Master Thesis

Impact of New OEM Business Models and Innovative Steering Systems on Traditional Automotive Industry Processes

Raphael Prior, B.Sc.

Institute of Engineering and Business Informatics
Graz University of Technology

Head of Institute:
o.Univ.-Prof. Dipl.-Ing. Dr.techn. Siegfried Vössner

Advisor:
Dipl.-Ing. Dietmar Neubacher

Graz, 2016

in cooperation with

thyssenkrupp Steering
Eschen, Principality of Liechtenstein

thyssenkrupp

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

....
date signature

“you cannot make something out of nothing”

Abstract

The importance of innovative products in today's modern society is ever increasing. Especially mechatronic products have changed both the society and the market in recent years. Products that were highly innovative years ago (e.g. smartphones or computers), are now often taken for granted in everyday life. Moreover, they have entered the automotive industry, one of the world's largest markets. *Diverse mobility connectivity*, *electrification* and *autonomous driving* are only some of the trends that recently entered the automobile industry and caused massive changes – both with regard to cars and current business models. Moreover, the emergence of new Original Equipment Manufacturers (OEMs) that possess highly innovative business models and technological capacities makes the automotive industry an increasingly complex market. This is reflected by mechatronics systems becoming ever more complicated and elaborate.

This calls for a structured procedure when facing modern innovations. *Systems engineering* is often cited, both in literature and in praxis, as a suitable model for approaching complex problems and products. In the present master thesis, it shall thus investigate the influence that new OEMs and innovative steering systems have on the company *ThyssenKrupp Steering* (TKS). Therefore, a case study outlines new and traditional OEMs and highlights their differences by illustrating their behavior on the market as well as their influence on existing processes and companies. Given the fact that it is widely assumed that autonomous driving will soon enable innovative steering systems such as Steer-by-Wire (SbW), systems engineering is used to identify possible scenarios. A detailed study investigates involved changes with regard to existing production processes by transferring the conceptualized steering systems of the case study to real products. This step is done in order to highlight the impact on these innovative products on existing TKS processes. Finally, recommendations regarding suitable indicators and possible strategic actions are be given.

Kurzfassung

Innovative Produkte nehmen einen wichtigen Platz in der heutigen modernen Gesellschaft ein. Besonders mechatronische Produkte trugen in den letzten Jahren maßgeblich zur Veränderung der Gesellschaft sowie des Marktes bei. Waren vor Jahrzenten Produkte wie Smartphones oder Computer noch reine Fiktion in Kinofilmen oder Büchern, so spielen sie heute eine immer wichtigere Rolle im täglichen Leben. Diese Trends machen auch vor der Automobilbranche nicht Halt, welche oft als größter Markt der Welt bezeichnet wird. Besonders den Trends Automatisierung, Vernetzung, Elektrifizierung und neuen Mobilitätskonzepten werden disruptive Eigenschaften zugesprochen und sie sollen die Automobilbranche gar in ihren Grundzügen revolutionieren. Neben dem Produkt Auto werden sich daher auch Geschäftsmodelle sowie die zukünftige Mobilität stark verändern. Durch neue Automobilhersteller mit neuen Geschäftsmodellen und technischen Möglichkeiten wird die Automobillandschaft von Tag zu Tag komplexer. Zusätzlich werden mechatronische Systeme, welche in modernen Autos Anwendung finden, komplizierter und aufwendiger.

