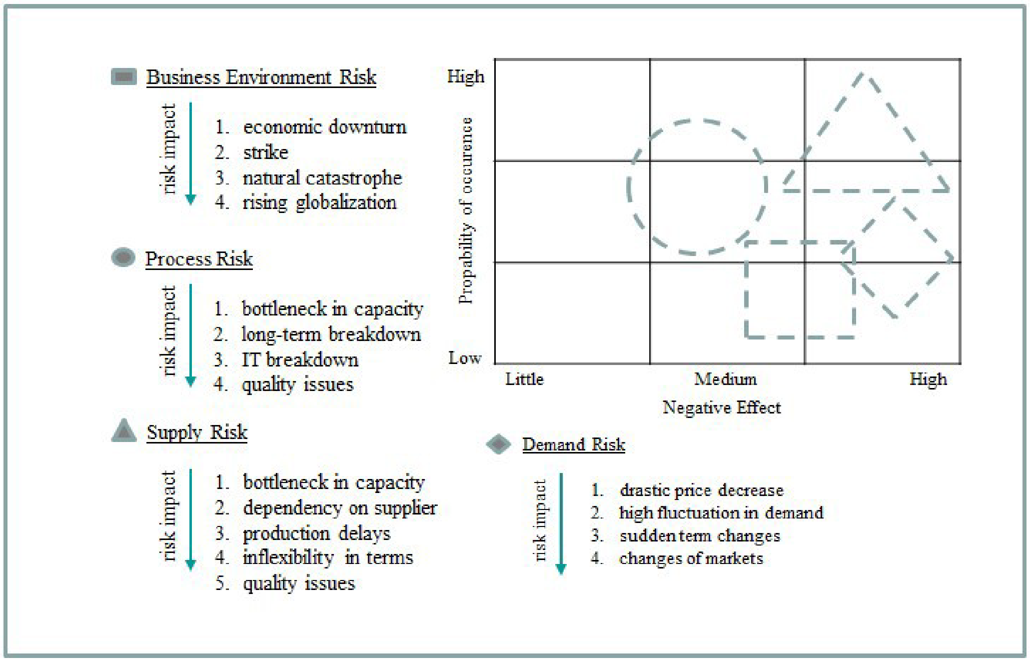


*Figure 2.1.3-4: Categorisation of Supply Chain Risks III*

In the area of Business Environment Risk, which is not necessarily exclusively threatening to supply chains, the World Economic Forum published on a yearly basis the Global Risk Reports (World Economic Forum, 2018). The World Economic Forum further more updated after the consolidating the most recent report and overview on the top ranked risks identified by the participants of the survey according to likelihood and impact.[5]

[5] World Economic Forum, S. http://reports.weforum.org/global-risks-2017/the-matrix-of-top-5-risks-from-2007-to-2017/ accessed September, 9th 22.27pm

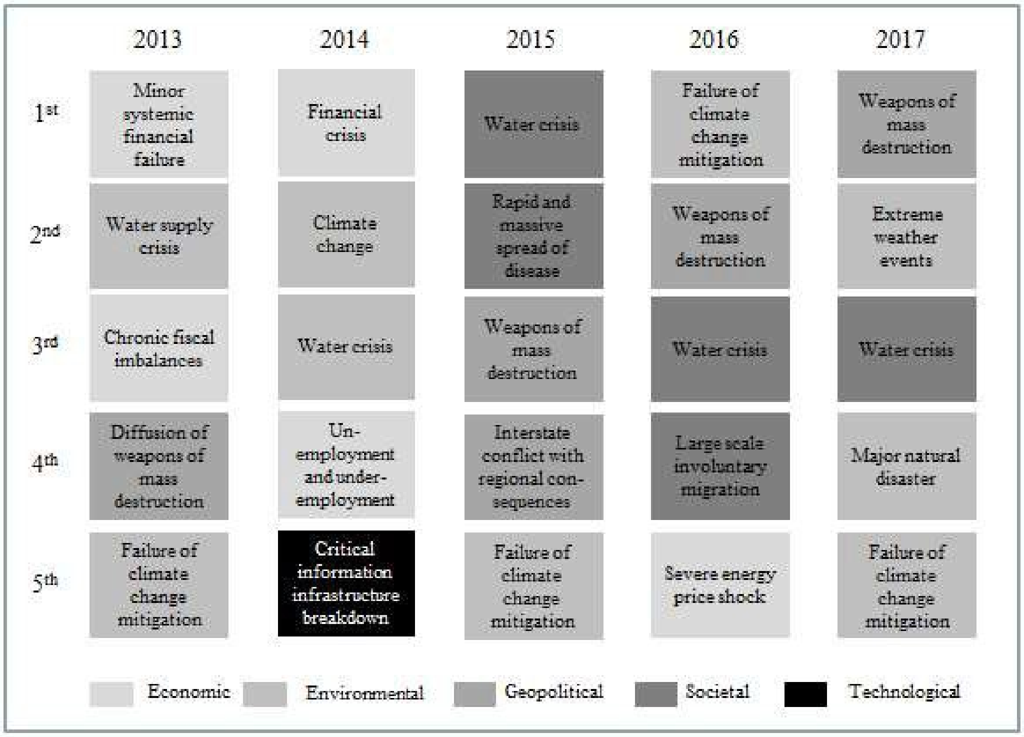


*Figure 2.1.3-5: Top 5 Global Risks in Terms of Impact (2013-2017)*

Further examples of supply chain risks have been collected by Norrman and Lindroth (Norrman & Lindroth, 2004, p. 17):

- Hurrican Floyd flooded a Daimler Chrysler plant, producing suspension parts in Greenville, North Carolina (USA). As a result, seven of the company's other plants across North America hat to be shut down for seven days
- Juettner, Peck and Christopher (Jüttner, Peck, & Christopher, 2003) are referring to a case where the Foot and Mouth Disease in the UK in 2001 impacted agricultural industry more than its last outbreak 25 years ago. The reason for this was that former local and regional supply networks had become national and international and that the industry was much more consolidated. Also, many other industries were impacted: luxury car manufacturer e.g. Volvo and Jaguar had to stop deliveries due to lack of high-quality leather
- Toyota was forced to shut down 18 plants for almost two weeks following a fire in February 1997 at its brake-fluid proportioning valve supplier (Aisin Seiki). Cost caused by the disruption were estimated at 195 MUSD and the sales loss was estimated at 70.000 vehicles

- Ericsson in Sweden lost many months of mobile phone production and major sales of customer products with a short "market window" in 2000 due to a minor fire at sub-supplier Philips Components in US. Business interruption cost was later evaluated to be about 200 MUSD

An additional example has been collected by Cavinato (Cavinato, 2004):

- Less than 100 workers in a longshoremen's union strike on the US West Coast caused significant disruption of an entire holiday season of consumer product sales in North America and Europe (involving land bridge movements from Asia across North America to Europe). Given the month-long round-trip cycle of ship movements across the Pacific, some containers took nearly six months to be delivered and for schedules to return to normal

All these examples in combination with the discussed increasing complexity in today's supply chain networks indicate an urgent need for a structured counteracting management approach.

#### 2.1.3.3 Introduction to risk management for the supply chain

The relevancy of a structured approach on supply chain risk management is omnipresent triggered by supply chain professional realising the direction their ever-changing environment is heading towards.

This hypothesis could be not only proved by the number of published articles, but also by the number and content of studies run on the subject. A study conducted by IBM and edited by Moffat (Moffat, 2009) in 2009 with the title: „The smarter supply chain of the future – Global chief supply chain officer study" revealed the following observations concerning supply chain risk management.

Figure 2.1.3-6 illustrates the current status versus future development in supply chain organisations based on interviews with 400 supply chain professionals.

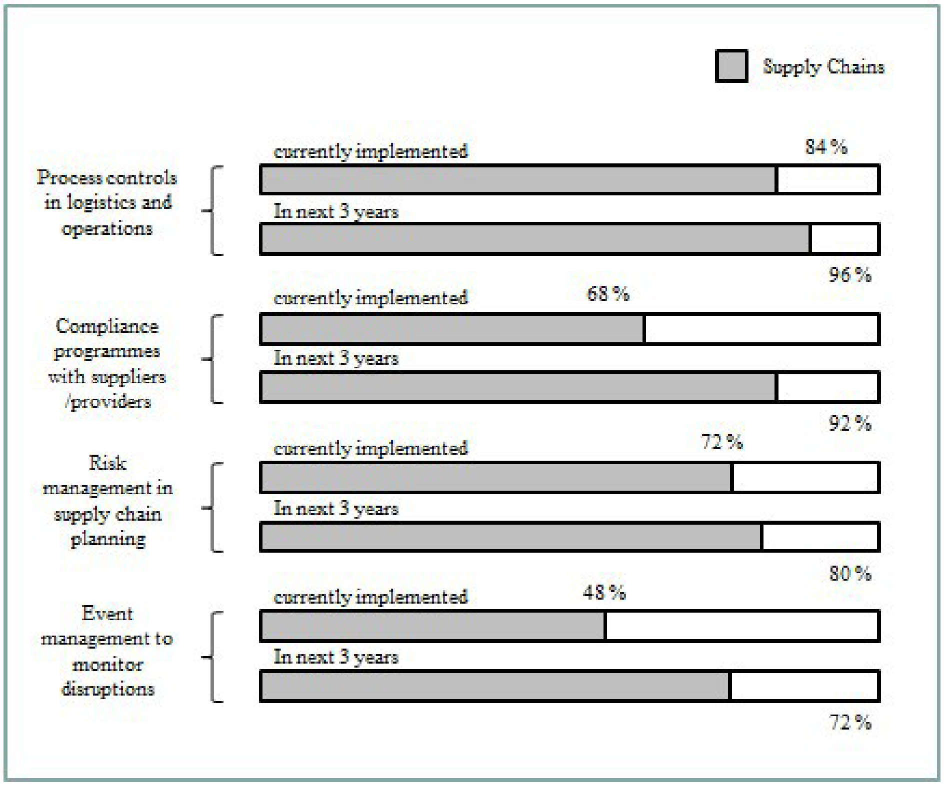


*Figure 2.1.3-6: Perception and Perspective of Supply Chain Risk Management*

When approaching supply chain risk management in a systematic manner it is natural to draw the link back to the already discussed concept of risk in general. Similar to other professional areas where risk management has already been implemented and been part of the corporate strategy for some time, supply chain risk management follows the same generic steps.

In the same year the MIT Global Scale Risk Initiative (MIT Center for Transportation and Logistics, 2010) conducted a survey interviewing more than 1400 supply chain professionals from over 70 countries. In terms of the overall results in the deployment and effectiveness of supply chain risk management the main findings have been:

- About 36% to 39% of companies are working effectively on SCRM or have a Business Continuity Planner (BCP) initiative
- Between 50% and 54% of respondents say that they are not working or not working effectively on SCRM or BCP

- About 50% of companies have a person or group to organize work on SCRM or BCP; but about one-third of these respondents indicated that the organizing person or group is not effective
- Attempts to work with suppliers and customers are effective only about half of the time, according to respondents
- Overall, about 10% of respondents don't know what their company is doing about SCRM

Like in a generic risk management process a risk needs to be **identified, estimated,** evaluated and, depending on an informed judgement, **mitigated.**

Putting this into the complex environment of a supply chain organisation the task of risk management not only becomes a structural but also a behavioural challenge. In his article: State of the art in supply chain risk management research, Pfohl et al. in reference to Kajueter (Kajueter, 2003) point out that, "with regards to supply chain risk management this means mutually [all involved parties] and communicating problems in order to abolish information asymmetries and prevent negative effects on firm performance. Systematic risk management may be conceptualised as a process that consists of risk identification, risk assessment, risk mitigation strategies and risk control." (Pfohl, Köhler, & Thomas, 2010, p. 36)

Waters defines (supply chain) risk management as "[…] the process of systematically identifying, analysing and responding to the risk throughout and organisation." (Waters, 2007, p. 75)

This perception of a supply chain risk management process seems to be in line with the general opinion referring to other authors, i.e. Hallikas et al. (Hallikas, Karvonen, Pulkkinen, Virolainen, & Tuominen, 2004), Khan and Burnes (Khan & Burnes, 2007), Autry and Bobbitt (Autry & Bobbitt, 2008), Manuj and Mentzer (Manuj & Mentzer, 2008) as well as Kleindorfer and Saad (Kleindorfer & Saad, 2005).

While all mentioned approaches are commonly agreeing on the generic steps of identifying, estimating and mitigating, at the same time they are already implying further detailed steps which need to be done in order to perform the individual step.

An example for the visualisation of the process offer Khan and Burnes (Khan & Burnes, 2007, p. 202) with a reference to White (White, 1995, p. 36).

Concluding from this, the overall target of supply chain risk management could be phrased in accordance with Waters, who refer to the overall goal of supply chain risk management is “[…] to ensure that supply chains continue to work as planned, with smooth and uninterrupted flows of material from initial suppliers through to the final customer.” (Waters, 2007, p. 86)

#### 2.1.3.4 Process steps and applied tools

Each step in the supply chain risk management process requires an individual approach considering applied tools and methodology. The individuality of this approach is strongly linked to the characteristics of both, the considered risk and the supply chain organisation respectively its product.

- Risk identification

  In the same way as for database analysis the input represents a crucial step; the risk identification represents a crucial task in supply chain risk management. Not only is the success of the entire process but in particular the the subsequent steps are highly relying on the quality of risk identification. With reference to Greene and Trischmann (Greene & Trieschmann, 1984), Tchankova formulises the importance of risk identification as, “[…] if managers are not able to identify all possible losses or gains that challenge the organisation, then these non-identified risks will become non-manageable.” (Tchankova, 2002, p. 290)

  Furthermore Tchankova (Tchankova, 2002, p. 291) describes three fundamental questions that the process of risk identification needs to answer:

  - How can the organisational resources be threatened?
  - What adverse effect can prevent the organisation from achieving its goals?
  - What favourable possibility can be revealed?

  As indicated by the reference that risks are influencing the organisation as a whole, Tummala and Schoenherr give the discussion an interesting spin by combining risk identification with Chopra and Sodhi's strategic view on supply chain management (Chopra & Sodhi, 2004).

"Care should be taken since some strategies may adversely affect other risks. Understanding the variety and interrelationships of supply chain risks is therefore important as well." (Tummala & Schoenherr, 2011, p. 476)

As part of their extensive work on the subject the Department For Transport of the Cranfield University has published two workbooks addressed to practitioners in the business analysing not only the topic of supply chain risk management itself, (Christopher, 2003), but also the wide tool box that might be used in the various risk management steps, (Peck, 2003).

The table 2.1.3-1 provides an overview of the generally known toolbox used in supply chain risk management throughout the whole process. The systematic by which the various tools are grouped in the process steps of identification, estimation and mitigation is transferred to the DMAIC[6] cycle used in Six Sigma.[7]

| Six Sigma methology (DIMAIC) | Supply Chain Process Risk Management (IMPARC) | Tools & Techniques | Scenario Planning | Delphi Forecasting | Brainstorming | FMEA | Flowcharting | Supply Chain Mapping | Critical Path Analysis | Bottleneck Identification | Statistical Process Control | Process Capability Analysis | Simulation Modeling | Root Cause Analysis | Fishbone Diagramme | Pareto Analysis | Process Decision Programme Chart | Benchmarking | Business Process Re-engineering | Time-based Process Mapping |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Define & Measure | Identify, Measure and Prioritize | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | |
| Analyse | Analyse | | | | | | | | | | X | X | X | X | X | | | X | | X |
| Improve | Reduce | | | | X | | | | | | | | X | | | X | X | X | X | X |
| Control | Control | | | | | | | | | | X | X | | | | | | | | |

*Table 2.1.3-1: Toolbox for supply chain risk management*

[6] DMAIC is an abbreviation for Define, Measure, Analyse, Improve and Control

[7] Six Sigma is a standardized manufacturing managing approach aiming for increasing process quality. The term six sigma refers to the maturity of the process, as it indicates that 99.97% of all manufactured parts are statistically without any defect.

The most commonly used tools for risk identification are **supply chain mapping, checklists, event-tree analysis, fault tree analysis, failure mode and effect analysis (FMEA) and the Ishikava diagram.**

- Risk estimation

The process of risk estimation picks up the collection of identified risks and assigns a certain priority to them. The general opinion in the literature is that risk estimation could be either conducted by applying qualitative or quantitative methods. Ziegenbein and Schoensleben describe the procedure as following, "there are qualitative techniques of risk assessment, which are primary based on subjective or empirical experience, or quantitative assessment techniques which are based on mathematical and statistical methods which normally require a vast amount of data to analyse." (Ziegenbein & Schönsleben, 2007, p. 53)

Furthermore, Ziegenbein and Schoensleben link, by referring to Romeike (Romeike, 2003), both approaches, quantitative and qualitative, to either an inductive or deductive approach. By applying the deductive approach, a specific undesirable event leads to the systematic cause while the inductive approach starts from the systematic cause analysing specific issues.

This approach ties in with the discussed approach on risk and the discussion if either the cause or the consequence could be seen as risk.

According to Waters, "[…] there are many types of quantitative analysis for risk, but they are all based on two factors, 1.) The likelihood of risky events occurring and 2) the consequence when the event does occur." (Waters, 2007, p. 128)

$$\textit{expected value} = \textit{probability} \times \textit{consequence}$$

According to Aven (Aven, 2016) this concept has also not changed in its core over the recent years, however it is to be overserved that especially in the business world application certain decision making processes have been established linking quantitative and qualitative aspects.

In his article Aven describes the process as conducted in today's business environment as a mixed approach between scientific and quantitative evaluation and ultimately a qualitative decision-making process involving experience and previously acquired knowledge. Besides the fact that this approach that this process from a quantitative perspective creates decision boards operating in "no man's land" (Aven, 2016, p. 3), it should also be acknowledged that this process under the consideration of shortness in resources and time is to be considered a practical one.

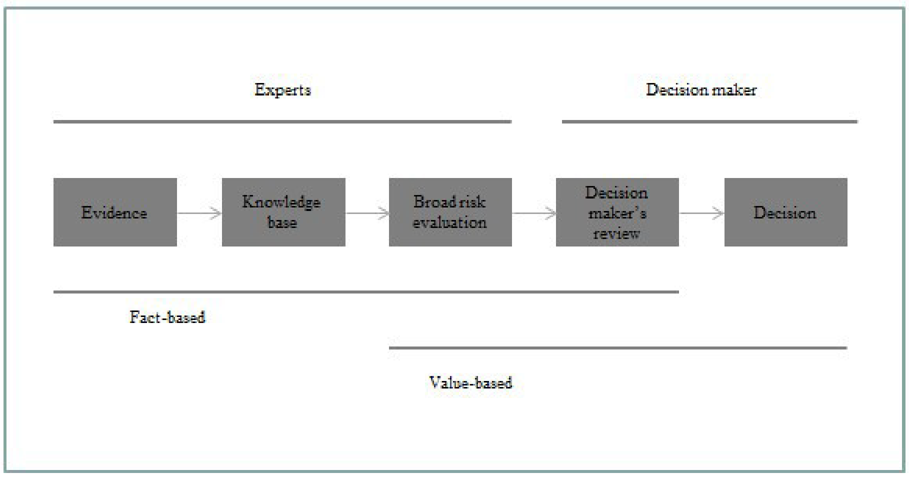


*Figure 2.1.3-7: A model for linking the various stages in the risk informed decision-making*

As just described, the lack of resources does not only apply to the decision-making process but also, and this to a far bigger extend, to the subsequent steps visualised in figure 2.1.3-7 taken from Aven (Aven, 2016, p. 3). The most apparent dilemma of the professional environment is the constant lack or stress of resources, whether this is connected to people, money or time (whereby resource people imply the two remaining ones). Similar to other decisions i.e., on investments for technologies or market entry, a cost of opportunity indicates price of the resource allocation. In the same way a prioritisation of risks by either qualitative or quantitative methods supports a supply chain organisation with the right or logical selection of with risks need to be approached and which could be neglected. Hopp (Hopp, 2011) visualises this in the figure 2.1.3-8 by setting the choice of risk mitigation measures in relation to the severity and likelihood of the risk. In case of the lowest combination the recommended actions are to neglect the risk.

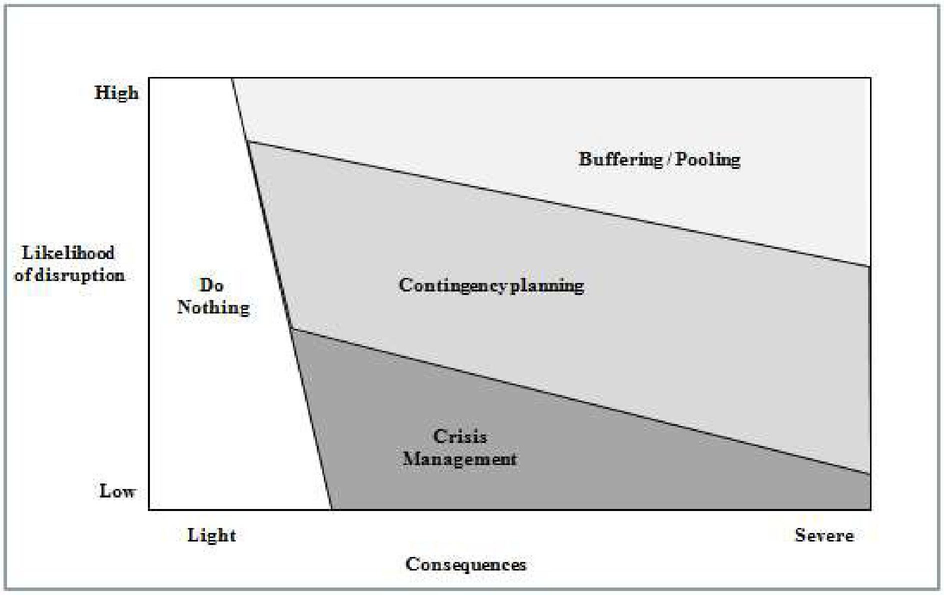


*Figure 2.1.3-8: Supply Chain Risk Assessment*

As an own remark to the discussion should be added that the choice whether a risk should be approached by risk management techniques is not a static but a dynamic question. Considering that magnitude of risk is party expressed either by its probability of occurrence or its severity in terms of financial cost, risk management techniques could subsequently lower this magnitude. The positive affect could arise from either a decrease in probability and/or cost. Linking this fact to the discussion on opportunity cost, a constant evaluation would show that with every additional effort to decrease a specific risk, the opportunity cost, respectively the incremental cost would rise.

- Risk mitigation

  In the applied split of the supply chain risk management process of identification, assessment and mitigation, the last step additionally considers controlling mechanism which ensure a successful change of the supply chain organisation either internally or externally, depending on the specific risk.

The actual process of risk mitigation is linked to a very wide field of activities in the supply chain management organisation. The considered actions might be both, strategic and operational nature. As an example of risk mitigation activities, the portfolio of activities described by Hopp will be discussed.

Hopp (Hopp, 2011, pp. 145–148) has identified four main activities in order to mitigate supply chain risk depending on likelihood and consequence of the risk, namely: **Buffering / Pooling, Contingency Planning and Crisis Management.**

Every of the mentioned risk management strategies is designed to counteract a specific risk, respectively fitting to a specific business or production set up. For example, the main concept of **Buffering and Pooling** strategy is to hold resources in readiness for an event. As this might imply a huge capital lockup it is only recommended to counteract quite frequent risks.

When Buffering and Pooling are uneconomical, **Contingency Planning** could be applied. The risk mitigation aspect here is that without physically storing buffer material backup scenarios for i.e., alternative supply is developed and evaluated. An example could be to switch from a single sourcing concept to a multiple sourcing concept, whereby the backup supply is only used to cover for the main supplier. Concerning the feasibility and the financing of the eventual add-on cost the previously performed risk assessment has to proof the business case.

Finally, **Crisis Management** is used for extraordinary situations which imply a chaotic situation, i.e., a recall of products. For this case the main preparation that has to be done is mainly organisational nature i.e., by setting up compliance rules and guidance for employees.

The following paragraph will exemplarily describe the process of **risk pooling**. The quintessence of risk pooling is that the relative fluctuation of demand in an aggregated demand is always smaller than the fluctuation of the non-aggregated demand. Basis for risk pooling is the central limit theorem, which generally says that for an approximately normal distributed population with an expected value of and a reasonable sample size of $n$ the standard deviation $\sigma$ is based on the following equation:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

The positive effect of the risk pooling is now achieved by the dependency created of the root, as the standard deviation is declining with an increasing size of the sample size. The following example will visualise the positive effect risk pooling. In a distribution network for four different products A, B, C and D every product initially is distributed from an individual location, meaning that each individual location faces the demand fluctuations per product type. By combining the distribution locations, the fluctuations per product type are combined and hence bundled.

Figure 2.1.3-9 visualises the positive effect that risk pooling has on the demand fluctuation of the various single product demand.

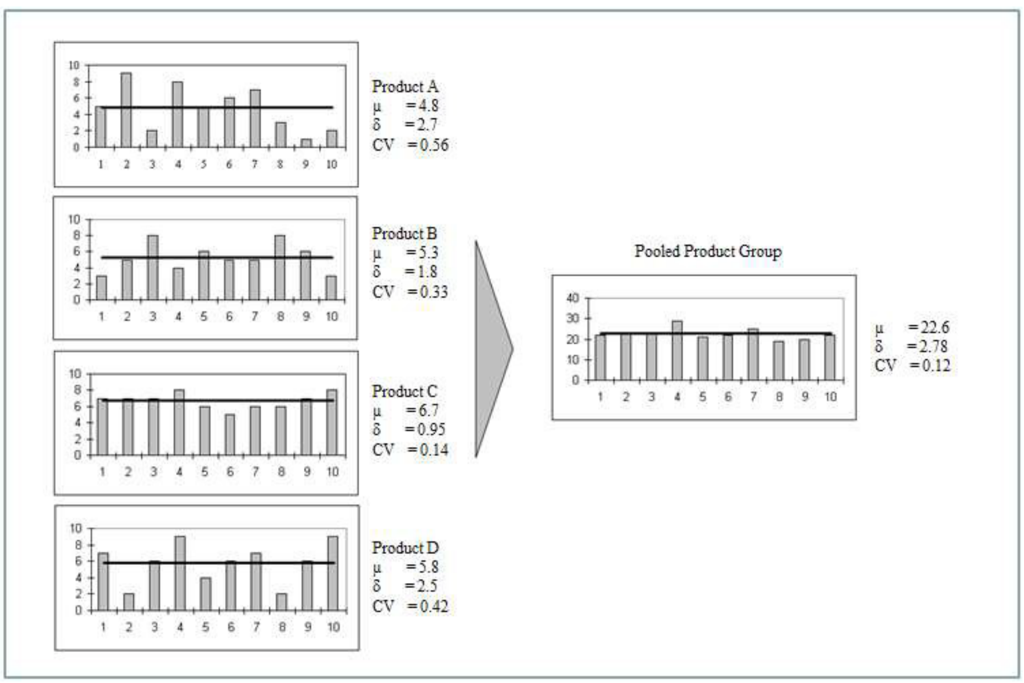


*Figure 2.1.3-9: Risk Pooling Example*

## 2.2. Business modelling and simulation in the context of supply chain risk management

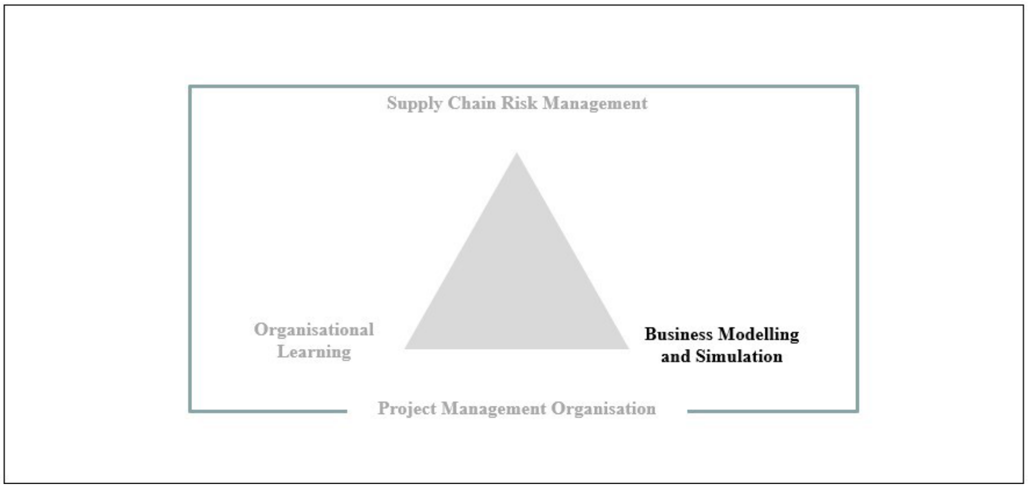


*Figure 2.2-1: Business Modelling and Simulation as part of the research triangle*

“Although supply chain engineering methods have advanced rapidly in sophistication over the past two decades, the application of modelling and methods to explicitly consider and manage uncertainties and risks in supply chain activities are required for firms to advance to the next level of sophistication.” (Basu et al., 2008, p. 9)
In the cited white paper study conducted by IBM in 2008 the phenomena supply chain risk management is analysed in various dimensions. Besides an evaluation of the potential sources of risks and their categorisation, the research team concludes that the application of business modelling and simulation is the appropriate vehicle to conduct sustainable supply chain risk management as indicated in figure 2.2-2 taken from Basu et al. (Basu et al., 2008, p. 10).

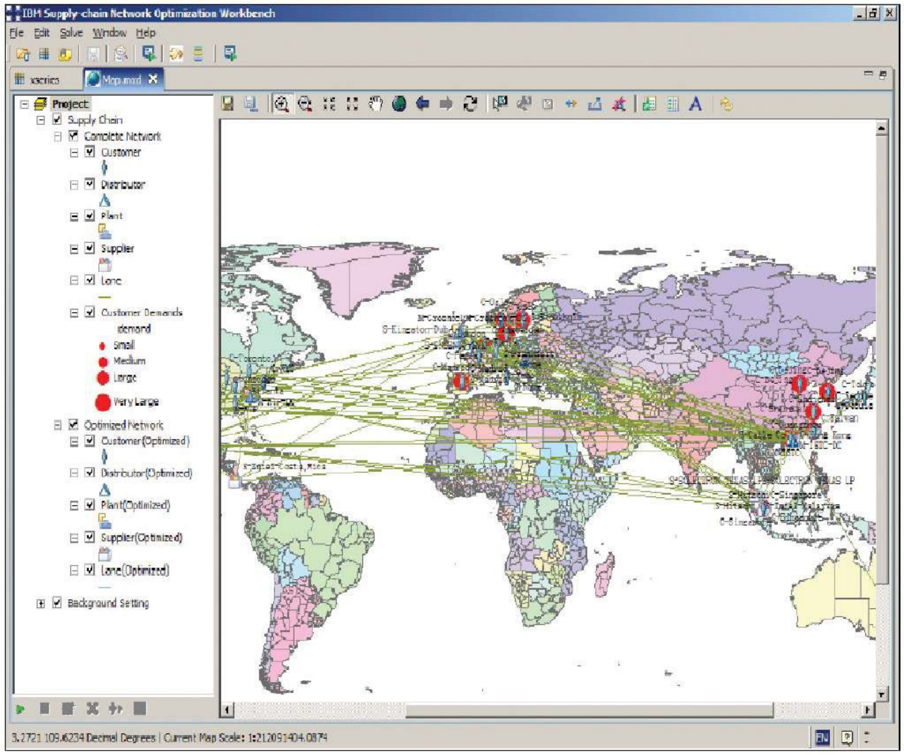


*Figure 2.2-2: Supply Chain Risk Management from IBM*

The application of business modelling and simulation in supply chain risk management has developed over time in correlation with the technical development of the simulation engine and paradigm (discussed in detail in chapter 3).

Application examples of SCRM in business modelling and simulation:

- Production scheduling and planning

  In his case study Hilletofth (Hilletofth & Laettilae, 2012) is evaluation the performance of a planning organisation across a multi-echelon planning system across the border of one organisation to its wholesale customer and supplier base. The described problem assesses the forecast accuracy and supply situation including various roles in the planning organization such as Demand Management, Master Production Scheduling and Material Requirement Planning. Furthermore, the complexity is increased by introducing a second product with different life-cycle parameters.

- Inventory behaviour affected by non-linear supply chain phenomena
  In the article "Using discrete-event based simulation for evaluating non-linear supply chain phenomena" Blanco and Godding (Blanco & Godding, 2011) are describing the behaviour of stock levels determined by replenishment principles faced by various, in today's business environment normal, effects. The authors are using a discrete-event based simulation to visualize the effects of waste, vulnerability, uncertainty, congestion, bullwhip, diseconomies of scale and self-interest. The main findings of this study conducted in collaboration with the Intel Corporation has been a quantified trade-off in form of a safety stock between waste and obsolete stock in the modelled system.

- Chan, Tang and Lau (Chan, Tang, & Lau, 2002) are building onto the concept of general stock level control by introducing further KPIs ultimately measuring delivery reliability towards the customer. The study assesses via a discrete-event based simulation Simprocess the concept of Constant Work in Progress (CONWIP) as per Spearman et al. (Spearman, Woodruff, & Hopp, 1990), workload regulating (WR) as per Goldratt and Cox (Goldratt & Cox, 1986), maximum shop load (MSL) as per Bobrowski and Park (Bobrowski & Park, 1989), starvation avoidance (SA) as per Glassey and Resende (Glassey & Resende, 1988), and waiting time heuristic (WT) as per Graves, Konorka and Milne (Graves, Konorka, & Milne, 1995).

- Vlachos, Georgiadis and Iakovou (Vlachos, Georgiadis, & Iakovou, 2007) target a similar assessment in the article:" A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains" however the method by which the analysis is conducted is based on system dynamic and not a discrete based approach, hence the result of the analysis is focussing on identifying general bottlenecks in the production / capacity rather than evaluating a discrete level of safety stock under given conditions.

- In order to assess dynamics and inventory levels Swaminathan, Smith and Norman (Swaminathan, Smith, & Norman, 1998) are applying an agent-based approach. Each individual agent is thereby following its deterministic characteristics interacting with other agents in a supply chain system. The simulation uses pre-defined variables as the bill of materials for products, lead time, transportation time, supply chain network, cost and supplier reliability and processes those into the measurable statistics of fill rates, inventory cost, work-in-progress, order turnaround time. It is noticeable that in comparison to the previously discussed cases studies of simulation applied in supply chain risk management the agent-based approach defined along the mentioned characteristics (or attributes) the level of knowledge that an individual agent has of other agents as well as their set of interactions throughout the simulation. Another good example for the application of agent-based simulation in the context of supply chain risk management is Seck (Seck, Rabadi, & Koestler, 2015).

Target of the illustration of the above examples for the application of business modelling and simulation in the field of supply chain risk management is to provide a broad overview which risks and variables are analysed. A detailed description and assessment of the various simulation paradigms is discussed in chapter 3.

## 2.3. The learning organisation

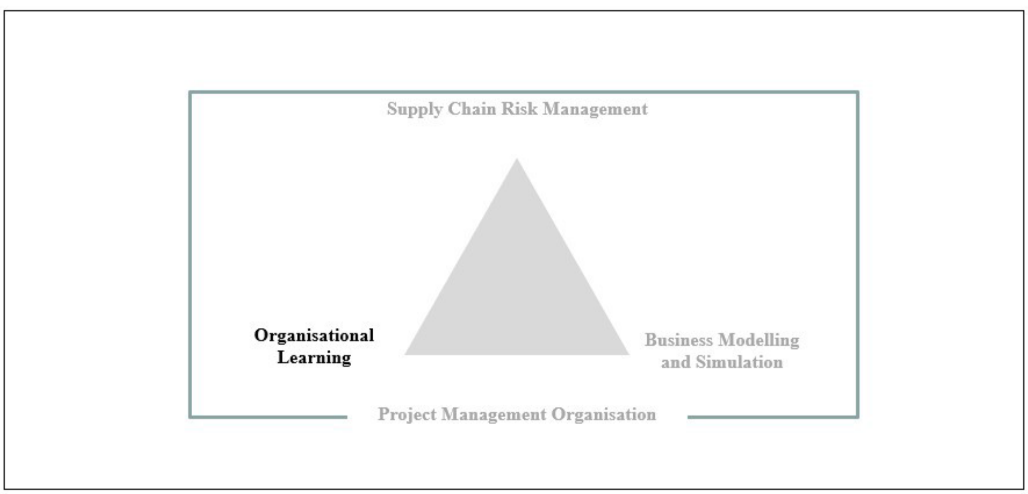


*Figure 2.3-1: Organisational Learning as part of the research triangle*

One common denominator of today’s business world is speed. Everything an organisation is doing would need to be judged in the context of time. How quick is the response rate towards a move of the competition, how quickly could a previously unpenetrated market share be harvested?
With all the emphasis on the pure reaction time it would be only short-sighted to purely focus on the quantitative parameter of time. In order to remain efficient organisations also need to continuously improve their qualitative ability of responding in the correct way towards today’s question in business.

“Organisational learning, innovation and internationalisation are key ingredients for the knowledge-based economy in the age of globalisation.” (Chiva, Ghauri, & Alegre, 2014, p. 687)
The topic of organisational learning is not new on the scientific world. Many of the most relevant researchers of the field have been publishing on the subject for more than two decades; however, time is grist on the mill for the topic as the quote above impressively shows.
Argote (Argote, 2011, p. 440) argues in her article “Organizational learning research: Past, present and future” that the development of research on the subject of organisational learning is rooted in three different streams represented by scientist that are still defining the field today. The first stream represented by authors like Argyris and Schoen (Argyris & Schön, 1996) emphasise the defensive routines in organisations that prevent learning and offers strategies to overcome them. Secondly, Cyert and James (Cyert & March, 1992) whose work was primarily motived by physiological aspects, and thirdly an approach focusing on the techniques of the learning curve which is widely used by the technical and economical school of organisational learning research. Two authors active in this field are Dutton and Thomas (Dutton, Thomas, & Butler, 1984). These authors have among many set the basis for some of the more publicly known research with its most popular example in Senge’s “The fifth discipline” (Senge, 2006)

### 2.3.1. Scientific streams in Organisational Learning

The framework in which today's landscape of organisational learning research is defined follows Wang and Ahmed's article "Organisational learning: a critical review" illustrated in the figure 2.3.1-1. (Wang & Ahmed, 2003, p. 10)

| Focus | The concept of organisational learning | Practices |
| --- | --- | --- |
| Individual learning | "Organisational learning occurs when individuals within an organisation experience a problematic situation and inquire into it on the organisational behalf" (Argyris and Schon) | Staff training and development |
| Process or system | Organisational learning is the process whereby organisations understand and manage their experience (Glynn et al.) | Enhancement of information processing and problem solving capability |
| Culture or metaphor | "A learning organisation should be viewed as a metaphor rather than a distinct type of structure, whose employees learn conscious communal processes for continually generating, retaining and leveraging individual performance of the organisational system in ways important to all stakeholders and by monitoring and improving performance" (Drew and Smith) | Creation and maintenance of learning culture: collaborative team working, employee empowerment and involvement, etc. |
| Knowledge management | Organisational learning is the changes in the state of knowledge (Lyles). It involves knowledge acquisition, dissemination, refinement, creation and implementation: the ability to acquire diverse information and to share common understanding so that this knowledge can be exploited (Fiol) and the ability to develop insights, knowledge, and to associate among past and future activites (Fiol and Lyles) | Creation and maintenance of learning culture: collaborative team working, employee empowerment and involvement, etc. |
| Continuous improvement | "A learning organisation should consciously and intentionally devote to the facilitation of individual learning in order to continuously transform the entire organisation and its context" (Pedler et al.) | The adoption of TQM practices |

*Table 2.3.1-1: A summary of the organisational learning concepts and practices*

- Individual learning

  Peter M. Senge's "The fifth discipline" is probably the most popular example to be found in the literature which concept fits into the category of individual learning.

  According to Senge the five capabilities or disciplines that an organisation needs to combine in order to become a learning organisation are **systems thinking, personal mastery, mental models, building a shared vision and team learning**. The concept is developed in a way that system thinking represents the key cornerstone and hence the fifth discipline representing the essential element of the framework

System thinking refers to the later described concept of system dynamics by Forrester (Forrester, 2013).

- Process or system

  The view of Glynn, Laut and Milliken (Glynn et al., 1992) propose that organisational learning is not to be considered as an isolated approach, but rather seen in the wider context of the environment the organisation itself is embedded in. Hence the focus is the multi-dimensional interaction between an organisation and all stakeholders directly or in-directly influencing it.

- Culture or metaphor

  A common saying when referring to, not only the importance but also dominance of culture in the business world is the quote which is largely assigned to Drucker: „Culture eats strategy for breakfast". The reason for putting this comment into the context of organisational learning is that culture is a construct which is equally powerful and inconceivable. Argyris, as one of the main authors in the field, is arguing that business culture and organisational learning follow a contrary development. He also argues by referring to the work of Schein (Schein, 2010) that he, Schein, regards the organisation as the group, and analyses organisational culture as a pattern of basic assumptions shared by the group, acquired by solving problems of adaptation and integration, working "well enough to be considered valid and, therefore, to be taught to new members as the correct way to be perceived, think, and feel in relation to those problems." (Argyris, 1999, p. 5)

  Following this line within the literature other authors are emphasising that the culture in the sense of an invisible bond between members of an organisation has a stronger and hence more import influence on the ability of an organisation to learn than for example a given structure and process. Some of the authors arguing along those lines are i.e. Torbert (Torbert, 1991), Jones (Jones, 2010), Minzberg (Mintzberg, 2013), Denison (Denison, 1997) and Smirchich (Smircich, 1983).

- Knowledge management

  The way how Wang and Ahmed structured the landscape of organisational learning concepts and practices, knowledge management and organisational learning are two individual concepts which are strongly but not necessarily interlinked. The aspect of knowledge management focuses on the aspect of "how" rather than "what" concerning organizational learning. In her article "Organisational learning research: Past, present and future", Argote (Argote, 2011) refers to various authors describing how the process of know knowledge management is supported, i.e. by social networks (Hansen (Hansen, 1999), Reagans and McEvily (Reagans & McEvily, 2003)), personal movement (Almedia and Kogut (Almedia, 1999), Kane, Argote and Levine (Kane, Argote, & Levine, 2005)), routines (Argote (Argote, 2013)), templates (Jensen and Szulanski (Jensen, 2007)), alliances (Gulati (Gulati, 1999)).

  Levitt and March (Levitt & March, 1988), two of the most prominent researchers in the field relate to the topic of knowledge management as organisational memory. In their article organisational learning they apply a three-step approach:

  - Recording of experience
  - Conservation of experience
  - Retrieval of experience

- Continuous improvement

  Continuous improvement represents one of the most common and a prominent concept in today's white- and blue-collar business environment. In Deming's work (Deming, 2013), he most prominent example of continuous improvement is to be found under the term Total Quality Management (TQM). In their article Wang and Ahmed refer to a number of authors linking the overall objective of a learning organisation as being an essential part, respectively objective of Total Quality Management.

### 2.3.2. Organisational Learning in the context of strategic management

The link between organisational leaning and the strategic management of an organisation in based in the underlying concept of adaptation as the result of a learning process. Beer et al. define this process as fitness which they define as:" the capacity to learn and change to fit new circumstances." (Beer, Voelpel, Leibold, & Tekie, 2005, p. 445). The approach of connecting the learning organisation to strategic management overall is not new and as explained by Bierly and Hämäläenen (Bierly & Hämäläenen, 1995) and Curado (Curado, 2006) is for example based in the strategic groundwork provided by Mintzberg already back in in the 1990s, being one of the ten strategic "schools". Another approach of putting organisational learning and strategic management into the same concept has been pursued by Bootz (Bootz, 2010), who is assessing in his article:" Strategic foresight and organizational learning: A survey and critical analysis" the connection and interdependence among the ability of an organization to assess future, strategic developments and its ability to foster organisational learning mechanisms. An interesting aspect of the research is that foresight is developed best when conducted in specialized groups as a joined exercise among experts (Bootz, 2010, p. 1593). While the concept of organisational learning as described above is focusing on the learning process within one organisation structure some others like Genc (Genç & İyigün, 2011) are evaluating the effects in a cross-organisational context and how strategic alliances benefit from it. Their assessment of a case study in Turkey showed that in this particular example all involved parties benefit in a learning context. Holt et al. (Holt et al., 2000) argue in a similar direction that it requires a learning organisation to achieve a competitive advantage in the context of a strategic alliance.

Jimenez-Jimenez and Sanz-Valle argue in their article: "Innovation, organizational learning, and performance" (Jiménez-Jiménez & Sanz-Valle, 2011) that organisational learning has a long-lasting positive effect on both, an organisations performance and as well an organisations ability to innovate. As both aspects are closely related to the strategic management of an organisation the following hypothesis are of a significant interest in regards to the above.

The second hypothesis which is tested by Jimenez and Jimenez is:" Organisational learning relates positively to performance." (Jiménez-Jiménez & Sanz-Valle, 2011,

p. 409). Followed by the third one:” Organisational learning related positively to organisational innovation.” (Jiménez-Jiménez & Sanz-Valle, 2011, p. 410).

The conducted interview-based research shows,” that […] organisational learning has a positive effect on both performance and innovation. In addition, organisational learning effect on innovation is higher than it is on performance. Taking into account the fact that innovation also proves performance, these results seem to reflect that innovation partially mediates the relationship between organisational learning and performance.” (Jiménez-Jiménez & Sanz-Valle, 2011, p. 413)

Another strong link between strategic management of an organisation and organisational learning has been presented by Shin et al. (Shin, Picken, & Dess, 2017). In their article:” Revisiting the learning organization” the authors assess the current relevance of the subject under the light of recent macro-economic developments. Part this assessment is a so called “Strategic Inventory – checklist” providing an overview of key concepts that are to be implemented from a strategic management perspective allowing and improving the learning organisation (Shin et al., 2017, p. 54).

Taking into account the vast body of research that assessed the phenomena of organisational learning in the context of strategic management it could be argued that organisational learning does not only support strategic management of an organisation but actually facilitates and improves it from several internal and external dimensions.

### 2.3.3. Organisational learning in the context of project management organisations

The organisational form that is in focus of this thesis is the project management organisation. As for every other aspect, organisational learning is to be considered in this special environment. The start is partially already bumpy.

Duffield and Whitty asses in their article “Developing a systemic lesson learned knowledge model for organisational learning through projects” that “both knowledge and project management literature suggests that in practice lessons learned processes rarely happen, and when it does, it is concerned with the lessons identification rather than organisational leaning. There are limited practical models for general management to use to conceptualise what organisational learning is and therefore how to enable it." (Duffield & Whitty, 2015, p. 311)

The rational of this observation is rooted in multiple causes linked to:

- the specific set up in which a project is defined and conducted with reference to the individuality to purpose and set up allowing proper management and steering of the project
- the discipline of the team to clearly follow through with the entire process of lesson learned identification to an active utilisation of the acquired knowledge (Duffield & Whitty, 2015, p. 312)

This general view is then relativized in regards to the industry, respectively the business area that is considered. Several authors argue that business areas with a strong focus on health and safety and environmental safety have already implemented relative comprehensive approaches (Hilliard et al. (Hilliard et al., 2012), Gordon (Gordon, Mendenhall, & O'Connor, 2013) and Matthews (Matthews & Thomas, 2007)).
It rather seems that the concept of lessons learned as a core pillar of the learning organisation is often not comprehensively applied in the general context of business projects. According to Duffield and Whitty this is not caused by a lack on concepts is existing, i.e. from the Project Management Institute (PMI) or the Association for Project Management (APM) but rather an issues linked to the human factor responsible for a compliant process (Duffield & Whitty, 2015, pp. 313–314).
Zedtwitz's research is arguing in a similar way. As part of joint research project at Cranfield University four main areas have been identified preventing a comprehensive lessons learned and organisational learning process in the context of post project reviews (Zedtwitz, 2002, p. 261):

- Phycological barriers
- Team-based shortcomings
- Epistemological constraints
- Managerial problems

Concluding from the above assessment of the existing literature, it could be stated that not only is the need for a stringent and comprehensive implementation of the organisational learning principles needed in the environment of a project management organisation, but it rather seems even more complex to do so successfully. The main effects causing this additional difficulty are linked to the negative feedback loop between the characteristics of a project itself and the combination how humans behave when approaching learning.

### 2.3.4. Organisational learning in the context of Industry 4.0

While the chapter 2.3.5 is specifically assessing the role and interaction of computer simulation and organisational learning is the objective of this paragraph to assess the current state-of-the-art in regards of the wider subject of digitalisation and Industry 4.0 and organisational learning.

The name "Industry 4.0" has become over the recent years the placeholder for a variety of developments in the way how companies steer, manage and control their entire product development, production planning and execution as well as the physical distribution network and customer relationship management. In the article:" The degree of readiness for the implementation of Industry 4.0" Pacchini et al. are introducing the term as:" the Internet Industry of Things, advanced manufacturing or smart manufacturing" (Pacchini, Lucato, Facchini, & Mummolo, 2019, p. 103).