Eine erfolgreiche Begegnung dieser Neuerungen ist ohne strukturiertes Vorgehen schwierig. Das Modell Systems Engineering wird in Literatur und Praxis oftmals als mögliche Methodik für die Handhabung solch komplexer Projekte und Produkte vorgeschlagen. In der vorliegenden Masterarbeit soll es daher die Einflüsse der neuen Automobilgeschäftsmodelle und innovativen Lenksysteme auf die bestehenden Prozesse des Lenksystemzulieferers ThyssenKrupp Steering (TKS) aufzeigen. Dabei werden im Rahmen einer Fallstudie neue und traditionelle Automobilhersteller untersucht und deren Unterschiede aufgezeigt. Des Weiteren werden das untypische Verhalten der neuen Automobilhersteller und ihre Einflüsse auf bestehende Prozesse – etwa den Angebotsprozess – aufgezeigt. Es wird davon ausgegangen, dass selbstfahrende Kraftfahrzeuge innovative Lenksysteme wie Steer-by-wire ermöglichen werden, was mithilfe von Methoden aus Systems Engineering und der Konzeption möglicher Lenkkonzepte veranschaulicht wird. Im Anschluss daran wird eine Detailstudie über mögliche Veränderung an bestehenden Fertigungs- und Operationsprozessen durch solch innovative Lenksysteme durchgeführt. Hierbei werden die erstellten Konzepte in reale Produkte überführt, um Fertigungsprozesse zu definieren und daraus Veränderungen an ihnen sowie an Randbedingungen und operativen Prozessen darzustellen. Anhand der resultierenden veränderten Maschinenanzahlen sowie der benötigten Arbeiter und Fabriksflächen werden im Anschluss zukünftige und mögliche strategische Handlungen aufgezeigt.

Foreword

First of all, I would like to thank Univ.-Prof. Dipl.-Ing. Dr.techn. Siegfried Vössner for giving me the opportunity to write this thesis at his institute. I would further like to express my sincere gratitude towards my advisor Dipl.-Ing. Dietmar Neubacher for his continuous support, for hiring me, for all our lively discussions, for the fun moments and for his never-ending patience, motivation, enthusiasm and immense competence.

I want to thank my supervisor M.A. Alexander Grupp of *ThyssenKrupp Steering* who provided both the vision and idea for this thesis. Thank you for leading and supporting me during the development of this thesis. Furthermore, I want to thank all members of Operation Service for their input and personal support while working on this thesis.

I would also like to thank my friends and colleagues from university – without you, I would never have come as far as I did. Further, I have to thank Chantal for the careful work when correcting and editing this thesis (she even corrected this very sentence).

Finally, I must express my profound gratitude to my parents Lisbeth and Adalbert, my brothers Joachim, Simon and Matthias, and to my love and partner Christina for providing me with never-ending support and continuous encouragement throughout my entire life, my years at university, both during research and while writing this thesis. This accomplishment would not have been possible without you all.

Thank you!

Raphael

List of Abbreviations

ADAS - Advanced Driver Assistant System
AV - Autonomous Vehicle
BbW - Brake-by-Wire
BMW - Bayrische Motoren Werke Aktiengesellschaft
CBU - Customer Business Unit
CFI - Cashout for Investments
COP - Carryover Product
BEV - Battery Electric Vehicle
ECU - Electronic Control Unit
EPS - Electric Power Assisted Steering
EUR - Euro
EV - Electric Vehicle
FbW - Fly-by-Wire
HPAS - Hydraulic Power Assisted Steering
MC - Manufacturing concepts
OEM - Original Equipment Manufacturer
R&D - Research and development
SbW - Steer-by-Wire
SE - Systems Engineering
SOP - Start of Production
SWOT - Strengths Weaknesses Opportunities Threats
TKS - ThyssenKrupp Steering
FIT - Failure in Time
VDI - Verein Deutscher Ingenieure e.V.

Table of Contents

1 Introduction

1.1 Initial Situation

For years, innovative products have played an increasingly important role in today's modern industries. In the automobile industry, such innovations mostly happened with regard to electronic stability control or adaptive cruise control. More recent new trends are diverse mobility connectivity, electrification and autonomous driving (Kaas, et al., 2016). These four technologies (Christensen, 2011) are highly disruptive to the present automotive landscape and will have lasting effects until 2030 as they will bring major technological and structural upheavals. New OEMs that do not come from the classical engineering sector penetrate the market with different business models, fast time-to-market strategies and new innovative technologies. This results in an increasingly complex automotive industry, where current and long-term automotive suppliers alike are faced with new situations and challenges. Also, these disruptive technologies directly and indirectly affect current systems and processes. It is widely believed that autonomous driving will soon enable Steer-by-Wire (SbW) steering systems (Polmans, 2015), an innovative steering system which is believed to be the next evolutionary step in the history of steering systems. The disruption will also extend towards processes, which means that manufacturing processes might change completely or have different requirements. However, disruptive technologies might contribute to systems becoming more complex (both with regard to the automotive landscape or innovative mechatronic products), which is why a structural and methodological procedure is required. With regard to this, systems engineering provides an interdisciplinary and methodological approach that seeks to successfully manage and design such highly complex systems. Additionally, it reduces possible risks as, being a systematic approach that covers the entire project life-cycle, it can be implemented from the pre-concept phase onwards.