In the same article the authors provide a comprehensive overview of the Industry 4.0 toolbox which is to be found in the literature. The items that are named with the most frequency are the internet of things, big data and cloud computing. Although simulation is also part of the list it is not one of the front runners (Pacchini et al., 2019, p. 114) which is partially due to the fact that simulation has been part of the tool landscape for quite some time while the recent focus has on generation and utilisation of data. An additional positive affect towards the field of simulation is, that the availability of high quality and quantity of input data will in turn improve the result of simulation models.

Lenart-Gansiniec (Lenart-Gansiniec, 2019, p. 98) is assessing with reference to multiple authors five requirements that an organisation needs to meet when implementing industry 4.0.:

- Ability to capture and generate data and transform them into valuable information facilitating the decision-making process
- Designate dedicated units for analysis data and applying analytical technologies
- Provide data security procedures
- Provide organizational structures and production infrastructure
- Ensure a high level of integration, communication, and cooperation between business processes

Across the described tool landscape Lenart-Gansiniec further summarizes the benefit of industry 4.0 in the context of organisational learning as follows:" In other words, Industry 4.0 allows organizations to re-interpret their problems and allows employees to create knowledge frameworks with which they can interpret new knowledge" (Lenart-Gansiniec, 2019, p. 103).

### 2.3.5. The interaction between organisational learning and computer simulation

Organisational learning and computer simulation are not two concepts interacting on an equal level as i.e., competing theories but computer simulation rather represents a vehicle that could be used in order to achieve sustainable and deeply anchored effects in an organisation when learning is done.

Andrews (Andrews, 2005) describes the differences in effectiveness of organisations in applying and living organisational learning with the result that organisations using simulation technology clearly outperform the ones that would need to rely on real time feedback-loops and experience.

In their article "System Thinking and Organizational Learning: Acting Locally and Thinking Globally in the Organization of the Future." Senge and Sterman (Senge, 1990) note, that not only the developments in today's business world require a more stringent approach to organizational learning, but that the nature of challenges, especially feedback loops, demanding dynamic decision making from mangers has been only becoming more complex requiring new tools like simulation to cope with them. “Dynamic decision making is particularly difficult, especially when decisions have indirect, delayed, nonlinear, and multiple effects. Yet these are precisely the situations in which managers must act. The turbulences of the late 20$^{th}$ century are in large measures due to increasing complexity of feedbacks among institutions and our inability to understand the dynamics they generate. Managers can no longer ignore the feedbacks between their decisions and the environment which condition the choices they will face tomorrow, next quarter, and four years to come.” (Senge, 1990, pp. 1008–1009)

An accelerating factor in the increasing importance of business modelling and simulation in relation their application is the technological development of the field. As discussed in chapter 3, computer simulation has developed over time depending on its application purpose creating a powerful learning environment for organisations simulation various purposes, being the material flow in a complex system assessing dependencies within the supply chain or the behaviour of competing businesses.

As a side remark on the subject of technological development it should also be mentioned that not only business modelling and simulation underwent a significant development, but also the development and popularity of so called Web 2.0 applications have not only conquered private life but also increased organisational learning in co-operations by providing new and interactive platforms for knowledge management pointed out by Perez-Aroz, Barber, Munive-Hernandez and Eldridge (Perez-Araos, Barber, Munive-Hernandez, & Eldridge, 2007).

# Chapter 3

## A simulation study – conceptual design

Planning and steering of complex production / manufacturing and logic systems often lead to using simulation as the preferred choice in today's business environment. The problem statements, which mainly affect economical processes of an enterprise, are often at the core of an intended application for simulation and business modelling.

By applying simulation predictions could be verified that are tested under various assumptions i.e., cost, production cycle time, resource consumption or the degree of capacity utilisation for production lines.

Business modelling and simulation according to Böhnlein (Böhnlein, 2004, p. 8) could be used for various purposes with a clear goal to:

- Visualize the behaviour of real systems by a "run-through" presentation, whereby the animation and the visualisation are the main objective
- Communicate with all involved stakeholders during development projects in order visualize planned or already existing processes
- Validate various scenarios of a planned system in order to judge a "real world" behaviour
- Anticipate critical conditions of a system, for example in the areas of construction analysis, crash tests or climate development. This procedure allows for a timely mitigation in order a critical status is detected
- Test changed environmental conditions to an existing system in order to optimize performance

The VDI[8] definition of definition is: „Simulation is the recreation of a system, including its dynamic processes, within an experimental model in order to gain experiences with might be transferred into reality." (Guideline, 3633, p. 3)

Along with this Banks defines Simulation as, "[…] the limitation of the operation of a real-world process or system over time. Simulation involves the generation of an

[8] VDI: Verband Deutscher Ingenieure

artificial history of the system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented.” (Banks, 1998, p. 3)

Next to the approach of business modelling and simulation applied for system analysis, each of them with its own justification in relation to the system that is analysed, following Böhnlein’s argumentation. (Böhnlein, 2004, p. 2)

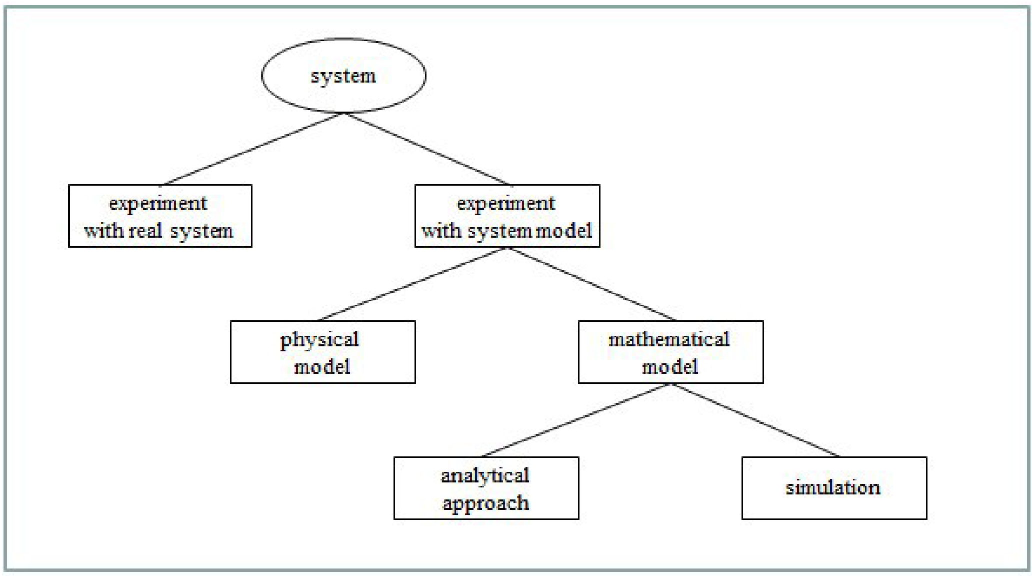


*Figure 2.3-1: Approaches to system analysis*

Simulation is, according to Kuhn (Kuhn, 1998, p. 7), considered to be one of the more extensive techniques for system analysis, however its application is considered reasonable when:

- Timely sequence of a system is to be analysed which behaviour is defined by oscillation of time
- Analytical approaches reached its constraints
- Experimentation on the real-world system is either not possible or too expensive
- The system which is to be analysed is, in essential aspects, new or under development so no empirical data could be used to determine the system’s behaviour

- Complex interdependencies prevent an analytical solution as the dynamic of the system could not be expressed in simple equations

Banks (Banks, 1998, p. 10) argues that, when the described characteristics are met, it is in general advantageous to use simulation as it allows, among other things, for:

- Testing of any given scenario within the designed model, hence changes could be applied and tested in a virtual environment rather on the real-life object
- Compressing or expanding time, meaning that phenomena could be investigated more thoroughly or a testing period that would require a long period of time could be compressed while simultaneously not jeopardizing the statistical results
- Illustrating graphically cause and effect modes within complex systems
- Updating and testing new policies that would require an enormous effort to be tested in the real world
- Diagnosing problems in either a ceteris paribus analysis or a dynamic environment

Besides the clear advantages of applying simulation as the method of choice for system analysis it also implies certain disadvantages that are discussed in the literature: (Banks, 1998, p. 12)

- Model building requires special training and has to be enhanced by experience, in addition any given model created by to different individuals might lead to the same result but consisting of a different structure
- Simulation results might be difficult to interpret as statistical validation would need to be applied to ensure significance to the results
- Simulation modelling and analysis can be time consuming and expensive as it is not uncommon of trying to solve comprehensive problems of i.e., one single organisation within a single simulation model
- Simulation might be used inappropriately i.e., when an analytical solution might be more suitable for the problem at hand

As the characteristic of the system that needs to be analysed represents the starting point, the choice of the analytical approach represents a crucial step. Derived from system theory, with Stachoviak (Stachowiak, 1973) as one its main contributors, a system could be split into the following components: the system boarder, the system's entry / exit, the system's elements and its attributes illustrated in figure 3.0-2.

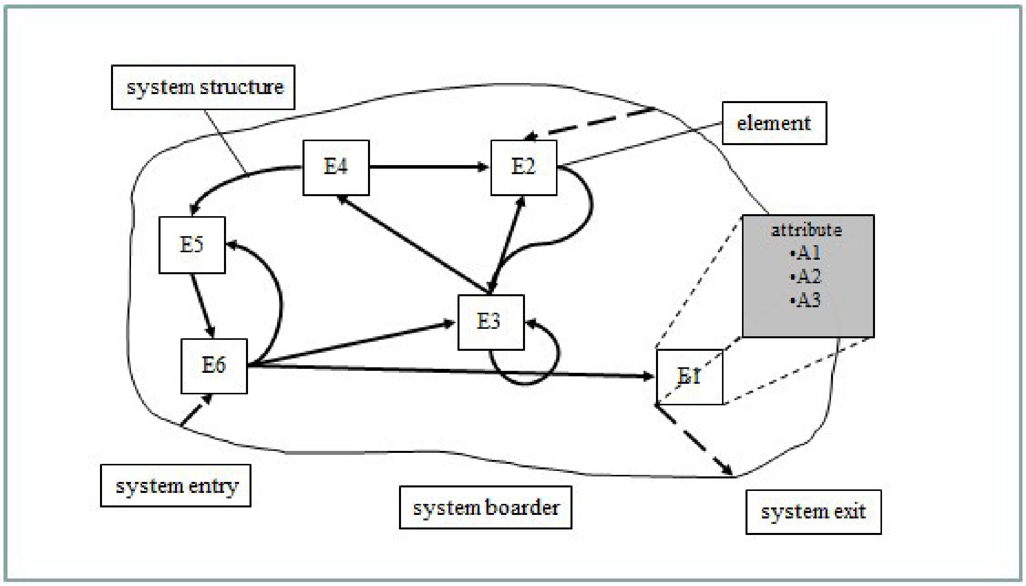


*Figure 2.3-2: Essential components of a system*

Every system consists of elements, which interact among each other in a structural relationship and order. All elements are characterised by specific attributes which make the individual and not inter-changeable. Attributes provide elements with an individual identity, whereby one distinguishes between declanatorial[9] and dynamic ones[10]. The single elements are connected distinctive structure. Within the field of system analysis, a main focus of the analysis lies on the feedback mechanisms within that given structure.

[9] Declanatorial attributes are fixed to a single element and are static over time viz. state variable

[10] Dynamic attributes are also fixed to a single element; however, they are changing over time, examples are results of a differential equation

The system boarder represents the frontier of the system in scope and its environment. Of particular interest is hereby the interaction between those two. In this context it is worthwhile mentioning the distinction between a sub- or partial system and total system. An example for a sub system is i.e., the supply logistic department of a company compared to the overall logic system. The interfaces of the individual sub systems are represented by system entries and exits.

One of the most crucial points, that decides on the usage of simulation and business modelling as an approach for system analysis is the dynamic of the system itself. When looking at the dynamic of a system, one has to distinguish between the structure ("what is a system") and the process ("what a system does"). As a conclusion, when applying a simulation compared to a static analytical approach not only the structure but the process is of a main importance.

Next to the argumentation for which circumstance the choice of a simulation model is the adequate one for a decision-making problem, respectively the analysis of a complex system, the following paragraphs introduce the main simulation paradigms System Dynamic, Discrete Event and Agent Based.

- System Dynamics

  The concept of System Dynamics as the most popular application of continuous simulation has been introduced by Forrester, who developed the concepts in the 1950s after joining the Alfred P. Sloan School of Management at MIT. According to Forrester System Dynamics "is the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise." (Forrester, 2013)

  The theoretical background used in this thesis is to big extend related to the work of Sterman (Sterman, 2000).

  The concept of System Dynamics is based on the abstraction of single events into an average flow influenced by defined policies which are described is a series of feedback loops (re-enforcing or balancing).

In the example of inventory management Sterman illustrates a company that holds a stock of finished inventory and fills orders as they arrive in the system. (Sterman, 2000, p. 710)

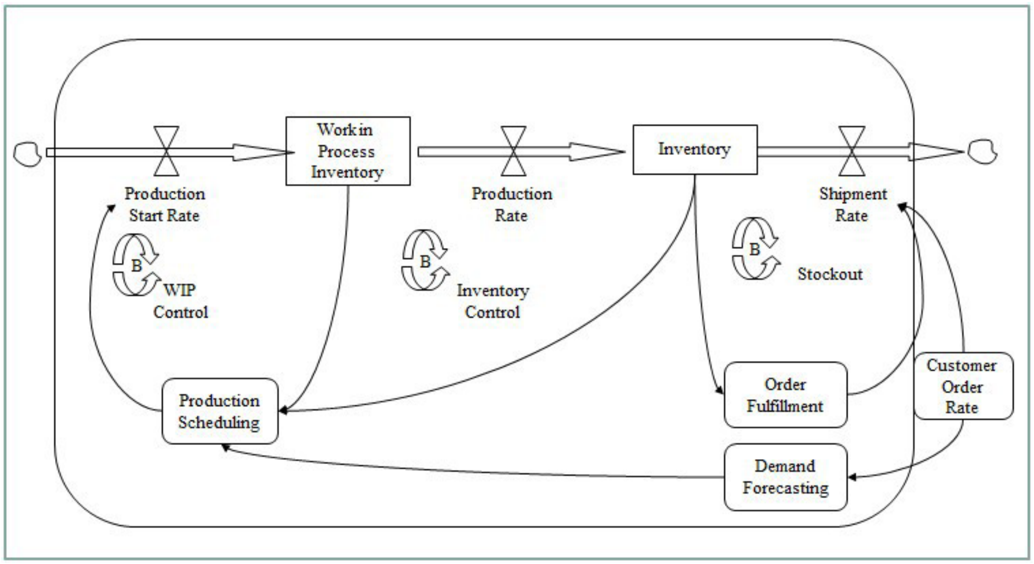


*Figure 2.3-3: The policy structure of inventory management*

In order to illustrate the approach of system dynamic the process step of Order Fulfilment will be further scrutinised. In Figure 3.0-5 the detailed interlinks between the various elements are displayed.[11]

[11] Example taken from Sterman, 2000, pp. 711–712.

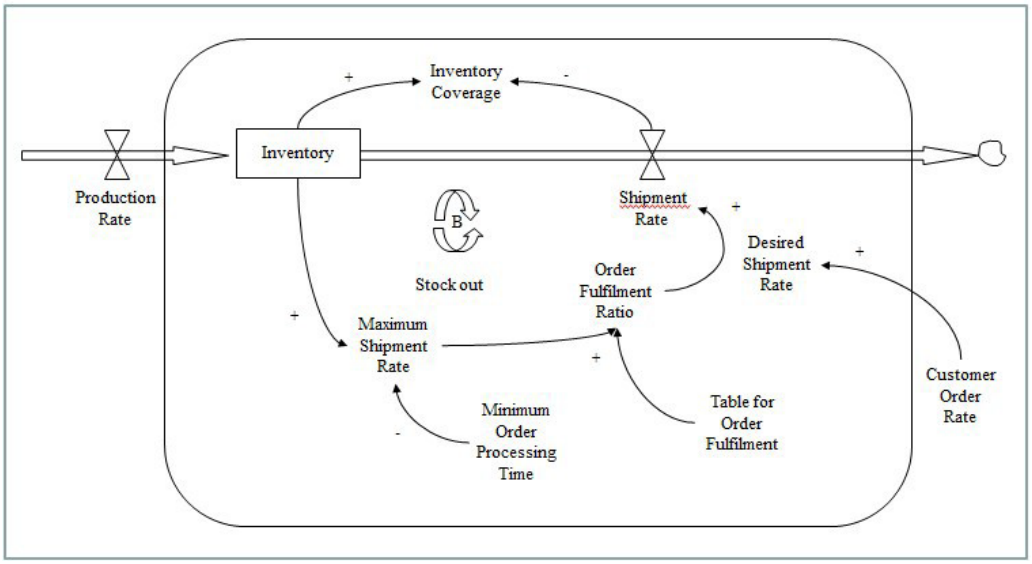


*Figure 2.3-4: The policy structure of order fulfilment*

The inventory coverage is the number of weeks; they could ship at the current rate given in its inventory:

$$Inventory\ \ Coverage = Inventory\ /\ Shipment\ \ Rate$$

$$Inventory\ \ Coverage = Int\ (\mathrm{Pr}\ oduction\ \ Rate - Shipment\ \ Rate\ ,\ Inventory_{t0}$$

The shipment rate normally equals the desired shipment rate, but if inventory is inadequate, some of the items, customer's request, will be out of stock, reducing the order fulfilment ratio (the ratio of orders filled to the desired fulfilment rates):

$$Shipment\ \ Rate = Desired\ \ Shipment\ \ Rate * Order\ \ Fuliflment\ \ Ratio$$

The order fulfilment ratio is a function of the ratio of the maximum shipment rate to the desired shipment rate; the values are specified by the Table of Order Fulfilment:

$$Table\ of\ Order\ \ Fulfilment = Table\ of\ Order\ \ Fulfilment\left(\frac{Maximum\ \ Shipment\ \ Rate}{Desired\ \ Shipment\ \ Rate}\right)$$

The maximum shipment level depends on the firm's current inventory level and minimum order fulfilment time:

$$Maximum\ \ Shipment\ \ Rate = Inventory\ /\ Minimum\ \ Order\ \ Fulfilment\ \ Time$$

The minimum order fulfilment time is determined by the firm's order fulfilment process, the complexity of the product, and the proximity of customers to the firm's distribution centres. It represents the minimum time required to process and ship an order.

In this simple model there is no backlog of unfilled orders, and all orders not immediately filled are lost as customers seek alternative suppliers, hence:

$$Desired\ Shipment\ Rate = Customer\ Order\ Rate$$

Where the customer order rate is exogenous from the point of view of the inventory and order fulfilment subsystems. A much simpler formulation is:

$$Shipment\ Rate = MIN\ (Desired\ Shipment\ Rate\ , Maximum\ Shipment\ Rate\ )$$

The example illustrates how System Dynamics approaches system analysis by applying by a set of mathematical differential equations.

- Discrete Event Based Simulation

  The core of Discrete Event Based Simulation is a concept of entities, resources and block charts describing a flow and sharing those resources. The application is rooted in a concept from Ware and Gordon (Ware & Gordon, 1961) who introduced the view of system block diagrams to a dynamic simulation environment.

  As Discrete Event Based Simulation considers time as deterministic a simulation using this paradigm always follows the same generic algorithm as described by Altiok und Melamed (Altiok & Melamed, 2007).

1. Set the simulation clock to an initial time (usually 0), and then generate one or more initial events and schedule them
2. If the event list is empty, terminate the simulation run. Otherwise, find the most imminent event and unlink it from the event list

3. Advance the simulation clock to the time of the most imminent event, and execute it (the event may stop the simulation)
4. Loop back to step 2

An example of the systematic Discrete Event Based Simulation taken from Kelton, Sadowski and Sturrock's (Kelton et al., 2007) work, is the simulation of a simple production process like a drilling operation that in its rudimentary form represents a queueing problem.

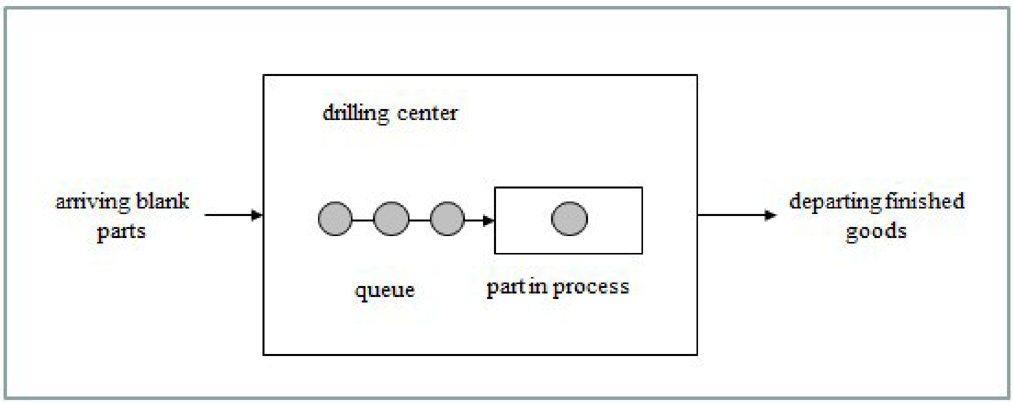


*Figure 2.3-5: A simple processing system*

The fundamental logic of the model is based on a queuing system as building blocks; a blank part arrives at the processing station. When the blank part arrives and the drilling centre is idle, it starts processing right away. Otherwise, it waits in a first-in, first-out (FIFO) queue. The time schedule for the model looks as following:

| Part Number | Arrival Time | Interarrival Time | Service Time |
|---|---|---|---|
| 1 | 0.00 | 1.73 | 2.90 |
| 2 | 1.73 | 1.35 | 1.176 |
| 3 | 3.08 | 0.71 | 3.39 |
| 4 | 3.79 | 0.62 | 4.52 |
| 5 | 4.41 | 14.28 | 4.46 |
| 6 | 18.69 | 0.70 | 4.36 |
| 7 | 19.39 | 15.52 | 2.07 |
| 8 | 34.91 | 3.15 | 3.26 |
| 9 | 38.06 | 1.76 | 2.37 |
| 10 | 39.82 | 1.00 | 5.38 |
| 11 | 40.82 | ... | ... |

*Table 2.3.5-1: Arrival-, inter arrival-, and service- times of parts (in minutes)*

The goal of the simulation study could for example be to measure on the one hand the overall number of parts produced and the average waiting time of parts entering the queueing system. $WQ_i$ is representing the waiting time in the queue of the $i^{th}$ part and the overall number of parts leaving the queue is represented by $N$ the average waiting time is calculated as:

$$\frac{\sum_{i=1}^{N} WQ_i}{N}$$

Furthermore, one of the most popular analyses done in Discrete-Event Based Simulation is the analysis of utilisation, in this case the drilling machine. The obvious benefit compared to a static calculation is a dynamic evaluation of positive and negative effects for a low and high utilisation. High utilisation is generally interpreted as good; however, a queuing model quickly shows the know-on effects of a sudden interruption has on highly utilised systems.

The formula for utilisation in this is for the busy function:

$$B(t) = \begin{cases} 1 \; if \;\; the \; drill \;\; press \;\; is \; busy \;\; at \; time \;\; t \\ \hline 0 \; if \;\; the \; drill \;\; press \;\; is \; idle \; at \; time \;\; t \end{cases}$$

The utilization is then divided by the length of the simulation run:

$$\frac{\int_0^{20} B(t)\,dt}{20}$$

Resource utilization is obviously interesting in many simulations, but it is hard to say whether you “want” them to be high (close to 1) or low (close to 0). Leading to the result that: „high is good since it indicates little excess capacity, but it can also be bad as it might mean a lot of congestion in the form of long queues and slow throughput.” (Kelton et al., 2007, p. 22)

- Agent-Based Simulation

  Compared to System Dynamics and Discrete-Event based simulation, Agent-Based simulation follows a different paradigm. In the former two approaches of simulation a system was designed, much as a “theme park ride” in which entities are passed through. According to Macal and North (Macal & North, 2009, p. 86), the essence of Agent-Based simulation is to “modelling systems comprised of autonomous, interacting agents.”

  Borshchev and Filippov (Borshchev & Filippov, 2004) put emphasis of the difference is hereby clearly on the word autonomous, the behaviour of the modelled system is no longer defined by the boundaries of the system but by the individual behaviour that its agents are equipped with. In the literature those models are also often referred to as decentralized or build in a “bottom up” approach.

  Following the same structure as used for the System Dynamics and the Discrete-Event Based simulation by the means of a simple example the approach will be explained in more detail.

  The example is taken from the AnyLogic 6 tutorial named Bass Diffusion. Agent Based Model.

The model describes a product diffusion process. Potential adopters of a product are influenced into buying the product by advertising and by word of mouth from adopters – those who have already purchased the new product. Adoption of a new product driven by word of mouth is likewise an epidemic. Potential adopters come into contact with adopters through social interactions. A fraction of these contacts results in the purchase of the new product. The advertising causes a constant fraction of the potential adopter population to adopt each time period. Agent-based model consists of multiple agents and their environment. Every agent is given a set of rules according to which it interacts with other agents; this interaction then generates the overall system behaviour.

In this model the volume of advertising and the probability that a potential adopter will adopt as the result of exposure to a given amount of advertising are assumed to be constant each period.

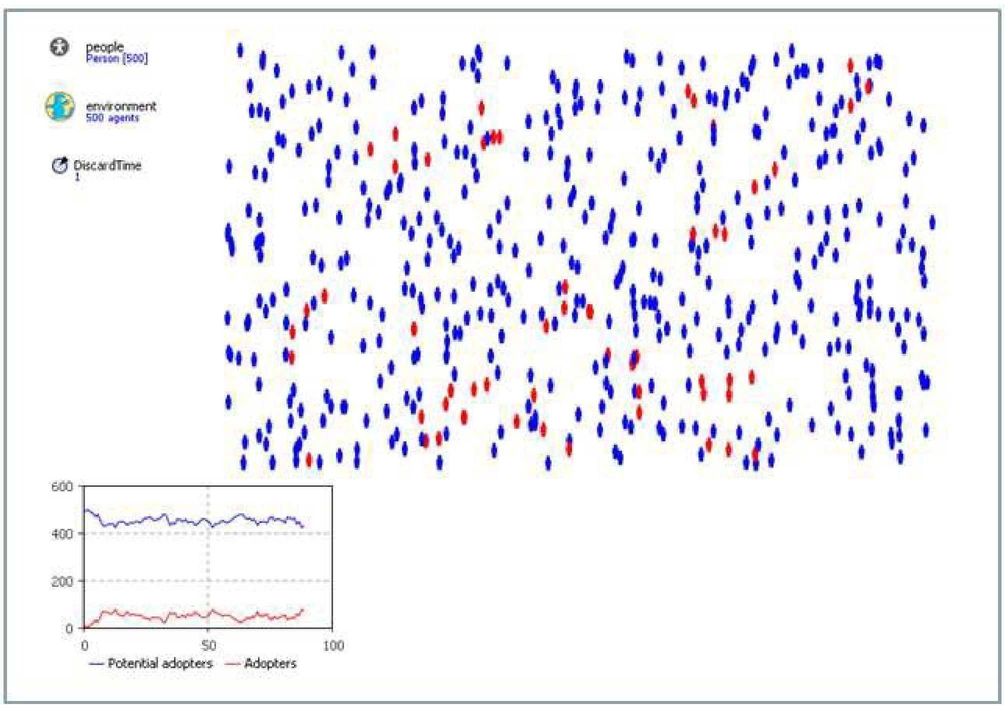


*Figure 2.3-6: Elements of Agent-Based Simulation*

**People** are the individual agents that are simulated in the model, in this example 500 potential consumers. The **Environment** describes the potential space for them meet and to interact. The two bars marked with **Potential Adopters** and **Adopters** contain the heuristic behaviour of the agents. The adjective which with they are equipped is the availability to persuade their peers to change from Potential Adopters to Adopters. In this simple example this is expressed with a statistical probability.

## 3.1. Assessment of simulation paradigms in the context of supply chain risk management

After assessing the selection process for using business modelling and simulation as a tool of choice for analysing complex systems and the general introduction of the most common simulation paradigms the following chapter assesses the effectiveness of those simulation paradigms in light of the specific challenges and characteristics of supply chain risk management.

However, it is prior to the detailed assessment relevant to point out that the general process of model creation and simulation is a highly creative one, meaning that in case the result and purpose are not impacted by choice of paradigm it remains the user's choice.

In order to systematically assess the effectiveness in the context of supply chain risk management three dimensions are to be considered:

- Level of abstraction in the supply chain simulation study
- Concept of time used in the model
- Distinction between active and re-active entities in the model

applied in the supply chain risk management simulation study.

- Level of abstraction in the supply chain simulation study

  While the general concept of abstraction is to be found in every (simulation) model the scale in which characteristics of the real system are not considered as relevant for the purpose of the model and are omitted represents a major implication regarding the choice of the simulation paradigm.
  Borshchev and Filippov (Borshchev & Filippov, 2004, p. 3) set the various paradigms in relation to the objective the simulation should fulfil as shown in figure 3.1-1 taken from their article:" From System Dynamics and Discrete Event to Practical Agent Based Modelling: Reasons, Techniques, Tools."

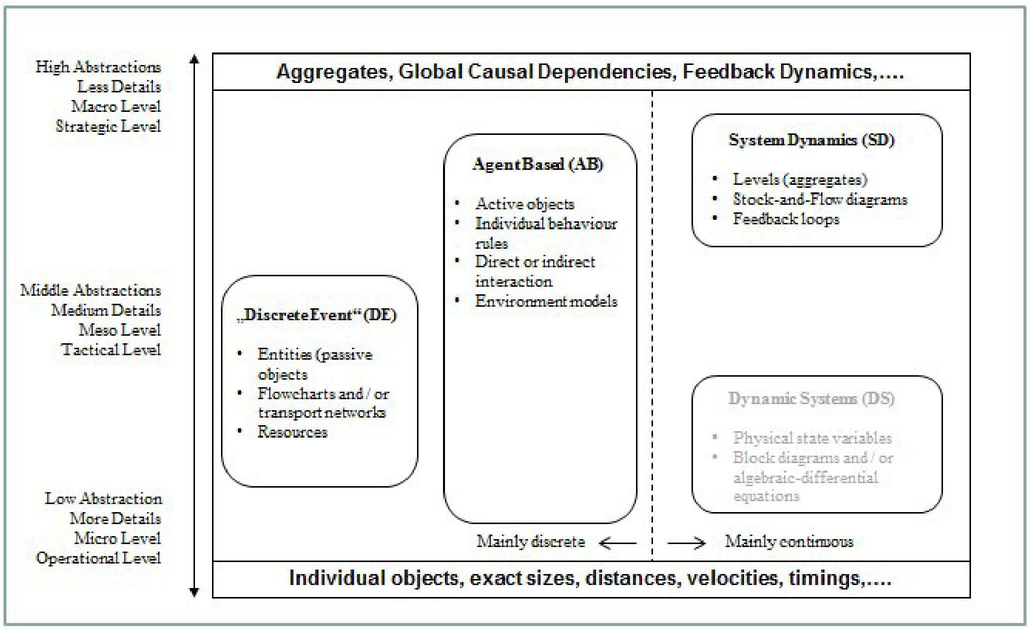


*Figure 3.1-1: Approaches (paradigms) in Simulation Modelling on Abstractions Level Scale*

  In regards to the abstraction of system elements it could be observed that the higher the level of abstraction is, the more System Dynamics applies as a paradigm simulation the general policy. In contrast, the lower the targeted abstraction level of the system is, the more Discrete Event based solutions apply. Following this guidance Brito et al. (Brito & Botter, 2011) analysed and compared the differences of application of Discrete Event Based and System

Dynamic applications. In reference to Tako (Tako & Robinson, 2012) the table 3.1-1 shows the comparison (Brito & Botter, 2011, p. 3919).

| Model Use | Discrete Event | System Dynamics |
| --- | --- | --- |
| Understanding | User does not understand the underlying mechanics | Model is transparent to the user |
| Validity (Credibility) | Both models are perceived and representative, provide realistic outputs and create confidence in decision-making | |
| Usefulness | Less used as learning tool; good communication tool | So-called "learning laboratories"; good communication tool |
| Results | Statistically valid estimates of performance; interpretation requires mathematical background | Easily interpreted; little or no statistical analysis is required |

*Table 3.1-1: Comparison between Discrete Event and System Dynamics I*

Setting this scale of abstraction into the context of supply chain risk management, Mourtzis et al. provide an interesting view of different simulation application in dependency of the targeted scope in product and production simulation (Mourtzis, Doukas, & Bernidaki, 2014) whereas the illustration 3.1-2 only focuses on the production scope with an adjustment on the supply chain scope (Mourtzis et al., 2014, p. 216).

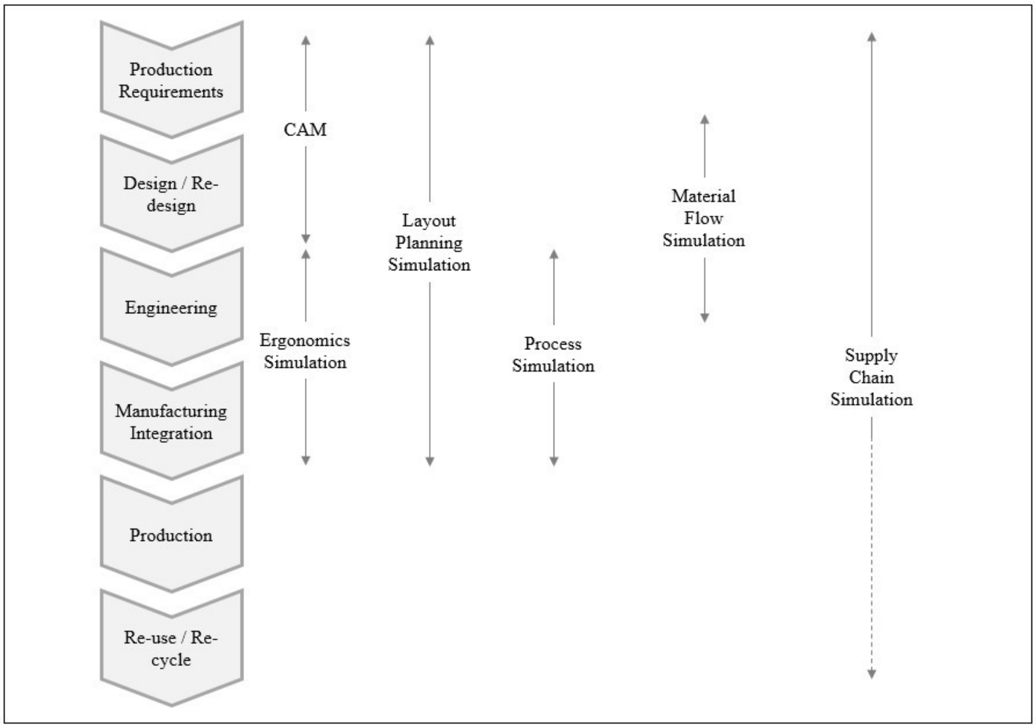


*Figure 3.1-2: Mapping of key enabling simulation technologies in production development*

In a similar manner Tako and Robinson (Tako & Robinson, 2012) argue that the general tendency in the scientific community is to address generic, more strategic issues with the paradigm of system dynamics, while more technical operational issues are to be best addressed via the application of discrete event-based simulation. Figure 3.1-3 shows the categorisation of logistic and supply chain relevant issues that are commonly assessed using business modelling and simulation (Tako & Robinson, 2012, p. 805).

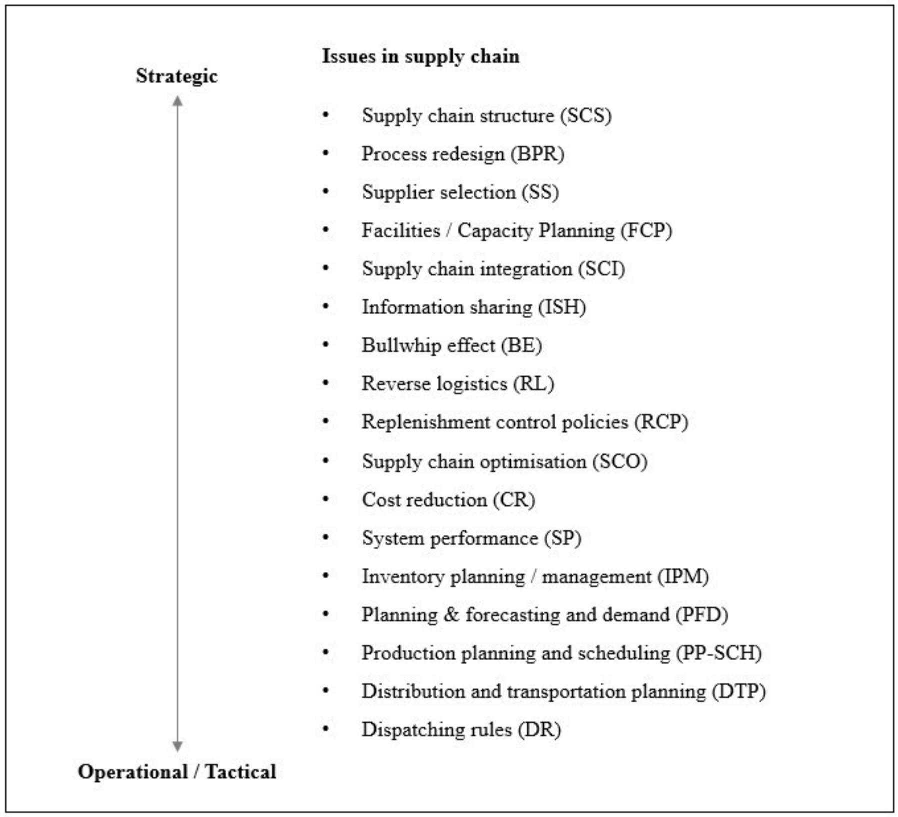


*Figure 3.1-3: Mapping of key enabling simulation technologies in production development*

While the conclusion in regards to the general issues to be assessed in the context of logistics and supply chain management continues to be relevant the subsequent assessment in relation to published articles is linked to the time of publication and might lead to an equal conclusion today.

The illustrated focus in combination with the discussed necessary level of abstraction indicate that the primary application of discrete event-based simulation is on individually assessed technical parts of the supply chain, while the most effective application for system dynamics lies in the policy shaping of entire supply chain simulations.

- Concept of time used in the model

The concept of time that is used in the simulation model has by far more implication than the unit of time in which the user can for example visualize simulation models or conduct a set of experiments (i.e., per seconds, minutes, days or years) but it is deeply anchored in the simulation paradigm's DNA.

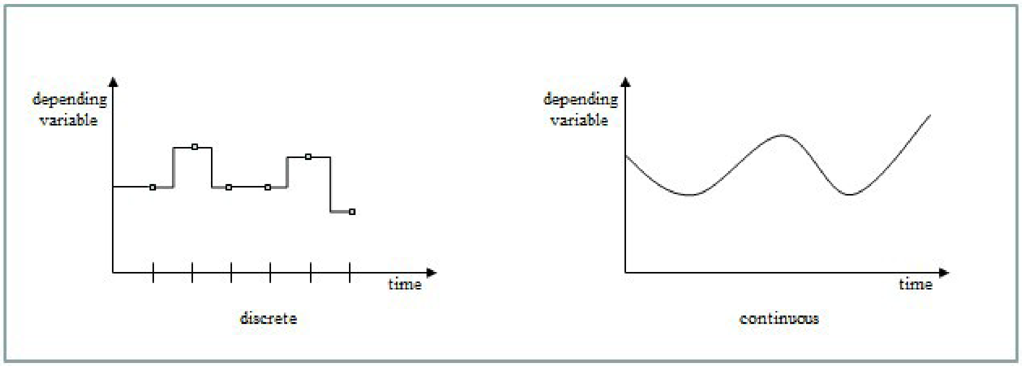


*Figure 3.1-4: Perception of time in simulation models*

Figure 3.0-3 shows the two approaches on simulation concerning their perception of time and aggregation of variables over time. Within this range of acknowledging time as the most important driver in a non-static simulation model the main paradigms have been developed in the area of business modelling and simulation, each of them to be used in a specific context or mode of analysis. Following Ossimitz and Mrotzek's arguments, the basic difference between the two approaches is linked to the mathematical expression of both, whereas, "[…] the concept of discrete time is based upon a distinction between time-points and time intervals, […] the concept of continuous time models time as a continuum of subsequent time-points. This implies that data given for some time-span are specified as a continuous function over time." (Ossimitz & M. Mrotzek, 2008, pp. 3–4).

In regards to the consequences and the subsequent choice of simulation paradigm in light of the discussed supply chain risk management issues this means a model following the system dynamic approach is applying a set of differential equations to indicate the change in state of defined variables while as the discrete event-based simulation adapts variables only at specific points in time that are either event driven or time step driven.

Brito et al. combine those aspects in the table 3.1-2 pointing out that due to the different way discrete event-based simulation and system dynamic simulations are build their characteristics are set apart.

| Aspect | DES | SD |
|---|---|---|
| Perspective | Analytic, emphasis on detail complexity | Holistic, emphasis on dynamics complexity |
| Model Nature | Stochastic | Deterministic |
| System Building Configuration | Network of queues and activities | Series of stocks and flows |
| Resolution | Individual entities, attributes, decision and events | Homogenized entities, continuous policy pressures |
| State Change | At discrete points of time; Event-stepped | "Continuous"; Finely-sliced time-stepped |
| Data | Numerical with some judgmental elements | Broadly drawn |
| Problem Scope | Operational | Strategic |
| User Perception | Opaque box | Transparent Box |
| Outputs | Point predictions and detailed performance measure | Understanding of structural source of behavior modes |

*Table 3.1-2: Comparison between Discrete Event and System Dynamics II*

- Distinction between active and re-active entities in the model

By bringing the concept of agent-based simulation into the comparison a crucial question that arises is how activity is triggered in a simulation environment. While system dynamic simulation is characterised by a continuous flow and the measurement of the “water level” at various points in order to detect the development of pre-defined variables discrete event-based simulation is characterised by an entity moving through a pre-defined path activating building blocks in the model while collecting statistical information. Especially in comparison to agent-based modelling approaches this could be considered as a rather “passive” approach. In accordance with a panel discussion at the UK Operational Research Society's Simulation Workshop 2010, Siebers summarizes the main advantage of agent-based simulation over discrete event-based, that: “[…] agent-based models can explicitly model the complexity arising from individual actions and interactions that arise in the real world” (Siebers, Macal, Garnett, Buxton, & Pidd, 2010, p. 206). Throughout the panel discussion Siebers collected several attributes shown in table 3.1-3 setting the two concepts aside.

| DES | ABS |
|---|---|
| Process oriented (top down modelling approach); focus is on modelling the system in detail, not the entities | Individual based (bottom up modelling approach); focus is on modelling the entities and interactions between them |
| Top down modelling approach | Bottom up modelling approach |
| One thread of control (centralised) | Each agent has its own thread of control (decentralised) |
| Passive entities, i.e. something is done to the entities while they move trough the system; intelligence (e.g. decision making) is modelled as part in the system | Active entities, i.e. the entities themselves can take on the initiative to do something; intelligence is represented within each individual entity |
| Queues are a key element | No concept of queues |
| Flow of entities through a system; macro behaviour is modelled | No concept of flows; macro behaviour is not modelled, it emerges from the micro decisions of the individual agents |
| Input distributions are often based on collect/measured (objective) data | Input distributions are often based on theories or subjective data |

*Table 3.1-3: Comparison between Discrete Event and Agent Based Simulation*

Summarizing the assessment of the three dimensions of differences among the various simulation paradigms it is to be concluded in consideration to their application in the field of supply chain risk management, that all three and the combination of those have their justified place in the area of supply chain risk management, however:

- System dynamic simulation is best to be applied for high-level strategic issues assessing supply chain policies
- Discrete event-based simulation is best applied for technical issues similar to waiting-queue issues
- Agent-based simulation is best applied for issues involving high complexity of individual entities

## 3.2. The model building cycle – elements and processes

Running a simulation study is always to be considered in the wider perspective of a problem-solving cycle following a strict methodology. The following overview is to be read in a way that the execution of the simulation project itself only represents one step in the overall problem-solving process, whereas for example one step is a verification of the appropriate solution approach towards the problem. As stated in the introduction to chapter 3, business modelling and simulation represent one out of many possible approaches towards a system analysis, the judgement of whether is the appropriate one for the problem at hand is also an integrated part of the problem-solving cycle.

The systematic which will be applied as part of this thesis follows the approach of System Engineering[12]. The German ASIM association adapted this concept to successfully conduct simulation projects. The figure 3.1-1 is taken from one of the organisation's publications (ASIM, 2004) and provides an overview of the structure and interdependency of System Engineering and the process of simulation analysis.

[12] According to the INCOSE - International Council on Systems Engineering, System Engineering is considered as "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (http://www.incose.org/AboutSE/WhatIsSE)

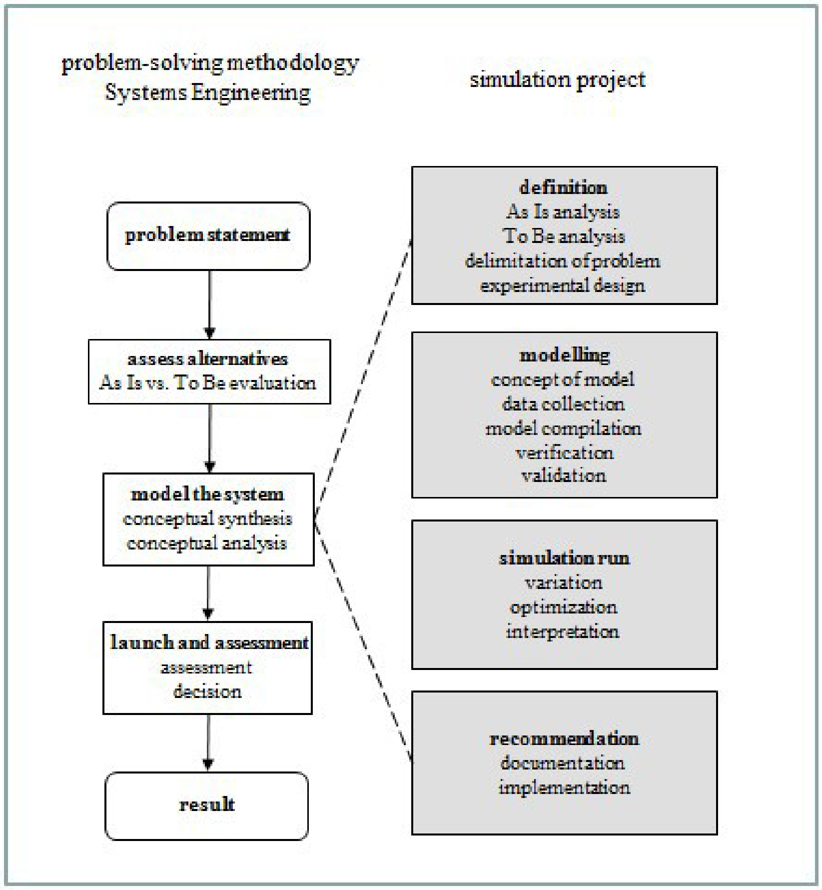


*Figure 3.2-1: System Engineering problem solving methodology*

- Problem statement

  Starting point of the overall process is the realisation of a problem and the acknowledgement of it. In this context a problem is defined as the delta between a current and a future state of a system, for example the difference in current and planned throughput of a production system

- Assessment of alternatives

  The main elements of the second step in system engineering are the analysis of the current situation and the conceptual formulation of the future state. According to Sphani (Sphani, 2000) the main purpose of an as-is analysis is to systematically structure the situation in order to allow for a proper problem definition in the first place. To Spahni it is important to assess the system from different perspectives with a clear focus on future development. Among others the mainly applied approaches are the:

- Failure mode and effect analysis (FMEA): Objective of investigation is the system as a total entity (Black-Box approach)
- Structural analysis: Object of investigation is the internal setting of the system
- Factorial analysis: Focus of the analysis is, in contrary to the structural analysis, the process within the system

Subsequent to the analysis of the current of a system is the definition of its future state, whereat it is important that the definition is formulised in a trend-setting and not a retrospective manner in order to justify pre-set hypothesis.
The following fundamentals according to Spahni (Sphani, 2000, p. 34) are to be part of every definition of a future state:

- The definition has to be neutral, meaning it must not contain any assumptions which would narrow the solution space
- The definition has to be neutral in regards to its effectiveness, meaning that all positive and negative affects need to accounted for
- In line with the decided objectives, it is advising to document all involved organisations and persons in order to guarantee that the objectives are understood and measurable for the ones involved

After concluding this initial analysis, the step of modelling the system is focusing on the development of the solution.

- Modelling the system

  Modelling the system is to be understood as the development of various solution alternatives. As part of this process a conceptual synthesis and analysis are conducted. Conceptual synthesis describes the gathering of various solution alternatives as a result of the conducted as is and to be analysis. Potential solution alternatives to business modelling and simulation, which is the focus of this thesis, could be experiments with the real system, a physical or a mathematical model.