1.2 Problem definition

The automotive supplier *ThyssenKrupp Steering* (TKS) is a company that is already dealing with the new situation in the automotive industry. The company is currently growing quickly and emerging OEMs request products with a very short acquisition phase. These emerging OEMs are not like typical customers, which recently resulted in new challenges because they requested carryover products from other projects with an extremely short acquisition process. Furthermore, the OEMs work in the mentioned new automotive trends, which is why TKS is interested in their background, business models and strategic alignment.

1.3 Objectives

The objective of this thesis is to investigate and evaluate impacts of innovative products and automotive trends on recent developments at TKS. For this, several research questions were defined in the beginning.

The first key questions is "*How do emerging OEMs behave in regard to their development process and requirements compared to traditional OEMs?*" With regard to this question, the impacts on TKS and its processes that exist because of these new OEMs are investigated.

From this arises the second research question that tries to provide an answer to the following problem: "*What are the impacts of emerging OEMs on current processes at PrestaWorld?*" With regard to this, steering systems and their evolution as well as innovative steering systems are evaluated, which then leads to the third question:

"*What could conceptualized innovative steering systems look like?"* It is assumed that if the development and/or market introduction of such innovative steering systems takes place, this will change several processes at TKS.

Thus, the fourth research questions "*What impacts do these innovative steering system have on operation processes?*" is treated with the aim to illustrating possible changes at TKS.

1.4 Approach

This master thesis uses the systems engineering[1] approach that was adopted from Haberfellner, et al., (2015). Systems engineering provides an interdisciplinary and methodological approach that seeks to successfully manage and design highly complex systems. Because of this, it seems highly suitable to provide answers to the research questions mentioned in the previous section.

Chapter 3 *New Trends in the Autmotive Industry* is seen as the *initiation* for the subsequent case study and it provides detailed information on the underlying problems that are investigated in the present thesis. With the help of systems engineering, the practical case study will draw up concepts of possible steering systems that might provide a solution to current problems in the automotive industry, which means that the case study is based on a conceptualized approach. As a matter of fact, this allows to run through a vast amount of possible solutions, which in turn enables to view the problem from different angles.

[1] For detailed information on systems engineering, see chapter 4.

1.5 Structure of this thesis

Chapter 1 provides an introduction to the present thesis, illustrating the initial situation of the company TKS. This is followed by a problem definition, a brief summary of the main objectives, as well as an outline of the approach and structure of this thesis.

In chapter 2, mechatronics systems are introduced and an overview of the structure is given. Furthermore, fly-by-wire and brake-by-wire are presented as examples of a successful integration of electronics in mechanical products.

In chapter 3, current trends in the automotive industry are described. Moreover, their impacts on the automotive landscape as well as the changes they entail are explained in detail.

Chapter 4 describes the systems engineering approach and its philosophy, which also includes the discussion of the systems engineering philosophy, as well as its components *systems thinking* and *action models* in order to determine suitable methods to solve the present problem. The procedure according to *HALL-ETH* and the *VDI 2206 Mechatronic Systems Engineering* are presented as generic action models.

In chapter 5, the impacts on TKS are investigated in the case study. First, the company TKS as well as its environment, problems and objectives are introduced. Next, selected OEMs are investigated (the focus being on new OEMs and their business models) and compared with one traditional OEM. The most important findings and impacts are highlighted. Additionally, steering systems and their evolution are explained in detail and a current system still in development is presented. Here, the creativity method *morphological scheme* is used to support the process of inventing such a system. In the end of this section, the findings of the concepts are illustrated and discussed. In the last sub-chapter, impacts on the manufacturing engineering process with regard to the concepts are displayed. By transferring the concepts to real products, manufacturing procedures can be defined and the changes concerning machinery, investment and real estate areas can be highlighted. Finally, the concepts are compared and the findings are analyzed and discussed.

Chapter 6 provides a brief summary of the entire research as well as a future outlook that tries to initiate a possible discussion of further issues.