- Launch and assessment

  After successful determination of all relevant solution alternatives a methodical approach for evaluation has to be applied. One example is the value benefit analysis. In German speaking countries the approach of Zangemeister has been frequently used and is considered as state of the art. “The value benefit analysis is a planning method preparing a systematic decision making among a variety of alternatives. It consists of the analysis of complex interdependencies with the purpose of assigning preferences of the decision maker as part of a multi-dimensional target system.” (Zangemeister, 1976, p. 45)

  As the value benefit analysis, shown in figure 3.1-2 according to Bechmann (Bechmann, 1978), is not considered a focus area of this thesis, the process of conducting the analysis will only be described in general terms.

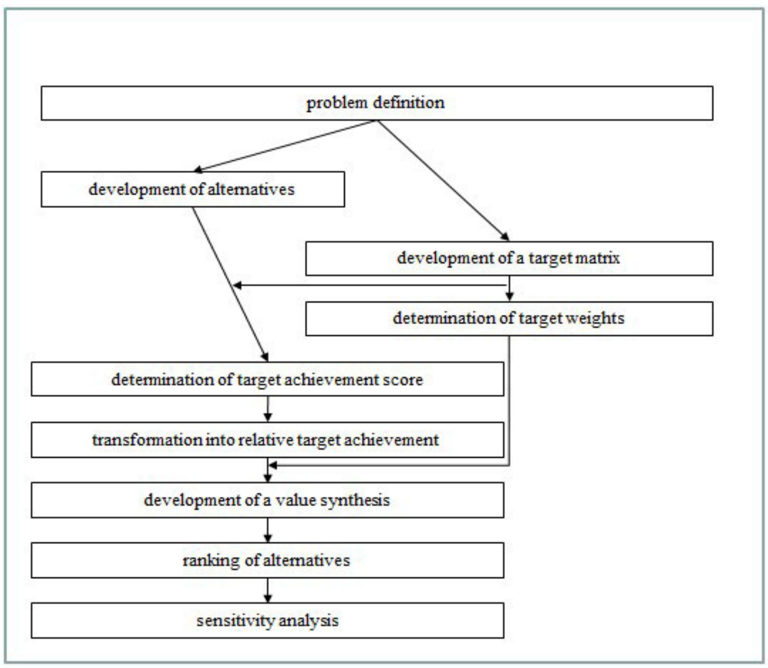


*Figure 3.2-2: Process steps of a value benefit analysis*

The problem definition defines which problem has to be solved by applying the value benefit analysis. As part of the next step all relevant alternatives that provide a solution to the described problem are listed. The applied target matrix by which the various alternatives are ranked is strictly hierarchical and only consisting of measurable indicators.

As not all indicators are equally important for the determination of the overall value of the alternative individual weights are applied which sum up to 1 or 100%. The determination of the target achievement score is describing the sum of weighted partial value in context of the overall value which is done in the process step of developing a value synthesis. A final proof of the concept is done in the sensitivity analysis.

## 3.3. Elements of a business modelling and simulation project

The following points are referring to the elements described in the figure 3.1-2 as part of a business modelling and simulation project. In terms of a continuous flow and focus on the subject of simulation, in contrary to a complete System Engineering project, this process is discussed separately. In difference to the previous paragraph a strict distinction in process and elements of a business modelling and simulation project will be applied.

### 3.3.1. Definition of application

Definition of application describes an adequate description of the simulation's objective which could be verified against its level of target fulfilment based on the described as is and to be analysis.
Depending on the complexity of the simulation project the documentation of an as is and to be state are further documented by support of project management instruments for example performance[13] and requirement specifications[14].

### 3.3.2. Model design

One way of describing model design or modelling is referring to the quote:" Modelling is a principal – perhaps the primary – tool for studying the behaviour of large complex systems […] when we model systems, we are usually (not always) interested in their dynamic behaviour. Typically we place our model at some point in phase space and watch it mark out a path through the future." (Simon, 1990)

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[13] Definition of performance specification according to DIN 69905:"A holistic description of the receivable towards the delivery and performance of the supplier."

[14] Definition of requirement specification according to DIN 69905:"

Another view on the topic, a more technical one, is provided by the German association of Engineers (VDI) which describes a model as:" a simplified replication of a planned or existing system and its processes into another physical or non-physical form. It only differs from the original object of investigation by a pre-defined tolerance." (Verein Deutscher Ingenieure, 2013, p. 3)
This definition could be applied to any kind of model. An example for this is displayed in the illustration 3.2-1 with a model of a production line from Klug (Klug, 2007, p. 92).

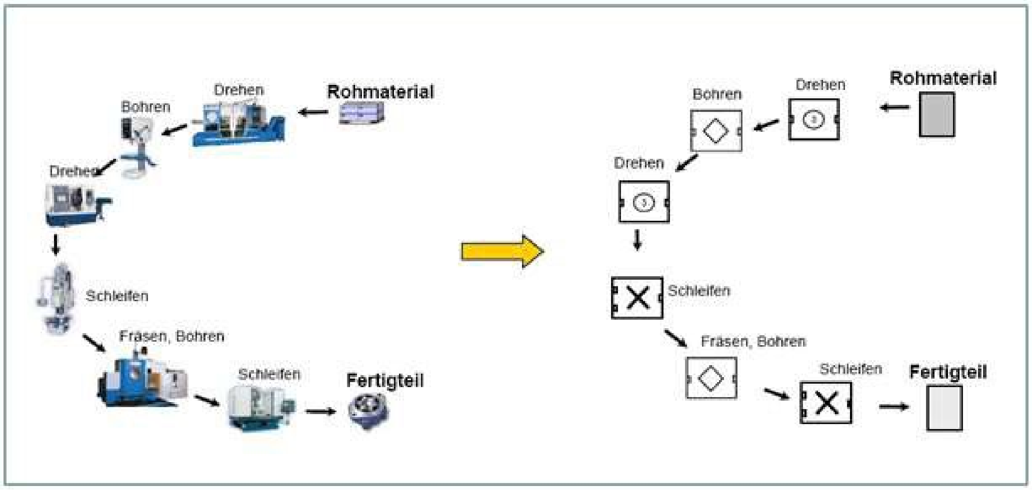


*Figure 3.3-1: Illustrative example of a production line*

The general concept of model creation and the interdependencies between the real system and the model are exemplified by Böhnlein's the image below (Böhnlein, 2004, p. 3). The attributes of the simulation are marked with an apostrophe.

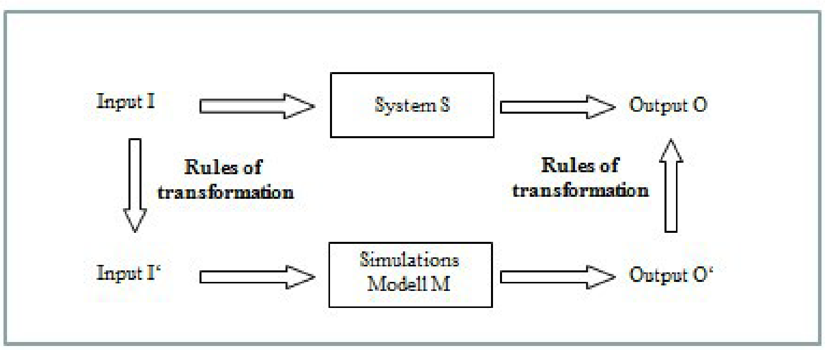


*Figure 3.3-2: Conceptual simulation of a system by a model*

The real system is described as an input, throughput and output equation. The transformation of the real input I to the simulated input I' which is transformed into the model output O'. The implications assessed in the model output O' are then influencing the output of the real output O.
According to Stachowiak (Stachowiak, 1973, pp. 131–133) all models possess three main attributes:

- Reproduction
  Models are always reproductions of natural or artificial originals which might be models themselves

- Reduction / Curtailment
  Usually, models are not reproducing all attributes of a real system, but only those which are relevant for the creator and user of the model

- Pragmatism
  Models are not necessarily unambiguously assignable to the original system. They fulfil clearly defined replacement functions within clearly defined time intervals

As part of the process evaluation in 3.3 the various attributes are described in further detail

### 3.3.3. Simulation runs

After finalizing the composition of the model simulation runs need to be performed in order to gain data as described by Wenzel (Wenzel, 2008, p. 139). In order to ensure the statistical validity of the data a clear methodology has to be applied during the process of composing the model and running the simulation.
Simulation runs that are based on random numbers must be optimized according to the parameters number of repetitions and simulation length. Depending on the type of simulation the user must consider the opposing relationship between cost per simulation run and the additional benefit gained from the extra simulation run. The result of this increased cost pressure is that users often tend to decrease the number of applied simulation-runs, which as a consequence leads to the fact that not all possible,

for the result necessary, outcomes of the organisation could be observed. This is the reason why the results of simulations have the characteristics of random samples.

Special events are besides the general link between number of simulation-runs and length of the simulation run of a major interest. All events of the system and consequently of the simulation model has to be recorded multiple times in order to gain statistical significance.

The use of confidence intervals, as explained by Wenzel, Rabe and Spieckermann (Wenzel, Rabe, & Spieckermann, 2006, p. 75), is commonly used in order to determine the correct length and number or simulation runs. Confidence intervals are defined as the left and right range next to the medium of the sample.

The estimation procedure using confidence intervals is a, so called, interval estimation. It considers the insecurity of the estimation by taking an interval into consideration which overlaps the true parameter with a pre-defined probability. Relating to Fahrmeir (Fahrmeir, 2010, p. 392), the width of the confidence interval is depending on the sample size and the confidence of the interval in combination with the previous knowledge on the type of distribution.

Subsequently this procedure will be explained including an example calculation. As a preparation the following parameters have to be defined:

- : probability of error within the confidence interval whereupon the interval is defined as $100 * (1 - \alpha)\%$
- $\sigma$ : standard deviation of the basic population
- $n$: sample size

Starting point for the determination of the confidence interval is an estimated value for unknown expectancy value . One obvious expectancy value is the arithmetic mean $\bar{x}$, which follows the normal distribution $N(\mu, \sigma^2 / n)$. $\bar{x}$ could be standardised to $\frac{\bar{x} - \mu}{\sigma / \sqrt{n}} \approx N(0,1)$.

The result is a statistic containing the unknown parameter ($\sigma$ is known) with a known distribution.

For this statistic a two-sided range could be determined in which the result is to be found with a probability of $1-\alpha$.It is imperative:

$$P\left( -z_{1-\alpha/2} \leq \frac{\bar{x} - \mu}{\sigma / \sqrt{n}} \leq z_{1-\alpha/2} \right) = 1 - \alpha$$ [1]

By further rearrangement of the formula the limits of the confidence interval could be determined:

$$\left[ \bar{x} - z_{1-\alpha/2} * \frac{\sigma}{\sqrt{n}}, \bar{x} + z_{1-\alpha/2} * \frac{\sigma}{\sqrt{n}} \right]$$

Concerning the widths of confidence interval, it should be noticed that in general they shrink with an increasing number of the sample size, meaning that increasing reliability is expressed by smaller confidence intervals. With a growing probability $1-\alpha$ (decreasing probability of error) the width of the confidence interval is decreasing.

Concerning the practical application, it remains to mention that the main issue is often in the correct determination which probability distribution to apply. Next to the normal distribution many different distributions could match the random variable, hence the choice is depending on a high level of statistical sensitivity[16] in order to take a correct decision. Next to the choice of the number of the needed simulation runs an additional choice on the condition of the starting values in the simulation model needs to be done. The choice is mainly driven by the characteristics of the system which is going to be modelled. A general distinction is made between terminating and non-terminating systems. The former one is defined by clear start and end data, e.g. following an example from Spiekermann (Spieckermann, 2008, 70 seq.) a normal shop with defined opening hours 8.00am – 10.00pm. Is the simulation, and by that the collection of statistical data, running from 8.00am – 10.00pm, the data could be considered complete and the simulation represents the real system. If the real system is for example a manufacturing of coachwork that is done in a three-shift model and the simulation starts with an empty assembly line the first throughput will distort the result of the simulation. The reason is that the first coachworks will pass the assembly process potentially quicker compared to an assembly line that is already blocked with the parts manufactured in the previous shift. In order to avoid this kind of statistical

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[15] The term $z_{1-\alpha/2}$ describes the quantile of the standard distribution resulting from the applied values

[16] Statistical sensitivity describes that the results of random experiments are to be considered sceptically, e.g., the pure orientation according to the average would be the opposite of statistical sensitivity

error simulation models usually operate with a “warm-up” time. Figure 3.2-3 illustrates this interdependency. Would already statistical data used at 00:05:00 the result would be wrong. However, if the system is operating with a warm up time till 01:45:00 the results could be considered statistically correct. Figure 3.2-3 is taken from Spiekermann (Spieckermann, 2008) showing the timely development of the model.

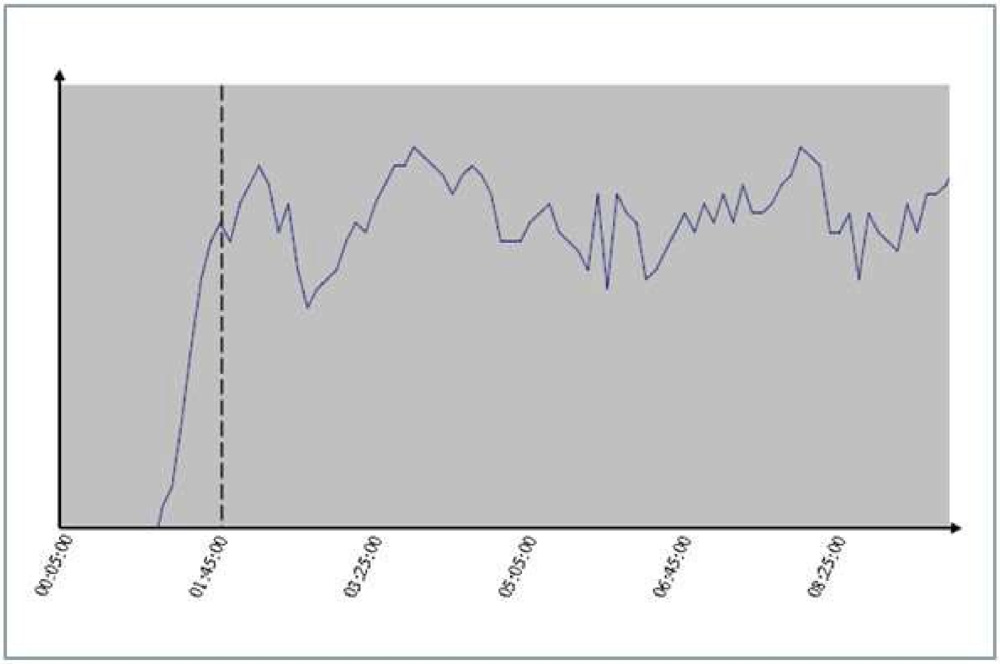



*Figure 3.3-3: Influence of warm up time on statistical analysis*

### 3.3.4. Improvements

Following the logic described in figure 3-2.2 the results of the simulation model need to be translated into the real system by applying the defined transformation rules. The level of transformation that needs to be done is mainly depending on the simulation characteristic of curtailment which is described by the process of abstraction and idealisation (both are described in paragraph 3.3.3). With a stronger presence of both characteristics the higher the effort will be to define clear improvement suggestions for the real system. Another influential factor is the impact of validity of the suggested improvement. Based on a comprehensive documentation of the project the results are normally presented to the ordering party. The measurement of success should be measured objectively based on the performance and specification requirements.

## 3.4. Processes

After describing the elements of a simulation project that are to be considered as the cornerstones of the model the following paragraph will focus on the processes that are connecting the described elements.

### 3.4.1. Situation analysis – target definition

The process of formulating the As Is situation and the target definition of the simulation project is an inherent part of the described approach of System Engineering. If the project is conducted according to this approach, the content is equal to the one described in 3.1-1.

### 3.4.2. Abstraction and idealisation

As soon as the real system has been sufficiently described as part of the As Is analysis the actual model building process is starting by conducting the abstraction and idealisation of the real system. Abstraction and idealisation represent the process steps by which the model characteristic of reduction and curtailment is mainly influenced. Abstraction describes the conscious decision to omit characteristics of the real system which are not considered as relevant for the purpose of the model. Klug provides the figure 3.3.2-1 to illustrate the effect. (Klug, 2007, p. 94).

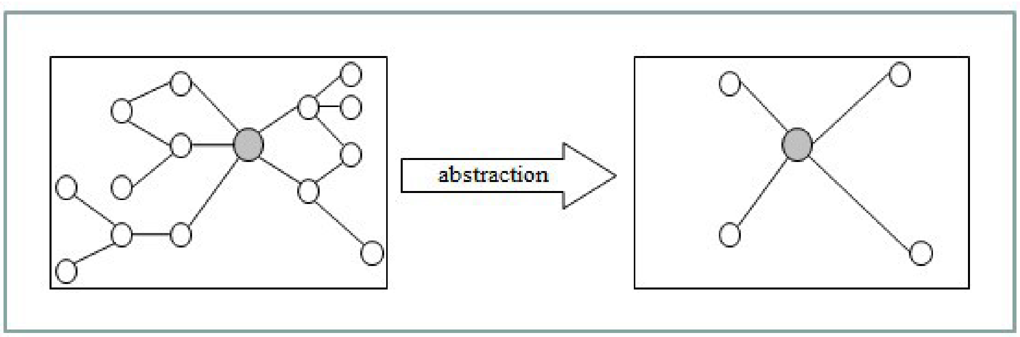



*Figure 3.4.2-1: Abstraction of a real system*

The process of omission is to a great extend a creative one as it is in the model designer's responsibility to select the characteristics and attributes which are relevant for the purpose.

An example of this is illustrated in 3.3.2.-1. The real system on the left side consists of a high number of elements with specific attributes leading to a comparable high external complexity. By applying the process of abstraction, the number of elements

is reduced for the purpose of the simulation model. Among other purposes it is one objective of the abstraction to simplify the real system. Klug (Klug, 2007, p. 104) points out that, if that would not be the case, the user could also conduct the targeted experiments with the real system. Idealisation represents the simplified design of elements or their attributes in the model. In contrast to the instrument of abstraction, idealisation does not decrease the number of the displayed items. The modelled production system in figure 3.3.2-2 shows the same components, elements and attributes on the left side in the real world and on the left side as part of the model. By applying idealisation, the model's elements are only of a schematic nature.
Analogue to the abstraction it is the idealisation's objective to simplify the model with the difference that the idealisation considers every element and attribute as worthwhile to be displayed as part of the model.

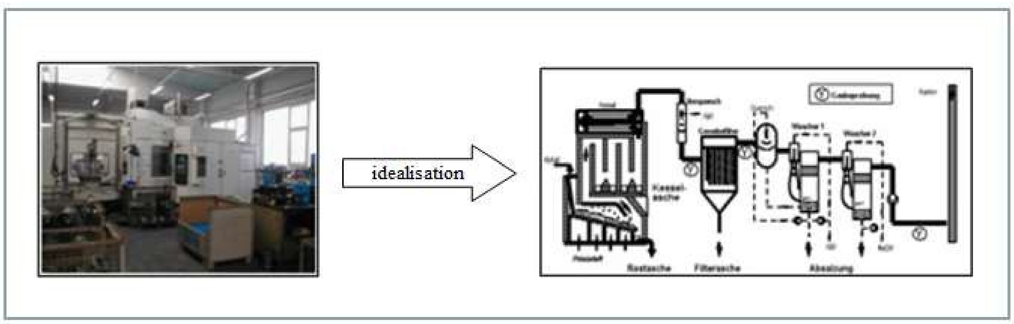



*Figure 3.4.2-2: Abstraction of a real system*

### 3.4.3. Data ascertainment and collection

Data ascertainment and collection as part of a simulation project are not only statistical duties that are performed once but need to be continuously implemented in the overall process. The difference in the data profile which is needed across the entire simulation project has a continuous impact on the way how data is treated. The process of data collection will be the main focus of this thesis and hence in the centre of a detailed description. As shown in figure 3.3.3-1 the distinction between information and data which results from this information is very crucial. The original data demand which is crucial for the successful application of the simulation model is derived from a target function. This data demand is now qualitatively and quantitatively cross-checked with the existing set of data. As a next step statistical method are used in order to gain usable data inputs for the simulation model. Examples for quantitative discrete data would be number of customers or orders, while examples for continuous data are production and waiting times.

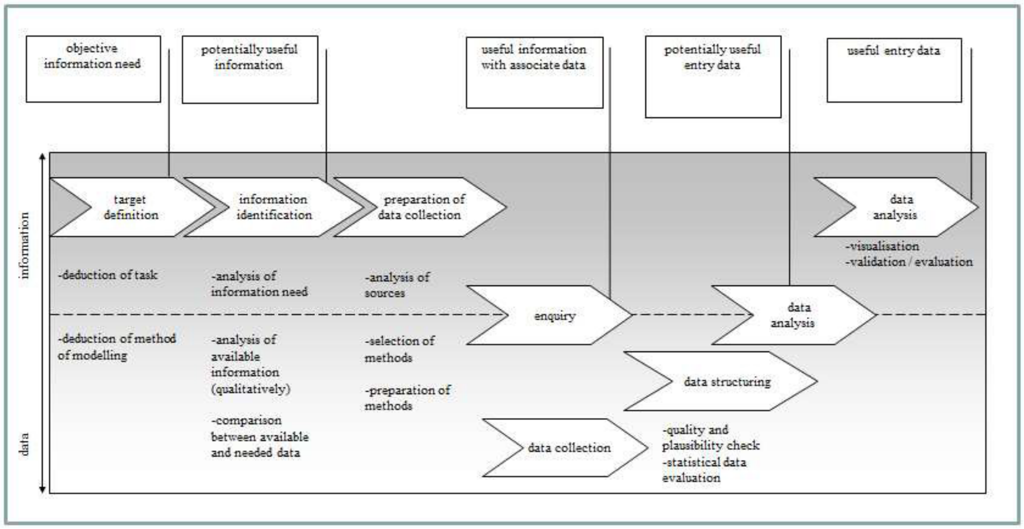



*Figure 3.4.3-1: Data collection process*

After a check for plausibility data is treated as potential entry data, which is tested by a validation process towards its suitability for the modelling process. The process of validation and verification is described in detail in paragraph 3.4. Summarising it should be stated that data ascertainment and collection due to its superior importance to business modelling and simulation has to be considered as one of the most crucial tasks. Independent of the size and complexity of the model, the quality of the entry data is directly proportional to the results of the simulation.

### 3.4.4. Validation and verification

Similar to the process of data ascertainment and collection, the process of validation and verification is not the seen as a singular event but a continuous exercise that has to be performed throughout the entire simulation process. In every phase of the simulation process new data that is imported to the model, and thereby changing the nature of the model, needs to be validated and verified.

Before a detailed description of the process of validation and verification is given a definition of the terms will separate and explain them. As part of verification the following question is to be answered: "Is the model correct?" meaning the process of verification does not examine the correctness of the model, but the correctness of the transformation process as part of the described system engineering approach. Opposed to this validation is testing the suitability of the model in light of the purpose for which it was built. Hence validation asks the question: “Is this the right model?” The following definitions of validation and verification follow Wenzel et al. (Wenzel et al., 2006, p. 1). The similarity to the process of model design is that validation and verification could be hardly measured by objective key performance indicators (KPI) as it a highly creative and individual task. In order to overcome this dilemma, Wenzel et al. (Wenzel et al., 2006, p. 3) describe in accordance with Carson the following Verification and Validation criteria (summarized in table 3.3.4-1). In case those criteria sufficiently fulfilled by the model designer, the model ought to be treated as verified and validated.

| V&V criteria | Object of investigation | |
|---|---|---|
| | Focus | Example |
| Completeness | Correctness of content and structure | • Structured examination in relation to missing information<br>• Determination on level of compliance towards modelled and real system |
| Consistency | Correctness of content and structure | • Conclusiveness of semantics<br>• Conclusiveness of structure<br>• Consistency in terminology |
| Accuracy | Correctness of content and structure and adequacy of the results | • Careful and flawless modelling<br>• Conscious choice on level of detail<br>• Correct choice of distribution of random numbers and granularity of data |
| Applicability | Adequacy of the results | • Accuracy of fit concerning usability and objective of the model<br>• Performance of the model |
| Plausibility | Adequacy of the results | • Traceability of the interdependencies in the model<br>• Conclusiveness of the results |
| Clarity | Adequacy of the results | • Conformability for the user<br>• Transparency of the building blocks in the model |
| Feasibility | Operability | • Technical feasibility of the requirements<br>• Reachability of the project goals<br>• Realistic implementation plan |
| Accessibility | Operability | • Accessibility of data and documents and proof of sources |

*Table: 3.4.4-1: V&V criteria for simulation*

Those criteria are now applied following a structured plan. The figure 3.3.4-1 describes the process.

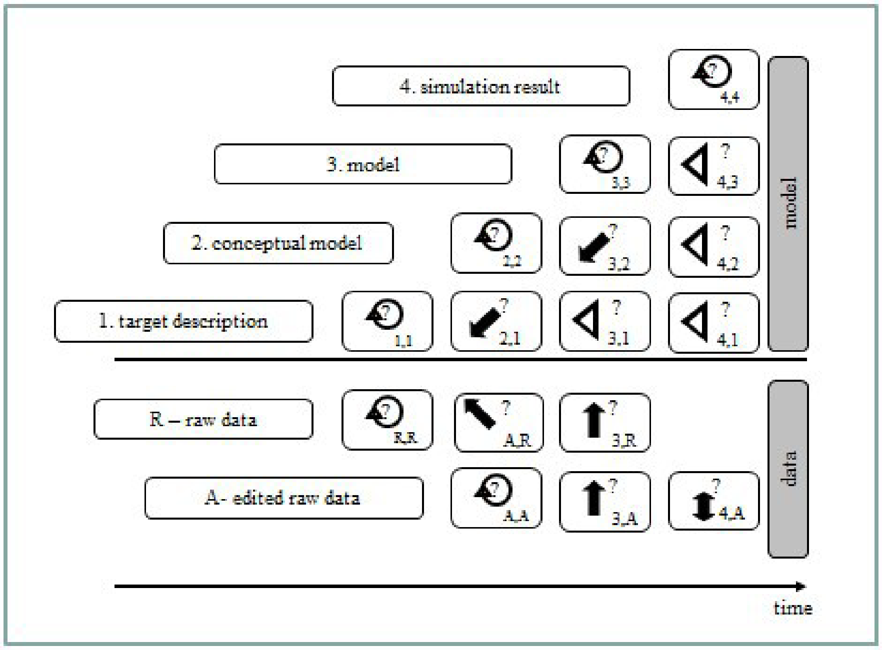



*Figure 3.4.4-1: Data collection process*

The model describes by the numeration from one to four using the terminology result of validation and verification phases. Data collection and editing are listed separately due to their continuous nature. The individual steps in the design process of a simulation model are not only checked for verification and validation once but multiple times. The type of examination as per Wenzel et al. (Wenzel et al., 2006, pp. 8–9) is represented by the displayed symbols.

- Index

  The first index within the box represents the result of the individual phase on which the verification and validation is executed. The second one represents a result of a phase with interdependency for this V&V element

- Circle

  This symbol stands for an intrinsic dependency, which means that the V&V activities are only performed on the result of this phase

- Arrow

  The arrow symbol refers to V&V activities linked to a previous result, whereby the arrow points into the direction of the dependency

- Double Arrow

  The symbol of the double arrow represents the dependency between the results of the phase of the modelling and the result of the data collection. The results are to the greatest possible extent independent hence the non-existence of a clear direction for validation

- Triangle

  The triangle refers to the testing of previous phase result under the prerequisite of further usage of the edited data

The general procedure follows the basic law of a continuous testing of the model's verification and validity by referencing to an already assessed phase in the model. By an examination of the causal interdependencies in combination of a holistic documentation an optimal degree of confidence of verification and validation ought to be realised.

According to Sargent (Sargent, 2011) a further consideration that needs to be applied as part of the V&V process is linked to the diminishing marginal utility. With every additional step of verification and validation the level of confidence into the model is increasing, however this increase is of a convex nature. In comparison the accumulated cost linked to the verification process are increasing exponentially the higher the targeted level of confidence is.

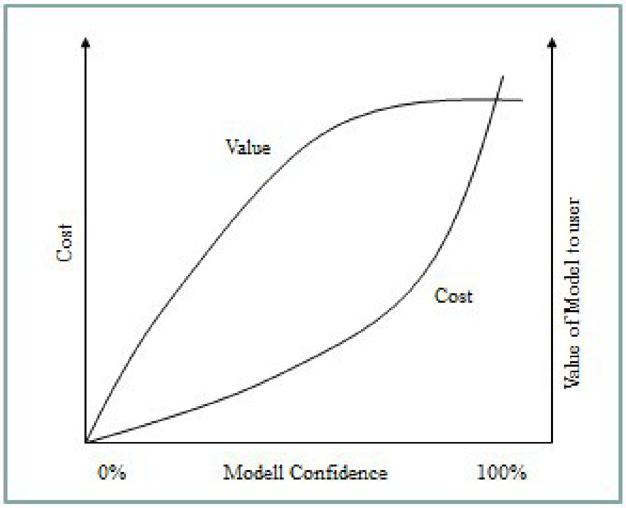



*Figure 3.4.4-2: Diminishing marginal utility of verification and validation process*

Taking this fact into account, the optimal level of confidence a designer of a simulation model has is less than 100%. Concluding on this verification and validation are essential tasks conducted in a successful simulation project. The process has to follow a pre-defined method and selection of criteria followed by a rigorous duty for documentation.

### 3.4.5. Scenario analysis

The process and activities between the different simulation runs is called scenario analysis. Scenario analysis is divided into variation and optimising. Variation refers to the planned change of model parameters with the objective of understanding the cause-and-effect chain of the model. Optimisation is the desired reaction of a parameter linked to the described planned changes. An example of an optimisation is the changes of the model parameters in order to minimise the throughput time of a product.

As argued by the ASIM organisation (ASIM, 2004, p. 7), an essential understanding is that business modelling and simulation as such is not an optimisation but only a tool showing the results of a user's variation.

The variation of model parameters is following the ceteris paribus principle, which refers to the execution of various simulation runs with multiple dependent variables. With every simulation run only one those variables is adjusted in order to determine the influence of the one variable on the overall result of the system. By applying this procedure, the described connection between cause and effect is explored. An optimisation of a simulation result could be achieved using two different approaches, with an exact mathematical solution using algorithms or by using an approximate approach via a heuristic solution. The algorithmic solution is the exact one as the result truly is the optimum. For the heuristic solution unsuitable solution alternatives are initially excluded from the analysis which minimizes the calculation effort. Again, it is important to emphasise that the simulation as such is not optimising a modelled system, however many of the commercially available simulation engines have an optimising tool included.

### 3.4.6. Realisation and documentation

The final process of a simulation project is the implementation of the findings that result from the conducted simulation runs. The implementation has to take part in the real or planned system, not in the simulation tool. Indirectly this final step is also a proof for a successful application of the discussed processes, as e.g., idealisation and abstraction could lead to a problematic disconnect between simulation model and real world. A further question that needs to be answered is of an economic nature. One example could be that the simulation model for example shows that real world system offers a tremendous possibility for reducing cost, however the investment needed in order to harvest this potential outweigh the benefit. Following this example all simulation results need to be analysed and evaluated according to their return on investment (ROI). A complete documentation of all conducted steps in the simulation project and the achieved results serves two purposes, first it allows for an objective evaluation of target fulfilment and second it provides assistance for further use of the model.

# Chapter 4

# An example of a project management organisation - the wind power industry

The following chapter has the objective to provide a contextual frame in which the concept of supply chain risk will be later on discussed with the majority of the targeted interview participants. The purpose is to provide a basic understanding the product, the market and its dynamics as well as an example structure on how project are being executed.

## 4.1. A brief history of the wind power industry

The Wind Power industry came a long way since its first industrialisation in the late 19th century. But while in its early years, which accounts for many other new technologies, Wind Power was considered something only attractive for the idealistic mind, it quickly became a multi-million-euro industry in the late 20th century. Zachary (Zachary, 2014) explains that this is mainly due to the ideal combination of engineering capacity in countries like Denmark, Europe and an initial push for green energy in the US that companies like Vestas and Bonus Energy laid the groundwork for the entire industry. Wind Power is divided into two applications, one covering the Onshore application, meaning installation of wind turbines on the land and the other is Offshore with the installation of wind turbines in the open sea applying various different foundation concepts. Today Wind Power represents a main pillar of the world's renewable energy mix.

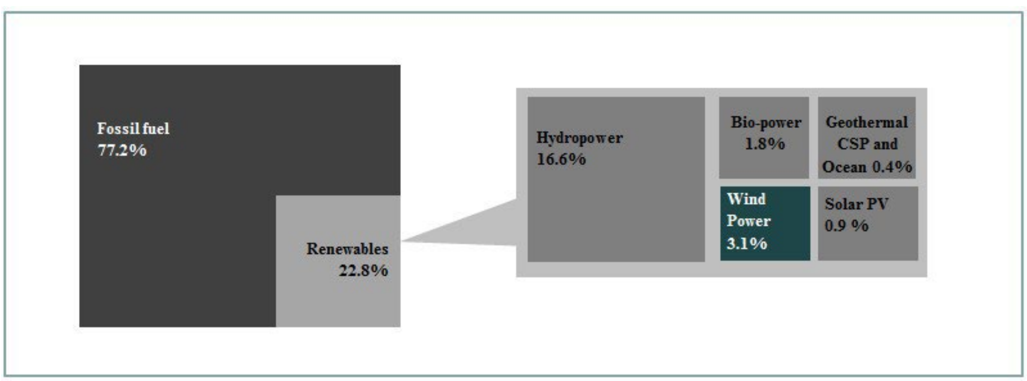



*Figure 4.1-1: Renewables as part of the energy mix*

Figure 4.1-1 published by the Renewable Energy Policy Network for the 21st Century (REN21) shows that Wind Power is after hydropower the main source of renewable energy world-wide. (Renewable Energy Policy Network for the 21st Century, 2015, p. 27)

Furthermore, according to REN21 the globally installed capacity of on- and offshore wind parks has reached around 370 GW in 2014 with the main growing markets in China, the US and Germany. (Renewable Energy Policy Network for the 21st Century, 2015, p. 71)

## 4.2. A basic understanding of the wind energy production and technology

The Power generated by the wind, following Wagner (Wagner, 2012, p. 5), is as any other form of power defined as:

$$P = \frac{E}{t} = \frac{1}{2} x\, A\, x\, p_a\, x\, v^3$$

Whereas:

$P$ : electrical power

$E$ : kinetic energy

$p_a$: specific density of the air

$v$ : wind velocity

As per the above calculation the electrical power generated by the wind could potentially be increased infinitively when increasing the various variables; however, this effect is not possible due to Betz's law which determines that only 59% of the kinetic energy could be harvested as a maximum. The simple reason for this effect is that the wind that moves through the rotors would need to keep enough kinetic energy to move further in order to make room for the subsequent air to pass. The formula determining this effect is stated below:

$$m = pA_1v_1 = pS_v = pA_2v_2$$

Whereas:

$m$: mass flow rate

$P$: fluid density

$A_n$: area of fluid before and after reaching turbine

$v_n$: wind speed before and after reaching turbine

The basic main components of a wind turbine, shown in figure 4.2-1 from Siemens Energy are the rotor equipped with three blades with is connected to the nacelle via the hub. The nacelle contains the majority of the electrical and mechanical machinery and control devices. Over the years two competing drive and generator concepts have been developed, a geared and a direct drive one. The entire turbine is connected to the ground via a foundation.

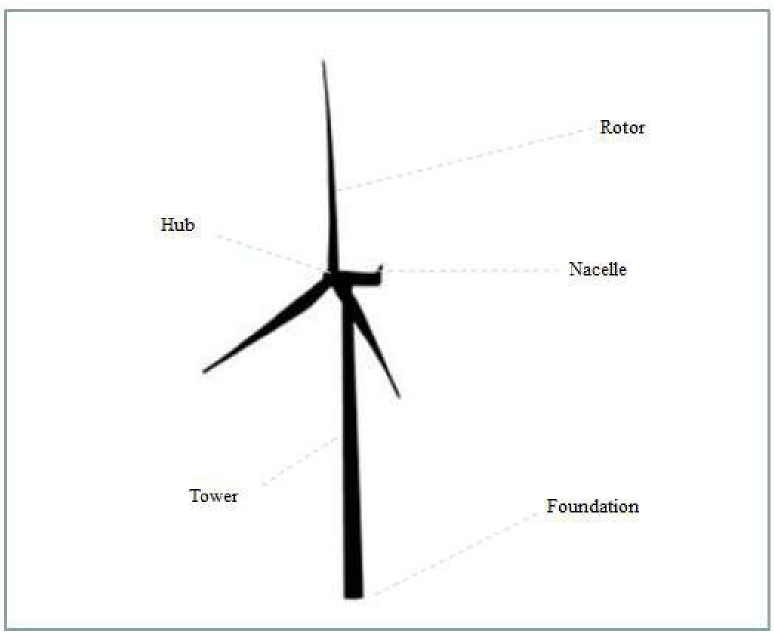



*Figure 4.2-1: Main Wind Turbine Components*

The following paragraphs provide an overview on the two mentioned generator concepts.

- Geared drive generator

  Yang (Yang, Patterson, & Hudgins, 2012) refers to the main principle of the gear driven generator as the kinetic force of the wind turning the rotor blades turning a main shaft on the slow moving end. The torque is transmitted via gearbox to a high-speed shaft that is connected to the generator.

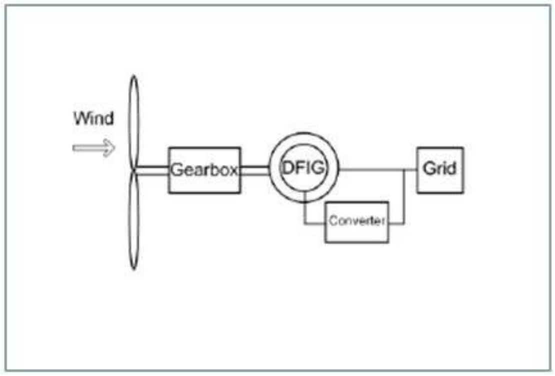



*Figure 4.2-2: Wind turbine system with asynchronous generator – variable speed DFIG*

  Figure 4.2-2 illustrated the schematics of the wind turbine including the gearbox, the DFIG (doubly-fed induction generators), the converter and grid access

- Direct drive generator

  Following Yang's explanation (Yang et al., 2012), the main design variation in comparison to the geared one is that only one stationary shaft is applied on to which the generator is connected to. The rotor in which is connected to the blades via the hub creates an electromagnetic field (either by permanent magnets (PM) or electrified magnets (EM)). Figure 4.2-3 illustrates the schematics of a wind turbine including a direct drive generator.

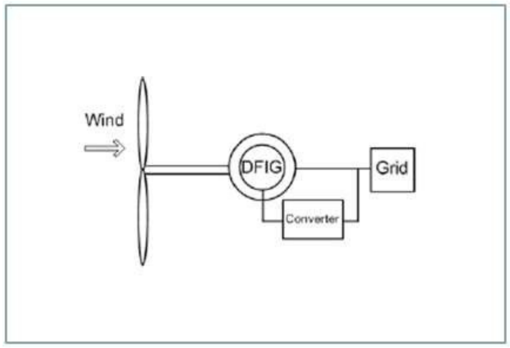



*Figure 4.2-3: Wind turbine direct drive with DFIG system*

Another technological aspect which significantly differs and hence influences cost and performance of the turbine is the design of the blades. The main materials which are used during the blade manufacturing process are fibre-reinforced epoxy or unsaturated polyester. The two general design approaches are called a butterfly blade and an integral blade.

- Integral blade design

  Grande describes integral blade manufacturing process in his internet article for Plastics Technology as:” […] technology [that] uses vacuum infusion to make glass/epoxy blades in a closed process. The moulding system has a closed outer mould and an expanding, flexible inner bladder. Epoxy resin is injected under a vacuum and the blade is cured at high temperature in the mould. After curing, the blade is removed from the outer mould while the inner bladder is collapsed with a vacuum and pulled from the blade. The result is a seamless one-piece blade.” (Grande, 2008)

- Butterfly blade design

  In contrary to the above the process for butterfly blades is described in the figure 4.2-4 following Wieland and Ropte (Wieland & Ropte, 2017, p. 2). During the butterfly production process two individual halves of the blade are prepared with glass fibre matts. In the process of vacuum assisted resin infusion the two blade parts are glued together.

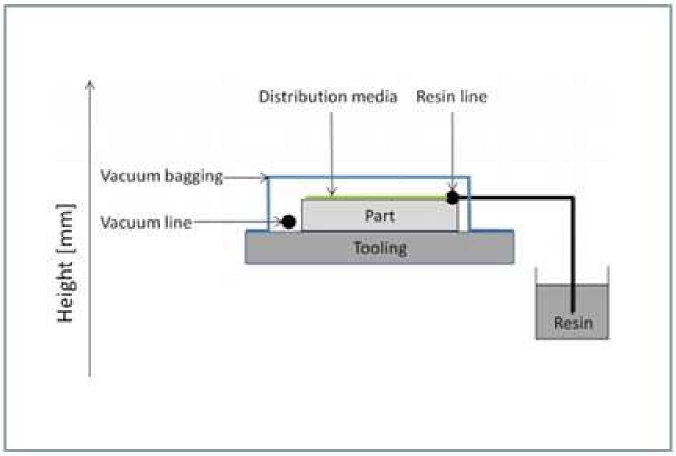



*Figure 4.2-4: Vacuum-assisted resin infusion (VARI) procedure*

## 4.3. The wind power supply chain and its relevance in a research context

Traditionally supply chains have either been characterized as product- or project-based. The main characteristics of the distinction among the concepts are linked to the specifications, individuality and production volume of its products. Generally speaking, supply chains with a higher level of individuality in their products and a lower yearly production volume are considered to be project based, the ones with a low level of individuality and high production volumes are considered product-based supply chains.

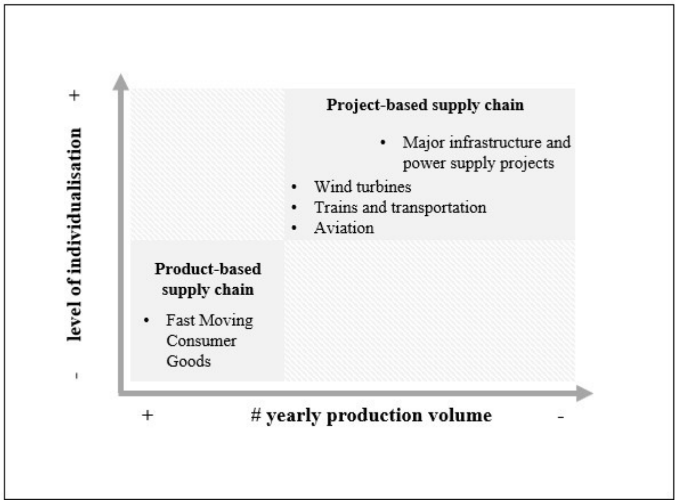



*Figure 4.3-1: Project-based vs. Product-based supply chains*

As shown in figure 4.3-1 a main example for a product-based supply chain is the Fast-Moving-Consumer-Good industry (FMCG). Supply and production processes of today's food industry are highly standardised and automated in order to benefiting from scale effects. A main example compared with this for a project-based supply chain is the one of a major infrastructure project like a conventional power plant, for which a high number of components are manufactured according to individual specifications.

Along with the supply chain of the wind turbine industry, the train and transportation as well as the supply chain for the aviation industry are to be considered a project-bases supply chain with certain characteristics of a product based one.

The wind power industry is part of a wider portfolio of energy sources. It shares the specifics of a project business solution with i.e., a gas turbine factory or complex combined power plant solutions. However, it is very relevant for the context and understanding of this thesis that the wind power supply chain also comprises significant differences in comparisons to the above-mentioned examples making it comparable to i.e., the supply of major aviation projects (A380) or the transportation and train industry like the ICE in Germany or the TGV in France.

An individual wind turbine for the application on land (onshore) has a nominal generator rating from approximately 2.5 – 4.5MW depending on the supplier and the wind site it is used, meaning that in order to establish an average wind farm with a comparable output to a gas turbine facility a significant number of turbines is needed. This obvious fact exemplifies that a gas turbine is complete designed towards the customers' needs and wished whereas a wind turbine model needs mange the dilemma between individual customer needs and mass production.

This paragraph aims at explaining the development and characteristics of the wind turbine industry and is separated into the following sections discussing **the market and customer, product, supplier networks, manufacturing and project execution, operation & maintenance and energy contracting.**

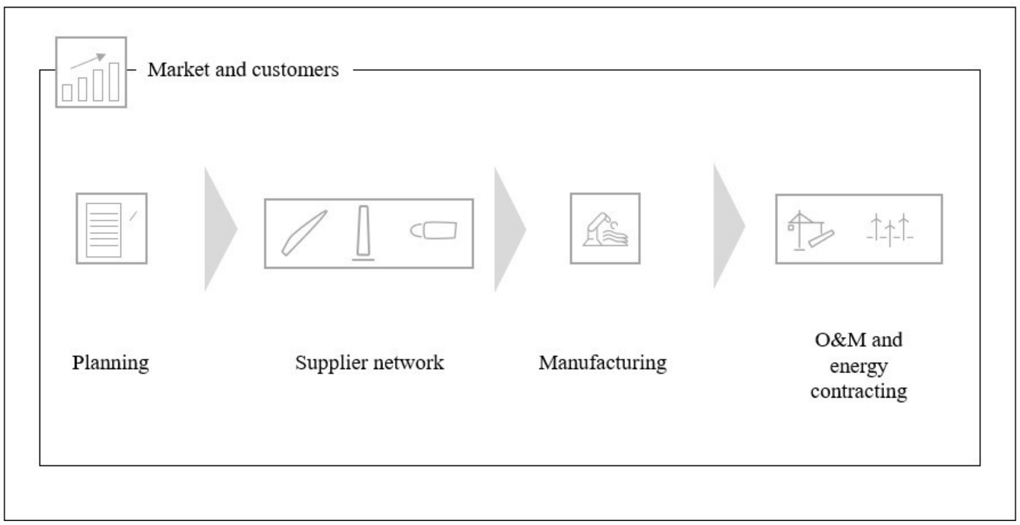



*Figure 4.3-2: Overview wind turbine supply chain assessment*

Based on the following assessment set out that the wider market and supply chain of wind turbines shows the same characteristics as described by Christopher (Christopher, 2003) discussed in chapter 1. Table 4.3-1 indicates the supply chain mechanisms requiring a comprehensive supply chain risk management as described in the literature and the corresponding effect described in the wind turbine supply chain throughout this chapter.

| Supply chain characteristic | Wind turbine supply chain |
|---|---|
| New rules of competition | Complex customer contracts requiring wind OEM to act as turnkey key providers result in close collaboration between strategic partners along the full value chain |
| Downward pressure on price | Change from fixed feed in tariffs to tender and auction systems resulting in significant price reductions |
| Globalisation of industry | Western OEMs increasingly under pressure from non-European competition |
| Customer taking control | Major utility companies, representing the most traditional customer base, gaining more R&D expertise in order place specific customer requirements as well as decreasing cost in i.e. service and maintenance business |

*Table 4.3-1: Characteristics in wind turbine supply chain requiring risk management*

### 4.3.1. Market and customer

Over the last 20 years the wind energy market for both, onshore and offshore application, has been constant variable in the increasing share of renewable energy. With an overall installed volume of 651 GW in 2019 onshore and offshore wind energy are fixed part of the world's energy supply. Figure 4.3.1-1 shows the accumulated development from 2001 to 2019 (Global Wind Energy Council, 2020, p. 43).

The yearly installation volumes have been growing with a CAGR of 12% over the same period of time shown in the graph 4.3.1-2 (Global Wind Energy Council, 2020, p. 42) considering a reduction in installation volume in 2013 and 2016 to 2018.

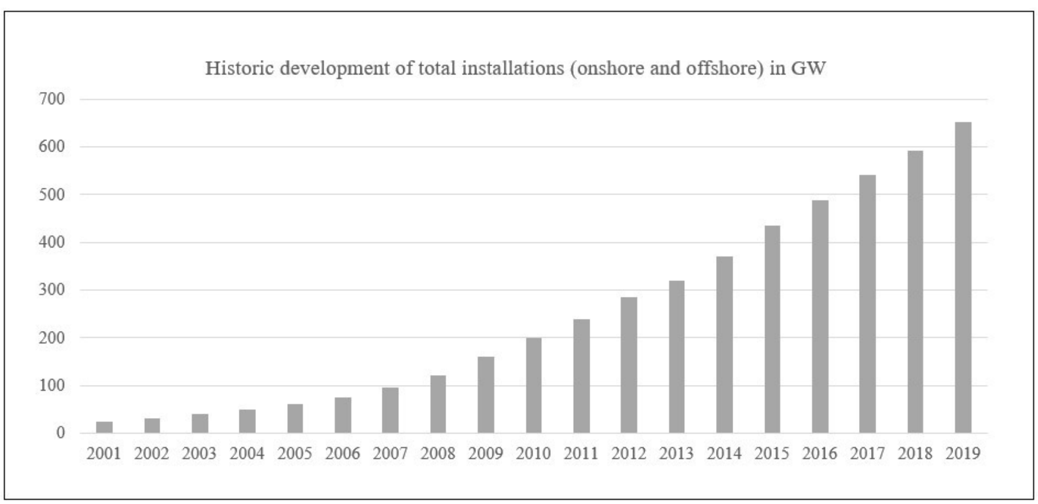



*Figure 4.3.1-1: Historic development of total wind turbine installations in GW*

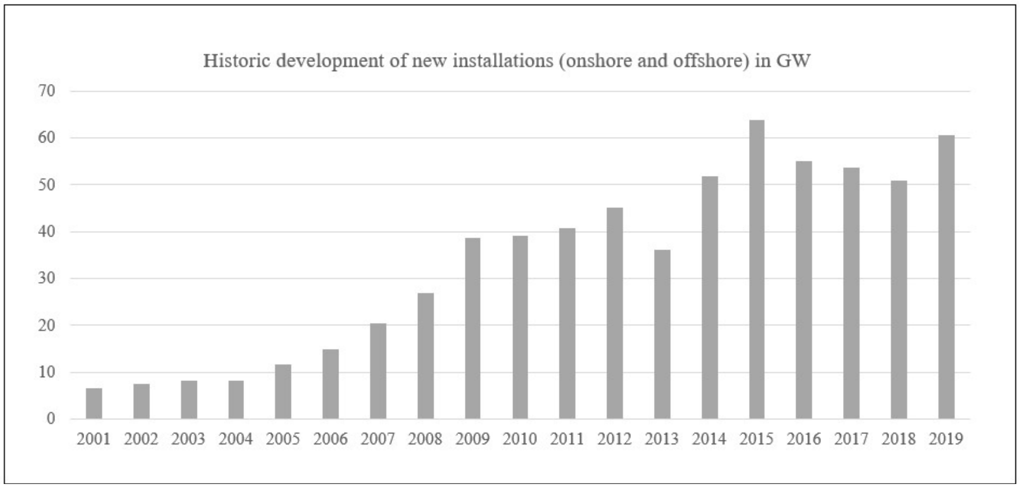



*Figure 4.3.1-2: Historic development of yearly wind turbine installations in GW*

The decline in the mentioned years has been mainly driven by the decline of regional markets i.e., the US in 2013 caused by the abrupt end of the wind production tax credit system (PTC) leading to a significant drop in installed units. The magnitude of this effects caught the industry by surprise as for example Steve Sawyer, Chairman of the Global Wind Association, explained in the 2014 yearly review:" For the first time in more than 20 years, the annual global market for wind energy shrank in 2013 We knew that this was likely to be the case when we did our forecast for 2013 one year ago, but we didn't expect the drop in the United States to be as dramatic as it was – going from 13 GW in 2012 to just 1 GW in 2013." (Global Wind Energy Council, 2014, p. 4).

**Total installations Onshore (%)**

| Country | Installed % |
|---|---|
| PR China | 37 |
| USA | 17 |
| India | 9 |
| Spain | 6 |
| Sweden | 4 |
| France | 3 |
| Mexico | 3 |
| Germany | 2 |
| Argentina | 2 |
| Australia | 2 |
| Rest of World | 16 |

**Total installations Offshore (%)**

| Country | Installed % |
|---|---|
| United Kingdom | 33 |
| Germany | 26 |
| PR China | 23 |
| Denmark | 6 |
| Belgium | 4 |
| Rest of World | 8 |

*Table 4.3.1-1: Overview on- and offshore installation in %*

The geographical split indicates that the onshore market has already been developed into a truly global market while the offshore geographical centre of the offshore business is still to be found in Europe with the PR China as the only non-European country among the top 5 as show in the table 4.3.1-1 (Global Wind Energy Council, 2020, p. 43).

The decline during the years 2016 to 2018 was linked to decrease of the onshore market in India and Germany[17].

The dynamics behind this sudden decline in market demand reveal the specific mechanisms of political regulation and governance that an industry is when transitioning out of a subsidy towards an unregulated scheme. While on- and offshore wind previously have been subsidised throughout most of the countries using different mechanisms the recent trend has been to cut back on direct or indirect subsidies and introducing competitive tendering systems.

Withing the recent past the overall market place of renewable energy and the within this portfolio the on- and offshore wind market has seen a shift from previously fixed feed-in tariffs towards auction systems. While researchers and market participants discuss the positive and negative effects of both approaches, it is to be generally pointed out that fixed feed in tariffs have been a useful measure to kick-start new technologies whereas the introduction of auctions ensures that ultimately the price for a given good is determined by applying a supply and demand view. While the present thesis is not aiming at a mutual comparison of the two concepts the following aspects are to be noted:

- Auction systems are becoming more and more popular. According to the International Renewable Agency (IRENA): ”In 2017-2018, some 55 countries used auctions to procure renewables-based electricity, raising the number of countries that have held at least one auction for renewables to 106 by the end of 2018 (International Renewable Agency, 2019, p. 8). IRENA further argues that the implementation of auction and tender system is the

[17] ETEnergyWorld, 2019.

main driver behind the year-over-year price reduction of i.e., 33% between 2010 and 2016

- Critical voices of the auction system like H.J. Fell from the Energy Watch Group argue that while tendering mechanisms are useful for bigger energy project with more than 100MW the main critique for smaller applications is that it supports an oligomictic market structure leading to ultimately fewer market participants. In regards to the prices on of the main arguments why auctions are not archiving a pure market driven price is the incomparability with other energy sources accounting for hidden subsidies (H.J. Fell, 2019, p. 1).

The customer segmentation in the wind power industry has changed quite substantially over the last years. Whereas during the beginning of the industrialisation of large-scale wind farm project traditional electricity utilities represented the main customer basis, nowadays the share of financial investors is constantly increasing in comparison to the its original distribution. Financial institutions like Unicredit and BlackRock ("BlackRock magnificant seven", 2018) are discovering the wind power, in particular the offshore wind power business as a main are of investment opportunity. This development has quite severe knock-on effect for the OEM industry. The big utilities such as Dong Energy, Eon and Vattenfall purchased purely components (Tower, Nacelle and Blades) from the OEMs and contracted the installation and commissioning. However, they build up a vast in-house experience in i.e., siting and wind farm development capabilities as well as distinctive knowledge about service activities as they often executed this part of the overall value chain themselves. As a consequence, the OEMs are more and more covering business activities traditionally owned by the utilities which are not in scope for financial investors.
Table 4.3.1-2 displays the ownership structure of the ten biggest on- and offshore wind farms worldwide illustrating the vast partnership of institutional and financial investors with traditional operating utilities.

**Top 10 biggest wind farms**

| Wind Farm | Country | Ownership structure |
|---|---|---|
| Jiuquan Wind Power Base | China | State Grid Corporation of China |
| Jaisalmer Wind Park | India | Various private and public companies |
| Alta Wind Energy Center | US | NRG Renew, BHE Renewables, Ever Power, Brookfield Energy Partners |
| Muppandal Wind Farm | India | Various |
| Shepherds Flat Wind Farm | US | Various |
| Roscoe Wind Farm | US | E.ON |
| Horse Hollow | US | NextEra Energy Resources |
| Capricorn Ridge | US | NextEra Energy Resources |
| Walney Extension Wind Farm | UK (OF) | Danish Pension Fund PKA and PFA |
| London Array | UK (OF) | E.ON, Masdar |

*Table 4.3.1-2: Top 10 biggest wind farms*

Arguing that the supplier landscape is as well increasingly expanding on a global scale would be correct but would also disregard significant market forces caused by the discussed price development leading to a significant level of consolidation.

The table 4.3.1-3 displays the summary of the global supply per OEM exemplary for 2017 (Zhao, 2017, p. 7).

**Summary of global wind market development in 2017- supply side**

| | | |
|---|---|---|
| Top 10 onshore wind turbine suppliers in 2017 | • #1 Vestas (17.3%)<br>• #2 Siemens Gamesa (13.2%)<br>• #3 Goldwind (11.3%)<br>• #4 GE Renewables (8.5%)<br>• #5 Enercon (7.4) | • #6 Evision (6.3%)<br>• #7 Nordex Acciona (5.8%)<br>• #8 Mingyang (5.2%)<br>• #9 Senvion (3.2%)<br>• #10 Suzlon (2.9%) |
| Top 10 offshore wind turbine suppliers in 2017 | • #1 Siemens Gamesa (46.6%)<br>• #2 MHI Vestas (22.8%)<br>• #3 Sewind (11.2%)<br>• #4 Senvion (8.4%)<br>• #5 Goldwind (4.0%) | • #6 Envision (3.8%)<br>• #7 CSIC Haizhuang (2.0%)<br>• #8 Mingyang (0.6%)<br>• #9 United Power (0.3%)<br>• #10 Taiyuang Heavy Industry (0.2%) |
| Top 10 wind turbine models by number delivered in 2017 | • #1 Goldwind GW115-2.0<br>• #2 Vestas V110-2.0<br>• #3 Siemens Gamesa G114-2.1<br>• #4 GE 2.3-116<br>• #5 Mingyang MY121-2.0 | • #6 Envision EN115-2.2<br>• #7 Goldwind GW121-2.5<br>• #8 Siemens Gamesa G114-2.0<br>• #9 Suzlon S97-2.1<br>• #10 Enercon E117-3.0 |

*Table 4.3.1-3: Global wind market development 2017 – supply side*

The three main trends and observations that could be observed in the global supplier landscape:

- The distribution of the market share in the onshore and offshore market are significantly different. While the onshore market is marked by a high level of competition, the offshore market remains up until now mainly supplied European companies (Siemens Gamesa, Vestas) or by Chinese companies manufacturing in accordance to European license agreements like Sewind.

- Western OEMs retain a dominant position on a global scale (Vestas, Siemens Gamesa, GE) while in heavily protected markets like PR China the majority of the market is supplied by local corporations like Goldwind or Envision. However recent developments indicate the Chinese companies are heavily investing into a local presence outside of China
- Linked to the described market development of moving from fixed feed in tariffs to auctions and the resulting prices pressure a wave of consolidation has captured the industry. This development targeting to counteract the increasing price pressure in the market aims at using economies of scales. The most recent examples are the merger of Siemens Wind Power and Gamesa, Nordex and Acciona as well as the insolvency of Senvion

#### 4.3.2. Product

The product is ultimately influenced by the development towards a lower LCoE base, meaning a reduction in cost per kWh for the customer. Two dimensions influencing the LCoE, the cost of the turbine and its supporting components and the output of the wind turbine, the annual energy production (AEP). Considering the magnitude in which both factors ultimately affect the LCoE the increase in nominal power of the generator and hence a higher AEP is over-compensating the incremental reduction in cost. However, cost reduction becomes the main level when OEM competes within a certain wind scheme, so called IEC classes.

Wind classes defined according to the IEC (International Electrotechnical Commission) define are split into two dimensions, the wind speed and the turbulence of the wind.

Within a certain wind class, it is for example not beneficial to increase the nominal power and the related blade size above a certain limit yielding at a higher power output but to compete on pure cost.

The main distinctions within the product are, besides the general choice of technology of the generator, the blade sizes. As a general guidance for the onshore business, it could be mentioned that a rotor diameter of approximately 120 meters is suitable for a high wind application, a rotor diameter of approx. 140 meters for a medium wind application and rotor diameters above 150 meters for low wind applications.

IEC wind classes

| | I (high wind) | II (medium wind) | III (low wind) | IV (very low wind) |
|---|---|---|---|---|
| Reference wind speed | 50 m/s | 42.5 m/s | 37.5 m/s | 30 m/s |
| Annual average wind speed (max.) | 10 m/s | 8.5 m/s | 7.5 m/s | 6 m/s |
| 50-year return gust | 70 m/s | 59.5 m/s | 52.5 m/s | 42 m/s |
| 1-year return gust | 52.5 m/s | 44.6 m/s | 39.4 m/s | 31.5 m/s |

*Table 4.3.2-1: Overview IEC categorisation*

The turbulence factor normally expressed via the letters a, b and c indicates a descending strength of the turbulence normally correlate with the wind speed. Besides the nacelle with the generator and the rotor, the wind speed also has a direct effect on the tower. Besides the obvious need for higher towers with an increase in rotor size, the tower height is additionally influenced by the shear factor of each specific wind site.

The wind shear describes the increase of the wind speed with a rise in altitude above ground. An example in which this effect becomes tangible is when a wind farm is build next to a forest. In case the wind turbine has the same height as the surrounding trees the wind is diverted by the trees. With an increasing height the wind speed and direct impact on the blade increases ultimately leading to a higher energy production. The formula used to determine this effect is the Hellmann power equation taken from Tong (Tong, 2010, p. 15):

$$u(z) = u(z_O)(\frac{z}{z_0})^a$$

Whereas:

$z$: height above earth surface

$z_0$: reference height

$n$: wind speed

$a$: wind shear factor coefficient

When considering the cost of the wind turbine modules nacelle, blade and tower the product or more specifically the design of the product has adapted over the recent years. The way how design adaptations are defined and carried out has as well adapted due to technology and the general development of the industry. One of the most significant technological developments is for certain the availability of big data and the possibility of processing those. Today all wind turbine OEMs are monitoring their existing fleet under service around the clock. The data which is provided by a vast number of sensors in turbine gives companies the chance to learn about the performance and resistance of the product in real time. Additionally, to the availability of technical applications it is possible to generate data sets today with a continuous increase in statistical significance as the installed fleet world-wide with an ever-bigger span of operational time exists. The European Technology and Innovation Platform on Wind Energy assessed in their 2016 research and innovation report the possibilities linked to big data. The figure 4.3.2-1 illustrates the improvement cycle to be achieved via data analysis. (European Technology and Innovation Platform on Wind Energy, 2016, p. 30)

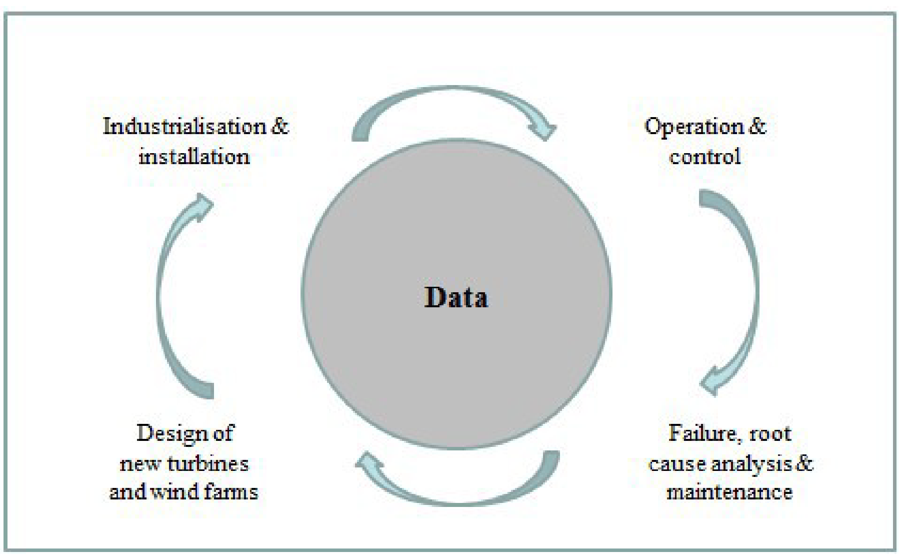



*Figure 4.3.2-1: Virtuous circle of wind turbine improvement through data*

Another aspect affecting the wind turbine design and hence the product is the increasing level of industrialization. As illustrated by the global level of installed capacity the demand or wind turbines has been steadily increasing over the years. This development opens the door for improvement levels already proven in other industrial such as the automotive industry. The way how a wind turbine is designed would need to further developed copying strategies out of those related industries to cope with increasing price pressure.

As a conclusion the following trends in wind turbine design could be observed influencing the final product.

- Modularisation; supporting make or buy strategies respectively supporting cost effective assembly processes
- Design to cost; especially towards saving weight and therefore raw materials in the components
- Optimization of transport and installation capabilities with bigger turbines
- Non-variable part strategy to increase purchasing power with suppliers

#### 4.3.3. Supplier networks

As for many industries the set-up of the supplier network and the underlying strategy how suppliers are selected, managed and included in product development is one the main success factors of an OEM. The wind turbine industry is no exception to this. The main aspects of a supplier strategy discussed in this thesis are global value sourcing (GVS), make or buy (MoB) evaluations and using supplier and production as levers for local content (LC) concepts.

- Global value sourcing

  As discussed in a previous paragraph around 85% of the value in a wind turbine nacelle is linked to procured components. For the entire wind turbine including towers and blades the value is at around 65%. The ability to source at a competitive price level serving a global market has become one the most relevant capabilities of today's wind turbine manufacturer. With an increasing number of produced and installed wind turbines this industry is slowly making its way out of a niche- towards a commodity market. Global value sourcing describes the concept of establishing suppliers in areas of the world in which most competitive pricing at a pre-defined standard is to be achieved. This concept has led to the effect of a constant shift from initially European sourcing towards a sourcing in the APAC (Asian Pacific) region. Reports from Wind Power Monthly (Wind Power Monthly, 2017) show that this effect has been further strengthened by the fact that today's fourth biggest manufacturer in the year 2017 of wind turbine is Chinese and many suppliers with in-depth knowledge of the industry has been established in this region. This trend has also not been disrupted by the OEMs assessment of so called Total Landed Cost (TLC) in which not only the pure purchasing price but also the logistic costs are the baseline for the assessment of overall supply scenarios.

- Make or Buy

  As the previous concept, Make or Buy assessments are by now an established concept in various industries. As per the name, companies are to evaluate whether it is of a strategic or commercial benefit to keep certain activities in-house or to outsource them to a 3rd party supplier.

  As first the organization has to make an evaluation assessing the strategic value and performance of every facility. The consultant company AT Kearny (Monahan, 2010) suggests a two-step approach in conducting this assessment. In a first step the above-named factors are evaluated based on the criteria displayed in table 4.3.3-1 (Monahan, 2010, p. 2).

Strategic value

| Elements | Weight |
|---|---|
| Profitability | 25% |
| Sales growth | 15% |
| Technical differentiation | 20% |
| Contract manufacturers capability | 15% |
| Proximity to markets | 10% |
| Trade implications | 10% |
| Macroeconomic situation | 5% |

Performance

| Elements | Weight |
|---|---|
| Conversion cost | 40% |
| Manufacturing flexibility | 20% |
| Defects per million | 10% |
| Beauty fill rate | 10% |
| Overall equipment effectiveness | 10% |
| Asset utilization | 10% |

*Figure 4.3.3-1: Sample criteria for evaluating strategic value and performance*

Following this assessment quantified results are transferred into the below matrix matching the existing portfolio of facilities and plants to the adequate Make or Buy strategy taken from Monahan (Monahan, 2010, p. 2).

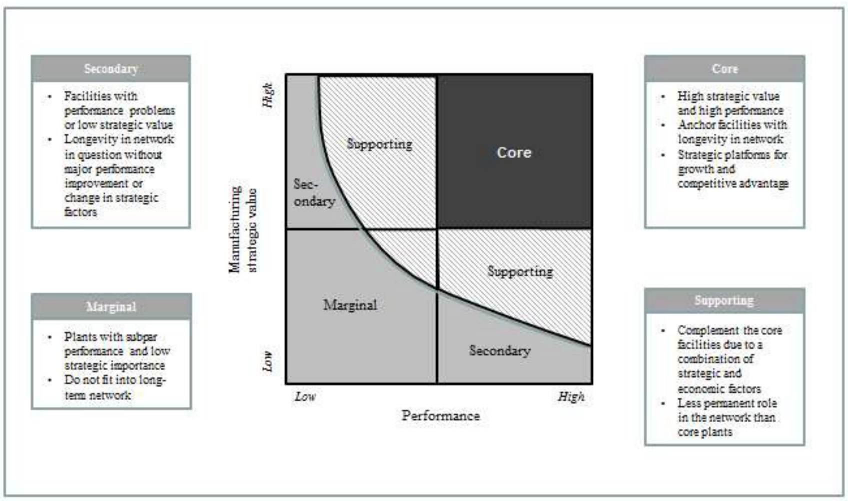



*Figure 4.3.3-2: Manufacturing assessment approach*

As a result of this approach AT Kearney suggests a portfolio of the following strategies covering:

- Make in-house
- Invest to make in-house
- Buy from contract manufacturer
- Invest to buy from contract manufacturer
- Re-define or do not make product

In a similar way Burt, Dobler and Starling (Burt, Dobler, & Starling, 2003) are addressing the issue. The authors emphasise to fist take strategic, then tactical and operational decisions on the matter. The main difference to the above is that Burt et al. in addition to the management decision further include factors like quality management and supplier capability which AT Kearney sees as a given.

- Local Content

  The last topic of local content has lately become of a bigger importance to wind turbine OEMs. In the context of this thesis local content describes the financial incentive or even legal obligation for OEMs to localize either their own production and/or parts of their supplier base in a country. An example for financial incentive is if the utility operating a wind farm receives a higher feed-in tariff if localized components are used in the wind farm. The rational of governments applying these mechanisms is to attract direct labour and technical knowledge of a future industry. Among others, countries which have been quite active in applying these kinds of rules are for example **Brazil, Argentina, Turkey, France, Taiwan and Russia.**

  Another indirect lever which could have an effect on the OEM considering deviating from sourcing decisions as per the total landed cost paradigm is for example export credit insurances. One example of those mechanisms is the Hermes credit issued by the Federal Republic of Germany. An OEM would qualify for this mechanism if the sourcing of its components is in compliance with the regulation set by the German Office for Foreign Trade.

  As a result of the described developments OEMs are increasingly pressured to increase the complexity of their production- and supply network at the expense of optimized global utilisation at a consistently increasing price pressure.

### 4.3.4. Manufacturing

The manufacturing process of a wind turbine comprehends of three very different concepts per its main component nacelle, blade and tower. From a perspective of the OEM the process of manufacturing a nacelle is to be biggest extend an assembly process. The blade manufacturing however is a process for which the word manufacturing is a very accurate description. Independent of the concept in the blade, glass fibre or carbon, blade manufacturing is highly manual and labour intense process. Finally tower manufacturing, which has been completely outsourced by most OEMs is mainly defined by the welding activities in which the tower segments are build.

- Nacelle assembly

  Approximation 80% of the total costs for a nacelle (geared or direct drive technology) are linked to materials OEMs normally purchase from their supplier base. The process steps done by the OEM are usually performing the incoming inspection, warehousing the parts, performing the assembly work and testing the final nacelle. The process of the assembly process has been, as the effects describing the design of the turbine, evolved with the development of the market. Whereas in the early 1970 nacelles have been manufactured in a significantly smaller size and number today's products increase in both. In the thesis it was previously mentioned that the wind turbine industry is starting to adapt principles from the automotive industry. This observation would need to further detailed, it not so much the passenger vehicle industry but more the commercial vehicle industry from which provides a very good blueprint for the industries development. The reason why it is not directly comparable with the primary industry is the fact that wind farms are to a big extend (with the exceptions of individual markets) rather project than product business meaning that the configuration and individual customer requirements are more comparable to a specific order in the commercial vehicle industry rather than for example a VW Golf from the passenger vehicle industry. As stated in the paragraph focusing on design one aspect of modularization is potential for simplifying the assembly process by using pre-assembled modules from suppliers. This reduces internal complexity in the entire manufacturing process but increases the pressure on process compliance towards suppliers and the quality compliance. The assembly of a nacelle is normally, depending on the technology, split into three main activities. The rear end assembly hosting all main electrical and mechanical components as well as serving as the connection to the tower including the yaw system allowing to turn the turbine remotely towards a favourable direct into of the wind. The generator (in case of the direct drive technology) is hosting the stator and rotor including the permanent magnets and the hub which connects the turbine blades to the nacelle. Besides the function of connection, the nacelle to the blades the hub also contains the mostly hydraulic pitch system which the angle of the blades is steered.

- Blade manufacturing

  The production process of a blade is by far more manual than the pure assembly process of the nacelle. As an example, the following process steps describe the single casting process of a blade.

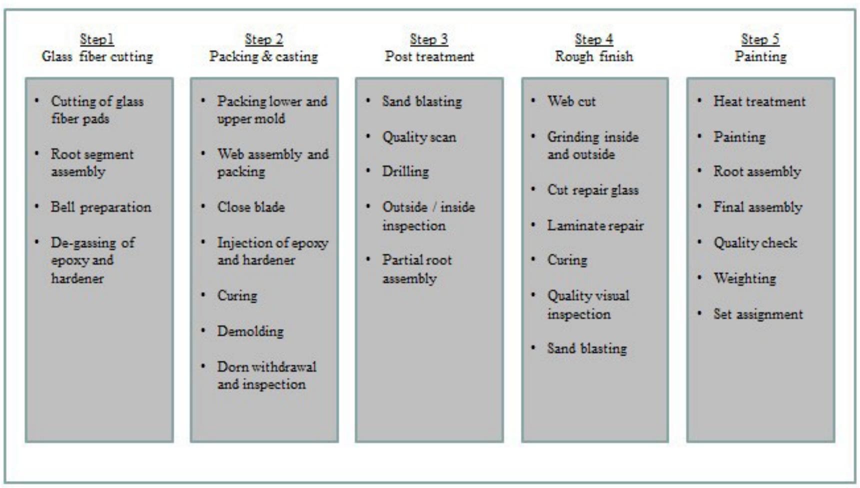



*Figure 4.3.4-1: Blade production of single casted blade*

The main challenge in the described blade manufacturing process is the constant increase in length of the blade. Over the last years the length of blades has increased from onshore application around 53 meters in 2010 to offshore applications with more than 80 meters produced by LM (LM Wind Power, 2018) in 2018. The result of the increasing length is that the weight of the blade is not allowed to proportionally increase meaning the quality of the used materials and production processes is pushed to its limits.

- Tower manufacturing

  The two main activities within the tower production process is the welding process and the assembly of the tower internals, meaning all the electrical wiring establishing a connection from the wind turbine to the electrical grid.

  Depending on the height of the wind turbine different tower designs are applied again affecting the production process. In the range of 80 – 130 meters the majority of towers are designed as a tubular steel design.

  Tubular steel design describes a design in which the entire tower is split into three, sometimes five sections which are individually welded and connected via flanges.

  For tower designs above the 130 meters tower manufacturers operate with different technologies involving for example hybrid solutions with steel and concrete by i.e. the company Max Bögel (Max Boegel Wind AG, 2018).

#### 4.3.5. Project execution

The transport, installation and commissioning of a wind turbine describes the project execution step in the value chain. It is obvious that the above-described challenges of increasing size and weight are not only asking the production environment to think in new and cost-efficient ways, but especially affect the project execution. In this process step it is important to make a distinction between the offshore and onshore applications of wind turbines whereas each application has its own characteristics and challenges. In the field of offshore application, the size of turbines has outgrown the onshore application in both, nominal generator size and consequential blade length. The reason is mainly linked to the lack of environmental limitations. Turbines installed on the sea are not bound to i.e. height restrictions as Onshore applications as per local legislation, i.e. (House of Commons, 2016). As a consequence, the manufacturing of sites of Offshore wind farm components are often located in proximity to harbour locations to allow for a direct access to loading vessels and limit costly on-land transport. For the onshore turbines however, this is only partly a solution as the final part of the transport by definition as the on land. The approach used by the OEMs varies from country to country and is extremely dependent on local legislation, infrastructure but also climate and weather conditions. Once all individual components and tooling is transported on site the installation or erection of the wind turbine starts. The main limitation factors during the installation are the capacity and speed of the main crane and the wind conditions during the installation period. The main crane is used for the main lifting operations on site, i.e., the lifting of the various tower segments, the nacelle lifting and the blade lifting. Among the different concepts the main distinction is the rotor or blade lifting. Some companies operate in a rotor lift, meaning that the full rotor of three blades is assembled on the ground and then lifted as a whole to be attached to the hub. The single blade lifting as the name suggests consisting of a consequential blade installation one after the other. The main advantage of the latter one the speed at which the operation could be done and in case two cranes are operating on the site, the one with less capacity could operate on the blade lifting, whereas the other one would lift the heaver components nacelle and tower. Considering the second limitation it is an obvious irony that one of the main reasons for a delay in installation is the wind condition on site. Due to strict safety regulations companies are only allowed to operate the main crane when the wind speeds are blow a certain threshold. Another side effect of the wind on the installation site is given for the offshore installation. Besides the difficulties operating in heights, the wind additionally pushes the waves making the installation work even more challenging. As a result, on an Offshore installation almost 50% of the time is considered as weather-down time, meaning not main operation is possible.

## 4.4. The wind power project management approach and its relevance in a research context

In many industries project management has become more and more the standard way how tasks, both, internal and external to the organisation are handled. An in indication for this development are the continuous increase in memberships of the two main project management associations, namely the project management institute (PMI) and the project management association accounting for a steady increase (Harrison & Hoek, 2007, p. 3). The basic description or main parameters of a project are the defined outcome or specification of the project, the time frame in which the project is to be completed and the monetary budget the project is allowed to cost. Figure 4.4-1 is illustrating those factors following Harrison & Hoek (Harrison & Hoek, 2007, p. 5).

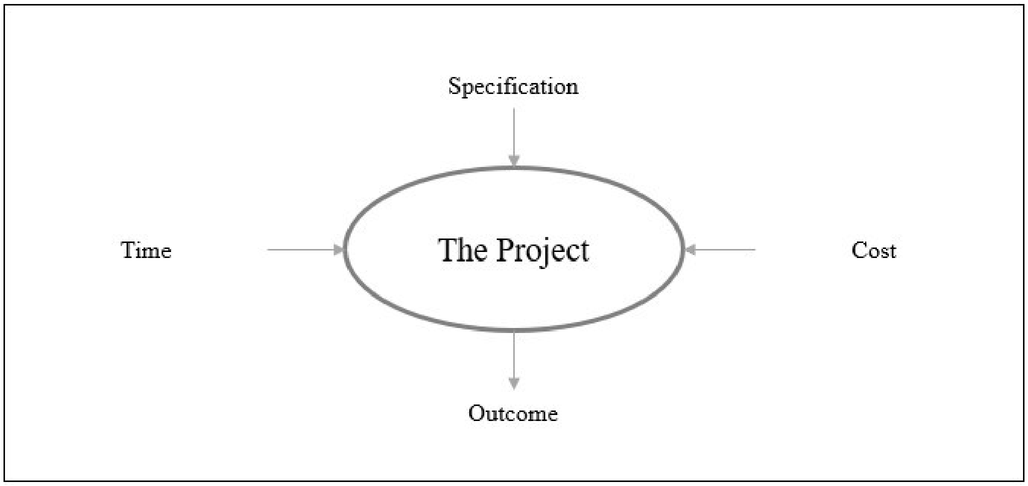



*Figure 4.4-1: Balancing the three primary project objectives*

Other authors additionally define different types of projects in regard to their application. Harrison and Lock defined four main types (Harrison & Lock, 2004, pp. 1–4):

1. Civil engineering, construction, petrochemical, mining and quarrying
2. Manufacturing
3. IT projects and projects associated with management change
4. Projects for pure scientific research

According to above authors each of the categories require a different focus on key aspect in project management in order to complete the task successfully. In the context of this thesis a wind power project is not accurately fitting into one single category. While the production part of the project clearly identifies with the characteristic of a manufacturing project, the execution and erection of the wind farm at its final location could be labelled a civil engineering or construction project.

The generic process of project management, regardless of the pursued approach, is following the same principles as illustrated in figure 4.4-2 according to Verzuh (Verzuh, 2008, p. 25).

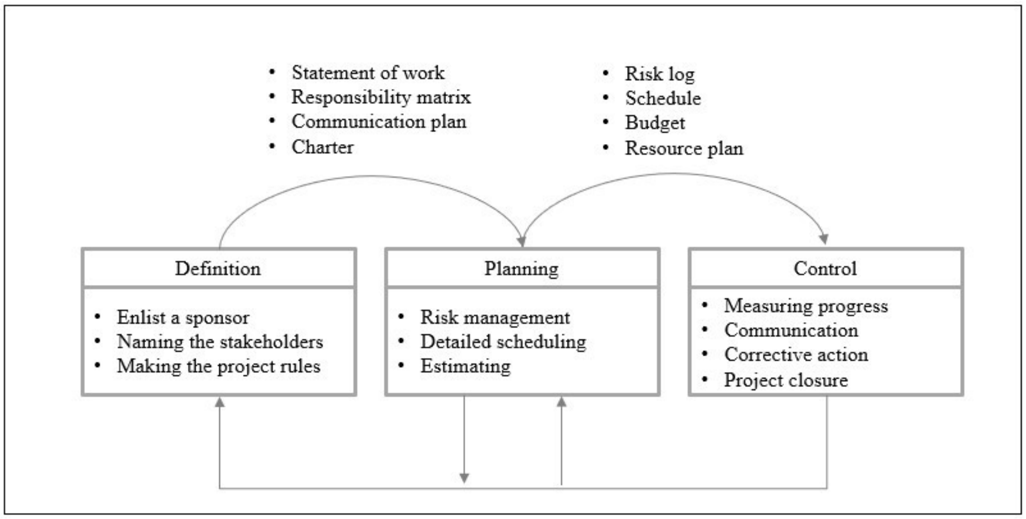



*Figure 4.4-2: The three project management functions*

The following paragraphs aim at explaining the standard project management structure of a major engineering and project execution organisation as an exemplary approach to project management representative for multiple standard approaches following a structured project management approach in an industrial project-driven industry.

PM@Siemens is structured into three main phases, the sales phase, the project execution and the warranty or service phase. Focus of this thesis is only the sales and project execution phase.

As with other project management guides PM@Siemens provides a structure to the project manager and the team to approach subsequently each phase of a project by clearing pre-defined milestones in which specific aspects of the project are checked. The main structure of the sales and project execution phase as per Hodgkins (Hodgkins, 2011) is described in figure 4.3-1 and 4.3-2 covering following phases with their purpose:

- **Lead Management** is describing the general strategic activities the company is pursuing.
- **Opportunity Development** is describing pre-sales activities in which i.e., key account managers discuss with individual client's what businesses they are about to invest and what trends the customer base is foreseeing. Those identified opportunities are already evaluated by the organization and set into the context of overall business strategy, targets and opportunity cost in form of other projects. The result of this phase is a Go / No Go decision whether the sales team has the authority to enter the bidding phase.
- **Bid Preparation** is covering already activities linked to a specific customer project or a tender. During this phase the sales team in a lead functions puts together the strategy, pricing and cost models for the project. Depending on the complexity this phase could cover a period of three to twelve months. In particular project tender involving local content (LC) which refers to a local value add as part of the tender or bid regulatory requires the strong involvement of functions covering procurement and / or manufacturing. Final step of the phase is the bid approval in which the management teams agree to the boundaries of the upcoming negotiations in case the project is won. The approval always comprehends of technical assessment of the scope and technology that will be supplied i.e., if new products are sold and a commercial evaluation in which the cash and gross margin, respectively cost calculations are discussed.
- **Contract Negotiation** covers the actual negation with the customer in which the terms and conditions of the contract are to be agreed on. The room for negotiations is determined as per the above approval.
- **Project Handover** is the final phase of the sales project and describes the switch into the project execution phase by a handover between the two teams, sales and project management team.

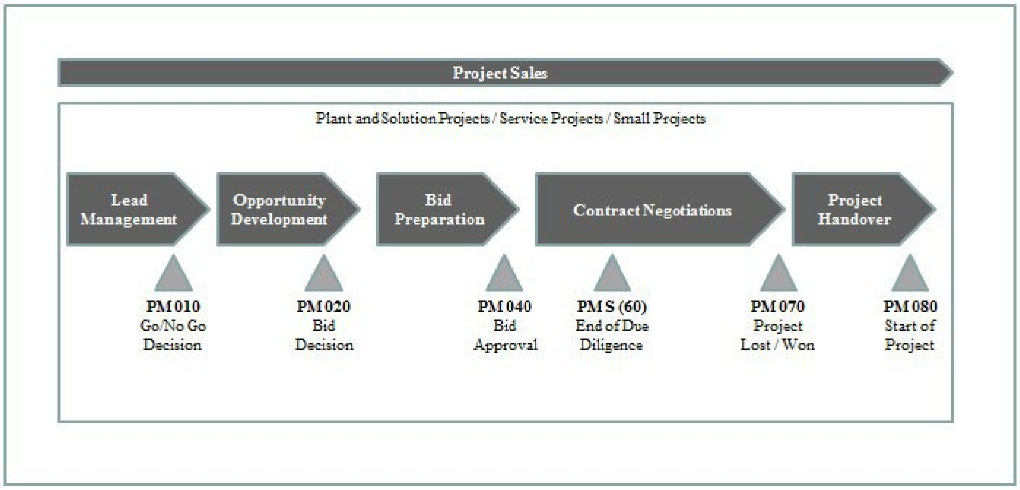



*Figure 4.4-3: PM@Siemens Sales Phase*

- **Project Opening and Clarification** represents the first phase of the actual project execution. Main purpose is the establishment of the cross-functional project team as well as the timeline and budget planning. This phase is considered the baseline of the project and will ultimately also serve as a baseline when comparing the actual result to the plan
- **Detailed Planning** is as the naming suggests the exercise in which the various team involved in the project plan their respective contribution in a way that each activity could be executed and tracked afterwards. The main areas in which detailed planning is conducted are **procurement, manufacturing, logistics, installation and commissioning.**
- The phase referred to as **Dispatch** represents the execution of the above-described detailed plan until the ex-works delivery of components. In the context of this thesis and the considered industry namely **Blades, Towers, Nacelles.**
- **Commissioning** describes in essence the delivery of a wind farm after installation of the various components by the OEM and contractors.
- **Acceptance** is the takeover done by the customer. Not considered in the scope of this thesis is the warranty and service activities which usually follow the acceptance.
- **Project Closure** is the internal step of concluding the project from a commercial and technical perspective. Main activity is a lesson learned

workshop including all involved faculties in order to document improvement potential and adjust the standard procedures if applicable.

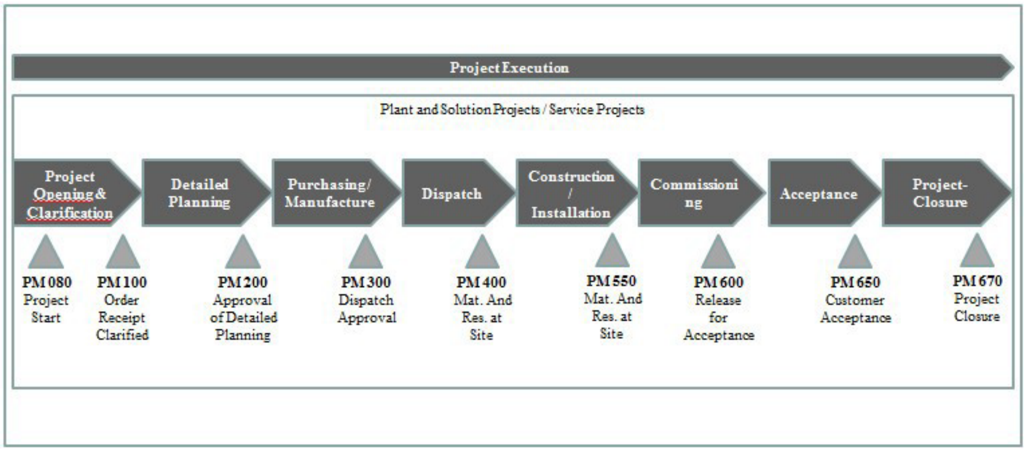



*Figure 4.4-4: PM@Siemens Project Execution Phase*

**In summary, the relevance of the wind power supply chain in the context of this thesis is based on several observations:**

- The underlying supply chain structure in projects, following a structured project management approach, represents the state of the art in key industries like energy, aviation and infrastructure

- The wind power supply chain, as the above industries, is influenced by the following key supply chain characteristics justifying its representability as a research object.
  The key supply chain characteristics from a managerial and market perspective are in line with Christopher (Christopher, 2004):

  - New rules of competition
  - Downward pressure on price
  - Globalisation of industry
  - Customer taking control

The key supply chain characteristics from a system perspective are in line with Robinson (Robinson, 2004):

- Variability
- Interconnection
- Complexity

# Chapter 5

# Model content – an empirical exploration

The following chapter consists of an introduction and a comprehensive simulation case study conducted using the simulation tool Any Logic.

## 5.1. Introduction to Any Logic

Any Logic is a multi-method simulation tool allowing to combine discrete-event based, system-dynamic (or continuous), and agent-based simulation. The software has been developed by a Russian company originally called xjTek with a first release of Any Logic 4.0 in 2000.

Throughout the years Any Logic has become the main companies' main product hence the company got re-named to its current name The Any Logic Company. The simulation tool is based on the programming language Java and supports various pre-defined model libraries.

Illustration 5.1-1 provides an overview. The user interface is mainly defined by four different areas which are used during the building process of the model.

The window on the left side of the window named **models in operation** offers the user the possibly to switch between several models. In the **modelling desktop** the model with its building blocks in built up and graphically illustrated. The window in which the user can perform further **coding operation** is displayed on the bottom of the entire desktop. The coding operation is generally used to adapt the standard settings Any Logic. The Any Logic libraries include all available building blocks available in the three available simulation paradigms, respectively building blocks connecting the different paradigms. Any Logic provides standard libraries for generic discrete-event, system-dynamic and agent-based simulation as well as standard libraries depending on applied themes, the following standard libraries are available in Any Logic University 6.7.1:

- Enterprise Process
- Pedestrian
- Rail
- Road traffic

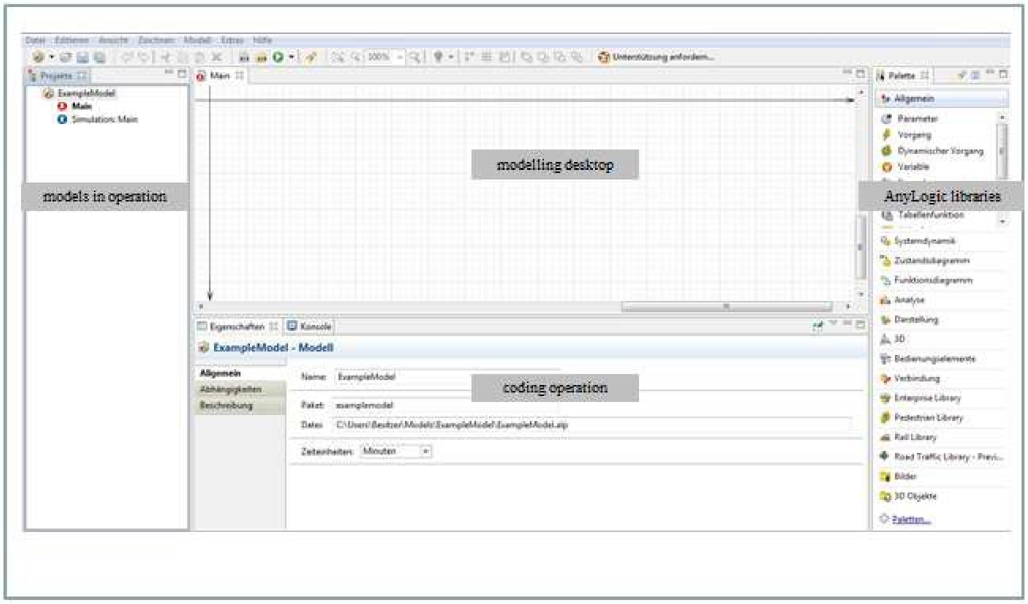



*Figure 5.1-1: Any Logic simulation user interface*

The various libraries contain pre-defined building blocks matching its theme, i.e., does the enterprise library contain assembly and operation objects. Given the focus of this thesis the main libraries which are to be used are the general ones and the enterprise library.

### 5.1.1. The Example Company – an introduction to Any Logic

This paragraph will introduce the process and explanations of building a model in Any Logic which is not linked to any real-world system and solely intended to serve this explanatory purpose.

The description of the model covers a summary of the purpose, a description of the building blocks as well an overview on the experimental phase and learning aspects from a supply chain risk management perspective.

The Example Company is a company offering one product names “AB” which is consists of two sub-components “a” and “b” which the company purchases and then assembles them to the final product requiring two pieces of sub-component “a” and one piece of sub-component “b”. As the final product often requires a significant level of customisation the time required for the assembly process varies between 30 minutes and 1.5 hours. The overall production system has been planned as a Kanban system where pre-defined safety stock levels and re-order quantities have been assigned. The production system has been simulated using a discrete-event based approach.

The market or customers of the Example Company have been simulated in a way that they can order the desired product around the clock via internet. A customer is attracted by the company via advertising or “Word of Mouth” meaning publicity between existing consumers. In case a customer has to wait an extensive amount of time between placing and receiving the order this customer abandoned and eventually frustrated, meaning he or she is lost as a future customer. The market and customer behaviour has been simulated using an agent-based approach.

Graphically the model has been divided into the following sections:

- **Overview:** covering a display of all variables, parameters, events and statistical data collection that are used in the model

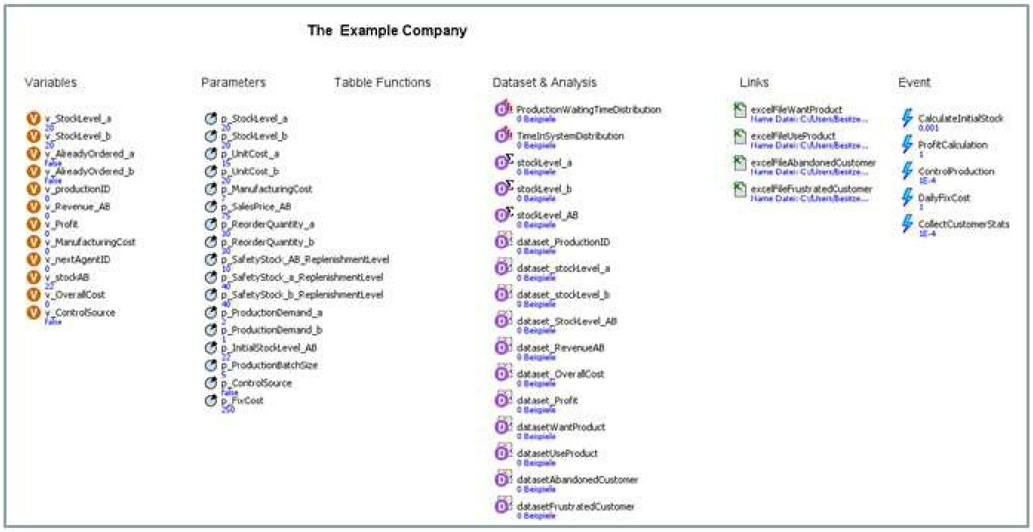



*Figure 5.1.1-1: Overview of variables, parameters, statistics and events used in Example Company model*

- **Process flow:** displaying the graphical flow of the discrete-event production and procurement process

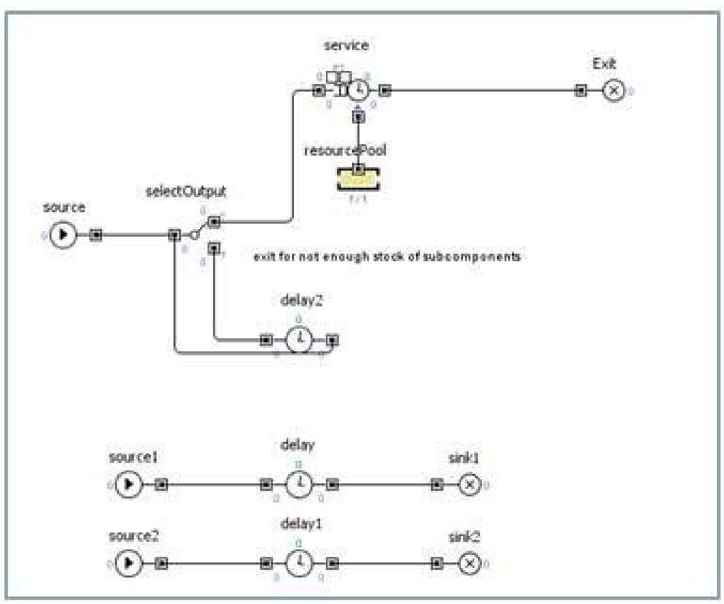



*Figure 5.1.1-2: Process flow of discrete-event based production and procurement process*

- **Agents:** graphically showing the market development by displaying all potential customer and indicating via colour code which status they are in


*Figure 5.1.1-3: Graphical overview of potential market*

- **Adjustable parameters:** showing all parameters that the user analysing the system can change in order to improve its performance

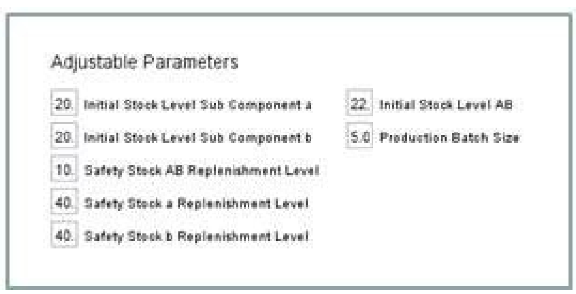



*Figure 5.1.1-4: Adjustable parameters in Example Company model*

- **Analysis:** displaying the performance of the system by continuously measuring the
    - state in which the customer / market participants are in
    - revenue, cost and consequential profit generated by the Example Company
    - stock level of sub-components "a" and "b" as well as final product "AB"

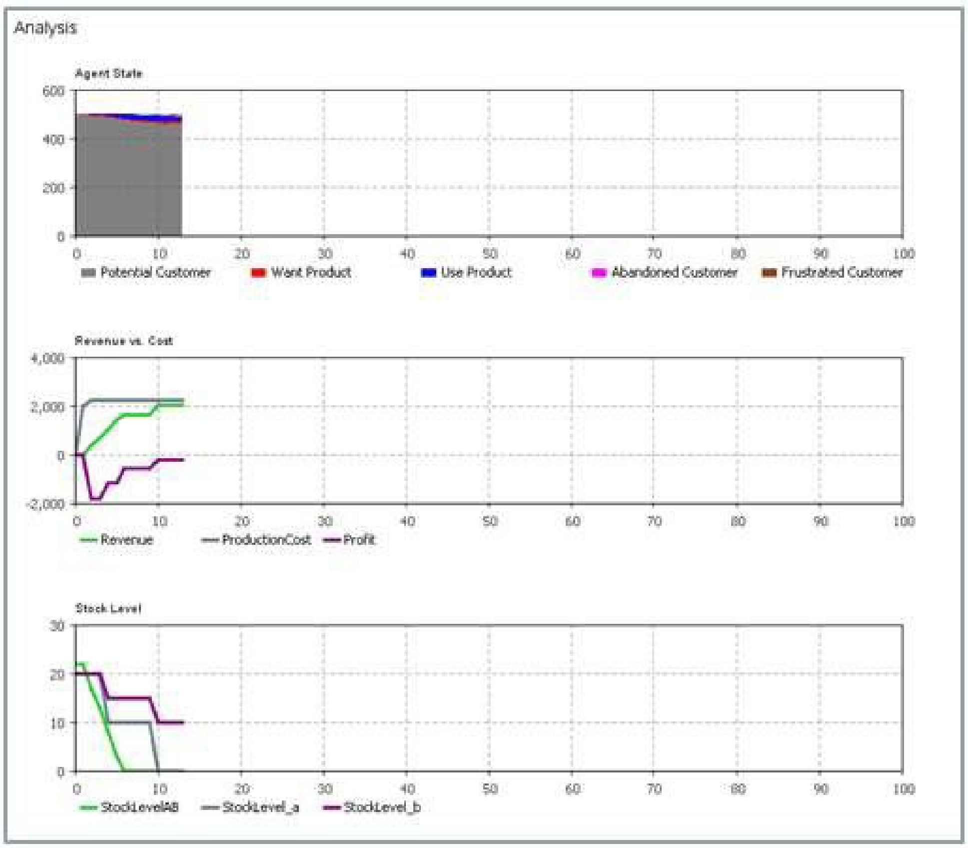



*Figure 5.1.1-5: Condition monitoring of agent, profit and stock level*

The following paragraphs will provide a detailed overview on the compilation and assessment of the model.