2 Mechatronic Systems

Innovative products play an increasingly important role in today's modern industries. Such recent innovations in the automobile industry are, for example, brake assistant systems and adaptive cruise control. Innovative systems like these require "*an interdisciplinary combination of mechanical engineering, electrical engineering and information technology*" (VDI 2206, 2004), which can all be subsumed with the technical term *mechatronics*. Mechatronics makes it possible to create both innovative products that are advantageous compared to currently used products, as well as completely new and yet unknown products. The successful realization of mechatronics systems has a huge importance for future vehicles and the competitiveness of automotive manufacturers (Wallentowitz & Leyers, 2014). The purpose of this chapter is thus to describe mechatronics and present successful realizations of mechatronics systems.

2.1 Definition

The term *mechatronics* – a combination of the words *mechanics* and *electronics* – was first used by the Japanese Tetsuro Mori and Ko Kikuchi in 1969 (Mori, 1969; Kyura & Oho, 1996). There exist several definitions of the term. Harashima, et al., (1996), for example, define mechatronics as "*the synergistic integration of mechanical engineering, with electronics and intelligent computer in the design and manufacturing of industrial product and processes*". This suggests that mechatronics is not merely the integration of components and functions, but that it also includes the integration of design and the production of mechatronics systems.

Isermann, (2008) believes that mechatronics "*is an interdisciplinary field in which the following disciplines interact: mechanical system and systems coupled with them, electronics system, and information technology. The mechanical system is dominant here with regard to the functions. Synergetic effects are aimed for, comprising more than the mere addition of the disciplines*".

As suggested, there exist numerous definitions of the term mechatronics in the literature. However, all seem to agree that mechatronics is an interdisciplinary combination and integration of mechanical engineering, electrical engineering and information technology (cf. Figure 1).

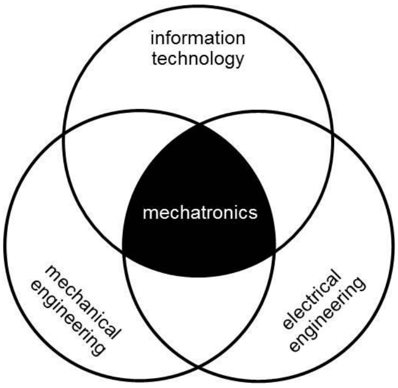


Figure 1 Mechatronics: a combination of different disciplines (adopted from Isermann, 2008)

Nowadays, the term mechatronics is known all around the world and various mechatronics systems have been designed either for personal or commercial use, while in the past, personal computers or CD players functioned as examples for mechatronics systems. As Isermann (2008) explains, the dominating part is the mechanical system. Due to fast technological advancing in the field of computer science engineering, the emphasis of mechatronics systems shifted from hardware to firmware and software (as shown in Figure 2). Smart devices (or smartphones) are mechatronics systems by nature, but possess increasingly sophisticated electronics and software together with a core of mechanical engineering parts. Current trends such as the *Internet of Things*, *Cyber-Physical Systems* and *Big-Data* are further advancing the development of mechatronics systems with sophisticated software and electronics (Hehenberger & Bradley, 2016).

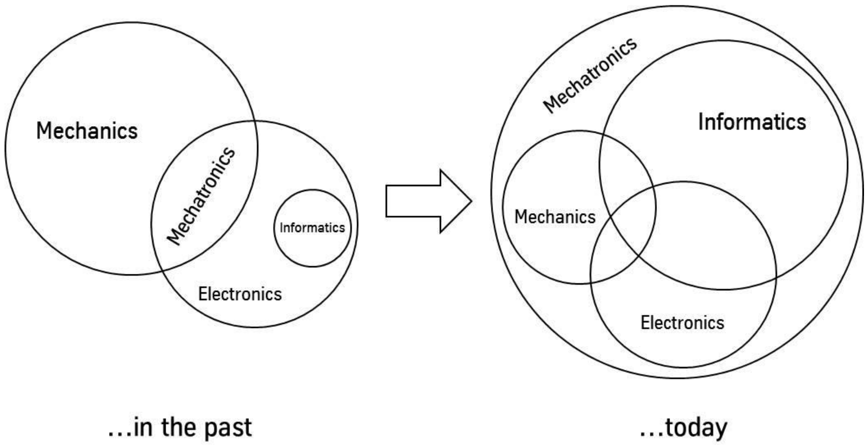


Figure 2 Change of mechatronic systems (adopted from Kühnl, 2010)

2.2 The Structure of Mechatronic Systems

This chapter briefly discusses the structure of mechatronics systems. Usually, it consists of a *basic system*, *sensors*, *actors* and *information processing* which is displayed in Figure 3. A mechatronic system's environment is also important (VDI 2206, 2004). VDI 2206, 2004 describes the elements as follows:

- Basic system: *"generally a mechanical, electro-mechanical, hydraulic or pneumatic structure of a combination*".
- Sensors: their task is to "*determine selected state variables of the basic system*" and to provide input variables for information processing.
- Information processing: via microprocessor, it determines the necessary effects "*to influence the state variables of the basic system*"
- Actors: they transmit these effects to the basic system

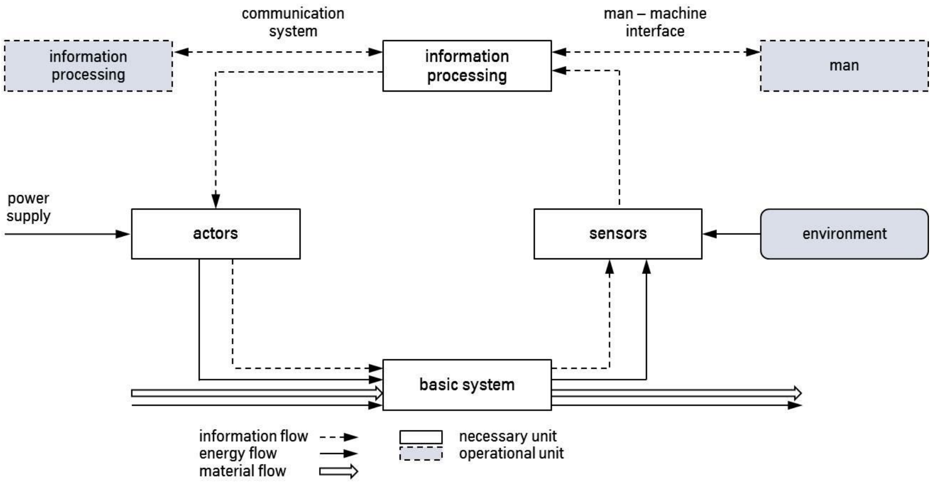


Figure 3 Basic structure of a mechatronic system (adopted from VDI 2206, 2004)

VDI 2206, 2004 describes the interrelation between the individual elements as *flows*. With regard to this, Pomberger & Blaschek, (1996) distinguish three types of flows:

- Material flow: solid bodies, objects being tested, objects being treated, gases or liquids as examples of material that flow between the elements
- Energy flow: any form of energy, i.e. mechanical, thermal or electrical energy and force or current
- Information flow: measured variables, control pulses or data

Complex mechatronics systems require a standard procedure model for development and implementation. In the literature, they are primarily titled *Mechatronic Systems Engineering* or *Systems Engineering* and they shall be discussed later. Further information on mechatronics can be found in several sources, e.g. VDI 2206, 2004; Isermann, 2008; Czichos, 2015; Hehenberger & Bradley, 2016.

2.3 Mechatronics systems as supporting systems

There are several examples for successfully integration of electronics in mechanical products. In this chapter the two products examples *Fly-by-Wire* and *Brake-by-Wire* are briefly discussed. Fly-by-Wire was chosen because it replaced the conventional manual flight controls of an aircraft within an electronic interface. Nowadays, *Fly-by-Wire* is taken as a benchmark for the current development trend *Drive-by-Wire* (Pruckner, et al., 2012) in the automotive industry. Both technologies are investigated and further advantages and disadvantages displayed. In addition, impacts and changes due to this new technologies should be displayed.