- Agent:

  In Any Logic agent-based models are developed using so called state charts. State charts are pre-defined building blocks describing the state in which an agent is in. In the case of the Example Company model those states are called **Potential Customer, Want Product, Waiting Customer, Use Product, Abandoned Customer** and **Frustrated Customers**. All blocks are connected via transitions illustrated by arrows between the state charts defining the conditions and activities that are to be performed when moving from one state to another.

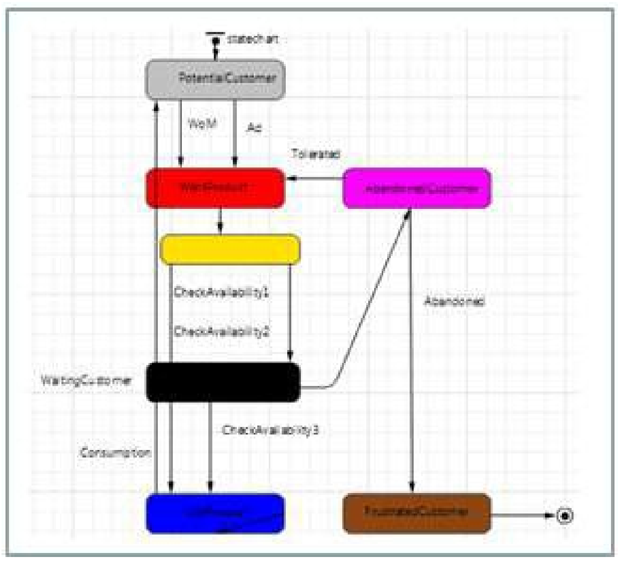



*Figure 5.1.1-6: Example Company – statechart for agent-based modelling*

Furthermore, the agent-based simulation is supported by several parameters the have been created defining the action and interaction of agents:

- **AdEffectiveness** is the fractional adoption rate from advertising
- **ContactRate** is the rate with which potential adopters come into contact with adopters
- **AdoptionFraction** is the person's cogency affecting the proportion of contacts that are sufficiently persuasive to induce his acquaintances to purchase the product

- **ToleranceRate** is the rate by which customers whose waiting time has exceed the defined limit are still willing to purchase the product
- **AbandonedRate** is the rate by which customers are not willing to purchase the product again after the tolerable waiting has been exceeded and the customer becomes frustrated and is lost
- **TolerarableWaitingTime** describes the time a customer is willing to wait for a product

In the designed model the initial population of 500 agents are "born" as potential customers. In order to become a customer that wants to purchase the product agents are either persuaded by the conducted advertisement, which successfully targets 0.8% of the population or an agent is convinced by another satisfied customer defined in the "Word of Mouth" (WoM) function. The success of the WoM campaign is defined by the contact rate that users of the product have among themselves and adaption fraction described in the paragraph above.

Once an agent has turned from a potential customer to a person wanting the product the simulation checks whether the demand of one unit can be satisfied. In case the demand can be satisfied the agent progresses further to being a consumer of the product, in case the demand cannot be satisfied the agent gets into a waiting mode.

If the demand is not satisfied within a defined amount of time, in this case seven hours, the agent turns into an abandoned one with a 30% chance of becoming a frustrated customer who exits the system without the chance of turning into a customer again. 70% of the disappointed customers are willing to give the Example Company another chance and become potential customers again.

In case the customer order is delivered the transition between that state of wanting and using the product deducts one product from the current stock of the final product "AB" and books the respective revenue. The formula below shows how this operation in Java using the defined variables:

```
get_Main().v_stockAB=get_Main().v_stockAB-1;
get_Main().v_Revenue_AB=get_Main().v_Revenue_AB+get_Main().p_SalesPr
ice_AB;
```

During the use of the product the customer can contact random potential customers in the rate of the combined factors for **ContactRate** and **AdoptionFraction**. After using the product and a waiting time of 10 hours the agent becomes again a potential customer closing the described cycle.

- Process flow

  The manufacturing and procurement system is modelled in the enterprise library using a discrete-event based approach. The following paragraph aims at explaining the structure and underlying logic of the entire supply process of the sub-components "a" and "b" as well as the manufacturing of the final product "AB".

  In general, a discrete event model starts with a source block and ends in a sink block. Between those two points entities are passed performing per-defined operations. Entities can represent different objects in the real-world system, for example individual orders, products or used a proxy only triggering an information flow.

  In case of the Example Company the source block creates an entity based on an event which controls every 0.1 hour if the following condition is met:

```
if(v_stockAB<p_SafetyStock_AB_ReplenishmentLevel &&
v_ControlSource==false)
    source.inject(1);
```

The condition monitors if the variable `v_stockAB` from which the demand generated in the agent-based model is deducted, is below the defined safety stock level `p_SafetyStock_AB_ReplenishmentLevel`. In case the stock level is too low the source block creates one entity.

After being created and before leaving the source block the entity triggers the following activities:

```
v_productionID=v_productionID+1;
dataset_ProductionID.add(v_productionID);
entity.enteredSystem=time();
v_ControlSource=true;
```

The first code triggers an incremental variable counting the number of entities created as part of the experiment. The next two lines of code create a log of this ID and monitors the time at which the entity has been created. The variable `v_ControlSource=true;` will be used at a later point of time and hence explained when relevant.

The following building block called selectOutput and has the generic ability to redirect entities according to a pre-defined condition. In the case of the Example Company model the selectOutput is checking whether the production has enough stock of the sub-components to realize the production of “AB”.

```
v_StockLevel_a>=p_ProductionDemand_a*p_ProductionBatchSize &&
v_StockLevel_b>=p_ProductionDemand_b*p_ProductionBatchSize
```

The condition tests whether the stock level of “a” and “b” is sufficient to produce the planned batch size in combination with the individual need of the sub-component. In the current model one unit of “AB” required two units of “a” and one unit of “b”. Furthermore, is an individual waiting time count initiated ultimately measuring how long a production order remains in the system.

In case the condition is to be found true meaning the stock level of the sub-components is sufficient for the production order the entity triggers the following activity when leaving the building block:

```
v_AlreadyOrdered_a=true;
v_AlreadyOrdered_b=true;
ProductionWaitingTimeDistribution.add(time()
entity.startProductionWaitingTime);
```

The first two assignments changing the boolean variable `v_AlreadyOrdered` for “a” and “b” is used to control the initiation of the re-order. In this case a re-ordering of sub-components is stopped.

In case the condition is to be found false the model triggers a re-ordering process of the missing sub-component either one of them or both, depending on the need. The respective order is the following one:

```
if(v_StockLevel_a<=p_ProductionDemand_a*p_ProductionBatchSize)
       if(v_AlreadyOrdered_a==true)
       source1.inject(1);
if(v_StockLevel_b<=p_ProductionDemand_b*p_ProductionBatchSize)
       if(v_AlreadyOrdered_b==true)
       source2.inject(1);
```

In contrary to the assignment of the variable `v_AlreadyOrdered` the boolean value “true” triggers the source blocks on the bottom of the process flow overview to launch the order of the needed sub-components.

The logic of the order process is equal for component “a” and “b”. When leaving the source block the entity is assigning the `v_AlreadyOrdered` with the value “false” indicating that to the above process that an order has been placed. In a next step a delay block is simulating the procurement process by assigning a pre-defined waiting time before updating the stock level of the sub-component and the overall cost.

```
v_StockLevel_a=v_StockLevel_a+p_ReorderQuantity_a;
v_OverallCost=v_OverallCost+p_ReorderQuantity_a*p_UnitCost_a;
```

After receiving sufficient sub-components to produce the planned number of final products the entity in the upper process flow is moving the service block with its adjacent resourcePool block. Objective of these two items is to simulate the assembly process of “AB”, the final product.

This assembly process could best be pictured as typical input-throughput-output function, in which the first formula when entering the block deducts the required sub-components from the stock, and then causes a delay representing the production time and finally as an output updating the stock of the final good with the produced batch size. The formulas triggering the events described are:

```
v_StockLevel_a=v_StockLevel_a-
p_ProductionDemand_a*p_ProductionBatchSize;
v_StockLevel_b=v_StockLevel_b-
p_ProductionDemand_b*p_ProductionBatchSize;

triangular( 0.5*p_ProductionBatchSize, 1*p_ProductionBatchSize,
1.5*p_ProductionBatchSize )
```

```
v_stockAB=v_stockAB+p_ProductionBatchSize;
v_OverallCost=v_OverallCost+p_ManufacturingCost*p_ProductionBatchSiz
e;
v_ManufacturingCost=v_ManufacturingCost+p_ManufacturingCost*p_Produc
tionBatchSize;
```

It is of relevance to mention that in this particular model the capacity of resources assigned to the production is considered sufficient, hence not

additional waiting time could be collected. The assigned production time is however depending on the performance of the resource and simulated with random distribution between 0.5, 1.0 and 1.5 hours per unit.
The exit block as a last item triggers another boolean variable controlling the launch of the overall production order system in dependency to the defined re-ordering point.

In the overview in figure 5.2-1, the user is able to manipulate all variables, parameters and statistical data collection sets that have been defined for the model. In addition to those, the overview shows a set events indicated by the symbol of a lightning strike. In Any Logic an event is simply a function triggering an action either after a certain period of time, a certain rate or condition. The event could either occur only once or multiple times in dependency of timing or the condition.
In the model of the Example Company four events are applied:

- CalculateInitialStock

  This event is only triggered once 0.1 seconds after the model is started to calculate the cost associated with the existing stock level within the production system.

  ```
  v_OverallCost=p_StockLevel_a*p_UnitCost_a+p_StockLevel_
  b*p_UnitCost_b+(v_stockAB*(p_ProductionDemand_a*p_UnitC
  ost_a+p_ProductionDemand_b*p_UnitCost_b+p_Manufacturing
  Cost))
  ```

- ProfitCalculation

  This event calculates every hour the profit the operation is generating which is then for example used in the charts described earlier in the chapter.

  ```
  v_Profit=v_Revenue_AB-v_OverallCost;
  ```

- ControlProduction

  The ControlProduction event is quite essential to the model is initiates the whole process flow by constantly monitoring the following condition:

```
if(v_stockAB<p_SafetyStock_AB_ReplenishmentLevel &&
v_ControlSource==false)
 source.inject(1);
```

- DailyFixCost

  This event adds every 24 hours a pre-defined sum to the overall cost generated by the system. The intention is to simulation the fix cost burden of an organization independently of its production output. The formula is as followed:

  ```
  v_OverallCost=v_OverallCost+p_FixCost;
  ```

- CollectCustomerStats

  CollectCustomerStats is an event which is triggered every hour of the model collecting statistics on the status of the agent population and transferring them into excel sheets which are used after multiple simulation runs to gather statistically significant results

This description covers the initial introduction to the different building blocks and applied structure used in the Example Company model. The following paragraph will focus on the results of the model and heuristic improvements the user can elaborate.

- Results and assessment

  The assessment of the model is done is way that a series of experiments is conducted all with a repetition of 25 simulation runs. For each run the results of key variables in model are collected and combined into an average. In the consequential two experiments parameters which are under the influence of the model are to be changed and an equal amount of simulation runs will be conducted.

  For the conducted experiment two variables are changed in order to assess their statistically significant influence on key performance indicators of the model.

  The variables are:

  - `p_ReorderQuantity_a`
  - `p_ReorderQuantity_b`

The KPIs based on which the overall performance of the system is measured is the profit as well as the number of satisfied customers.

The results and overview on key performance indicators are shown in the table 5.1.1-1:

| Simulation Results after 336 hours | Number of Runs | 25 |
|---|---|---|
| Parameters | Setting A | Setting B |
| Re-order quantity a | 50 | 120 |
| Re-order quantity b | 50 | 100 |
| Safety stock AB replenishment level | 20 | 20 |
| Safety stock a replenishment level | 40 | 40 |
| Safety stock b replenishment level | 40 | 40 |
| Initial stock Level AB | 22 | 22 |
| Production batch size | 5 | 5 |
| Average | | |
| Number of potential customers | 664 | 687 |
| Number of satisfied customers | 244 | 199 |
| Number of abandoned customers | 234 | 268 |
| Number of frustrated customers | 75 | 80 |
| Revenue | 18.303 | 14.952 |
| Cost | 18.415 | 14.167 |
| Profit | -112 | 785 |

*Table 5.1.1-1: Overview of 25 simulation runs*

The result of this experiment is that by decreasing the amount of re-ordered material for both sub-components the profit of the company could be turned positive at the expense of customer dissatisfaction recorded in the number of satisfied, abandoned and frustrated customers.

## 5.2. Empirical exploration by applying semi-structured interviews

Semi-structured interviews are itself a controversial discussed method of gathering empirical data. In her article: “The qualitative research interview.” Qu and Dumay (Qu

& Dumay, 2011) are referring to various authors assessing the semi-structured interview as unreliable and not objective, respectively referring to the result of a semi-structured interview in case the preparation has not been proper as a wasted opportunity.

Findings like the above make it an essential pre-requisite to evaluate the method of choice for gathering empirical data and its preparation thoroughly.

Other aspects to be considered when applying semi-structured interviews have been raised by Adams in his chapter in the work of Wholey et al. (Wholey, 2010) conducting semi-structured interviews as part of the handbook for practical program evaluation have been the extensive work the enormous amount of works that comes with its assessment and the connected question which sample size allows for a proper conclusion on the subject in question. The question regarding the sample size is by a general consensus in the scientific community depending on the subject or group that is being analysed. Boddy (Boddy, 2016, p. 429) remarks in regard to various authors that sample sizes of then might be adequate when assessing a homogenous group, whereas 20 to 30 sample sizes are to be applied following a grounded theory approach. However, when properly prepared, Carruthers (Carruthers, 1990) argues with reference to Bugher (Bugher, 1980, p. 2) that “the person-to-person interview is the best for obtaining in-depth opinions.” Furthermore, the best results are accomplished when:” (1) the respondent knows the purpose of the interview, (2) when the questions are properly worded, and (3) complete anonymity is guaranteed in respect to the interviewee’s responses. These can best be met through personal contact.”

### 5.2.1. Interview and rational of questionnaire

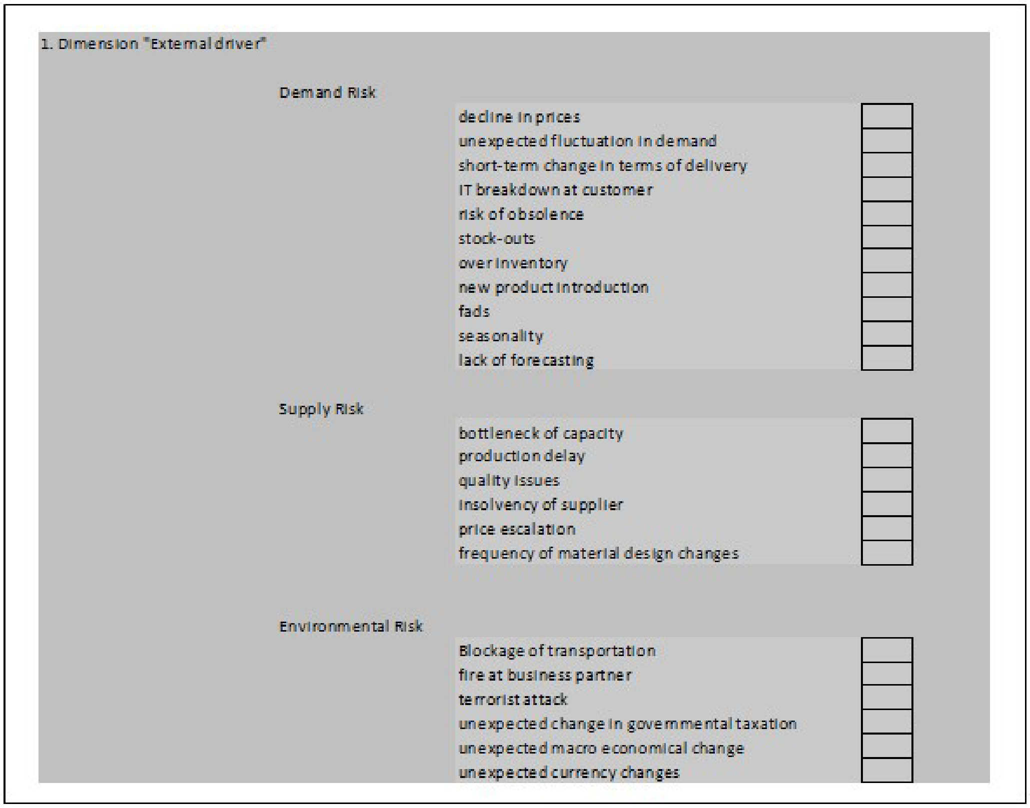
The empirical basis for this thesis is a series of semi-structured interviews conducted with supply chain professionals currently, or for a significant amount of time in their carrier working in a project management organisation which are active in what could be described in the heavy industry business. Products that are part of this homogeneous group among industrial goods are first and foremost wind turbine generators but also major industrial products as trains or gas- respectively steam turbines. The semi-structured interview covers a range of topics from a ranking of supply chain risks to potential mitigation activities and decision-making process in complex organisations to the application of principles following the theory of the leaning organisation. The following paragraph will introduce the questions in detail and discuss the purpose of their application.

- **Question 1:** Would you please explain your current role in your organisation as well as your professional experience in the wider field of supply chain management, or as it is referred to in other organisations (industrial-) operations?
  The first question of the questionnaire serves two main purposes, first it should function as an ice-breaker in the interview allowing the interviewee to introduce him- or herself with references to the respective personal experience, and secondly as a source of information on the context in which the interviewee will approach the following questions.

- **Question 2:** Would you please explain the nature of the business you are working in with reference to the type of product or project, the general planning approach (MTS or MTO) and the collaboration structure up- and downstream in your supply chain?
  Following the approach of the first question, the second one is also of an introductory nature. Objective is to understand form the interviewee's perspective the general principle of the considered organisation and the basic mechanics of its supply chain which is i.e., relevant when selecting improvement procedures for the simulated supply chain risks.

- **Question 3:** The following overview shows a list of different risks, internal and external to organisation. Please rate each of the risks from a scale of 0 (not threat to the supply chain) to 5 (high threat to the supply chain). The rating should be independent of existing supply chain risk management measures.
  The ranking of the risks displayed in question three represent one of the core findings of the questionnaire. As part of an existing framework which is referring to the MIT Centre of Transportation and Logistics (MIT Center for Transportation and Logistics, 2010) and to Manuj (Manuj & Mentzer, 2008) the interviewee rates 31 risks grouped into the two main dimensions "External

Drivers" and "Internal Driver" determining whether risk is originating from outside or inside the organisation. Furthermore, is the questionnaire distinguishing within the first dimension between demand risk (originating in the interface to the customer), supplier risk (originating in the interface with the supplier) and environmental risk (originating outside of the above).



1. Dimension "External driver"

Demand Risk

- decline in prices
- unexpected fluctuation in demand
- short-term change in terms of delivery
- IT breakdown at customer
- risk of obsolence
- stock-outs
- over inventory
- new product introduction
- fads
- seasonality
- lack of forecasting

Supply Risk

- bottleneck of capacity
- production delay
- quality issues
- insolvency of supplier
- price escalation
- frequency of material design changes

Environmental Risk

- Blockage of transportation
- fire at business partner
- terrorist attack
- unexpected change in governmental taxation
- unexpected macro economical change
- unexpected currency changes

*Figure 5.2.1-1: SCRM questionnaire "External Drivers"*

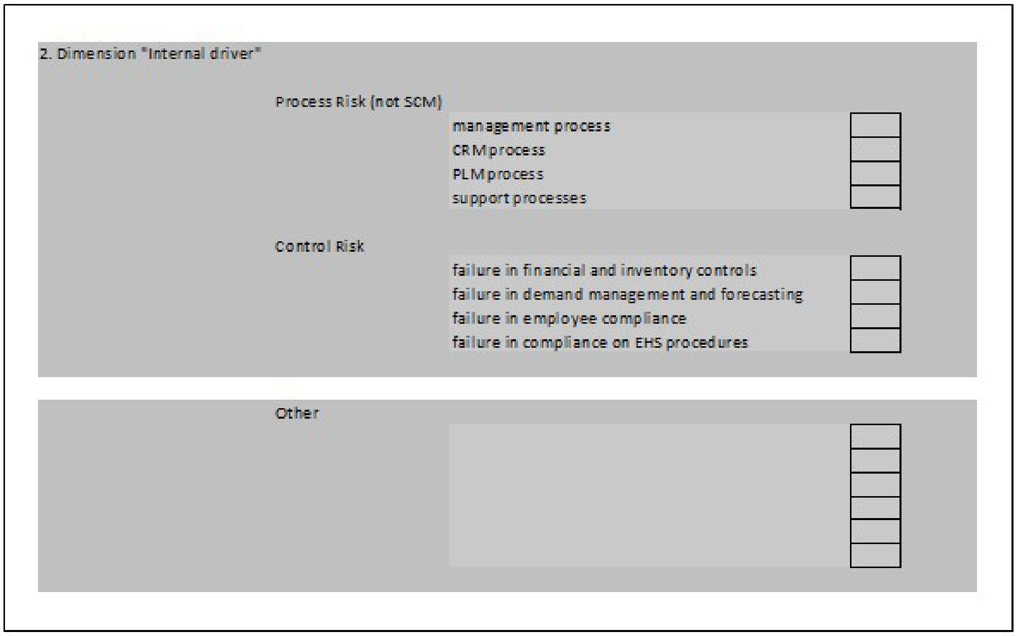



*Figure 5.2.1-2: SCRM questionnaire "Internal Drivers"*

Additionally, the questionnaire offers the interviewee the possibility to add any specific risk and rating which is, according to the interviewee, not considered in the two dimensions and thereby ensuring a comprehensive approach. The result of this rating is a holistic rating of supply chain risks without the consideration on their mitigation possibilities allows a detailed understanding of how SCM professionals in the project management business judge supply chain risk in today's complex environment of OEM, supplier, customer and environmental interfaces. Furthermore, the results are used to apply a proper prioritization in the targeted supply chain model.

- **Question 4:** Does your organisation follow supply chain risk management like:
  - Planning (early warning)
  - Crisis management (flexibility)
  - Emergency planning (redundancy)
  - Decreasing variability, buffering and pooling

After gaining a detailed understanding of the risk threatening the interviewee's supply chain, the question four is targeting whether in the interviewee's organisation potential supply chain risk management are in practice, and how those are executed. The proposed range of supply chain risk mitigation actions are in line with the theoretical options discussed in chapter 2.1. The underlying purpose is to establish knowledge of the existing supply chain risk management applied in the respective project management organisation.

- **Questions 5:** Does the decision-making process on SCRM in your organisation include any feedback loops from the subsequent to the latter step in the organisation?

  Question 5 is aiming to understand the dynamics that are happening during the process supply chain risk management, respectively its mitigation. Intention is to understand to what extent modern project management organisations are working as an integrated system rather than knowledge silos existing side by side and, in addition, how hieratical layers in one function influence decision-making and communication.

- **Question 6:** Which tools support the SCRM process in your organisation during the phases of identification, evaluation and mitigation?

  This question aims to understand whether computer and business simulation have already become a standard item in the tool box complex project management organisation use when addressing supply chain risk management. Furthermore, the question aims at understanding whether the process of supply chain risk management is quantitatively or qualitatively driven.

- **Question 7:** To what extent is decision-making training part of the SCRM process?

  The aspect of the learning organisation becomes of the questionnaire in question 7. In combination with the following question the aim is to understand how complex organisation ensure that its employees, for which it is relevant, are properly trained in the cause-and-effect mechanisms arising in a modern supply chain resulting in supply chain risks.

- **Question 8:** Does your organisation encourage organisational leaning by supporting its sub-concepts:

    - System Thinking
        - Evaluating complex supply chain risks from a holistic perspective
        - Sensitising involved parties towards their scope of influence
        - Applying dynamic tools like simulation in order to show cause-and-effect chains
    - Personal Mastery
        - Implementing individual development paths within SCM job descriptions
        - Encouraging employees to widen their knowledge about SCM interfaces in the company
    - Mental models
        - Encouraging cross-functional teams to discuss and analyse non-linear and disruptive developments in their supply chain
    - Building shared vision
        - Measuring the performance of SCM sub-organisations in context to the overall SCM performance of SCM
        - Emphasising individual contribution and awareness towards overall objectives
    - Team learning
        - Organise inter-departmental workshops on SCRM including i.e., engineering, manufacturing or purchasing
        - Installation of a common lessons-learned concept to capture inter-departmental knowledge on SCRM

Question 8 aims to understand in detail in a qualitative way which dimensions, theoretically discussed in chapter 2.3 covering the learning organisation and its principles according to Peter M. Senge. The objective in principle is to understand whether an organisation is encouraging that the 5 disciplines are adapted in the organisation or whether this is not the case.

### 5.2.2. Results of semi – structured interviews

The following chapter provides the main key aspects of the conducted semi-structured interviews and provides the detailed results.

- Number of interviews and participants

  As part of the qualitative research 13 interviews have been conducted. 12 interviews have been recorded. One interview has been conducted via phone and has been registered by taking notes. Two interviews did not cover the entire eight questions but only question one to three including the questionnaire.
  If conducted in full length the average time for an interview was approximately 75 minutes. The selection of the participants has been conducted according to the following two three principles:

    - A minimum requirement of greater 10 years professional experience and a senior or executive position level
    - A targeted industry has been the wind industry along with selected comparable industries (i.e., mobility, aviation or energy business)
    - A representation of the main functions collaborating in a state-of-the-art supply chain organisation

  The following overview describes the current role and experience level for the individual interview partners.

- Introduction of participants

  The principal aspect which is to be discussed in further detail is the selection of participants as part of the main functions represented in the supply chain. As evaluated in chapter 2.1.1 whether the focus of the respective research on the supply chain and its aspects might be functional, linkage, information or integration the common theme is a collaboration of various departments along the organisations´ value chain. In case of the conducted interviews covers:

  - Product development and product lifecycle management

    In his interview interviewee 7 describes his responsibility as being the program director of a specific product platform. He is arguing that: "around […] the platform you have the possibility to arrange different products when you are making a modular approach for blades, power, gearboxes, so internal components most of them very much related to the supply chain problem. […] In this particular position I am engaged in and motivated for the supply chain management, because [it] spins around the cost of energy and the competitiveness of the program and the product as a result of the program. And the competitiveness of this specific product is related to the supply chain capacity because we are in this very tough market where we are having a hard competition to reach those very low cost of energy thresholds." This introduction shows the close interaction between various functions that are collaborating under the umbrella of a holistic PLM function being ultimately responsible for the development of a competitive product. The conducted interview provides valuable insight in how a complex project management organisation is set up and steered facing a competitive market environment.

  - Sales

    Considering the sales phase of a project interviewee 4 provide a comprehensive overview from his more than 30 years' experience in the project industry and a significant time in the offshore wind industry.” I´ve been in the offshore wind industry for some 11 years now and for most of the time I have been dealing with sales and always in offshore and this is then obviously dealing with major projects. All offshore projects are major projects. And then for quite a long period of time I have been working in Asia. I spent 6 years in Asia, so in addition to sales it has also been general management to build up the offshore industry in Asia. And part of this has been in the company set up with a Chinese partner to also approach the Chinese market, which is special. And now I am working as a consultant in the offshore industry.”

Focus of this interview has been to gain further understanding of the impact of sales activities on the supply chain but as well the impact of supply chain activities on the project finalisation as well.

- Procurement of goods and services

  Interviewee 5 describes her current and previous experience in the procurement field as:” I am working as head of project procurement offshore, so that means I am procuring together with the team all components that are needed for the sites and also what is needed to install turbines and to commission [them]. Previously I have always worked in direct material [procurement] so all the components that are delivered to the production line and [within this] for different kinds of components, small ones like bolts, nuts and screws, so C-parts, and the bigger ones as well, so those are all the roles which are relevant for supply chain activities.”

  The procurement of services and goods represents one of the key pillars in an industrial project management supply chain environment. The conducted interview is focusing on understanding the interactions of a procurement organisation in the wider concept of supply chain management.

- Strategic planning

  The interviews covering the strategic planning aspects of supply chain management have been conducted with interviewee 2 and interviewee 3. interviewee 2 describes the responsibilities of his position head of footprint planning within the Onshore Industrial Operations department as he is: “basically responsible for new plant projects, so every time there is a new project started for evaluating whether a new production plant is needed. The job is actually to take care of the whole business case and the whole evaluation to come to a board decision whether to go or not to go forward with this investment. But that also includes the extension of existing facilities or adaptation of existing facilities.” Interviewee 3 as part of the strategic planning team in the offshore industry refers to the role of the department in the following way:” I am part of the offshore operations organisation and I am working in the strategic planning department which is focusing on overall planning of the supply chain and also strategic projects for improvements in the supply chain.”

- Industrialisation of new products and serial production

  Interviewee 8 as part of a governance function in supply chain management has over 30-year experience in the field. He describes is current role in which he has the:” the responsibility of a department that introduces a new product in the production environment for the nacelle business and we also have the responsibility for introducing standards, new processes, technologies and systems. So, systems and tools for production.” In order to better understand the operational part of supply chain management an interview with interviewee 9 has been conducted who is responsible for a part of a major industrial player’s transformer business in the US. While he has comprehensive responsibilities along the supply chain one key aspect in the interview has been production related topics. The description of his task has been the following:” My current role, I am general manager of the transformer factory […] for 2 years, so I started […] 2017. I am fully responsible of the business here, so that means the factory operation, including manufacturing, engineering, sales and marketing and quality of course. So, all supply chain operations."

Supply chain operations in which the production is outsourced to a supplier have been the main talking point with interviewee 10, he describes is role as:" as the formal title is head of operations towers and external blades in our regions that we call North Europe Middle East. Basically, that means that I am responsible for the manufacturing and the delivery of our products that we call or that are part of our wind turbine, the tower as well as the blades that we manufacture externally. There basically we manage a supply chain on approximately 12 tower manufacturers and 2 external blade companies. And then as well we work with numerous other suppliers. So, we are overall responsible for ensuring the product delivery at the respective quality at the respective time and cost that we have agreed."

- Project execution

  In order to understand the complexity during the project execution phase as part of a major commercial project interviewee 6 provided valuable input by sharing his experience in project management in general and out of the railway or mobility business," In 97 I changed for the first time from sales to project management. It was a project in Russia, it was export business, from then on, I had several positions in operational project management, as well in governance [functions] of project management. The current employment is that I am CFO of one of the biggest projects in [the organisation]."

- Service and maintenance activities

  For the final and increasingly relevant part of the project business model, service and maintenance activities three interviews has been conducted with covering different business applications, gas turbine service operations, healthcare and aviation. Interviewee 1 who is working for the gas turbine service business describes his role as:" […] the Senior Operations Leader, so a plant manager for a service centre for a [major industrial company]. So, our service centre is over 100 years old. We service primarily the nuclear and the coal-fired energy markets. With nuclear generators, steam turbines, looking at stators, so the power train for working in a power plant, a traditional power plant."

Interviewee 11 is working for a company in the healthcare industry and describes her current role as being:" really in a program management role for our […] project. [The product] is our newest diagnostic system, that comprises of a number of different modules it maybe chemical analysis, it may be amino acid analysis, as a main module it really has the ability to analyse more than 160 different tests, […] for a hospital. So my role has been to review, really the goal of the project, and its entirety is to bring transparency to the progress that we made for the all of the opportunity of the sales phase when we first communicated with the customer through to the installation phase when we understand what the status of each of those is, who is the responsible individual so that we can follow up and determine if […] it is a little bit reactionary, we are talking about risks here, but it really is at the very front stages brining transparency of the implementation of our newest product." The third interview conducted in the area of service and maintenance with interviewee 12 has been conducted as a telephone interview. Interviewee 12 described his responsibility as organising the supply chain management of one of the biggest aviation service facility in Germany. The main responsibilities are planning and organising the material management regarding fleet management.

Table 5.2.2-1 provides and overview of the interview's participants and their professional profile.

| Name | Position | Industry | Professional experience |
|---|---|---|---|
| Interviewee 1 | Senior Operations Manager O&M | Conventional Energy | >15 years |
| Interviewee 2 | Head of Footprint Planning Onshore | Renewable Energy | >15 years |
| Interviewee 3 | Senior Strategic Planner | Renewable Energy | >15 years |
| Interviewee 4 | Head of Sales Offshore Asia Pacific (retd.) | Renewable Energy | >40 years |
| Interviewee 5 | Head of Project Procurement Offshore Wind | Renewable Energy | >10 years |
| Interviewee 6 | Senior Commercial Project Manager | Mobility | >20 years |
| Interviewee 7 | Head of PLM for a Product Platform | Renewable Energy | >20 years |
| Interviewee 8 | Head of Industrialization Nacelles ON | Renewable Energy | >20years |
| Interviewee 9 | Plant manager Transformer Business | Conventional Energy | >20years |
| Interviewee 10 | Head of Tower / Main Component Operations | Renewable Energy | >10years |
| Interviewee 11 | Healthcare O&M | Healthcare | >20years |
| Interviewee 12 | Head of SCM O&M | Aviation | >10years |
| Interviewee 13 | Head of Regional Industrial Operations | Renewable Energy | >20 years |

*Table 5.2.2-1: Overview interview participants*

- Nature of project business

  Following the introduction of the responsibilities the second question covering the nature of the respective business and therein the relationship between own organisation and customer, respectively supplier provide valuable input to characterise the considered supply chain in full. The general finding is, that among all participants, the once that described their business a project driven consequentially define the supply chain is following a make-to-order principle. However, the organisations of the interview partners from healthcare and transformer business describe their market as a product driven, make-to-stock approach. Assessing in detail the answers from the targeted wind power industry it becomes obvious that there are indications for significant developments in the field. In his interview, interviewee 4 in his capacity as former sales head for the region Asia-Pacific pointed out that:” I would say that the offshore industry is far away from a consumer good context. And when I started in the industry it was very much on a collaboration basis with the customer, but I also think as the industry has grown more mature it has gone more in the direction of a consumer industry. It has more been driven by procurement departments trying to optimise the different parts of the project instead of looking at it more in a holistic view and more from a technical perspective also. So, I think there has been a move in the industry from when I have started until now." Concerning the supplier side, the general conclusion is of a similar nature. Interviewee 10, responsible for tower operation for a main wind turbine OEM in the region North Europe and Middle East describes that when it comes to tower supply the strategy is so seek long-term partnerships for the main important commodities. This obviously does not cover the entire purchasing volume as an industrial product will always comprehend of A, B and C-materials. A similar approach is common practice in the train industry. Interviewee 6 is describing the approach handling different part categories as follows:" […] things like screws or isolations, those are more state of the art products, or components that you can buy on best price evaluation, but there are other things like articular systems, breaks, traction control, which are very complicated and these are highly critical and these we have to develop in a partnership. So that means that the suppliers need to have a financial strength to survive the next 40 years, so there are not a lot of manufacturers our in the market that can provide this kind of financial stability as well as the technical knowledge about it."

Resulting from the conducted interviews the conclusion is to be drawn that project business is generally considered a make-to-order business with a high level of collaboration among suppliers as well as customers. Where possible the customer side of the transaction is pushing for a further commoditisation in order to create a more competitive business environment.

- Supply chain risk ranking

  The following paragraph will present the results concerning question three, assessing the level of threat to an organisation´s supply chain coming from various risks internal or external to the organisation prior to any mitigation activity.

External Driver – Demand Risk

With a standard deviation of 1,46 among the individual answers the risk with the most severe impact in combination of the highest probability prior to mitigation have been a decline in prices, unexpected fluctuation in demand and new product introduction. As for the wind industry, the decline is price is affecting the two applications, onshore and offshore wind, at a very different pace. While the answer from participants from the onshore application clearly indicate a significant risk, the assessment in the offshore industry is not that clear and would require some conclusive follow up whether the delta arises from the difference in considered time frame or exposure towards the risk.

Fluctuation in demand is the answer with the least standard deviation among the top ranked risks showing that in a considered almost full make-to-order environment transparency of the future demand is essential to mitigate and prevent supply chain risks.

The risk for the supply chain that goes along with the introduction of new product has been ranked equally high with the exception from the conventional gas turbine service operation which is to be explained by the fact that generally speaking the level of impact for the supply chain is minor for a product that far ahead in the product lifecycle in comparison to renewable energy applications. Despite the fact that the collaboration with the customer has been pointed out as quite crucial in question two, the common answer on the threat caused by an IT breakdown at customer is very low. The only different rating provided comes from the aviation service industry which has the basic need to be connected to their customer have on a constant basis. Another example for which the participants found an almost equal rating with a standard deviation of 0,65 are fads and the common opinion that industrial make-to-order business are not affected by this risk.

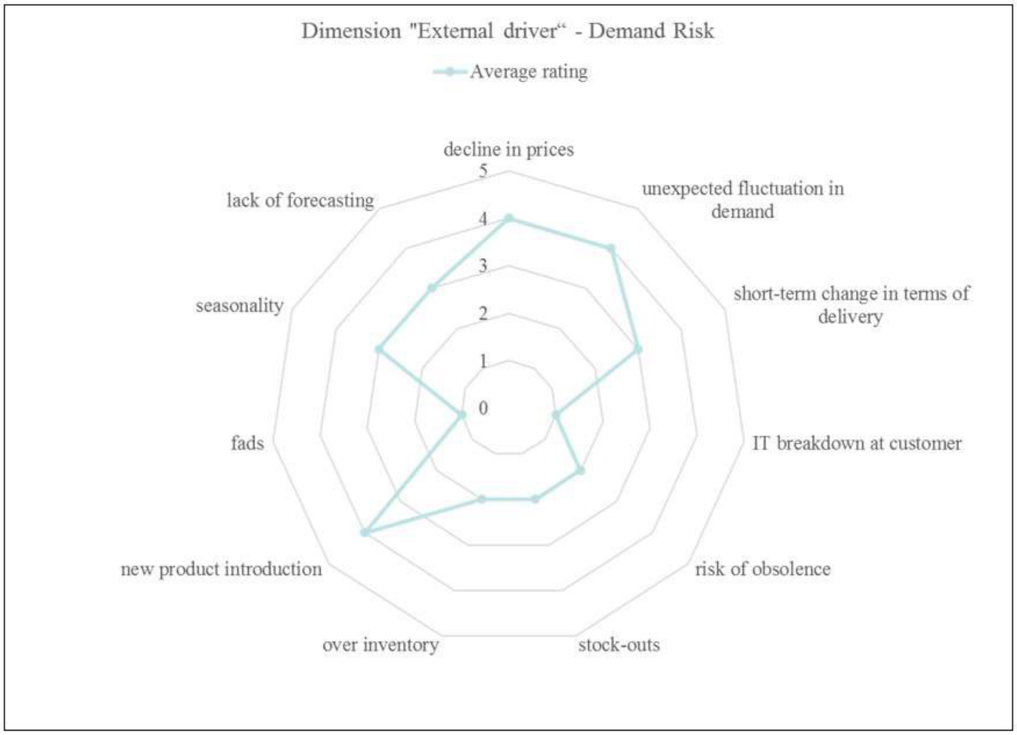



*Figure 5.2.2-1: External Supply Chain Risks – Demand Risk*

<u>External Driver – Supply Risk</u>

The on average highest rated risk by the interview participants was a production delay at their supplier base. Given the fact that the effect of a bottleneck in capacity and insolvency of a supplier is also leading to the similar effect that no parts are available for production it is important to mention that according to the provided information most organisation follow a multi sourcing strategy making the two risks mentioned less prominent that a delay for an already placed order. Not a clear answer was given for the risk related to frequency of design changes leading to the conclusion that this risk is again highly linked to the questioned industry but also considered function.

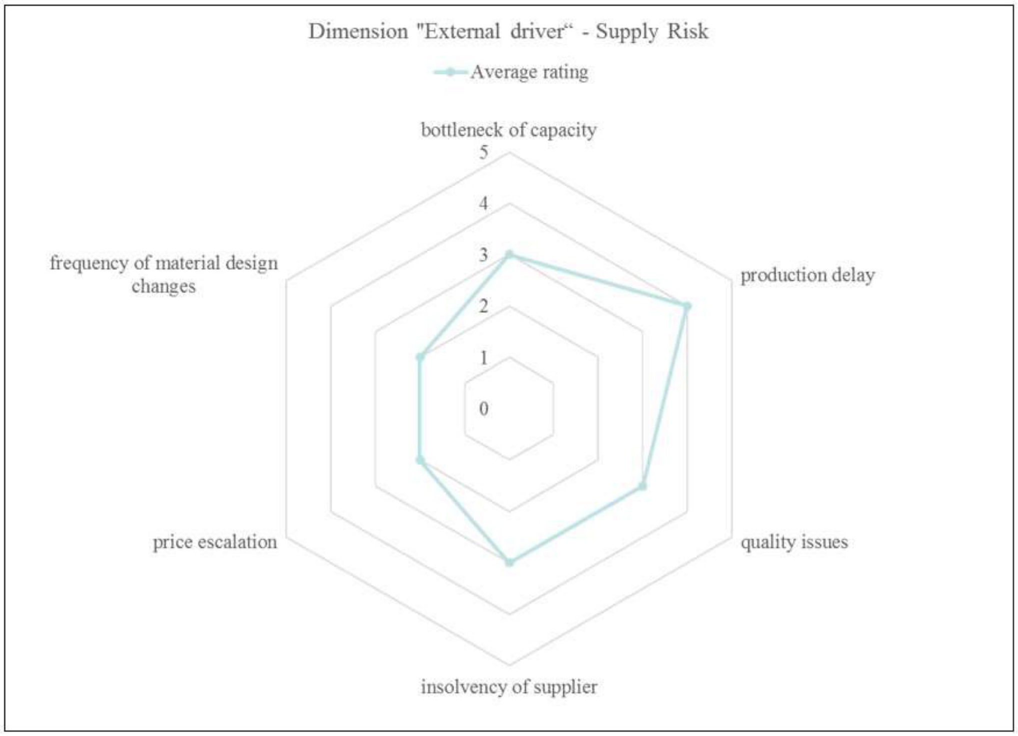



*Figure 5.2.2-2: External Supply Chain Risks – Supply Risk*

<u>External Driver – Environmental Risk</u>

The general tendency in this category has been that the risk examples addressing a more comprehensive, macro dimension are considered more relevant. A main reason for this has also been the fact that many of the considered organisations have a private but also public customer base and therefore directly affected by i.e., changes in governmental policy. The risk in currency changes has clearly been described as an increasing one resulting also from the continuous expansion of companies on a global scale. For example, interviewee 10 points out in this interview:" Another very real one [risk]. And this is one as we do trade a lot in currencies both, from our customers, so where we install and the ones, we have those contracts with but as well from a supply side where we purchase components in a lot of different currencies. I guess the ones most relevant for us besides the EUR is the USD, the RMB maybe specifically in our region the Turkish lira and the Russian Rubel and we do see a lot of changes there, some of them anticipated but some of them that are very unexpected have massive consequences on our business. So actually, seeing what has happened over that last year or two, I think this might be maybe as high as a 5." Other examples in which the currency risk has not been evaluated with the same gravity are for examples form interview partners who are based in the US with a primarily domestic supplier and customer base.

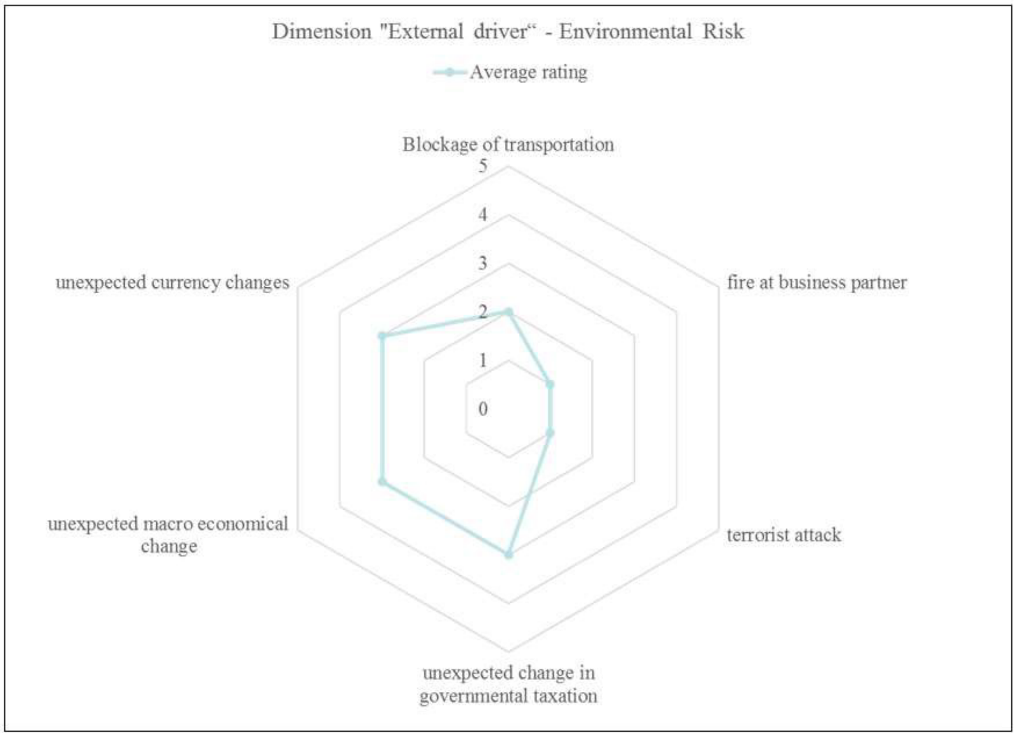



*Figure 5.2.2-3: External Supply Chain Risks – Environmental Risk*

Internal Driver – Process Risk (not SCM)

Considering the main internal processes in an organisation the result of the conducted interviews has been that the management as well as the customer relationship management process are to be considered as the most critical one, however the clear understanding among the participants that the product lifecycle management, if not conducted properly, represents a significant risk as well. The main argument for the management process is that as part of this process the strategic direction of an organisation is decided ultimately affecting all later processes.