2.3.1 Fly-by-Wire

The introduction of the electrical or Fly-by-Wire (FbW) flight control systems was a milestone with regard to aircraft development and has so far enabled great technical advancing hat had been not possible before. The first electrical flight control systems were introduced in military and experimental aircrafts. In the late 1970s, *Concorde* was the first civil airplane into which an analog FbW system was installed. In the next years, the first FbW using digital technology was used in several civil aircrafts such as *Airbus A310*. FbW replaced the conventional mechanical flight control with an electronic interface (see Figure 4). Thereby, the pilot's operation of the flight controls is converted to electrical signals which are then interpreted and modified by computers. These control computers determine which actuators have to move, and how, and determine the right position. FbW offers a variety of advantages, the most notable of course being the reduction in mechanical complexity because aircraft manufacturers are no longer restricted to route control cables from the cockpit to the wing or tail (Briere, et al., (2001) and Traverse, et al., (2004)).

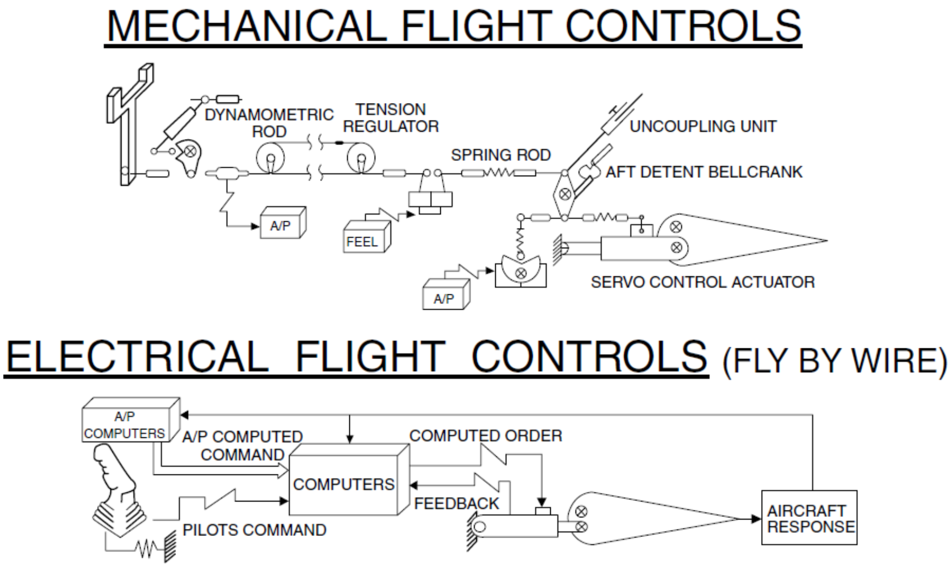


Figure 4 Mechanical and electrical flight control (adopted from Briere, et al., 2001)

Besides the reduction of the complex mechanical connections, Collinson, (2011) presents several additional advantages of a well-designed FbW control system:

- Increased performance: FbW allows for "*a smaller tail plane, fin and rudder to be used, thereby reducing both aircraft weight and drag, active control of the tail-plane and rudder making up for the reduction in natural stability*". This makes possible technical and special configurations for civil and military aircrafts (better maneuverability and handling, additional freight)
- Reduced weight: electric elements are lighter compared to the mechanical signal controls. FbW eliminates several complex mechanical parts and their disadvantages (friction, backlash, structure flexure problems). A reduced weight allows to build lighter aircrafts which can lift bigger freights.
- FBW control sticks/passive FBW inceptors: smaller and compact pilot control sticks and thus a more flexible layout for the cockpit are possible.
- Automatic stabilization: the pilot can release the control systems and the airplane will automatically go back to a horizontal position (also called hands-off stability).
- Carefree maneuvering: an automatic limit which ensures that the pilot's command inputs do not enter an "*unacceptable attitude or approach too near its limiting incidence angle"* of the aircraft.
- Ability to integrate additional control: *"These controls need to be integrated automatically to avoid an excessive pilot workload".*
- Ease of integration of the autopilot: the existing electrical interface and the maneuver command control make the autopilot integration task simpler.
- Aerodynamics: FBW flight control is essential to provide acceptable, safe handling across the flight envelope during stealth flights.