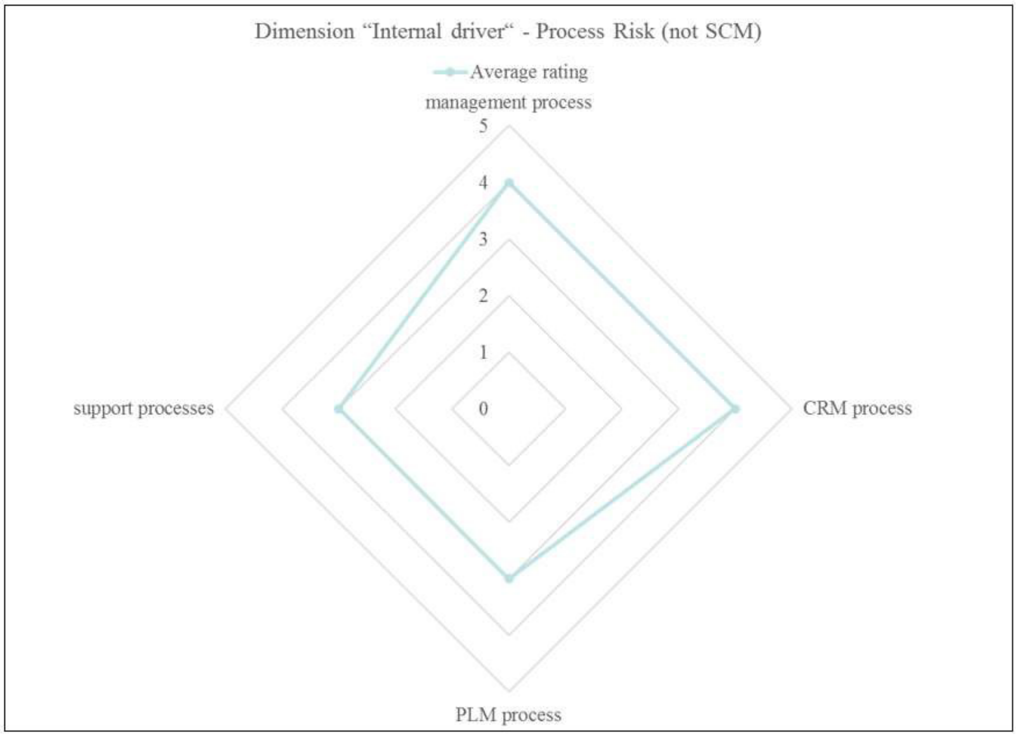



*Figure 5.2.2-4: Internal Supply Chain Risks – Process Risk (not SCM)*

Internal Driver – Control Risk

Within the group of control risks, the risks with the highest average score have been a failure in demand management and forecasting and a failure in EHS compliance. The failure in employee compliance has been discussed as relevant but considering the complexity in today´s organisations the common opinion has been that a single breach of compliance does only under special circumstances threaten the supply chain of the respective organisation. The difference to EHS compliance is obviously, besides the moral obligation to keep employees safe, the legal consequences linked to EHS related risks.

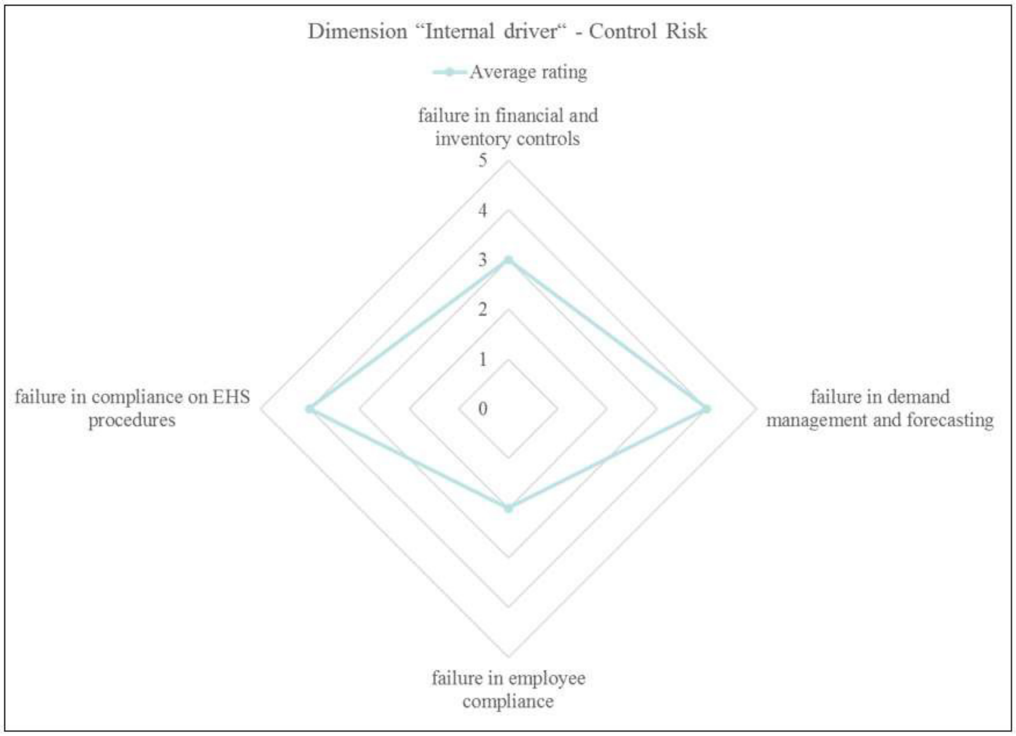



*Figure 5.2.2-5: Internal Supply Chain Risks – Control Risk*

<u>Other risks</u>

Throughout the interview the participants had the chance to add risks that in according to their experience have been under represented. The results are to be found in table 5.2.2-2.

| **Risk** |
|---|
| environment and weather |
| people and skills |
| failure of production equipment |
| general competition |
| import duties / trade mechanisms |
| change in government strategy |
| organizational set up (region vs. corporate) |
| readiness of customer infrastructure |
| product integrity / liability / product safety |

*Table 5.2.2-2: Overview other risks*

- Supply chain risk management process

  When it comes to risk management overall the participants agree that their organisation is engaged in risk management. Predominantly the interviewees agree that their organisation is operation on in a multi-layer planning to cope with i.e., demand risk like fluctuating demand but also to provide feedback regarding supplier performance interfering with their production. In line with previous comments the offshore wind industry for example allows for a comparably long-term planning. Interviewee 3 working a strategic supply chain planning describes the process as follows:" long-term we have the strategic plan, coming from a demand and going into a footprint planning and then also an investment plan for new factories or extensions. […] It covers 6 years. So basically, that is the long-term planning, let´s say from 4 to 6 years and this is built on demand or potential demand form the customer and some planning scenarios for our footprint and capacities. And then on the mid-term we have the load plan which basically covers the year 1 to 3 and this is more a plan to split the demands over the capacity of the factories. So, to allocate the demands to the individual factories. And then we have a short-term planning which is then the factory planning itself. It assesses in which order and at which exact production dates the parts are produced." This comprehensive approach allows for a detailed supply chain and ultimately production planning. When considering a more commoditized good such as the transformer and the time horizon of the operational plan is compared to the one in the offshore project management industry is significantly shorter." […] we have for example demand forecasts and this is something that helps us of being overloaded or underutilized. So, I think I can say we are doing this, and the horizon is like 3 to 6 months." Interviewee 9 explains the planning process horizon in this transformer factory. One controversial aspect regarding the launch of production orders as part of the planning process has been addressed by Interviewee 7, which is the point in time a non-binding planning turn into a firm commitment with suppliers resulting in a potential risk of creating obsolete stock. The approach described in the discussed organisation has not been fully solved as the point in time by when the order is firmly confirmed by the customer the contracted lead-time in light with the utilization of the capacity in the production network might not be sufficient.

Interviewee 5 provides an insight form the procurement perspective that on an operational procurement level the visibility that is shared with supplier besides frame agreements is 6 months broken down into a weekly planning cycle to synchronize deliveries and to detect risks of material shortages.

Concerning the feedback regarding the two approaches of crisis management and emergency planning the general answers have not been entirely consistent which is partially linked to maturity of the business itself. While traditional organisations out of the i.e., gas turbine or medical business describe that practices of crisis and emergency planning are available and put into use, the feedback our out of the wind industry is mixed. For example following Interviewee 5's descriptions if the organisation is engaging in those management practices the answer is:" Actually not really and that is probably one of the biggest weaknesses, we usually only focus on demand peaks this is then done via the forecast if there is a huge drop we of course also share it with the supplier if it is part of the planning, if it is unexpected we usually do not share it because we have financial impact which we then do not want to show openly to the supplier […]."

According to the interviews conducted, the approach of buffering and pooling is widely used, however decisions regarding this approach seem to be highly linked to the physical nature of the good and its transportability and required cost in comparison to the avoided underutilisation in a production facility. Another relevant input regarding this factory has been discussed with Interviewee 3 relating local content requirements that by definition limits an organisation´s ability to perform pooling activities." […] for example, local content requirements to produce the parts in specific area or country. And we also see different customer requirements that make it difficult to keep this. We did this with one factory but now we are back with two factories, which comes back to the crisis management and a certain redundancy in the supply chain. So, we are more focused in reducing risk and trying to orient ourselves towards the customer requirement than to do this internal optimisation."

- Description of risk management process and utilisation of supporting IT infrastructure

  The various discussions in the interviews regarding questions five and six aimed to evaluate whether in first instance a clear process is described and lived in an organisation handling the risk management process, and in a second step to understand if this process is supported by an IT environment.

  It seems that based on the feedback that the first part of the question that in general, and not surprisingly, organisations have established a feedback loop in order to detect, mitigate and prevent supply chain risks, however in the same way, it seems that this process is rather defined by the collaboration and experience of the people working in it, rather than a comprehensive process supported by an IT environment. Interviewee 3 describes it as," there is no dedicated process of [risk management] let´s say a risk materializing and we have this crisis situation. It is more a fire fighting and [using] common sense. On the other side, I would say there is a high collaboration between the different departments and if a crisis occurs and to get solutions in place." However, in the same way he describes initial attempts to get this process into a structured approach:" What we do in terms of risk management is basically is that we have kind of a strategic and comprehensive process and this is then implemented in all units, in all factories and then also aggregated towards the whole unit or department. So, what it is basically, it starts with the risk identification, here we use either risk identification workshops to identify the risk in the individual units. So, we go to every plant and function and identify risks and then we also do that together with the experts in the respective area and then the risks are also described and rated so that we also know what is a bigger risk and a smaller risk. And then for every risk there is also a dedicated risk owner nominated with then makes sure that for each of the risks we assign mitigation measures. Which allows us then also to see which of the risks can be mitigated in a good way and which of the risks will leave us with a high contingency. And then after the initial identification of the risks we on-board that to a quarterly management process which means the risks are reviewed and reported to the top management or to the head of operations in a structured and continued way at each quarter and here we see the top risks and also the changes in risk and then make sure, and can check that we have mitigations in place for the risk."

Regarding the utilisation of IT systems, the feedback has been that no further IT application is used to support supply chain risk management processes with the exclusion of SAP, however the described ERP environment is not used to i.e., simulate scenarios but to control the actual data.

When assessing the application of IT as part of the risk management process Interviewee 5 states that this despite the utilisation of SAP the aspect of risk management, for example in creating a "line-of-balance" for the production as still to be done by partially manual interaction.

The only exception has been the feedback from Interviewee 12 who provided a very good insight in regard to the simulation that is done in the aviation service industry to optimize i.e., stock levels and net-working capital based on simulation programs factoring in previous material consumption, seasonality and characteristic of the planes under service, for example type, age and most common routes. Based on those complexes, and by external companies supported, simulation studies it is possible to further improve the above mentioned KPIs. Concluding on this description in combination with the feedback provided by the other interviewees the question of application for advanced simulation and business modelling applications is a question of maturity of the organisation. Furthermore, is can be noted that business modelling and simulation is far from being a standard tool that is used in the supply chain risk managing process of project management organisations.

- Aspect of decision-making as part of on-boarding process for new employees

  All participants stated that a special risk management training is not part of any particular job description, but the general approach is a training on the job, meaning that once risk arise in a particular job profile, i.e., supply chain planner experienced other colleagues are to support in the management process. The only exception to this is in some organisations the project manager training for which risk management in projects represents a standard building block. Interviewee 9 being very familiar with the project management process and training described in chapter 4.3.1 explains the approach as follows:" It is kind of learning on the job but we also have project management functions and this is an essential part of project management. Project managers are trained for those kind of things […]."

When discussing the aspect of training in risk management and decision-making Interviewee 1 stated that this aspect is "[…] very weak. We focus a lot on compliance, what are the different laws and regulations. We focus a lot on product knowledge, which is a large component of any training routine. We do not focus that much on risk if you are not in a specialist's function like quality or EHS it probably does not get as much attention as it needs."

Summarising the results, it could be concluded that supply chain risk management is not subject of a particular training and / or part of the on-boarding process for new resources in key functions.

- The learning project management organisation – theoretical framework vs. implementation

  As previously described is the aim of the last question to understand to what extend do today´s project management organisation implement and consequentially live and encourage its employees to take ownership on the five-different dimension defined in the theoretical framework of organisation learning. An important remark prior to discussing the results is that the naming of each of the dimensions in a practical context could be different then in the original concept. Of relevance is only the application of its values.

  Then general feedback collected in the conducted interviews is that modern project management organisations are trying to adapt concepts similar to the ones of the learning organisation principles. The most successful adaptation seems to be the concepts of personal mastery, building shared vison and team learning. All questioned professionals provided clear examples how the organisation is encouraging the intended behaviour.

  For example, provided Interviewee 9 in his capacity the following statement regarding personal mastery:" Yes, we have clear job profiles, we have clear job profiles, and this is across the business and it is for all factories [at the OEM] including my factory. So, each individual person is part of a job profile and for each job profile we have a competency identified, a minimum and a maximum level of the required skill level is part of the business unit, for example supply chain management or purchasing or engineering or production, they need to update their job profiles and competence levels and we are making regular competence assessments.” Concerning building a shared vision interviewee 7 pointed out that the focus of the management team for this topic is a crucial success factor:”. Building a Shared Vison is also a thing that probably we are not so bad. I think for example the integration process we had suffered has made a lot of focus on this. Ok, so this helps us to focus on we are one company, focus on the cost of energy, safety, so these mantras, everyone can see that. And the communication tools that have been used by email, meetings I think they made something at the end of the day. Top management also spend a lot of time to have these visits to the main offices and so. So, I think they made a good effort in that.” Interviewee 5 provided a detailed description on how the dimension of team learning is connected to a yearly supplier evaluation conducted in the procurement organisation with its main stakeholders:” I would like to differentiate here between project procurement and direct procurement, so direct procurement to take this part first, we have a yearly supplier evaluation and each interacting function, so supply chain, quality, engineering and procurement is going through a detailed questionnaire of evaluation for the supplier and the questions that are asked are actually supply chain risk related. So, procurement has to put in financial stability scorecards and so on. And this is a process where each function gives input, then it is discussed in one of the commodity team meetings and a final score across all 4 functions is set per supplier. If the score is below a certain number, that will either in case it is very low to exclusion of business and if it is lower than the average then you have to put in place whatever the reason for this low performance is and to put a supplier development plan in place if you would like to use this supplier further, the supplier development is even signed on a procurement management level together with the management of the supplier, so these are the kind of things that are done on a yearly basis. In the project procurement world, for the big contractors on site, so the vessel suppliers, the installation suppliers, this whole evaluation is done with the project, normally after the first part of the project, so you still have the second part of the project to enhance the supplier performance. And then also after each project and this evaluation is then used for this organisational learning about the risk related to this supplier is then also considered in future awarding decisions."

However, those positive examples of clear commitment towards organisational learning cannot overcompensate the fact that the clear feedback regarding the two dimensions system thinking and mental models has been that the organisations are either not engaged in related activities or the current status is by far not sufficient to harvest the full benefit of the concept and is still under development. Interviewee 3 describes the approach started in his offshore organisation as follows:" I think for the first one, the System Thinking it is quite positive or applied and enabled from our organisation. For example, we do have different forums for evaluating different scenarios in the supply chain, in the delivery. It starts with different footprint scenarios we have to do [in order to] comply to the demand of the customer and this is also then shared in a quite big group of people from all different functions. Or we also have risk simulations or analysis for example stress tests, like for example will we be able in the next period of time, for example next year, be able to supply all our demand to the customer if in certain dimensions there are some crisis? For example, we will lose some capacity, we will have some delays. […] I would say it has some aspects of the dynamic one but it is not really dynamic. So, for example what we are doing to the capacity check, we are using the output numbers per week from the existing plants from the last years and we are putting that into excel and then having this, what is it called? Random number generator picking from these outputs in the last years, just taking one in a totally random way and then we see different lines which might fulfil or not fulfil then our demand. And then at the end we see how many scenarios are there and [can judge] which risk is there to not fulfil the demand. So, it is a static [approach] plus some dynamic elements added I would say. So, we are going a little bit into that one but it is not a complete purpose build tool or so. And we do it especially in situations where we see it will get tight and we might run into a risk. We also do that once a year for every plant and the entire supply chain." According to interviewee 7, who has in his capacity as a program director a good overview across the entire value chain, provided the feedback that he does not see the organisation engaging in system thinking and mental models, leading to the overall conclusion that while the concept of the leaning organisation is partially lived, its full potential is not entirely exploited.

- Sensitivity assessment

  In order to put the risk ratings conducted during the interviews into a comparable context and to draw further conclusions from the results, the following comparisons are to be assessed:

  - Onshore vs. offshore wind business
  - Service vs. new product manufacturing business

<u>Onshore vs. offshore wind business</u>

The following paragraph compares the results provided from supply chain professional working in the offshore and onshore wind industry in order to understand similarities and differences and causalities concerning risk threatening the respective supply chains.

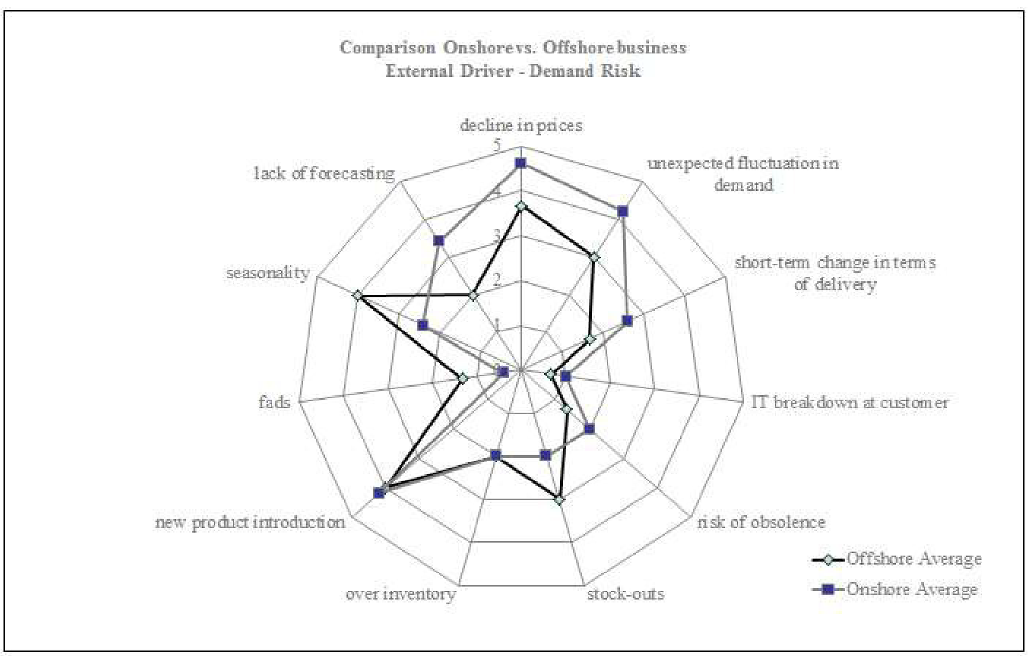



*Figure 5.2.2-6: Comparison Onshore vs. Offshore Business Demand Risk*

The differences in the profile of demand risks rooted in the different characteristics and structure in which the businesses are conducted. While the offshore wind industry currently benefits from a comparably stable business environment concerning the ability to plan future demand and the development of prices, the business is a lot more volatile regarding its project execution which becomes obvious by i.e., the higher rating in the risk effect of seasonality.

The onshore business on the other hand is characterised by a risk of short-term development in market prices and demand development.

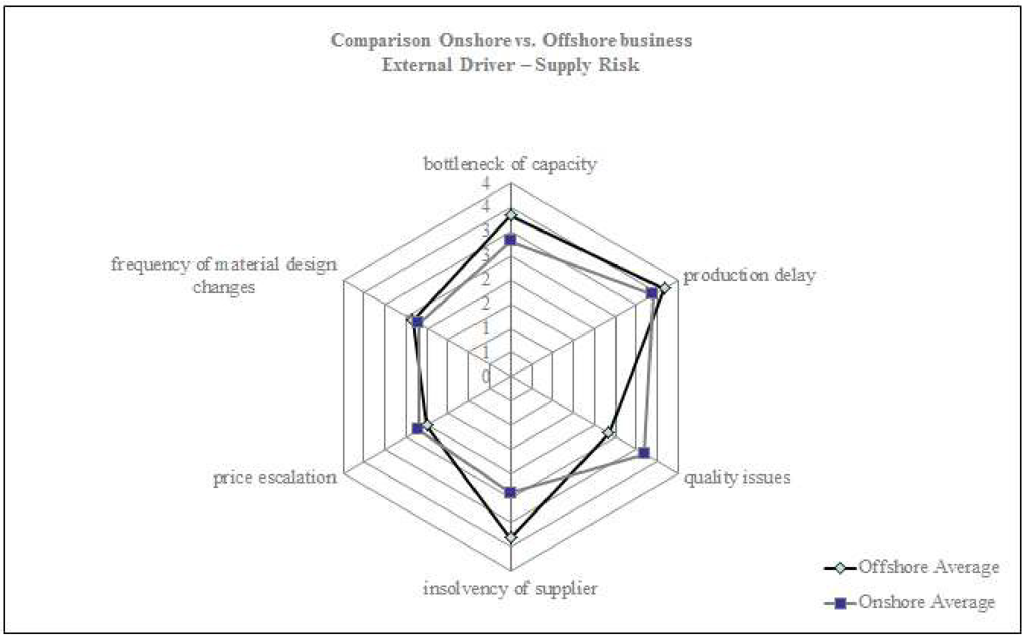



*Figure 5.2.2-7: Comparison Onshore vs. Offshore business Supply Risk*

The slight differences identified in the area of supply risks are linked to the different structure of the used supply chain in the on- and offshore market. As discussed in chapter 4 the overall volume in the onshore market is significantly bigger but growing on a smaller scale than the offshore business hence operating with a more stable supply chain in comparison to the offshore business in which a smaller number of suppliers has to keep up with the market growth to support the recent development.

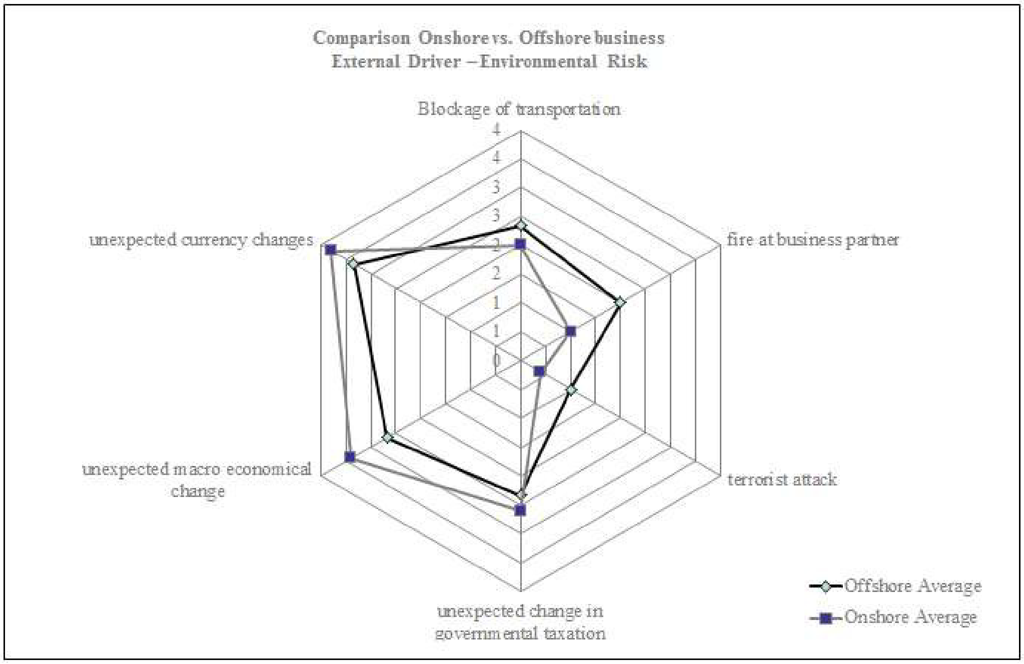



*Figure 5.2.2-8: Comparison Onshore vs. Offshore business Environmental Risk*

The rationale leading to the different rating of risks within the group of environmental risks among the onshore and offshore business as per the interviewed supply chain professionals as the one applied in the demand risks. The general development in market towards onshore applications has been more volatile i.e., regarding governmental subsidies. The rational for a higher risk in currency exchange rate is linked to the fact that the majority of the current offshore business is done in euro whereas the onshore business is conducted in various currencies.

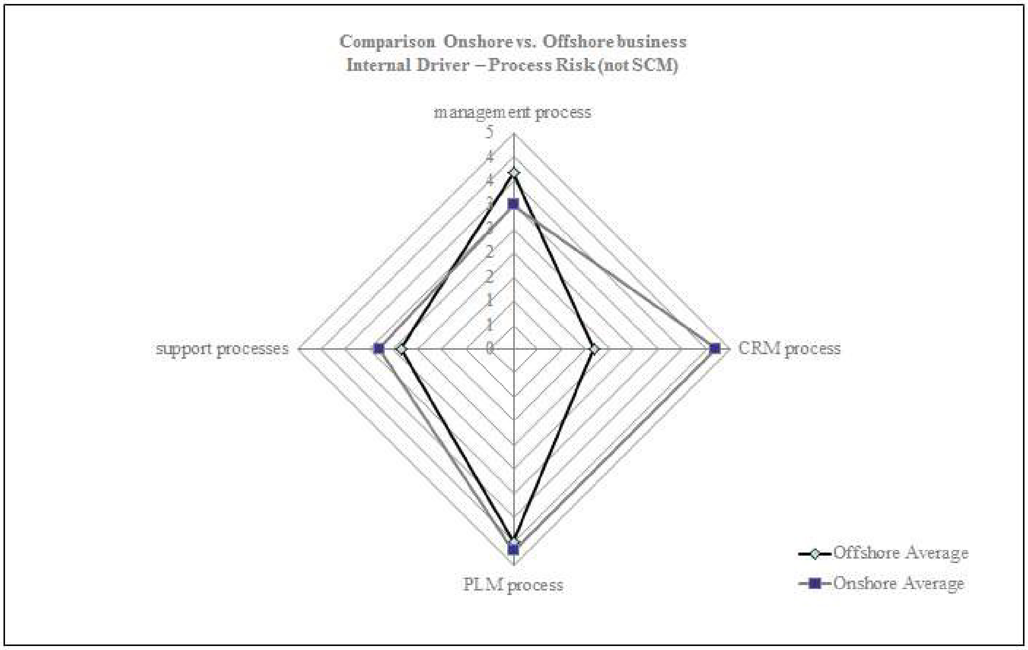



*Figure 5.2.2-9: Comparison Onshore vs. Offshore business Process Risk (not SCM)*

Causative to the significant difference in perception of the risk associated with the CRM process is the number of projects that are sold and executed in the two applications. While, according to interviewee 4, the number of offshore projects allows for a high level of personal and individual involvement of the OEM team the number of onshore projects executed in the same amount of time is significantly higher requiring a higher necessity for robust processes.

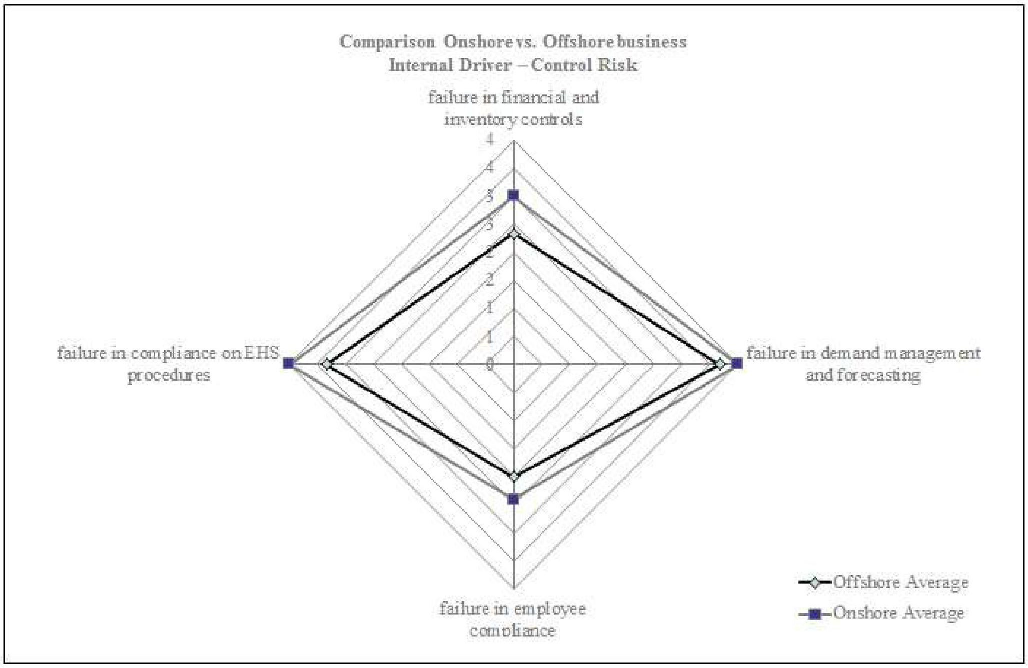



*Figure 5.2.2-10: Comparison Onshore vs. Offshore business Control Risk*

Besides the observation that the risk threatening the supply is rated higher for the onshore business the general trend considering control risk is equal for the on- as for the offshore wind business.

<u>Service vs. New product manufacturing business</u>

Another relevant comparison is the difference between service- and new product business. Linked to their fundamentally different business approaches the following conclusions are to be drawn from the assessed supply chain risks.

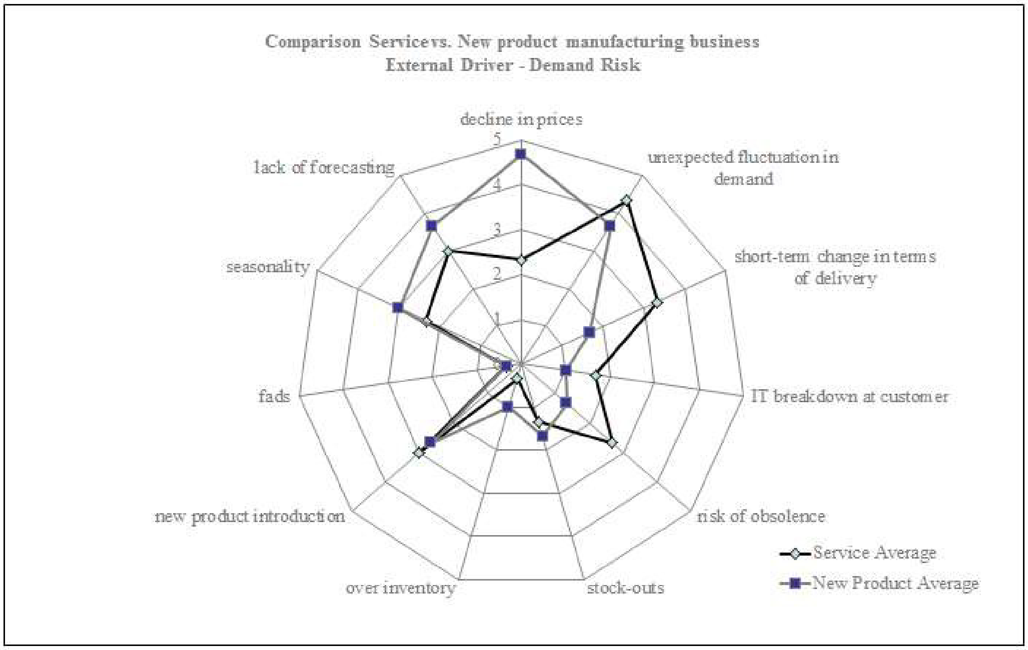



*Figure 5.2.2-11: Comparison Service vs. New product business Demand Risk*

It is to be observed that the general tendency shows that the service business is less exposed to price development while being confronted with a higher risk of creating obsolete stock and the difficulty in projecting future demand. When considering the general nature of the service business it is however surprising to see the results regarding the risk linked to the lack of forecasting is perceived higher in the new unit business than in the service business.

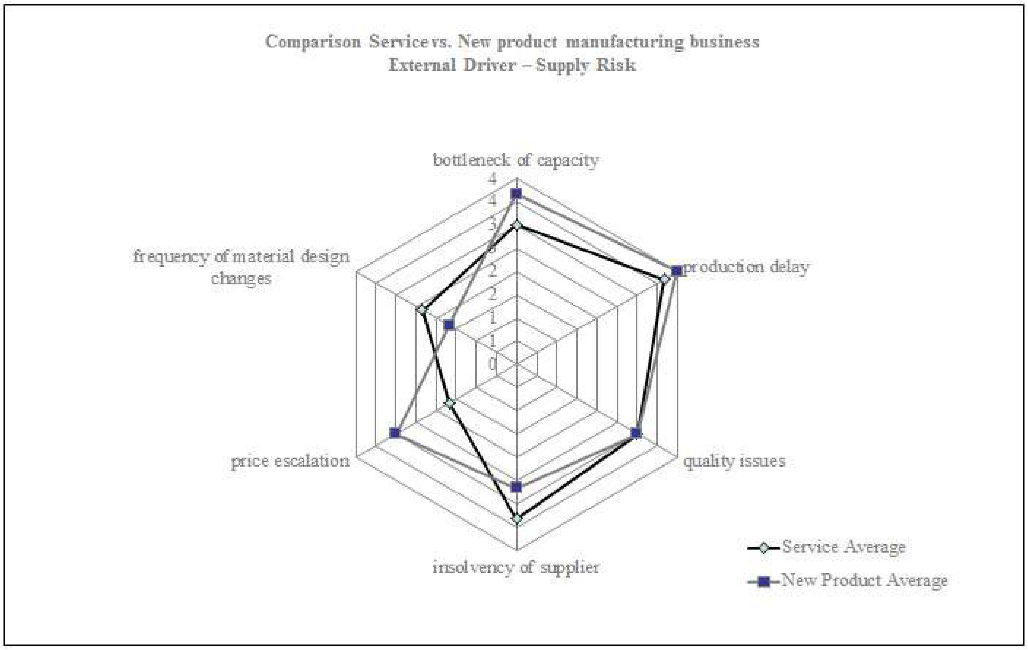



*Figure 5.2.2-12: Comparison Service vs. New product business Supply Risk*

The significant difference considering the risk rating between service and new product business in the area of price escalation in the area of price escalation might be due to the fact that service organisation often purchases spare parts from the respective new product manufacturing units at a fixed price, but this could not be established with sufficient certainty during the interviews.

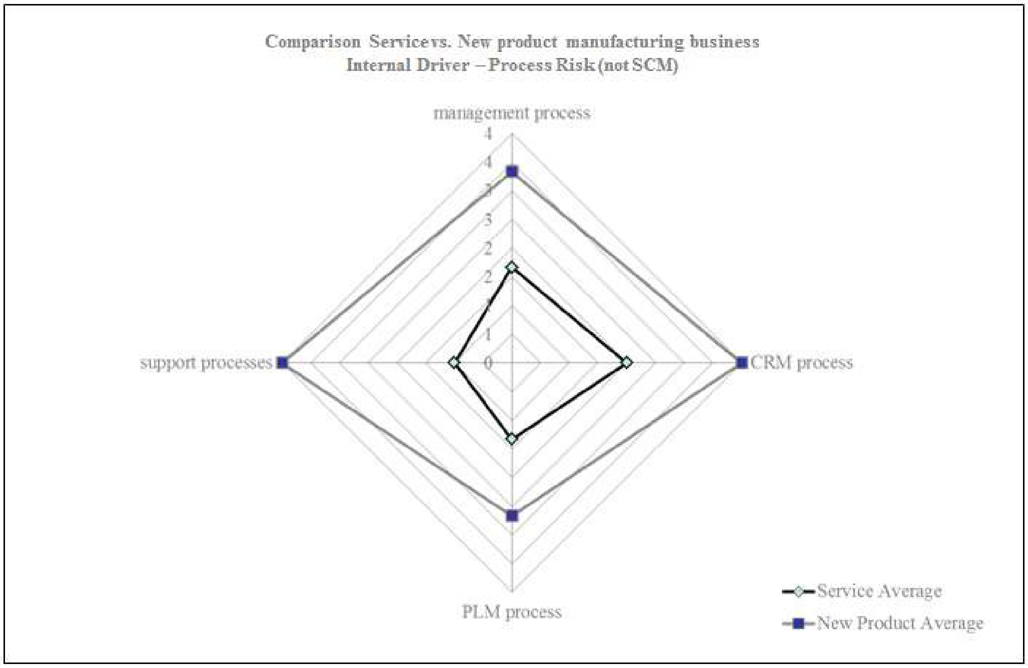



*Figure 5.2.2-13: Comparison Service vs. New product business Process Risk (not SCM)*

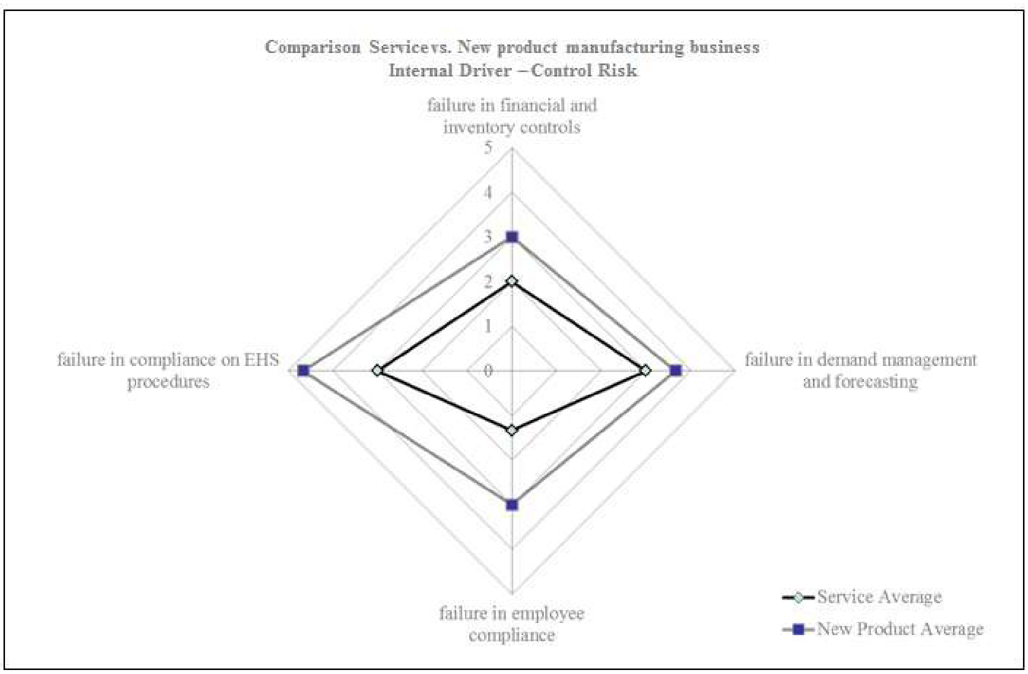



*Figure 5.2.2-14: Comparison Service vs. New product business Control Risk*

Another significant difference in perception of supply chain risk between the service organisation and the OEMs part is the process risk. One explanatory hypothesis is that the perception of risk, respectively its threat is lower in the service business due to the general higher level of achieved profit margins.

Summarizing the main finding form the empirical assessment the following conclusions are to be drawn:

- Project management business is to be seen as a **make-to-order business**
- The main risks threatening a project management organisation's supply chain are **decline in price**, **new product introduction** and **demand fluctuation** from an internal perspective. **Production delays** are of a major concern on the supplier side. Concerning the governmental and policy environment **currency changes, macro-economic trends** and **government taxation** are considered to be the highest risks, with the last one being under special consideration when accounting for subsidy effects for renewable energy sources. Regarding the internal processes the **overall management process including strategic target setting** and the **customer relationship process** are judged to be most critical ones when not conducted properly. Regarding internal control mechanisms **EHS** and **demand management and forecasting** have been selected as the most curial ones
- Supply chain risk management is a vital part of every function participating in the interview; however, the process is **almost entirely relying on the experience** of individuals within the organisation
- **Planning, buffering** and **pooling** are the **most mature approaches** in supply chain risk management. **Emergency and crisis planning are not employed in same magnitude** rooted in the ratio of probability occurrence and effort for implementation
- **Supply chain risk management is not subject of a particular training** and / or part of the on-boarding process for new resources in key functions

- **Business modelling and simulation are far from being a standard tool** that is used in the supply chain risk managing process of project management organisations
- Besides the dimensions of personal mastery, building shared vision and team learning, **system thinking and mental models** are the two dimensions from the learning organisation framework that **are not fully embedded in the organisations policies** and are simultaneously the ones that are to be assessed and improved by applying business modelling and simulation

## 5.3. Exemplary wind turbine manufacturer SCM model

The conducted empirical assessment identified demand fluctuations as one of the main risk threatening the supply chain of a project management organisation, based on this result the following chapter will describe an exemplary model illustrating the how the identified risk are turned into a simulation model which then potentially is to be used supporting the ability to increase the organisation's awareness and learning capabilities relating those risk addressing the part of the applied research question how an organisation can ensure that the individuals managing the supply chain risk process are aware of the cause-and-effect loops within a complex system.

### 5.3.1. Elements of a Wind Turbine manufacturer SCM business modelling and simulation project

<u>Definition of application</u>

The described exemplary model simulates the assembly process of a generator with the target of assessing the impact on cost linked to either long-term employed or temporarily employed workers in a volatile demand situation. Objective of the model is to understand the correlation and impact of different staffing patterns, as well as the flexibility of employment, in context to three volume scenarios, namely a normal, high and low volume scenario. The single KPI that is used to judge the performance of the production system are cost, collected with the following attributes. **Productive cost** describing the cost occurring during an active production step. **Non-productive cost** describing the cost associated with resources being idle and not performing active,

value-adding work. **Cost for own employees** collecting all cost, productive and non-productive associated with blue collar employees employed by the respective organisation and **cost for temporary employees** collecting all cost, productive and non-productive associated with blue collar employees employed by a third party.
The simulation offers the user to assess multiple scenarios for each of the mentioned demand volumes consisting of an initial staffing plan for each defined work station as well as the option to in- or decrease the amount of both, own or temporary employees in dependency of individual notice periods and severance payments.

Model design

The system which is subject to the simulation is the assembly process of a wind turbine generator as part the nacelle, one of the major components of a wind turbine. As many industrial assembly-processes the real-world application includes a high level of complexity driven by various factors like the number of individual parts that are assembled, number of different warehouses, assembly, testing and repair activities.
The overall process prior to abstraction and idealisation is shown in the illustration 5.3.1-1.

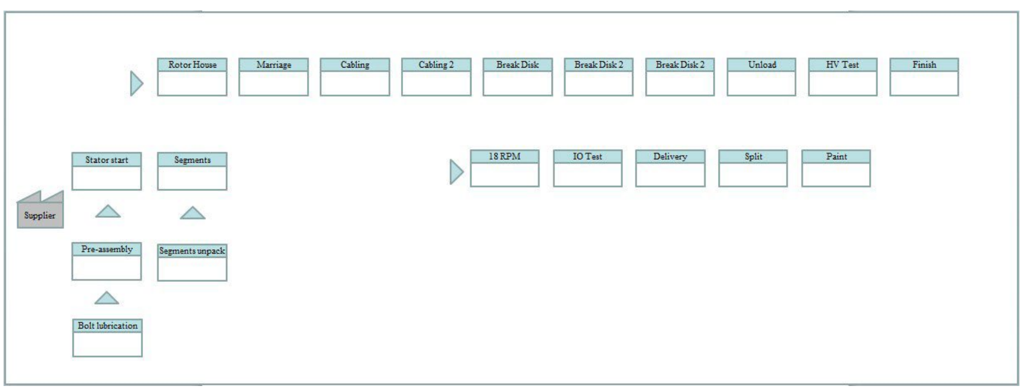



*Figure 5.3.1-1: Generator assembly process*

Regarding the choice of simulation paradigms, the model follows a strict discrete event-based approach. The simulation time is defined as weeks and stops after the last generator of the last project has successfully been assembled.
The logic by which the generator production is simulated is based on a per project basis meaning that a defined number of generators are part of one project.

Table 5.3.1-1 shows the defined number of generators per project and time of launch for each of the volume scenarios.

Wind Turbine Manufacturer - Dynamic Staffing Model

| Project Number | Week of launch | Normal Volume | Low Volume | High Volume |
|---|---|---|---|---|
| 1 | 3 | 17 | 12 | 22 |
| 2 | 4 | 7 | 5 | 9 |
| 3 | 7 | 10 | 7 | 13 |
| 4 | 8 | 1 | 1 | 1 |
| 5 | 13 | 12 | 8 | 16 |
| 6 | 18 | 4 | 3 | 5 |
| 7 | 25 | 6 | 4 | 8 |
| 8 | 26 | 1 | 1 | 1 |
| 9 | 29 | 8 | 6 | 10 |
| 10 | 30 | 13 | 9 | 17 |
| 11 | 34 | 12 | 8 | 16 |
| 12 | 36 | 3 | 2 | 4 |
| 13 | 37 | 12 | 8 | 16 |
| 14 | 40 | 6 | 4 | 8 |
| 15 | 45 | 6 | 4 | 8 |
| 16 | 47 | 9 | 6 | 12 |
| 17 | 48 | 8 | 6 | 10 |
| 18 | 49 | 20 | 14 | 26 |
| 19 | 51 | 5 | 4 | 7 |
| 20 | 52 | 8 | 6 | 10 |
| | | **168** | **118** | **218** |

*Table 5.3.1-1: Overview volume scenarios for dynamic staffing model*

Graphically the model has been divided into the following sections.

- **Overview:** covering a display of all variables, parameters, events and statistical data collection that are used in the model

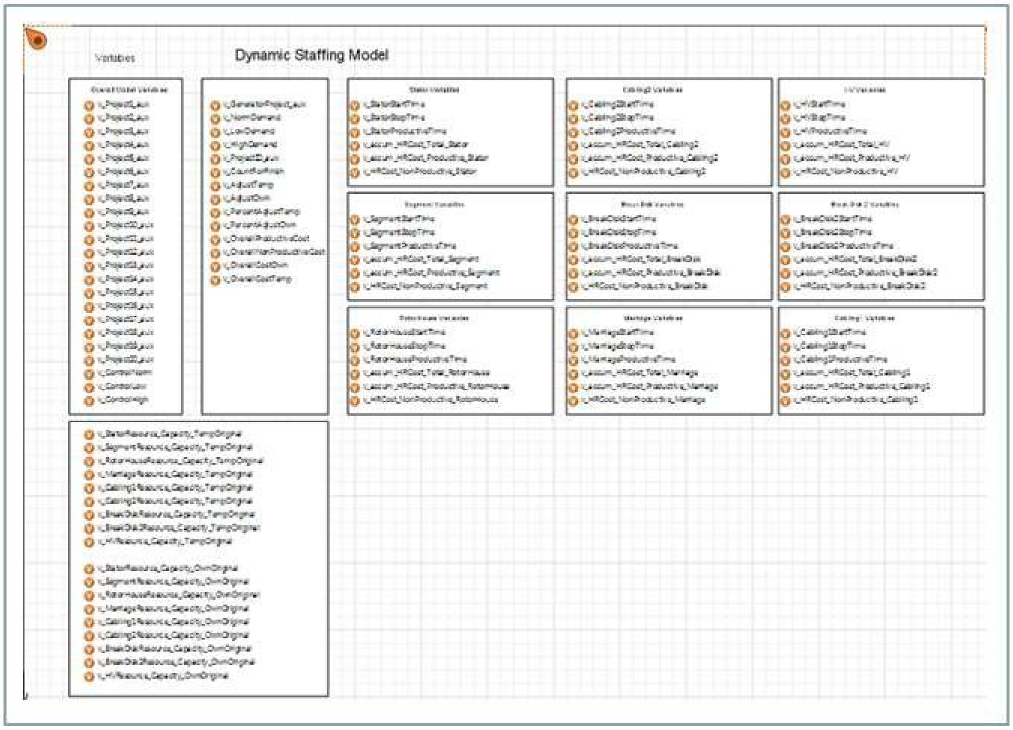



*Figure 5.3.1-2: Overview variables in dynamic staffing model*

Illustration 5.3-2 shows the applied variables in the model divided into the ones affecting the entire model on the left side and the ones affecting each of the simulated production steps on the right side grouped into nine boxes.
The illustration below shows the in a similar approach the applied parameters, schedules and events grouped into a comprehensive utilisation in the model and a specific one for each of the nine production steps.

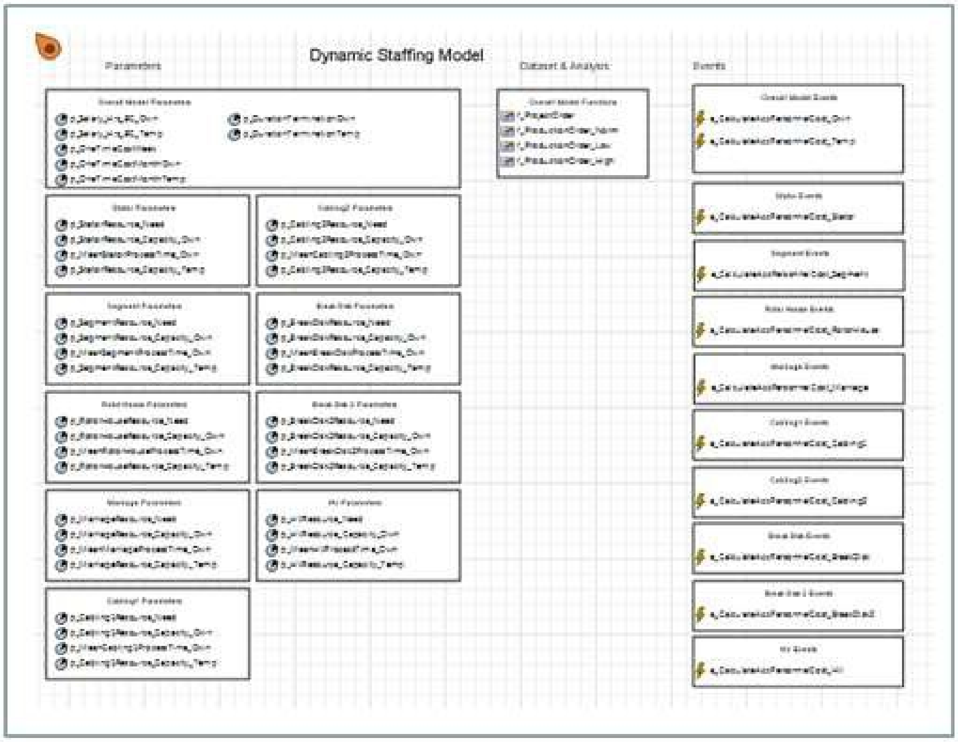



*Figure 5.3.1-3: Overview parameter and events in dynamic staffing model*

- **Process flow:** The process flow of the model is divided into two sections. The section called “Model Project Ordering and Control” and the section named “Model Production Ordering”.

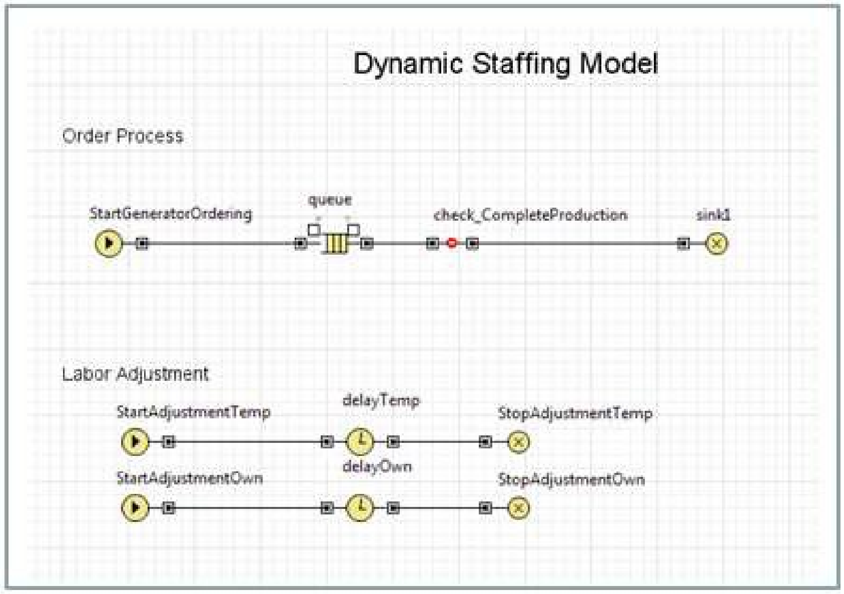



*Figure 5.3.1-4: Control mechanism for project order process and labour adjustment*

The section "Model Project Ordering and Control" fulfils the purpose of steering launch of each individual project according to a defined time schedule. Project entering the model are marked with an individual identity.

```
v_ProjectID_aux++;
entity.v_ProjectID=v_ProjectID_aux;
```

The following queue and hold module "check_CompleteProduction" servers the purpose of blocking entities from moving towards the sink prior to all generators that are part of the respective project have been produced. The opening of the block module is steered by a variable applied in the generator production process. The final sink module collects statistics about the finalised project and sets the variable opening the block to a value closing the module again. This has to be done for each project individually as each of them consists of a different number of generators. As an example, the below condition for the first project.

```
//Project 1
if(entity.v_ProjectID==1)
       v_Project1_aux=0;
check_CompleteProduction.setBlocked(true);
```

The process flow for the assembly process of the generator is shown in figure 5.3.1-5 illustrating the start of the production in dependence of the chosen volume scenario and the first part of the production cycle, the stator assembly, representative for the remaining process steps.

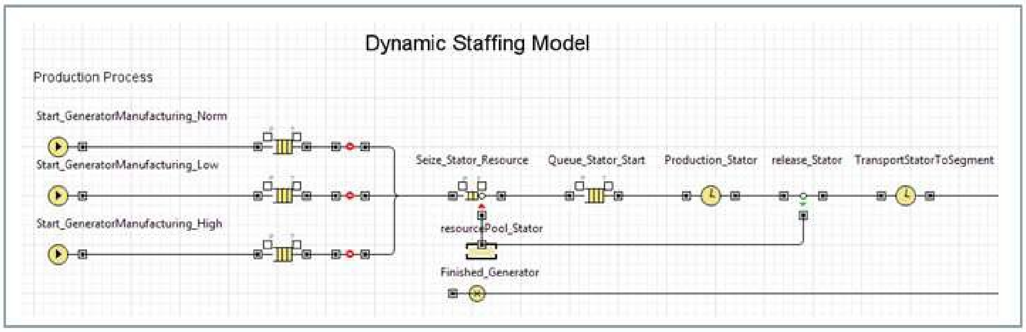



*Figure 5.3.1-5: Control mechanism for production process*

The initial logic consisting of a start-, a queue, and a hold module is controlling the inflow to the model depending on the user's choice which volume scenario is to be applied. It prevents the generator orders from the non-selected scenarios to flow into the model. The actual assembly process starts with the stator assembly.

The building block Seize_Stator_Resource is requesting the, by the parameter `p_StatorResource_Need` defined, number of resources for the first production process. The adjoining resource pool is called resourcePool_Stator. An additional task that the first process step is fulfilling is to register each generator in accordance with the project number, below the example for the first project.

```
//Project 1
if(v_ProjectID_aux==1){
	v_GeneratorProject_aux=1;
	entity.v_GeneratorProjectID=v_GeneratorProject_aux;
	}
```

The applied logic for the resource need and capacity is that for each type, own employees and external temporary labour, the model allows to enter an individual combination of the two defined by separate parameters (p_StatorResource_Capacity_Own and p_StatorResource_Capacity_Temp). The following queue block has the only function to store generator entities in case the assembly process for a generator has not been finished prior to the arrival of a new one. The actual production is simulated in the block Production_Stator whereas the required production time is determined by the statistical function around a defined mean value. In dependency of the amount of applied third party employees the required time is extended by 5% per resource up to 15% in order to account for a lower productivity level of external blue collars in comparison to the internal workforce.

```
p_StatorResource_Capacity_Temp==1?p_MeanStatorProcessTime_Own*1.05:
p_StatorResource_Capacity_Temp==2?p_MeanStatorProcessTime_Own*1.10:
p_StatorResource_Capacity_Temp==3?p_MeanStatorProcessTime_Own*1.15:
p_MeanStatorProcessTime_Own
```

An additional calculation that is performed in each production step is the calculation of productive and non-productive time, by recording the actual production time using a start and a stop time (v_StatorStartTime=time() and v_StatorStopTime=time()). The cost calculation follows the logic bleow using pre-assigned variables.

```
v_StatorStopTime=time();
v_StatorProductiveTime=v_StatorStopTime-v_StatorStartTime;
v_accum_HRCost_Productive_Stator=v_accum_HRCost_Productive_Stator+(
v_StatorProductiveTime*((p_Salary_Hrs_BC_Own*8*5*p_StatorResource_C
apacity_Own)+(p_Salary_Hrs_BC_Temp*8*5*p_StatorResource_Capacity_Te
mp)));
v_HRCost_NonProductive_Stator=v_accum_HRCost_Total_Stator-
v_accum_HRCost_Productive_Stator;
```

The release_Stator block finally releases the resources working on the assembly step before the next queue block simulates the inbound transport to the next workstation.

After the final assembly station, the entity reaches the sink module called Finished_Generator. This building blocks conducts a final count of the generator per project and once the last generator entity passed the hold module blocking the project entity from the "Model Project Ordering and Control" logic is released. The code of the first project is:

```
//NORMAL DEMAND
//Project 1
if(v_NormDemand==true)
```

```
if(entity.v_GeneratorProjectID==1)
      v_Project1_aux++;
if(v_Project1_aux==17)
      check_CompleteProduction.setBlocked(false);
```

The final code closed the simulation once the overall number of generators has been produced.

```
//Finish Simulation with normal demand
if(v_NormDemand==true)
      v_ControlNorm++;
 if(v_ControlNorm==168)
      getEngine().finish();
```

- **Adjustable parameters:** The model offers the user various scenarios to be created by adjusting parameters.

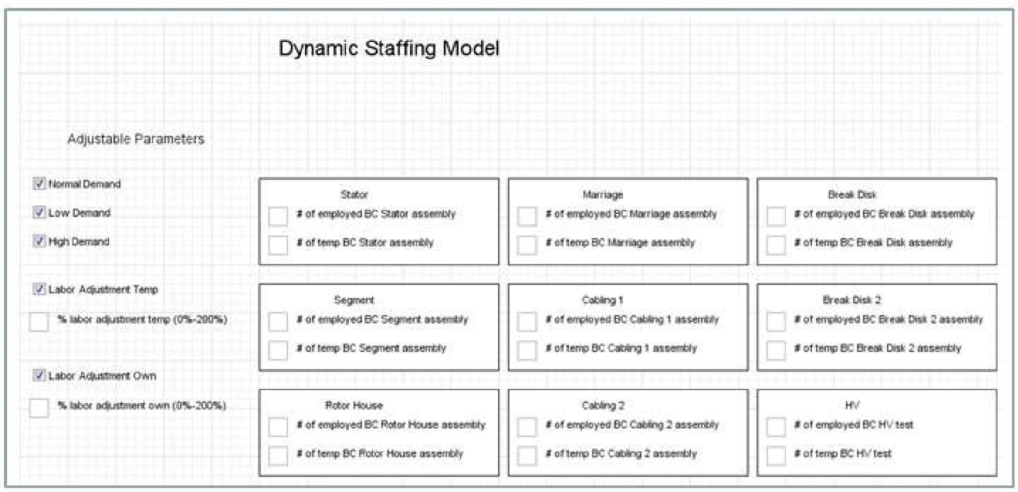



*Figure 5.3.1-6: Overview of adjustable parameter in dynamic staffing model*

The initial choice is to select the volume scenario, in order to determine the behaviour of the production system the described three scenarios of normal, low and how volume have been developed. Furthermore, the user can choose the staffing assigned to each assembly station and distinguish between blue collar resources employed by the organisation or hired as 3rd party temporary workers. The last selection is concerning the how the level of head count is kept throughout the simulation. In accordance with the real-world system a reduction of staff is possible after a notice period of three month for external employees and six months for internal resources. The associated one-time costs are calculated in relation to the hourly rates.

- **Analysis:** Following the initial remarks when describing the purpose of the model the single purpose is to assess the accumulated cost in dependence of produced volume and its split to productive and non-produce shares.


*Figure 5.3.1-7: Overview of analysis window in dynamic staffing model*

The implemented statistics collect the resulting cost split into productive and non-productive cost as well as labour cost (accounting for cost linked to own employed workers) and temp cost (accounting for cost linked to third party employees).
Additionally, the model collects one-time cost related to the layoff of employees.

<u>Simulation runs</u>

With entering the phase of running the simulation the user is now able to observe in a statistically significant manner how the results are influenced by the various scenarios selected in combination with the factor of probability.

In regards to the tested scenarios the different simulation runs are to combine the following settings:

- All employees employed by own organisation to be assessed for normal-, low- and high-volume scenario
- 50% / 50% mix of employees employed by own organisation and third-party employment to be assessed for normal-, low- and high-volume scenario
- All employees employed by own organisation to be assessed for normal-, low- and high-volume scenario including head count adjustment for low-volume scenario
- 50% / 50% mix of employees employed by own organisation and third-party employment to be assessed for normal- and low-volume scenario including head count adjustment for low-volume scenario

In order to ensure a statistical significance among the results each defined scenario is conducted 20 times (*n=20*) each. In addition to the KPIs assessing the overall cost development in the various scenarios the tables below offer an assessment of the coefficient of variation (CV) measuring the dispersion of the values as a result of stochastic influence. For each of the assessed cases the CV is below 1 meaning the standard deviation of each data set is smaller than its mean.

- Baseline (normal volume) - 100% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 73,73 | 7.823.870,11 | 5.316.129,89 | 13.140.000,00 | 0,00 | 0,00 | 0,00 | **26.280.000,00** |
| 2 | 71,57 | 7.887.452,64 | 4.892.547,36 | 12.780.000,00 | 0,00 | 0,00 | 0,00 | **25.560.000,00** |
| 3 | 70,52 | 7.633.322,46 | 4.966.677,54 | 12.600.000,00 | 0,00 | 0,00 | 0,00 | **25.200.000,00** |
| 4 | 71,42 | 8.086.156,86 | 4.693.843,14 | 12.780.000,00 | 0,00 | 0,00 | 0,00 | **25.560.000,00** |
| 5 | 74,3 | 7.961.105,98 | 5.358.894,03 | 13.320.000,00 | 0,00 | 0,00 | 0,00 | **26.640.000,00** |
| 6 | 74,32 | 7.884.955,64 | 5.435.044,36 | 13.320.000,00 | 0,00 | 0,00 | 0,00 | **26.640.000,00** |
| 7 | 69,21 | 7.652.362,49 | 4.767.637,51 | 12.420.000,00 | 0,00 | 0,00 | 0,00 | **24.840.000,00** |
| 8 | 69,94 | 7.623.975,47 | 4.796.024,54 | 12.420.000,00 | 0,00 | 0,00 | 0,00 | **24.840.000,00** |
| 9 | 72,81 | 8.130.755,41 | 4.829.244,59 | 12.960.000,00 | 0,00 | 0,00 | 0,00 | **25.920.000,00** |
| 10 | 73,6 | 8.075.467,24 | 5.064.532,76 | 13.140.000,00 | 0,00 | 0,00 | 0,00 | **26.280.000,00** |
| 11 | 72,82 | 7.656.024,75 | 5.303.975,25 | 12.960.000,00 | 0,00 | 0,00 | 0,00 | **25.920.000,00** |
| 12 | 71,88 | 7.899.347,81 | 4.880.652,19 | 12.780.000,00 | 0,00 | 0,00 | 0,00 | **25.560.000,00** |
| 13 | 71,44 | 7.725.312,76 | 5.054.687,24 | 12.780.000,00 | 0,00 | 0,00 | 0,00 | **25.560.000,00** |
| 14 | 70,53 | 7.900.059,60 | 4.699.940,40 | 12.600.000,00 | 0,00 | 0,00 | 0,00 | **25.200.000,00** |
| 15 | 74,06 | 7.898.572,66 | 5.241.427,34 | 13.140.000,00 | 0,00 | 0,00 | 0,00 | **26.280.000,00** |
| 16 | 74,49 | 7.647.462,31 | 5.672.537,69 | 13.320.000,00 | 0,00 | 0,00 | 0,00 | **26.640.000,00** |
| 17 | 71,61 | 7.381.303,66 | 5.398.696,34 | 12.780.000,00 | 0,00 | 0,00 | 0,00 | **25.560.000,00** |
| 18 | 70,61 | 7.849.022,33 | 5.290.977,67 | 13.140.000,00 | 0,00 | 0,00 | 0,00 | **26.280.000,00** |
| 19 | 72,29 | 7.797.456,63 | 5.162.543,37 | 12.960.000,00 | 0,00 | 0,00 | 0,00 | **25.920.000,00** |
| 20 | 73,98 | 7.987.035,52 | 5.152.964,48 | 13.140.000,00 | 0,00 | 0,00 | 0,00 | **26.280.000,00** |
| **Stdv.** | **1,62** | **187.566,27** | **277.318,77** | **283.704,81** | | | | **567.409,63** |
| **CV** | **0,022** | **0,024** | **0,054** | **0,022** | | | | **0,02** |
| **Median** | **72,085** | **7.866.988,99** | **5.108.748,62** | **12.960.000,00** | | | | **25.920.000,00** |
| **Avrg.** | **72,26** | **7.825.051,12** | **5.098.948,88** | **12.924.000,00** | | | | **25.848.000,00** |

*Table 5.3.1-2: Baseline (normal volume) - 100% own employment with no adjustment of head count*

The production schedule used as a baseline results in an average overall cost of 25.848 kEUR and 72,26 weeks concluding the assembly of 168 generators.

- Baseline (high volume) - 100% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 83,56 | 10.121.430,55 | 4.818.569,45 | 14.940.000,00 | 0,00 | 0,00 | 0,00 | **29.880.000,00** |
| 2 | 79,08 | 9.693.629,79 | 4.346.370,21 | 14.040.000,00 | 0,00 | 0,00 | 0,00 | **28.080.000,00** |
| 3 | 86,41 | 10.118.431,05 | 5.361.568,95 | 15.480.000,00 | 0,00 | 0,00 | 0,00 | **30.960.000,00** |
| 4 | 86,38 | 10.198.254,20 | 5.281.745,80 | 15.480.000,00 | 0,00 | 0,00 | 0,00 | **30.960.000,00** |
| 5 | 83,17 | 10.201.495,28 | 4.558.504,72 | 14.760.000,00 | 0,00 | 0,00 | 0,00 | **29.520.000,00** |
| 6 | 82,64 | 9.971.754,52 | 4.788.245,48 | 14.760.000,00 | 0,00 | 0,00 | 0,00 | **29.520.000,00** |
| 7 | 86,34 | 10.094.901,65 | 5.385.098,35 | 15.480.000,00 | 0,00 | 0,00 | 0,00 | **30.960.000,00** |
| 8 | 85,87 | 9.846.812,16 | 5.453.187,84 | 15.300.000,00 | 0,00 | 0,00 | 0,00 | **30.600.000,00** |
| 9 | 79,59 | 9.819.344,83 | 4.400.655,17 | 14.220.000,00 | 0,00 | 0,00 | 0,00 | **28.440.000,00** |
| 10 | 89,92 | 10.665.008,21 | 5.354.991,79 | 16.020.000,00 | 0,00 | 0,00 | 0,00 | **32.040.000,00** |
| 11 | 85,77 | 10.345.278,91 | 4.954.721,09 | 15.300.000,00 | 0,00 | 0,00 | 0,00 | **30.600.000,00** |
| 12 | 89,21 | 10.420.694,20 | 5.599.305,80 | 16.020.000,00 | 0,00 | 0,00 | 0,00 | **32.040.000,00** |
| 13 | 82,7 | 9.994.617,46 | 4.765.382,54 | 14.760.000,00 | 0,00 | 0,00 | 0,00 | **29.520.000,00** |
| 14 | 89,38 | 10.324.529,31 | 5.695.470,69 | 16.020.000,00 | 0,00 | 0,00 | 0,00 | **32.040.000,00** |
| 15 | 88,02 | 10.256.232,92 | 5.403.767,08 | 15.660.000,00 | 0,00 | 0,00 | 0,00 | **31.320.000,00** |
| 16 | 82,38 | 9.779.388,35 | 4.980.611,66 | 14.760.000,00 | 0,00 | 0,00 | 0,00 | **29.520.000,00** |
| 17 | 83,87 | 9.947.917,10 | 4.992.082,90 | 14.940.000,00 | 0,00 | 0,00 | 0,00 | **29.880.000,00** |
| 18 | 91,34 | 10.493.932,43 | 5.886.067,57 | 16.380.000,00 | 0,00 | 0,00 | 0,00 | **32.760.000,00** |
| 19 | 85,78 | 10.124.837,15 | 5.175.162,85 | 15.300.000,00 | 0,00 | 0,00 | 0,00 | **30.600.000,00** |
| 20 | 87,08 | 9.923.660,32 | 5.556.339,68 | 15.480.000,00 | 0,00 | 0,00 | 0,00 | **30.960.000,00** |
| **Stdv.** | **3,22** | **247.018,89** | **421.744,41** | **596.653,17** | | | | 1.224.306,46 |
| **CV** | **0,039** | **0,025** | **0,084** | **0,040** | | | | 0,04 |
| **Median** | **85,825** | **10.119.930,80** | **5.228.454,32** | **15.300.000,00** | | | | 30.600.000,00 |
| **Avrg.** | **85,42** | **10.117.107,52** | **5.137.892,48** | **15.255.000,00** | | | | 30.510.000,00 |

*Table 5.3.1-3: Baseline (high volume) - 100% own employment with no adjustment of head count*

The production schedule in scenario shown in table 5.3.1-3 results in an average overall cost of 30.510 kEUR and 85,42 weeks concluding the assembly of 218 generators.

- Baseline (low volume) - 100% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 62,21 | 5.214.649,42 | 5.945.350,58 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 2 | 62,27 | 5.490.454,18 | 5.669.545,82 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 3 | 61,91 | 5.464.349,22 | 5.515.650,78 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 4 | 62,59 | 5.559.887,56 | 5.600.112,44 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 5 | 62,08 | 5.535.366,79 | 5.444.633,79 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,58** |
| 6 | 62,02 | 5.415.154,62 | 5.564.845,38 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 7 | 62,2 | 5.466.266,36 | 5.693.733,65 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 8 | 62,13 | 5.452.092,24 | 5.527.907,76 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 9 | 61,75 | 5.481.311,86 | 5.498.688,14 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 10 | 62,19 | 5.417.722,16 | 5.562.277,84 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 11 | 62,25 | 5.761.155,26 | 5.398.844,74 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 12 | 62,48 | 5.386.576,91 | 5.773.423,09 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 13 | 62 | 5.524.465,72 | 5.455.534,28 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 14 | 62,46 | 5.655.996,80 | 5.504.003,20 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 15 | 62,46 | 5.374.240,29 | 5.785.759,71 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 16 | 62,7 | 5.684.406,85 | 5.475.593,15 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 17 | 62,25 | 5.437.150,95 | 5.722.849,05 | 11.160.000,00 | 0,00 | 0,00 | 0,00 | **22.320.000,00** |
| 18 | 61,62 | 5.473.780,23 | 5.506.219,77 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 19 | 61,84 | 5.433.293,56 | 5.546.706,44 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| 20 | 62,09 | 5.512.933,24 | 5.467.066,76 | 10.980.000,00 | 0,00 | 0,00 | 0,00 | **21.960.000,00** |
| **Stdv.** | **0,27** | **115.564,70** | **136.280,43** | **90.000,00** | | | | 184.676,07 |
| **CV** | **0,004** | **0,022** | **0,025** | **0,008** | | | | 0,01 |
| **Median** | **62,195** | **5.470.023,29** | **5.537.307,10** | **11.070.000,00** | | | | 22.140.000,29 |
| **Avrg.** | **62,18** | **5.487.062,71** | **5.582.937,32** | **11.070.000,00** | | | | 22.140.000,03 |

*Table 5.3.1-4: Baseline (low volume) - 100% own employment with no adjustment of head count*

The production schedule in scenario shown in table 5.3.1-4 results in an average overall cost of 22.140 kEUR and 62,18 weeks concluding the assembly of 118 generators.

- Scenario (normal volume) - 50% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 72,55 | 7.064.795,96 | 3.821.604,04 | 6.480.000,00 | 4.406.400,00 | 0,00 | 0,00 | **21.772.800,00** |
| 2 | 76,44 | 7.055.877,52 | 4.435.322,48 | 6.840.000,00 | 4.651.200,00 | 0,00 | 0,00 | **22.982.400,00** |
| 3 | 74,96 | 7.265.179,63 | 3.923.620,38 | 6.660.000,00 | 4.528.800,00 | 0,00 | 0,00 | **22.377.600,00** |
| 4 | 77,85 | 7.701.360,15 | 3.941.039,85 | 6.930.000,00 | 4.712.400,00 | 0,00 | 0,00 | **23.284.800,00** |
| 5 | 73,4 | 7.010.622,20 | 4.026.977,80 | 6.570.000,00 | 4.467.600,00 | 0,00 | 0,00 | **22.075.200,00** |
| 6 | 77,32 | 7.494.210,33 | 4.148.189,67 | 6.930.000,00 | 4.712.400,00 | 0,00 | 0,00 | **23.284.800,00** |
| 7 | 75,77 | 7.181.800,27 | 4.158.199,73 | 6.750.000,00 | 4.590.000,00 | 0,00 | 0,00 | **22.680.000,00** |
| 8 | 74,5 | 7.091.283,21 | 4.097.516,79 | 6.660.000,00 | 4.528.800,00 | 0,00 | 0,00 | **22.377.600,00** |
| 9 | 74,92 | 7.211.066,76 | 3.977.733,24 | 6.660.000,00 | 4.528.800,00 | 0,00 | 0,00 | **22.377.600,00** |
| 10 | 73,66 | 7.047.078,81 | 3.990.521,19 | 6.570.000,00 | 4.467.600,00 | 0,00 | 0,00 | **22.075.200,00** |
| 11 | 72,54 | 6.898.749,14 | 3.987.650,86 | 6.480.000,00 | 4.406.400,00 | 0,00 | 0,00 | **21.772.800,00** |
| 12 | 77,17 | 7.400.069,91 | 4.091.130,09 | 6.840.000,00 | 4.651.200,00 | 0,00 | 0,00 | **22.982.400,00** |
| 13 | 78,34 | 7.316.320,07 | 4.477.279,93 | 7.020.000,00 | 4.773.600,00 | 0,00 | 0,00 | **23.587.200,00** |
| 14 | 77,26 | 7.250.830,96 | 4.391.569,04 | 6.930.000,00 | 4.712.400,00 | 0,00 | 0,00 | **23.284.800,00** |
| 15 | 76,92 | 7446103,256 | 4.045.096,74 | 6.840.000,00 | 4.651.200,00 | 0,00 | 0,00 | **22.982.400,00** |
| 16 | 76,26 | 7.073.217,36 | 4.417.982,68 | 6.840.000,00 | 4.651.200,00 | 0,00 | 0,00 | **22.982.400,05** |
| 17 | 78,39 | 7.606.609,57 | 4.168.990,44 | 7.020.000,00 | 4.773.600,00 | 0,00 | 0,00 | **23.569.200,00** |
| 18 | 75,38 | 7.412.898,22 | 3.927.101,78 | 6.750.000,00 | 4.590.000,00 | 0,00 | 0,00 | **22.680.000,00** |
| 19 | 75,39 | 6.903.810,39 | 4.436.189,61 | 6.750.000,00 | 4.590.000,00 | 0,00 | 0,00 | **22.680.000,00** |
| 20 | 78,07 | 7.100.150,99 | 4.542.249,01 | 6.930.000,00 | 4.712.400,00 | 0,00 | 0,00 | **23.284.800,00** |
| **Stdv.** | **1,81** | **220.281,67** | **214.610,11** | **163.183,18** | **110.964,56** | | | **561.151,49** |
| **CV** | **0,025** | **0,031** | **0,053** | **0,025** | **0,025** | | | **0,02** |
| **Median** | **76,015** | **7.196.433,52** | **4.094.323,44** | **6.795.000,00** | **4.620.600,00** | | | **22.831.200,00** |
| **Avrg.** | **75,85** | **7.226.601,73** | **4.150.298,27** | **6.772.500,00** | **4.605.300,00** | | | **22.754.700,00** |

*Table 5.3.1-5: Scenario (normal volume) - 50% own employment with no adjustment of head count*

The production schedule in scenario shown in table 5.3.1-5 results in an average overall cost of 22.140 kEUR and 62,18 weeks concluding the assembly of 118 generators.

- Scenario (high volume) - 50% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 98,36 | 9.322.884,00 | 5.494.716,00 | 8.820.000,00 | 5.997.600,00 | 0,00 | 0,00 | **29.635.200,00** |
| 2 | 99,28 | 9.664.771,86 | 5.304.028,14 | 8.910.000,00 | 6.058.800,00 | 0,00 | 0,00 | **29.937.600,00** |
| 3 | 91,27 | 9.159.458,04 | 4.599.741,96 | 8.190.000,00 | 5.596.200,00 | 0,00 | 0,00 | **27.545.400,00** |
| 4 | 89,75 | 9.305.512,98 | 4.151.287,02 | 8.010.000,00 | 5.446.800,00 | 0,00 | 0,00 | **26.913.600,00** |
| 5 | 90,47 | 9.100.356,75 | 4.507.643,25 | 8.100.000,00 | 5.508.000,00 | 0,00 | 0,00 | **27.216.000,00** |
| 6 | 87,91 | 9.350.490,68 | 3.803.909,33 | 7.830.000,00 | 5.324.400,00 | 0,00 | 0,00 | **26.308.800,00** |
| 7 | 91,08 | 9.452.274,47 | 4.155.725,53 | 8.100.000,00 | 5.508.000,00 | 0,00 | 0,00 | **27.216.000,00** |
| 8 | 89,23 | 9.116.601,77 | 4.340.198,23 | 8.010.000,00 | 5.446.800,00 | 0,00 | 0,00 | **26.913.600,00** |
| 9 | 96,27 | 9.376.489,91 | 5.138.710,09 | 8.640.000,00 | 5.875.200,00 | 0,00 | 0,00 | **29.030.400,00** |
| 10 | 90,18 | 9.426.702,01 | 4.030.097,99 | 8.010.000,00 | 5.446.800,00 | 0,00 | 0,00 | **26.913.600,00** |
| 11 | 95,87 | 9.372.234,37 | 4.991.756,63 | 8.550.000,00 | 5.814.000,00 | 0,00 | 0,00 | **28.727.991,00** |
| 12 | 93,75 | 9.211.167,45 | 4.850.432,55 | 8.370.000,00 | 5.691.600,00 | 0,00 | 0,00 | **28.123.200,00** |
| 13 | 95,43 | 9.272.196,64 | 5.091.803,36 | 8.550.000,00 | 5.814.000,00 | 0,00 | 0,00 | **28.728.000,00** |
| 14 | 93,91 | 10.096.694,83 | 3.964.905,17 | 8.370.000,00 | 5.691.600,00 | 0,00 | 0,00 | **28.123.200,00** |
| 15 | 96,25 | 9.589.344,25 | 4.925.855,75 | 8.640.000,00 | 5.875.200,00 | 0,00 | 0,00 | **29.030.400,00** |
| 16 | 93,88 | 9.294.739,35 | 4.766.860,65 | 8.370.000,00 | 5.691.600,00 | 0,00 | 0,00 | **28.123.200,00** |
| 17 | 90,6 | 9.416.641,67 | 4.191.358,33 | 8.100.000,00 | 5.508.000,00 | 0,00 | 0,00 | **27.216.000,00** |
| 18 | 92,31 | 9.892.405,40 | 4.017.994,60 | 8.280.000,00 | 5.630.400,00 | 0,00 | 0,00 | **27.820.800,00** |
| 19 | 93,13 | 9.512.538,66 | 4.397.861,34 | 8.280.000,00 | 5.630.400,00 | 0,00 | 0,00 | **27.820.800,00** |
| 20 | 89,36 | 9.238.900,35 | 4.217.899,65 | 8.010.000,00 | 5.446.800,00 | 0,00 | 0,00 | **26.913.600,00** |
| **Stdv.** | **3,14** | **243.345,27** | **482.276,04** | **291.772,17** | **197.950,47** | | | **1.005.284,67** |
| **CV** | **0,035** | **0,027** | **0,109** | **0,036** | **0,036** | | | **0,04** |
| **Median** | **92,72** | **9.361.362,52** | **4.452.752,29** | **8.280.000,00** | **5.630.400,00** | | | **27.820.800,00** |
| **Avrg.** | **92,91** | **9.408.620,27** | **4.547.139,28** | **8.307.000,00** | **5.650.110,00** | | | **27.912.869,55** |

*Table 5.3.1-6: Scenario (high volume) - 50% own employment with no adjustment of head count*

The production schedule in scenario shown in table 5.3.1-6 results in an average overall cost of 27.913 kEUR and 92,91 weeks concluding the assembly of 210 generators.

- Scenario (low volume) - 50% own employment with no adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 63,54 | 5.194.671,44 | 4.330.928,56 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 2 | 64,2 | 5.176.425,75 | 4500,374,253 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **14.853.225,75** |
| 3 | 64,56 | 5.454.407,96 | 4.222.392,04 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.599,99** |
| 4 | 64,14 | 5.016.434,83 | 4.509.165,17 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 5 | 64,31 | 5.007.354,33 | 4.669.445,67 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 6 | 64,29 | 5.174.820,90 | 4.501.979,11 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 7 | 65,01 | 5.261.621,37 | 4.415.178,63 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 8 | 63,97 | 5.084.800,64 | 4.440.799,36 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 9 | 63,02 | 4.931.849,33 | 4.442.550,67 | 5.580.000,00 | 3.794.400,00 | 0,00 | 0,00 | **18.748.800,00** |
| 10 | 63,52 | 5.156.971,82 | 4.368.628,18 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 11 | 64,41 | 5.250.862,24 | 4.425.937,77 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 12 | 63,05 | 4.926.146,55 | 4.448.253,45 | 5.580.000,00 | 3.794.400,00 | 0,00 | 0,00 | **18.748.800,00** |
| 13 | 63,49 | 5.135.384,40 | 4.390.215,60 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 14 | 62,95 | 4.892.595,30 | 4.481.804,70 | 5.580.000,00 | 3.794.400,00 | 0,00 | 0,00 | **18.748.800,00** |
| 15 | 64,25 | 5289562,127 | 4.387.237,87 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 16 | 64,46 | 5.161.635,67 | 4.515.164,33 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 17 | 64,5 | 5.141.321,62 | 4.535.478,38 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 18 | 63,39 | 5.096.403,05 | 4.429.196,95 | 5.670.000,00 | 3.855.600,00 | 0,00 | 0,00 | **19.051.200,00** |
| 19 | 64,78 | 5.172.154,73 | 4.504.645,27 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| 20 | 64,36 | 5.222.757,75 | 4.454.042,25 | 5.760.000,00 | 3.916.800,00 | 0,00 | 0,00 | **19.353.600,00** |
| **Stdv.** | **0,59** | **132.370,57** | **89.471,98** | **66.136,22** | **44.972,63** | | | **989.290,51** |
| **CV** | **0,010** | **0,026** | **0,021** | **0,012** | **0,012** | | | **0,05** |
| **Median** | **64,225** | **5.159.303,74** | **4.442.550,67** | **5.760.000,00** | **3.916.800,00** | | | **19.202.400,00** |
| **Avrg.** | **64,01** | **5.137.409,09** | **4.223.652,20** | **5.706.000,00** | **3.880.080,00** | | | **18.947.141,29** |

*Table 5.3.1-7: Scenario (low volume) - 50% own employment with no adjustment of head count*

The production schedule in scenario shown in table 5.3.1-7 results in an average overall cost of 18.947 kEUR and 64,01 weeks concluding the assembly of 118 generators.

- Scenario (normal volume) - 50% own employment with adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 76,98 | 4.324.823,09 | 2.792.376,91 | 4.455.000,00 | 2.662.200,00 | 480.000,00 | 108.800,00 | **14.823.200,00** |
| 2 | 74,62 | 4.261.450,33 | 2.704.549,67 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 3 | 74,83 | 4.370.083,57 | 2.595.916,43 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 4 | 72,06 | 4.326.234,96 | 2.412.965,05 | 4.230.000,00 | 2.509.200,00 | 480.000,00 | 108.800,00 | **14.067.200,00** |
| 5 | 73,23 | 4.384.120,92 | 2.506.279,08 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| 6 | 74,45 | 4.286.730,82 | 2.679.269,18 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 7 | 74,03 | 4.375.008,62 | 2.515.391,38 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| 8 | 76,63 | 4.419.093,76 | 2.698.106,24 | 4.455.000,00 | 2.662.200,00 | 480.000,00 | 108.800,00 | **14.823.200,00** |
| 9 | 73,85 | 4.350.227,91 | 2.540.172,09 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| 10 | 73,78 | 4.294.494,48 | 2.595.905,52 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| 11 | 76,09 | 4.326.863,16 | 2.714.736,84 | 4.410.000,00 | 2.631.600,00 | 480.000,00 | 108.800,00 | **14.672.000,00** |
| 12 | 73,61 | 4.238.488,67 | 2.651.911,33 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| 13 | 76,16 | 4.562.566,74 | 2.479.033,26 | 4.410.000,00 | 2.631.600,00 | 480.000,00 | 108.800,00 | **14.672.000,00** |
| 14 | 75,09 | 4.098.947,81 | 2.867.052,19 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 15 | 75,24 | 4342576,136 | 2.699.023,86 | 4.410.000,00 | 2.631.600,00 | 480.000,00 | 108.800,00 | **14.672.000,00** |
| 16 | 70,56 | 4.236.736,99 | 2.426.863,01 | 4.185.000,00 | 2.478.600,00 | 480.000,00 | 108.800,00 | **13.916.000,00** |
| 17 | 74,21 | 4.373.673,22 | 2.592.326,78 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 18 | 74,83 | 4.377.787,94 | 2.588.212,06 | 4.365.000,00 | 2.601.000,00 | 480.000,00 | 108.800,00 | **14.520.800,00** |
| 19 | 75,67 | 4.243.159,42 | 2.798.440,58 | 4.410.000,00 | 2.631.600,00 | 480.000,00 | 108.800,00 | **14.672.000,00** |
| 20 | 73,4 | 4.338.198,78 | 2.552.201,22 | 4.320.000,00 | 2.570.400,00 | 480.000,00 | 108.800,00 | **14.369.600,00** |
| **Stdv.** | **1,50** | **89.178,85** | **121.120,30** | **65.016,82** | **44.211,44** | **0,00** | **0,00** | 224.131,67 |
| **CV** | **0,021** | **0,021** | **0,047** | **0,015** | **0,017** | **0,000** | **0,000** | 0,02 |
| **Median** | **74,535** | **4.332.530,97** | **2.595.910,97** | **4.365.000,00** | **2.601.000,00** | **480.000,00** | **108.800,00** | 14.520.800,00 |
| **Avrg.** | **74,47** | **4.326.563,37** | **2.620.536,63** | **4.353.750,00** | **2.593.350,00** | **480.000,00** | **108.800,00** | 14.483.000,00 |

*Table 5.3.1-8: Scenario (normal volume) - 50% own employment with adjustment of head count*

The production schedule in scenario shown in table 5.3.1-8 results in an average overall cost of 14.483 kEUR and 64,01 weeks concluding the assembly of 168 generators.

- Scenario (low volume) - 50% own employment with adjustment of head count

| Simulation run | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employement (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| 1 | 63,21 | 3.209.472,68 | 2.924.927,33 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 2 | 62,59 | 3.002.173,49 | 3.056.626,51 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| 3 | 63,82 | 3.171.576,22 | 2.962.823,78 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 4 | 63,65 | 3.079.851,77 | 3.054.548,23 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 5 | 63,5 | 3.223.889,18 | 2.910.510,82 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 6 | 63,01 | 3.144.343,09 | 2.914.456,91 | 3.852.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.733.400,00** |
| 7 | 62,77 | 2.989.400,30 | 3.069.399,70 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| 8 | 63,52 | 3.106.504,21 | 3.027.895,79 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 9 | 62,88 | 3.053.169,75 | 3.005.630,25 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| 10 | 63,67 | 3.166.797,24 | 2.967.602,76 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 11 | 63,49 | 3.202.097,35 | 2.932.302,65 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 12 | 63,2 | 3.106.315,73 | 3.028.084,27 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 13 | 63,97 | 3.167.631,79 | 2.966.768,21 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 14 | 63,74 | 3.196.274,06 | 2.938.125,94 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 15 | 63,31 | 3.117.150,55 | 3.017.249,45 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 16 | 63,7 | 3.154.524,78 | 2.979.875,22 | 3.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **12.857.600,00** |
| 17 | 63,54 | 3.189.818,65 | 2.944.581,35 | 2.870.000,00 | 2.264.400,00 | 480.000,00 | 108.800,00 | **11.857.600,00** |
| 18 | 63,05 | 3.191.529,85 | 2.867.270,15 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| 19 | 62,95 | 3.122.064,47 | 2.936.735,53 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| 20 | 62,81 | 3.045.817,58 | 3.012.982,42 | 3.825.000,00 | 2.233.800,00 | 480.000,00 | 108.800,00 | **12.706.400,00** |
| **Stdv.** | **0,39** | **67.180,09** | **54.530,28** | **215.583,72** | **14.595,27** | **0,00** | **0,00** | 223.166,80 |
| **CV** | **0,006** | **0,022** | **0,019** | **0,058** | **0,007** | **0,000** | **0,000** | 0,02 |
| **Median** | **63,4** | **3.149.433,93** | **2.967.185,48** | **3.870.000,00** | **2.264.400,00** | **480.000,00** | **108.800,00** | 12.857.600,00 |
| **Avrg.** | **63,32** | **3.132.020,14** | **2.975.919,86** | **3.805.600,00** | **2.253.690,00** | **480.000,00** | **108.800,00** | 12.756.030,00 |

*Table 5.3.1-9: Scenario (low volume) - 50% own employment with adjustment of head count*

The production schedule in scenario shown in table 5.3.1-9 results in an average overall cost of 12.756 kEUR and 63,32 weeks concluding the assembly of 118 generators.

- Overview simulation results for dynamic staffing model

| | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employment (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| Baseline (normal volume) - 100% own employement with no adjustment of head count | 72,26 | 7.825.051,12 | 5.098.948,88 | 12.924.000,00 | 0,00 | 0,00 | 0,00 | 25.848.000,00 |
| Baseline (high volume) - 100% own employement with no adjustment of head count | 85,42 | 10.117.107,52 | 5.137.892,48 | 15.255.000,00 | 0,00 | 0,00 | 0,00 | 30.510.000,00 |
| Baseline (low volume) - 100% own employement with no adjustment of head count | 62,18 | 5.487.062,71 | 5.582.937,32 | 11.070.000,00 | 0,00 | 0,00 | 0,00 | 22.140.000,03 |
| Scenario (normal volume) - 50% own employement with no adjustment of head count | 75,85 | 7.226.601,73 | 4.150.298,27 | 6.772.500,00 | 4.605.300,00 | 0,00 | 0,00 | 22.754.700,00 |
| Scenario (high volume) - 50% own employement with no adjustment of head count | 92,91 | 9.408.620,27 | 4.547.139,28 | 8.307.000,00 | 5.650.110,00 | 0,00 | 0,00 | 27.912.869,55 |
| Scenario (low volume) - 50% own employement with no adjustment of head count | 64,01 | 5.137.409,09 | 4.223.652,20 | 5.706.000,00 | 3.880.080,00 | 0,00 | 0,00 | 18.947.141,29 |
| Scenario (normal volume) - 50% own employement with adjustment of head count | 74,47 | 4.326.563,37 | 2.620.536,63 | 4.353.750,00 | 2.593.350,00 | 480.000,00 | 108.800,00 | 14.483.000,00 |
| Scenario (low volume) - 50% own employement with adjustment of head count | 63,32 | 3.132.020,14 | 2.975.919,86 | 3.805.600,00 | 2.253.690,00 | 480.000,00 | 108.800,00 | 12.756.030,00 |

*Table 5.3.1-10: Overview simulation results for dynamic staffing model*

- Overview simulation results per generator for dynamic staffing model

In order to better assess the results of the simulation and in order to draw correct conclusions as part of the following improvement step it is essential to level the result to a common unit, in this example a single generator, allowing for a direct comparison among the scenarios.

| | Time for completion (weeks) | Variable cost productive (EUR) | Variable non-productive (EUR) | Variable cost own employment (EUR) | Variable temporary employment (EUR) | One-time cost own employment (EUR) | One-time cost temporary employment (EUR) | Sum |
|---|---|---|---|---|---|---|---|---|
| Baseline (normal volume) - 100% own employement with no adjustment of head count | 0,43 | 46.577,69 | 30.350,89 | 76.928,57 | 0,00 | 0,00 | 0,00 | 153.857,14 |
| Baseline (high volume) - 100% own employement with no adjustment of head count | 0,39 | 46.408,75 | 23.568,31 | 69.977,06 | 0,00 | 0,00 | 0,00 | 139.954,13 |
| Baseline (low volume) - 100% own employement with no adjustment of head count | 0,53 | 46.500,53 | 47.313,03 | 93.813,56 | 0,00 | 0,00 | 0,00 | 187.627,12 |
| Scenario (normal volume) - 50% own employement with no adjustment of head count | 0,45 | 43.015,49 | 24.704,16 | 40.312,50 | 27.412,50 | 0,00 | 0,00 | 135.444,64 |
| Scenario (high volume) - 50% own employement with no adjustment of head count | 0,43 | 43.158,81 | 20.858,44 | 38.105,50 | 25.917,94 | 0,00 | 0,00 | 128.040,69 |
| Scenario (low volume) - 50% own employement with no adjustment of head count | 0,54 | 43.537,37 | 35.793,66 | 48.355,93 | 32.882,03 | 0,00 | 0,00 | 160.568,99 |
| Scenario (normal volume) - 50% own employement with adjustment of head count | 0,44 | 25.753,35 | 15.598,43 | 25.915,18 | 15.436,61 | 2.857,14 | 647,62 | 86.208,33 |
| Scenario (low volume) - 50% own employement with adjustment of head count | 0,54 | 26.542,54 | 25.219,66 | 32.250,85 | 19.099,07 | 4.067,80 | 922,03 | 108.101,95 |

*Table 5.3.1-11: Overview simulation results per generator for dynamic staffing model*

<u>Improvements</u>

The element of improvement represents the core step in conducting supply chain risk management by applying business modelling and simulation. The simulation runs have revealed the current performance of the system considering facing the evaluated risk of demand fluctuation. The element of improvement provides now the opportunity to understand those results in the context of applied changes.

Based on the conducted experiments two different lines of questions could be assessed. The first being **how does the proportion between required time to execute the project pipeline develop in comparison to the development of the overall cost** and secondly, **how does the relation between productive and non-productive cost develop in case volume of generators drops and the management of the factory either decides not to change the headcount structure and number, or applies measures to do so.**

The initial observation is that the overall performance of the assembly line at the given normal volume increase when on-boarding temporary workers, whereas the average amount of weeks needed to execute the production increases by 5% the overall cost is reduced by 12%.

When introducing the option at a given volume the option to additionally adjust the headcount by 50% after a 3-month period for temporary workers and 6 months for own employees at a pre-defined severance payment the positive effect up to 44% in cost saving with a 3% average increase in time indicating that described system is not at an optimal base stage.

The structure of the model provides the opportunity assess both impacts for a scenario a volume drop and an increase. The following results focus on the scenarios with lowering the demand volume.

The initial observation in case of a volume drop in regards to the proportion among productive and non-productive cost the conclusions so longer be drawn assessing the total cost but the weighted average per scenario.

The conducted experiments show that when the staffing of the assembly process is not changed the share of the productive costs as part of the overall cost drops by 11 percentage points when facing a volume decline from normal to low-volume scenario. In comparison to the scenario of using a mixed staffing approach where the cost share of productive work is only decreasing by 7%. The effect however is turned around when the head count is set to release and the share of the productive work is decreasing by 13% in comparison to the baseline.

This effect is caused by the combination of generators assigned to the successive project and the mean working time of each group of blue collars, own employed and temporarily employed.

### 5.3.2. Processes of a Wind Turbine manufacturer SCM business modelling and simulation project

Abstraction and idealisation

Abstraction and idealisation both serve the purpose in keeping the model focused on its purpose without distracting the results due to over-simplification or changes in the structure of the real-world system.

In the case of the described example model the real-world system has been reduced to the minimum required to focus on the targeted cost assessment.