Collinson, (2011) explains that an FbW system must be as safe as the replaced mechanical control system. The safety level is defined in terms of the probability of a failure in the system (for whatever reason), which results in a loss of control over the aircraft. In general, the probability of failure or the failure in time-rate (FIT-rate) differs between military and civil aircrafts. For military aircrafts, the FIT-rate is defined at 10^7 and for civil aircrafts at 10^-9, the latter describing that one failure is expected in one billion operating hours. Most of these requirements are directly defined by Aviation Authorities (FAA, EASA, etc. refer to FAR/JAR 25, (2016)). Collison, (2011) argues that such low FIT-rates are difficult "*to appreciate and also impossible to verify statistically*". Furthermore, he calculates that a fleet of 3,000 aircrafts with a FIT-rate of 10^-9 would result in one catastrophic failure of the FbW system in 100 years, which makes a FIT-rate of 10^-7 more realistic for him.

Traverse, et al., (2004) display several threats (i.e. failures caused by physical faults, design and manufacturing errors, accidents in the man-machine interface) and describe further solutions for FbW systems. For components redundancy, Traverse, et al., (2004) and Collison (2011) present the quadruplex actuation system as a possible solution. This includes four completely independent "first stage" actuators that operate the system. Collison, (2011) explains that the "*failure survival philosophy of a quadruplex actuation system is that if one actuator fails, the three good ones can override it*." An aircraft and the overall FbW system with all interconnected sensors, computers and actuators could thus overcome two failures (for whatever reason they happened). The quadruplex is a good solution with regard to the number of redundant channels and the required redundancy. Besides the electronic and mechanic parts of the FbW system, the software gets special attention: in fact, its development is one of the most challenging tasks in FbW design and accounts for 60% to 70% of the total development costs of the complete system. The difficulty lies with the software's size and complexity and thus the required verification and validation to guarantee its safety (Collinson, 2011). Collinson describes the V-model as a software development process to manage the complexity. Further information about FbW systems and their redundancy is provided by Briere, et al., (2001), Traverse, et al., (2004) and Collison (2011).

2.3.2 **Brake-by-Wire**

Besides Fly-By-Wire, Brake-by-Wire (BbW) systems are often used as a benchmark for the current trend *Drive-by-Wire* in the automotive industry. VDI 2206 (2004) believes that the brake is an impressive example for illustrating the evolution from a purely mechanical to a mechatronic system and the "*synergetic cooperation between the domains of mechanical engineering, electrical engineering and information technology*" as well as how "*existing functions can be improved and new functions can be generated*". As far back as the beginnings of the automotive industry, brake systems, apart from steering systems, have always been one of the most important safety features of a vehicle. They "*must be absolutely failsafe and capable of bringing the vehicle to a standstill over the shortest distance under all driving conditions, while maintaining stability*" (VDI 2206, 2004).

At first, the development of the brake was strongly related to improving mechanical parts and increasing the braking force by adding an additional hydraulic brake system. The limits of a purely mechanical brake system were reached and developers needed complex control tasks. In 1978, the first anti-lock braking system was introduced in which several additional systems (sensory, electronic control devices, hydraulic shift valves, etc.) had been added to the mechanical brake. The ABS function prevented a locking up of the wheels even under extreme driving conditions, so that the driver is able to steer the vehicle in any situation. Over the next years, the brake system was further improved but the ABS is still referred to as a mechatronic system of the first stage. A mechatronic system of the second stage was the revolutionary electronic stability program ESP which was introduced in 1995. Importantly, it needed the development of mechatronic brake systems and the ABS in order to construct the ESP, an electric driver assistant system that improves the vertical vehicle stability by detecting a loss of steering control. The system automatically brakes to support the steering of the vehicle: every wheel's brake is automatically and individually applied, thus enabling the driver a controlled corner steering while preventing under- and oversteering (Breuer & Bill, 2012).