- **Abstraction:** The intentional exclusion of objects and their complexity covers the following main aspects:
    - Warehouse activities including the individual commissioning of direct and indirect material
    - Distinctive production and testing activities that are performed not a part of the core assembly process:
        - Bolt lubrication
        - 18 RPM test
        - IO Test
        - Delivery
        - Split of generator
        - Painting

- **Idealisation:** The intentional simplification of objects and their complexity covers the following main aspects:
    - The main simplification in the model is the product itself. The representation of the generator is limited to a single entity not considering the complexity or cost of the component itself.

- Sub-Sumption of certain aspects of the real-world system, namely the stator pre-assembly and the unpacking of the segments. Both processes that are set up individually from the subsequent process have been in included in the model sub-process “Production_Stator” and “Production_Segment”.
- Simplification of the working and shift model using a single shift model consisting of eight hours theoretical working time in comparison of the real-life applications consisting of a locally applied legal framework regulating working and break time.

Data ascertainment and collection

As the model follows an example of the assembly process of a direct drive generator the applied data is used as a proportional representation of the existing system serving the models purpose of comparing individually compiled scenarios. The relevant characteristics that are to be collected are the:

- Number of generators that are to be produced either in a representative time period or the average of subsequent periods, respectively to simulate the applied low- and high-volume scenarios.
- Collection of empirical data of the required productive working time per simulated production step. The collected data is to be used to establish a distribution.

Validation and verification

The process of validation and verification is to be considered as a continuous process that is to be performed throughout the construction of the model. The purpose of the model must always remain in the centre of this process. The various characteristics that are to be considered as part of the process could be distinguished in qualitative and quantitative ones.

- Qualitative characteristics
  - Completeness
  - Applicability
  - Clarity

        - Feasibility
    - Quantitative characteristics
        - Consistency
        - Accuracy
        - Plausibility
        - Accessibility

Whereas the validation and verification of qualitative characteristics is to be performed in series of interviews and discussions with experts working in the real-world system, this process is to be performed for the quantitative characteristics by switching from a stochastic to a deterministic model. As the production process in the model follows the same logic per simulated assembly step the validation and verification is performed using the stator assembly process.

The initial check is regarding the launch of the first project (project #1) and the production order of 17 generators on Monday morning of the simulation's third week. The simulation starts on Sunday, October 1$^{st}$ 2017, with the first launch of both, project and production order on Monday, October 16$^{th}$ 2017 at 7.59am, respectively 8.02am.

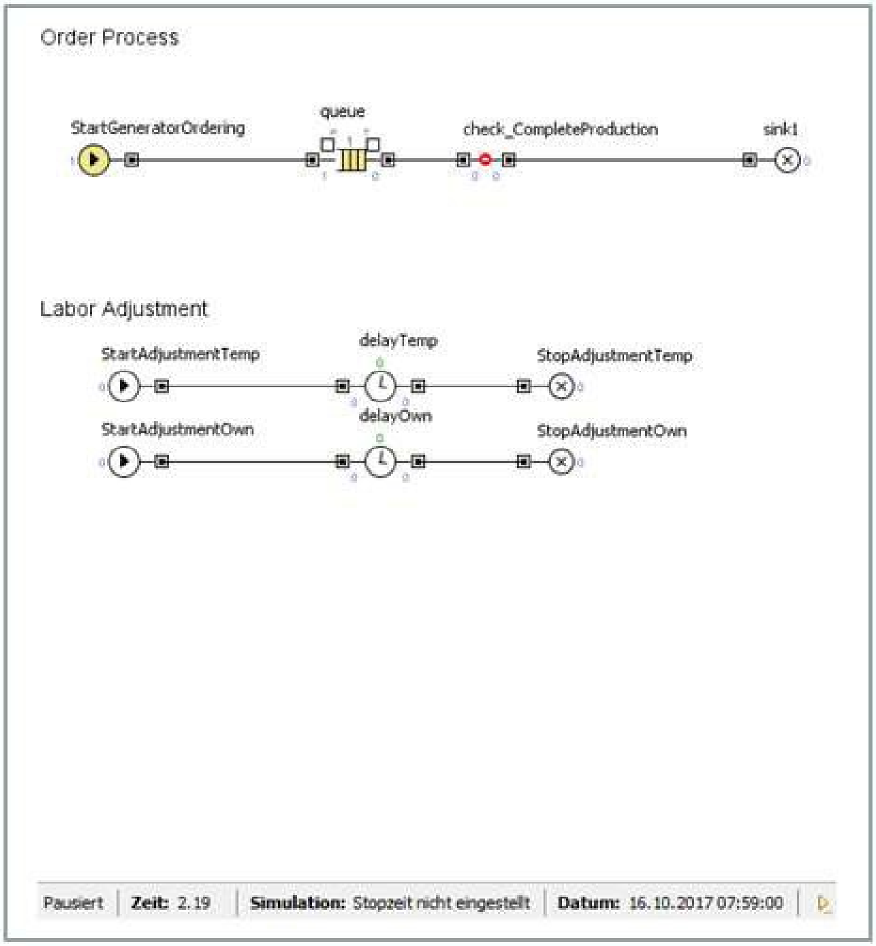



*Figure 5.3.2-1: Validation & Verification of project order process*

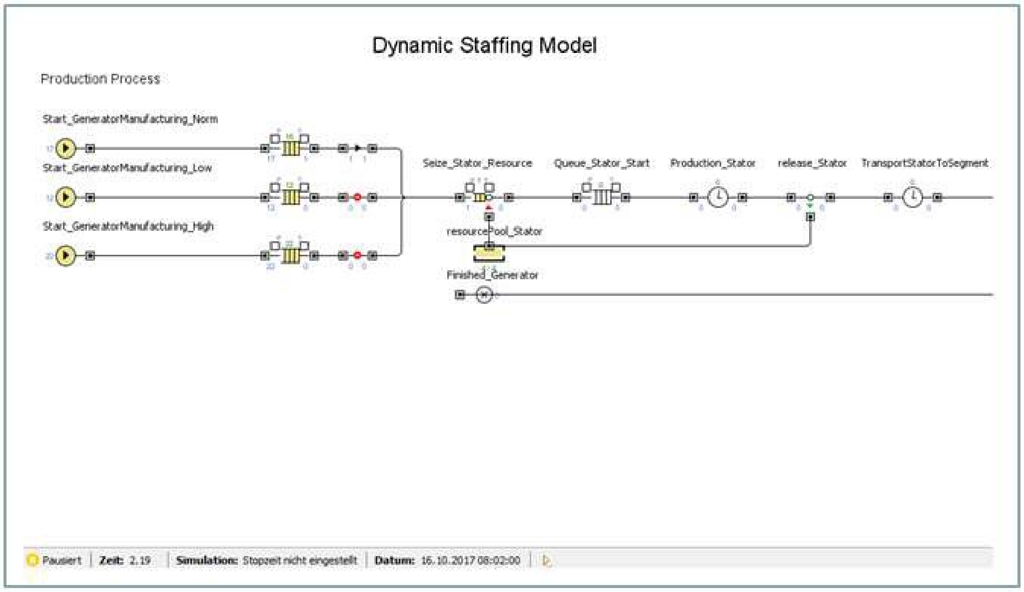



*Figure 5.3.2-2: Validation & Verification of production process I*

The following part of the validation and verification process is focusing on the assembly process itself assessing if the number of resources that are to be seized and the required process time is simulated correctly and adequately. In order to allow for a deterministic evaluation, the production time for stator has been modified to the time unit 1 requiring 2 resources from the assigned resource pool. As described above the point in time when the first generator is released into the system is Monday, October 16$^{th}$ 2017 at 8.00am or in the model time 2.19 weeks as the first generator will not suffer a shortage of resources, the calculated release time of the stator production ought to be 3.19 weeks after start of the simulation. The figure 5.3.2-3 shows the point in time the first generator leaving the assembly station at 3.19 weeks.

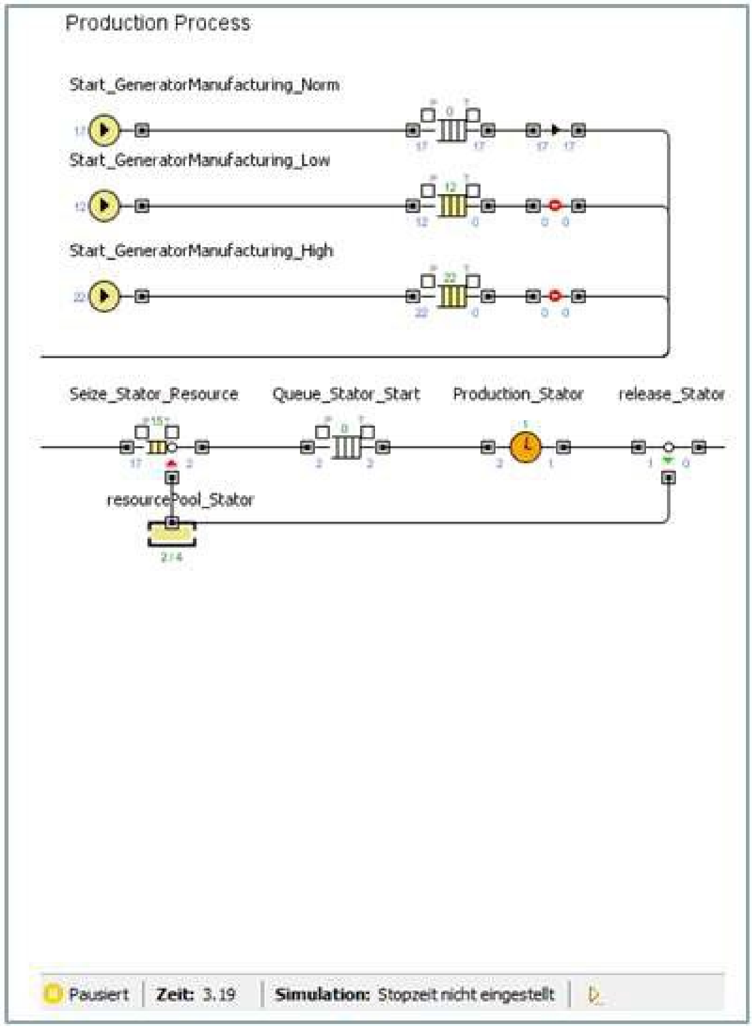



*Figure 5.3.2-3: Validation & Verification of production process II*

The following validation and verification are conducted on mechanism implemented to simulate the reduction of headcount after a pre-defined time, 3 months for temporary employees and 6 months for own employed resources. The figure 5.3.2-4 shows the point in time at which the number resources have been adapted by 50%.

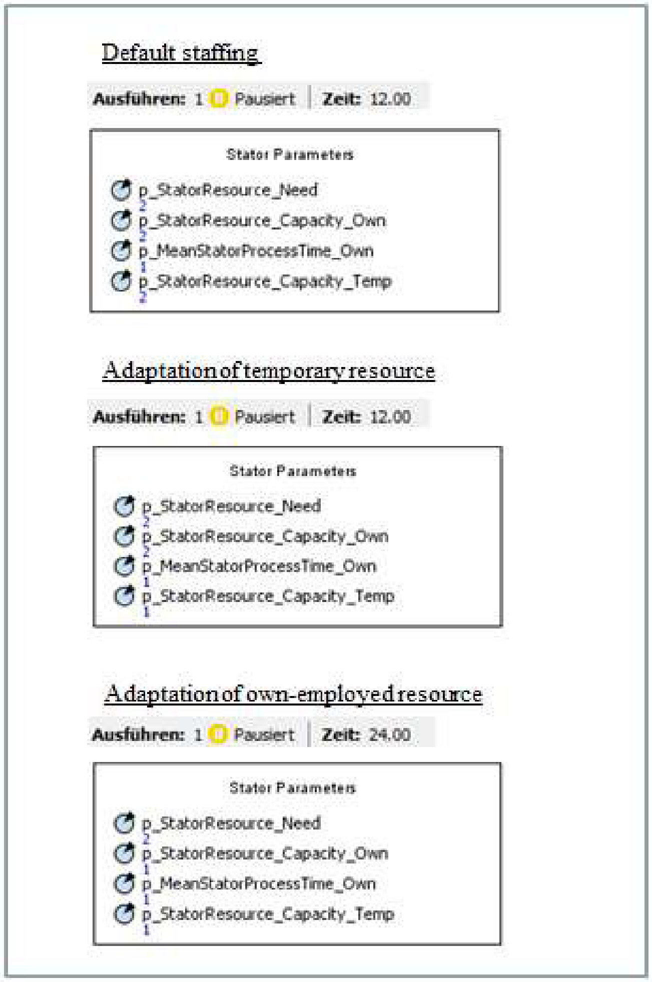



*Figure 5.3.2-4: Validation & Verification of adjusted head count*

The final validation and verification are done on the commercial aspects of the model considering initially the calculation of the weekly cost for own employed personnel and external resources.

The theoretical calculation of the combined value per week is:

```
(# of available resources own employees*days per week*hours per
day*hourly rate in EUR) + (# of available resources temporary
employees*days per week*hours per day*hourly rate in EUR)
```

The theoretical calculation of the combined productive cost per workstation is:

```
(# of available resources own employees*amount of throughput time
per workstation*working hours per day*# of working days per
week*hourly rate in EUR) + (# of available resources temporary
employees*amount of throughput time per workstation*working hours
per day*# of working days per week*hourly rate in EUR)
```

Given the deterministic approach of 4 own resources per assembly station and a throughput time of 1 week per station the values for both calculations are:

`36*5*8*125 = 180.000,00 EUR`

The calculation of the productive cost for the entire assembly process after the first week of operation given the defined throughput time per production step of 1 week is:

`4*1*8*5*125 = 20.000,00 EUR`

The controlling results from the deterministic model are shown in figure 5.3.2-5.


*Figure 5.3.2-5: Validation & Verification of analysis window*

<u>Scenario analysis and documentation</u>

The objective of the model is to assess in a heuristic approach the staffing strategy of a generator assembly line. The baseline and the scenarios which are to be assessed are:

- All employees employed by own organisation to be assessed for normal-, low- and high-volume scenario
- 50% / 50% mix of employees employed by own organisation and third-party employment to be assessed for normal-, low- and high-volume scenario

- All employees employed by own organisation to be assessed for normal-, low- and high-volume scenario including head count adjustment for low-volume scenario
- 50% / 50% mix of employees employed by own organisation and third-party employment to be assessed for normal- and low-volume scenario including head count adjustment for low-volume scenario

The results of each simulation are collected in an excel file summarizing the following results per run:

- Time for completion (weeks)
- Variable cost productive (EUR)
- Variable non-productive (EUR)
- Variable cost own employment (EUR)
- Variable temporary employment (EUR)
- One-time cost own employment (EUR)
- One-time cost temporary employment (EUR)

Besides the collection of each result per simulation run the entirety of the simulation runs is assessed according to its average results, median, standard deviation and the coefficient of variance.

# Chapter 6

# Conclusion and future research

## 6.1. Summary and conclusion

The backbone and guiding principle of this thesis has been the research triangle bringing together the areas of supply chain risk management, business modelling and simulation and organisational learning under the umbrella of project management set up located in the renewable energy wind business. The synthesis of those topics has offered a unique and new approach to the scientific community how a state-of-the-art organization can manage its supply chain risk while further enabling their organizational learning skills using new business modelling and simulation techniques.

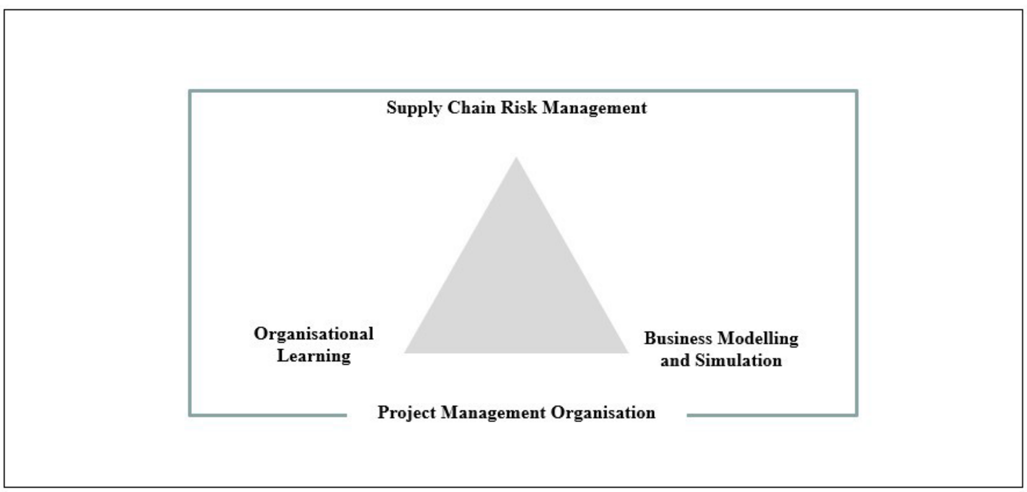



*Figure 6.0-1: Research triangle*

The core contribution to knowledge of this thesis have been:

- A confirmation concerning the identified research gap of a missing comprehensive approach regarding risk management process and tools which at the same time adequately represent the characteristics of today's project management supply chains by including educational aspects of organisational learning

- An in-depth understanding gained by conducting primary research about the implementation of the supply chain risk management process, which in accordance to the literature is a vital part of every function participating in the interviews, however, the approach is almost entirely relying on the experience of individuals within the organisation as training on the job has been identified as the single way to gain experience in the field starting as a new employee
- In regards to the implementation of the core organisational learning principles in a project management organisation the study shows that besides the dimensions of personal mastery, building shared vision and team learning, system thinking and mental models are the two dimensions from the learning organisation framework that are not fully embedded in the organisations policies and are simultaneously the ones that are to be assessed and improved by applying business modelling and simulation achieving a sustainable educational effect
- An example of the application of business modelling and simulation to a real-world manufacturing system demonstrating how the characteristics that have been identified earlier in as part of the literature review are to incorporated into the model and therefore into the learning experience completing the contribution to knowledge following the idea of the research triangle

The following paragraph aims at outlining the concluding aspects to the above summary.

Following this synthesis, the thesis has been approaching three main lines of research assessing **(1) an organisations' ability and approach when building up a supply chain risk management process, (2) which tools and techniques are used in this process and finally (3) how the organization is training itself to account for the complex characteristics of today's supply chains.**

Derived from the above considerations the main hypothesis of the thesis follows the main hypothesis that **in order to achieve sustainable learning in its' SCRM process**

**of risk management and monitoring a project management driven organisation needs to apply business modelling and simulation as a virtual world environment.**

The research has been conducted in three stages, **a literature review,** covering 232 sources published between 1921 and 2020, in order to determine the current state of the art in the respective field and to identify existing shortcoming demonstrating the validity of the declared contribution to knowledge. **An empirical study** among supply chain professionals in order to understand and rank the most immanent threats to today's supply chains and to understand the current state and gaps in today's supply chain organisations considering supply chain risk management and organisational learning. Finally, the results of the empirical assessment have been used to **demonstrate the capabilities of simulation and business modelling** in the context of a project management organisation in the field of renewable energy.

The journey by which this thesis is build up is part of a learning curve, covering the existing body of literature as well as the findings from the primary research that has been conducted concluding in its contribution to knowledge and practise. Each of those steps is closely knitted by design.

The common theme in the literature covering supply chain risk management follows **two main argumentative lines. The first** being that the main effects causing the need for a consistent approach of supply chain risk management are in accordance to Christopher (Christopher, 2004):

- New rules of competition
- Downward pressure on price
- Globalisation of industry
- Customer taking control

Robinson (Robinson, 2004), Hopp (Hopp, 2011) and Sterman (Sterman, 2000) are assessing the topic from a technological perspective, concluding that the main characteristics elevating the risk exposure in a modern supply chain are:

- Variability
- Interconnection
- Complexity

**The second** one being, that practitioners in the research community such as Jüttner (Jüttner, 2005) and Peck (Peck, 2005) point out the fact that the above characteristics and trends lead to an increased exposure to supply chain risk, however at the same time acknowledging that despite an increasing effort done by organisations in general, supply chain risk management in its holistic approach across the entire value chain has not been achieved. Other authors like Mikus (Vahrenkamp & Amann, 2007) join their assessment by adding that the crucial issues of future research are:

- The analysis of the cause-and-effect chains and their coherences
- The development of management toolkit assessing and mitigating supply chain risk

The conclusive result of this assessment shows that while the negative effects and re-enforcing characteristics are well known the existing framework has still not been fully adapted by the business community resulting in a sustainable and comprehensive supply chain risk management.

As well as the area of supply chain risk management, the thesis' second core area of **business modelling and simulation is pursuing three main dimensions. The first one** being how business modelling and simulation fits into the portfolio of tools and methods available to businesses to approach challenges and solve problems. **The second** being to assess which simulation paradigm suits which real world problem and in particular supply chain risk management problems, and **the third** one being which steps are to be followed in a simulation study.

Multiple authors like Banks (Banks, 1998), Kelton (Kelton et al., 2007) and Robinson (Robinson, 2004) are clearly pointing out that in comparison to a deterministic problem the medium business modelling and simulation offers to the user the possibility and convenience to solve stochastic and complex problems exactly matching the earlier described characteristics of today's supply chains.

When discussing the selection of a specific simulation paradigm to be followed Tako (Tako & Robinson, 2012), (Ossimitz & M. Mrotzek, 2008) and Siebers (Siebers et al., 2010) combined provide a comprehensive guidance regarding the simulation paradigm to select.

When relating the findings of the literature review regarding business modelling and simulation to the outcome of the research it important to note that while multiple authors describe successful applications of business modelling and simulation in the area of supply chain risk management, **the aspect that remained unexplored in the current scientific discussion, is the learning and educational effect on a project management organisation**. The main authors to be names are among others providing case studies in the area of supply chain risk management are Tiehl (THIEL, 1996), Chang (Chang, 2001), Riane (Riane, 2002), Datta (Datta, 2007), Forget et al. (Forget et al., 2008), Chinbat et al. (Chinbat et al., 2009) and Schmitt et al. (Schmitt et al., 2009).

**The final, and third focus area of the research, organisational learning,** is completing the picture. Senge (Senge, 2006) introduced the concept of organisational learning in a wider framework better known by the 5$^{th}$ discipline. Along with other authors like Argyris (Argyris, 1999) or Argote (Argote, 2013) he clearly describes the concept of organisational learning.

Further assessments as part of the thesis have shown the direct link between organisational learning and strategic management of an organisation or the link between organisational learning and a project management set up, respectively the application of business modelling withing the field of organisational learning.

While as a result of the literature review is to be emphasised that the concept of organisational learning as well as its application in various business areas is supporting an organisation's performance, **a clear indication or examples regarding its real-**

**life implementation and execution given today’s technological possibilities is missing.** This observation again is closely connected to the questions discussed with the interview participants as part of the semi-structured interviews.

Figure 6.0-2 provides an exemplary overview of the connection between the authors of text books and state of the art literature considering the individual topics reflected in the research triangle, respectively a selection of authors that have been conducted case studies based on the existing theoretical frame work.

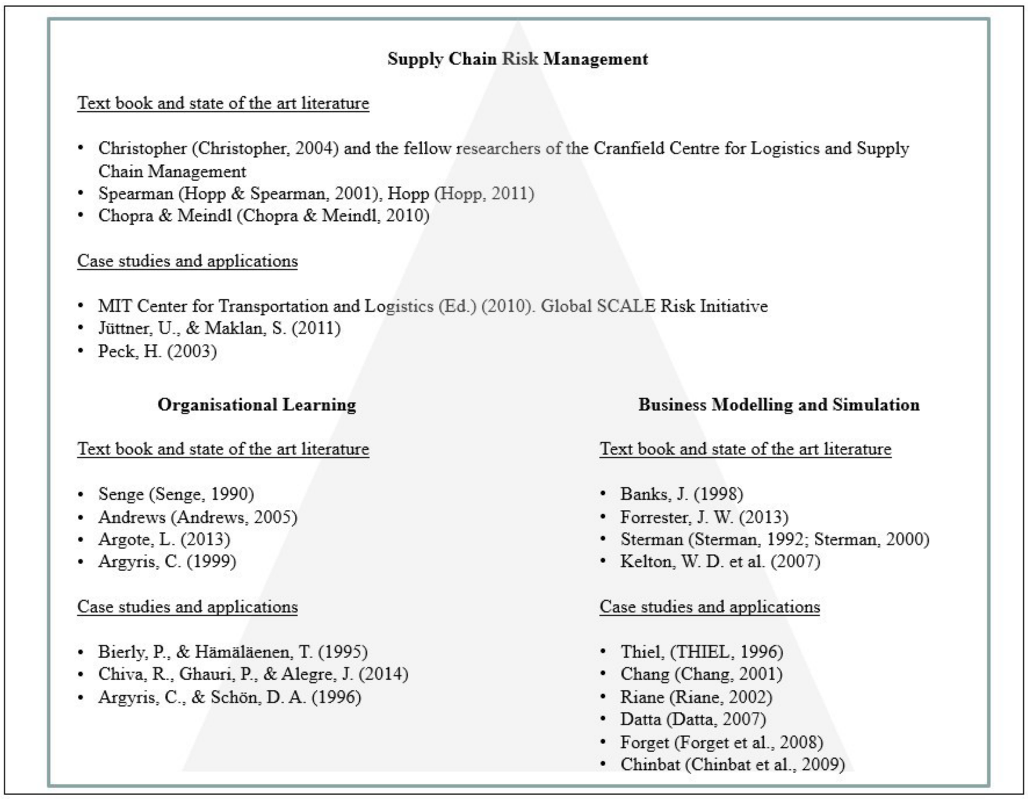



*Figure 6.0-2: Connection between main authors and practitioner’s work in the research triangle*

In summary, the literature review confirms the initially identified research gap of **a missing comprehensive approach regarding risk management process and tools which at the same time adequately represent the characteristics of today’s project management supply chains by including educational aspects of organisational learning establishing the ground work for this new research field combining three formally separated fields.**

**The conducted primary research in the form of semi-structured interviews** provide a conclusive view on how today´s project management organisations consider risk and its management as part of their strategic considerations and daily business.

The main findings have been that supply chain professionals, working in a project management environment, consider their business a make-to-order business where the main risks threatening a project management organisation's supply chain are a decline in price, new product introduction and demand fluctuation from an internal perspective. Production delays are of a major concern on the supplier side. Concerning the governmental and policy environment currency changes, macro-economic trends and government taxation are considered to be the highest risks, with the last one being under special consideration when accounting for subsidy effects for renewable energy sources.

Regarding the internal processes the overall management process including strategic target setting and the customer relationship process are judged to be most critical ones when not conducted properly. Regarding internal control mechanisms EHS and demand management and forecasting have been selected as the most curial ones.

Furthermore, concluding from those findings it has been identified that a growing complexity in supply and demand networks created out of intrinsic motivation of revenue and profit maximisation in the combination of the global demand for newest technology increases the risks threatening entire supply chains.

**Regarding the implementation of the supply chain risk management process, it became obvious that, while the objective of managing and mitigating risk is a vital part of every function participating in the interviews, the approach is almost entirely relying on the experience of individuals within the organisation as training on the job has been identified as the single way to gain experience in the field starting as a new employee. This observation directly corresponds to the identified gaps as part of the literature review creating an important link.**

This development, as consequence, increases the pressure on the management team of every organisation in setting strategic goals and directions even more. In order to manage those complex risks, organisations are almost entirely relying on experience rather than using statistical IT-based management mechanisms, despite the fact that the monetary volume of i.e., offshore wind projects is growing over time and hence

the associated risk, the use of IT based support for example in for of business modelling and simulation is far from being the standard case.
Considering the application of the learning organisation´s principles the conducted **interviews show that besides the dimensions of personal mastery, building shared vision and team learning, system thinking and mental models are the two dimensions from the learning organisation framework that are not fully embedded in the organisations policies and are simultaneously the ones that are to be assessed and improved by applying business modelling and simulation.**

The result of the empirical study in combination with the conducted literature review represent the unique contribution to the scientific discussion and knowledge proving that the **existing theoretical frameworks have not found a path of holistically addressing the main described threats towards today's project management supply chains and that the educational and therefore sustainable aspect of risk management can only be accelerated when applying a business modelling and simulation environment.**

In a final step the results of the interviews have been used to develop an example model applying the effects from one of the main risks identified, namely demand fluctuations and use the structure of the assembly of wind turbine generator as a blueprint to illustrate which assessment are to be conducted allowing an organisation to assess its effects on an industrial production system in a visual and repeatable manner putting a majority of the learning organisations' principles into action.
It illustrates the effects of various staffing models regarding the overall cost position of an assembly process when confronted with different demand patterns. This model allows the user to assess the consequences and likelihood of different scenarios accounting for the main factors driving supply chain risk established in the beginning of the thesis, namely dynamic feedback loops, parallelism and influence of probability.

The two main areas of investigation in the model are how does the proportion between required time to execute the project pipeline develop in comparison to the development of the overall cost and secondly, how does the relation between productive and non-productive cost develop in case volume of generators drops and the management of the factory either decides not to change the headcount structure and number, or applies measures to do so.

The main observation is that the overall performance of the assembly line at the given normal volume increase when on-boarding temporary workers, whereas the average amount of weeks needed to execute the production increases by 5% the overall cost is reduced by 12%. When introducing the option at a given volume the option to additionally adjust the headcount by 50% after a 3-month period for temporary workers and 6 months for own employees at a pre-defined severance payment the positive effect up to 44% in cost saving with a 3% average increase in time indicating that described system is not at an optimal base stage.

The simulation study additionally shows **in how the characteristics that have been identified earlier in as part of the literature review are to incorporated into the model and therefore into the learning experience completing the contribution to knowledge following the idea of the research triangle.**

Combining the findings from the literature review, the empirical study conducting semi-structured interviews and the case study implementation as part of a business modelling and simulation project represent a unique piece of research, proving that the initial hypothesis **that in order to achieve sustainable learning in its' SCRM process of risk management and monitoring a project management driven organisation needs to apply business modelling and simulation as a virtual world environment is to be accepted.**

## 6.2. Future research

The conducted research only represents a starting point in the journey of combining the three fields supply chain risk management, business modelling and simulation and the learning organisation. Combining the findings of the literature review and the conducted interviews it became obvious the business world in which project management organisations interact and compete are only about to increase its complexity.

Today's and future organisations have to ensure that in a global business and production network each node is capable of assessing its role and level of influence in a world of non-linear connections and inter-dependencies.

Further research might aim at assessing the effectiveness of on-boarding trainings for new employees focusing of the supply chain of this specific organisation, or a further assessment on the applicability of business modelling and simulation for different business models, for example fast moving consumer goods in comparison the project business.

# Annex

| | | 1 | 2 | 3 | 5 | 4 | 7 | 6 | 13 | 10 | 8 | 11 | 9 | 12 | weighted average | standard deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Dimension "External driver" | | | | | | | | | | | | | | | | |
| Demand Risk | | | | | | | | | | | | | | | | |
| | decline in prices | 2 | 5 | 1 | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 1 | 5 | 4 | **4** | **1,460** |
| | unexpected fluctuation in demand | 5 | 4 | 3 | 3 | 3 | 5 | 1 | 4 | 4 | 4 | 4 | 3 | 4 | **4** | **1,044** |
| | short-term change in terms of delivery | 4 | 4 | 4 | 0 | 1 | 4 | 4 | 1 | 1 | 3 | 2 | 1 | 4 | **3** | **1,561** |
| | IT breakdown at customer | 0 | 1 | 2 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 | 1 | 5 | **1** | **1,345** |
| | risk of obsolence | 4 | 3 | 1 | 3 | 0 | 3 | 2 | 1 | 2 | 1 | 0 | 1 | 4 | **2** | **1,382** |
| | stock-outs | 2 | 2 | 5 | 1 | 3 | 3 | 5 | 1 | 1 | 3 | 2 | 1 | | **2** | **1,443** |
| | over inventory | 1 | 1 | 4 | 2 | | 3 | 1 | 3 | 1 | 2 | 0 | 0 | | **2** | **1,286** |
| | new product introduction | 1 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 0 | 4 | **4** | **1,391** |
| | fads | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | | **1** | **0,651** |
| | seasonality | 3 | 1 | 5 | 4 | 3 | | 0 | 4 | 4 | 3 | 0 | 2 | 4 | **3** | **1,658** |
| | lack of forecasting | 5 | 1 | 1 | 1 | 4 | 5 | 1 | 4 | 4 | 3 | 4 | 4 | | **3** | **1,621** |
| Supply Risk | | | | | | | | | | | | | | | | |
| | bottleneck of capacity | 2 | 3 | 4 | 3 | 3 | 3 | 5 | 1 | 4 | 3 | | 4 | 3 | **3** | **1,030** |
| | production delay | 3 | 4 | 4 | 4 | 3 | 3 | 5 | 2 | 5 | 3 | | 4 | | **4** | **0,924** |
| | quality issues | 1 | 4 | 4 | 3 | | 5 | 5 | 3 | 3 | 1 | 3 | 5 | | **3** | **1,433** |
| | insolvency of supplier | 5 | 2 | 3 | 4 | 3 | 4 | 4 | 3 | 2 | 1 | 1 | 5 | | **3** | **1,379** |
| | price escalation | 1 | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | 1 | 5 | | **2** | **1,084** |
| | frequency of material design changes | 4 | 1 | 2 | 4 | 1 | 5 | | 2 | 2 | 1 | 1 | 2 | | **2** | **1,421** |
| Environmental Risk | | | | | | | | | | | | | | | | |
| | Blockage of transportation | 1 | 1 | 2 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 0 | 4 | 4 | **2** | **1,256** |
| | fire at business partner | 1 | 2 | 3 | 1 | 2 | | 1 | 1 | 1 | 1 | 0 | 2 | | **1** | **0,809** |
| | terrorist attack | 2 | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | | **1** | **0,778** |
| | unexpected change in governmental taxation | 4 | 3 | 3 | | 4 | 5 | 2 | 1 | 3 | 1 | 3 | 5 | | **3** | **1,375** |
| | unexpected macro economical change | 5 | 4 | 4 | 2 | 2 | 5 | 4 | 3 | 4 | 1 | 3 | 4 | | **3** | **1,240** |
| | unexpected currency changes | 1 | 4 | 4 | 3 | 3 | 5 | 4 | 4 | 5 | 1 | 1 | 2 | | **3** | **1,505** |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-1: Supply chain risk questionnaire results – External drivers*

| | | 1 | 2 | 3 | 5 | 4 | 7 | 6 | 13 | 10 | 8 | 11 | 9 | 12 | weighted average | standard deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2. Dimension "Internal driver" | | | | | | | | | | | | | | | | |
| Process Risk (not SCM) | | | | | | | | | | | | | | | | |
| | management process | 5 | 2 | 5 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | | 4 | | **4** | **0,934** |
| | CRM process | 2 | 4 | 4 | | 1 | 5 | 4 | 4 | 3 | 5 | 4 | 4 | | **4** | **1,206** |
| | PLM process | 1 | 5 | 4 | 4 | 4 | 5 | 2 | 4 | 3 | 4 | 3 | 1 | | **3** | **1,371** |
| | support processes | 2 | 2 | 2 | 3 | 2 | | 2 | 4 | 5 | 3 | 1 | 4 | | **3** | **1,191** |
| Control Risk | | | | | | | | | | | | | | | | |
| | failure in financial and inventory controls | 1 | 3 | 3 | 4 | | 4 | 4 | 4 | 2 | 2 | 5 | 5 | | **3** | **1,286** |
| | failure in demand management and forecasting | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | | **4** | **0,515** |
| | failure in employee compliance | 2 | 3 | 2 | 2 | 2 | 2 | 4 | 1 | 1 | 5 | 2 | 3 | | **2** | **1,165** |
| | failure in compliance on EHS procedures | 5 | 3 | 4 | 4 | 2 | 5 | 5 | 3 | 4 | 5 | 4 | 5 | | **4** | **0,996** |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-2: Supply chain risk questionnaire results – Internal drivers*

| | | 1 | 2 | 3 | 5 | 4 | 7 | 6 | 13 | 10 | 8 | 11 | 9 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Other | | | | | | | | | | | | | | |
| | Environment Weather | | | 2 | | | | | | | | | | |
| | People and skills | | | 3 | | | | | | | | | | |
| | Failure Production equipment | | | 4 | | | | | | | | | | |
| | General Competition | | | | 4 | | | | | | | | | |
| | Import duties / trade mechanisms | | | | | | | | | 4 | | | | |
| | change in government strategy | | | | | | | | | 4 | | | | |
| | organizational set up (region vs. Corporate) | | | | | | | | 4 | | | | | |
| | readiness of customer infrastructure | | | | | | | | | | | 3 | | |
| | product integrity / liabilility / product safety | | | | | | | | | | | | 5 | |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-3: Supply chain risk questionnaire results – Other drivers*

| | | | Offshore wind business | | | | | Onshore wind business | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3 | 5 | 4 | average | standard deviation | 2 | 7 | 13 | 10 | 8 | average | standard deviation |
| 1. Dimension "External driver" | | | | | | | | | | | | | | |
| | Demand Risk | | | | | | | | | | | | | |
| | | decline in prices | 1 | 5 | 5 | 4 | 2,309 | 5 | 4 | 5 | 5 | 4 | 5 | 0,548 |
| | | unexpected fluctuation in demand | 3 | 3 | 3 | 3 | 0,000 | 4 | 5 | 4 | 4 | 4 | 4 | 0,447 |
| | | short-term change in terms of delivery | 4 | 0 | 1 | 2 | 2,082 | 4 | 4 | 1 | 1 | 3 | 3 | 1,517 |
| | | IT breakdown at customer | 2 | 0 | 0 | 1 | 1,155 | 1 | 1 | 1 | 1 | 1 | 1 | 0,000 |
| | | risk of obsolence | 1 | 3 | 0 | 1 | 1,528 | 3 | 3 | 1 | 2 | 1 | 2 | 1,000 |
| | | stock-outs | 5 | 1 | 3 | 3 | 2,000 | 2 | 3 | 1 | 1 | 3 | 2 | 1,000 |
| | | over inventory | 4 | 2 | 0 | 2 | 2,000 | 1 | 3 | 3 | 1 | 2 | 2 | 1,000 |
| | | new product introduction | 4 | 4 | 4 | 4 | 0,000 | 4 | 5 | 4 | 4 | 4 | 4 | 0,447 |
| | | fads | 1 | 1 | 2 | 1 | 0,577 | 1 | 0 | 0 | 0 | 1 | 0 | 0,548 |
| | | seasonality | 5 | 4 | 3 | 4 | 1,000 | 1 | 0 | 4 | 4 | 3 | 2 | 1,817 |
| | | lack of forecasting | 1 | 1 | 4 | 2 | 1,732 | 1 | 5 | 4 | 4 | 3 | 3 | 1,517 |
| | Supply Risk | | | | | | | | | | | | | |
| | | bottleneck of capacity | 4 | 3 | 3 | 3 | 0,577 | 3 | 3 | 1 | 4 | 3 | 3 | 1,095 |
| | | production delay | 4 | 4 | 3 | 4 | 0,577 | 4 | 3 | 2 | 5 | 3 | 3 | 1,140 |
| | | quality issues | 4 | 3 | 0 | 2 | 2,082 | 4 | 5 | 3 | 3 | 1 | 3 | 1,483 |
| | | insolvency of supplier | 3 | 4 | 3 | 3 | 0,577 | 2 | 4 | 3 | 2 | 1 | 2 | 1,140 |
| | | price escalation | 2 | 2 | 2 | 2 | 0,000 | 2 | 3 | 2 | 2 | 2 | 2 | 0,447 |
| | | frequency of material design changes | 2 | 4 | 1 | 2 | 1,528 | 1 | 5 | 2 | 2 | 1 | 2 | 1,643 |
| | Environmental Risk | | | | | | | | | | | | | |
| | | Blockage of transportation | 2 | 2 | 3 | 2 | 0,577 | 1 | 3 | 2 | 3 | 1 | 2 | 1,000 |
| | | fire at business partner | 3 | 1 | 2 | 2 | 1,000 | 2 | 0 | 1 | 1 | 1 | 1 | 0,707 |
| | | terrorist attack | 2 | 0 | 1 | 1 | 1,000 | 1 | 0 | 1 | 0 | 0 | 0 | 0,548 |
| | | unexpected change in governmental taxation | 3 | 0 | 4 | 2 | 2,082 | 3 | 5 | 1 | 3 | 1 | 3 | 1,673 |
| | | unexpected macro economical change | 4 | 2 | 2 | 3 | 1,155 | 4 | 5 | 3 | 4 | 1 | 3 | 1,517 |
| | | unexpected currency changes | 4 | 3 | 3 | 3 | 0,577 | 4 | 5 | 4 | 5 | 1 | 4 | 1,643 |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-4: Supply chain risk questionnaire results – Offshore vs. Onshore I*

| | | | Offshore wind business | | | | | Onshore wind business | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3 | 5 | 4 | average | standard deviation | 2 | 7 | 13 | 10 | 8 | average | standard deviation |
| 2. Dimension "Internal driver" | | | | | | | | | | | | | | |
| | Process Risk (not SCM) | | | | | | | | | | | | | |
| | | management process | 5 | 3 | 3 | 4 | 1,155 | 2 | 3 | 4 | 3 | 3 | 3 | 0,707 |
| | | CRM process | 4 | 0 | 1 | 2 | 2,082 | 4 | 5 | 4 | 3 | 5 | 4 | 0,837 |
| | | PLM process | 4 | 4 | 4 | 4 | 0,000 | 5 | 5 | 4 | 3 | 4 | 4 | 0,837 |
| | | support processes | 2 | 3 | 2 | 2 | 0,577 | 2 | 0 | 4 | 5 | 3 | 3 | 1,924 |
| | Control Risk | | | | | | | | | | | | | |
| | | failure in financial and inventory controls | 3 | 4 | 0 | 2 | 2,082 | 3 | 4 | 4 | 2 | 2 | 3 | 1,000 |
| | | failure in demand management and forecasting | 4 | 4 | 3 | 4 | 0,577 | 4 | 4 | 4 | 4 | 4 | 4 | 0,000 |
| | | failure in employee compliance | 2 | 2 | 2 | 2 | 0,000 | 3 | 2 | 1 | 1 | 5 | 2 | 1,673 |
| | | failure in compliance on EHS procedures | 4 | 4 | 2 | 3 | 1,155 | 3 | 5 | 3 | 4 | 5 | 4 | 1,000 |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-5: Supply chain risk questionnaire results – Offshore vs. Onshore II*

| | | Service Business | | | | | New Product Business | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 11 | 12 | average | standard deviation | 2 | 3 | 5 | 4 | 7 | 6 | 13 | 10 | 8 | 9 | average | standard deviation |
| 1. Dimension "External driver" | | | | | | | | | | | | | | | | | | |
| Demand Risk | | | | | | | | | | | | | | | | | | |
| | decline in prices | 2 | 1 | 4 | **2** | **1,528** | 5 | 1 | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 5 | **5** | **0,577** |
| | unexpected fluctuation in demand | 5 | 4 | 4 | **4** | **0,577** | 4 | 3 | 3 | 3 | 5 | 1 | 4 | 4 | 4 | 3 | **4** | **0,577** |
| | short-term change in terms of delivery | 4 | 2 | 4 | **3** | **1,155** | 4 | 4 | 0 | 1 | 4 | 4 | 1 | 1 | 3 | 1 | **2** | **1,155** |
| | IT breakdown at customer | 0 | 0 | 5 | **2** | **2,887** | 1 | 2 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 1 | **1** | **0,000** |
| | risk of obsolence | 4 | 0 | 4 | **3** | **2,309** | 3 | 1 | 3 | 0 | 3 | 2 | 1 | 2 | 1 | 1 | **1** | **0,577** |
| | stock-outs | 2 | 2 | 0 | **1** | **1,155** | 2 | 5 | 1 | 3 | 3 | 5 | 1 | 1 | 3 | 1 | **2** | **1,155** |
| | over inventory | 1 | 0 | 0 | **0** | **0,577** | 1 | 4 | 2 | 0 | 3 | 1 | 3 | 1 | 2 | 0 | **1** | **1,000** |
| | new product introduction | 1 | 4 | 4 | **3** | **1,732** | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 0 | **3** | **2,309** |
| | fads | 1 | 0 | 0 | **0** | **0,577** | 1 | 1 | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | **0** | **0,577** |
| | seasonality | 3 | 0 | 4 | **2** | **2,082** | 1 | 5 | 4 | 3 | 0 | 0 | 4 | 4 | 3 | 2 | **3** | **1,000** |
| | lack of forecasting | 5 | 4 | 0 | **3** | **2,646** | 1 | 1 | 1 | 4 | 5 | 1 | 4 | 4 | 3 | 4 | **4** | **0,577** |
| Supply Risk | | | | | | | | | | | | | | | | | | |
| | bottleneck of capacity | 2 | 3 | 4 | **3** | **1,000** | 3 | 4 | 3 | 3 | 3 | 5 | 1 | 4 | 3 | 4 | **4** | **0,577** |
| | production delay | 3 | 4 | 4 | **4** | **0,577** | 4 | 4 | 4 | 3 | 3 | 5 | 2 | 5 | 3 | 4 | **4** | **1,000** |
| | quality issues | 1 | 4 | 4 | **3** | **1,732** | 4 | 4 | 3 | 0 | 5 | 5 | 3 | 3 | 1 | 5 | **3** | **2,000** |
| | insolvency of supplier | 5 | 2 | 3 | **3** | **1,528** | 2 | 3 | 4 | 3 | 4 | 4 | 3 | 2 | 1 | 5 | **3** | **2,082** |
| | price escalation | 1 | 2 | 2 | **2** | **0,577** | 2 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 2 | 5 | **3** | **1,732** |
| | frequency of material design changes | 4 | 1 | 2 | **2** | **1,528** | 1 | 2 | 4 | 1 | 5 | 0 | 2 | 2 | 1 | 2 | **2** | **0,577** |
| Environmental Risk | | | | | | | | | | | | | | | | | | |
| | Blockage of transportation | 1 | 1 | 2 | **1** | **0,577** | 1 | 2 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 4 | **3** | **1,528** |
| | fire at business partner | 1 | 2 | 3 | **2** | **1,000** | 2 | 3 | 1 | 2 | 0 | 1 | 1 | 1 | 1 | 2 | **1** | **0,577** |
| | terrorist attack | 2 | 1 | 2 | **2** | **0,577** | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | **0** | **0,577** |
| | unexpected change in governmental taxation | 4 | 3 | 3 | **3** | **0,577** | 3 | 3 | 0 | 4 | 5 | 2 | 1 | 3 | 1 | 5 | **3** | **2,000** |
| | unexpected macro economical change | 5 | 4 | 4 | **4** | **0,577** | 4 | 4 | 2 | 2 | 5 | 4 | 3 | 4 | 1 | 4 | **3** | **1,732** |
| | unexpected currency changes | 1 | 4 | 4 | **3** | **1,732** | 4 | 4 | 3 | 3 | 5 | 4 | 4 | 5 | 1 | 2 | **3** | **2,082** |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-6: Supply chain risk questionnaire results – Service vs. New Product Business I*

| | | Service Business | | | | | New Product Business | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 11 | 12 | average | standard deviation | 2 | 3 | 5 | 4 | 7 | 6 | 13 | 10 | 8 | 9 | average | standard deviation |
| 2. Dimension "Internal driver" | | | | | | | | | | | | | | | | | | |
| Process Risk (not SCM) | | | | | | | | | | | | | | | | | | |
| | management process | 5 | 0 | 0 | **2** | **2,887** | 2 | 5 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | **3** | **0,577** |
| | CRM process | 2 | 4 | 0 | **2** | **2,000** | 4 | 4 | 0 | 1 | 5 | 4 | 4 | 3 | 5 | 4 | **4** | **1,000** |
| | PLM process | 1 | 3 | 0 | **1** | **1,528** | 5 | 4 | 4 | 4 | 5 | 2 | 4 | 3 | 4 | 1 | **3** | **1,528** |
| | support processes | 2 | 1 | 0 | **1** | **1,000** | 2 | 2 | 3 | 2 | 0 | 2 | 4 | 5 | 3 | 4 | **4** | **1,000** |
| Control Risk | | | | | | | | | | | | | | | | | | |
| | failure in financial and inventory controls | 1 | 5 | 0 | **2** | **2,646** | 3 | 3 | 4 | 0 | 4 | 4 | 4 | 2 | 2 | 5 | **3** | **1,732** |
| | failure in demand management and forecasting | 5 | 4 | 0 | **3** | **2,646** | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | **4** | **0,577** |
| | failure in employee compliance | 2 | 2 | 0 | **1** | **1,155** | 3 | 2 | 2 | 2 | 2 | 4 | 1 | 1 | 5 | 3 | **3** | **2,000** |
| | failure in compliance on EHS procedures | 5 | 4 | 0 | **3** | **2,646** | 3 | 4 | 4 | 2 | 5 | 5 | 3 | 4 | 5 | 5 | **5** | **0,577** |

Risk examples partially taken from: BME (Pfohl) 2004, Mentzer 2004, Cranfield University 2003, MIT Risk Survey 2010

*Table A.1-7: Supply chain risk questionnaire results – Service vs. New Product Business II*

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