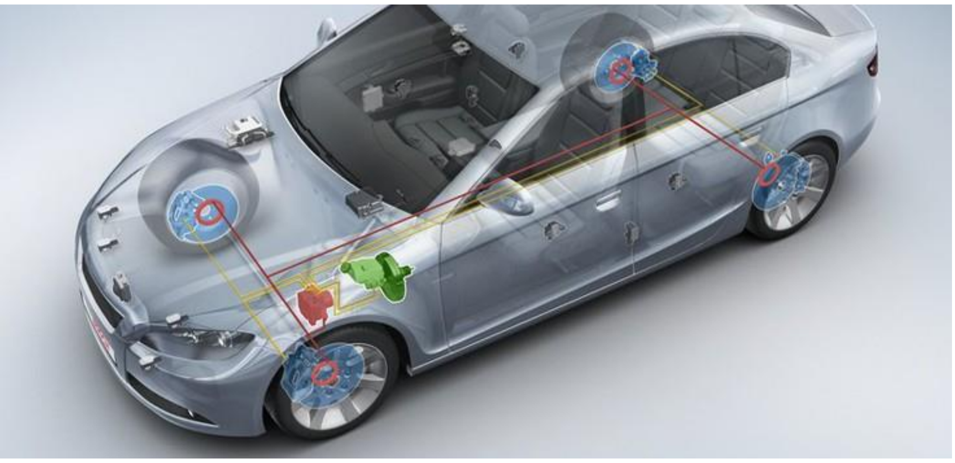


Figure 5 View of a vehicles brake system (Bosch Automotive, 2016)

2001 saw the next evolutionary step of the brake system: the separation of the connection between the wheel brakes and the pedal. The brake pedal was replaced by an actuating unit that transmits signals via electronic channels to the controller. The BbW controller unit sends these signals together with information from other electronic assistance systems (e.g. ABS, ESP, etc.). Subsequently, the control unit calculates the braking commands to ensure maximum deceleration and vehicle stability. Depending on the driving situation, the ideal braking pressure is calculated for each wheel. In 2006, the step towards a purely electric mechanical BbW system was made by replacing the hydraulics with electrical parts (e.g. only used for the parking brake). The use of electronics reduced maintenance of the brake systems and made the expensive disposal of the brake fluid no longer necessary. Furthermore, the ergonomic arrangement and the reduced operational force resulted in a stopping distance reduced by 20 % at a speed of 100 km/h. The smaller physical size (provided by using mechatronic parts) additionally resulted in more installation space in the passenger compartment (VDI 2206, 2004).

The hydraulic fallback system provides the electrohydraulic brake with a fail-safe redundancy. Even in the case of complete failure or a loss of energy, the driver can still stop the vehicle by applying pedal force, even if the purely electronic BbW system has no failsafe redundancy. The individual brakes do not need to be redundant but in case of a failure, it has to be ensured that the brakes do not block the wheels. Breuer & Bill, (2012) further explain that a fallback brake solution has to be provided so as to guarantee braking of the drive gear. If this fallback solution is an actuating device, then it also has to ensure complete fault tolerance. Moreover, it has to be ensured that the systems do not block each other and that enough energy is available (Breuer & Bill, 2012). Breuer & Bill, (2012) ascertain that purely electrical BbW systems still require considerable development.

Currently, several advanced driver assistant systems ADAS are being developed based on the cooperation of electric braking systems with electric (and superimposed) steering systems and additional sensors (Pfeffer & Harrer, 2013). Pfeffer & Harrer, (2013) name lane keeping support, lane departure warning and park assistants as examples for such ADAS; the collision avoidance system which was recently introduced and intervenes in the last possible moment of braking is another example (Breuer & Bill, 2012). It helps to avoid collisions at great velocities and allows for higher stopping distances (Isermann, 2016). The current development of ADAS and electronic systems will result in more intelligent driver assistant systems that will immensely reduce the workload for the driver and increase driving safety as they will prevent that drivers are distracted while driving. Another current trend is automated driving, i.e. an intelligent driving assistant system enabled by connecting already existing ADAS with new sensors and software (Breuer & Bill, 2012).

3 New Trends in the Automotive Industry

130 years ago, Karl Benz designed and built the world's first automobile, the *motorwagen,* with an internal combustion engine (Daimler AG, 2016). Since then, the automotive industry and its actors have made enormous progress. This can be seen in today's cars' performance, their fuel consumption and safety as well as the immense improvements with regard to driving comfort and providing additional information. Moreover, innovations such as the seatbelt or airbags allowing for greater safety as well as a reduced fuel consumption per 100 kilometers with the same or even higher performance speak for themselves. Additionally, the vehicles' quality and interior has been greatly improved even though vehicle prices dropped in comparison to earlier years (Wolters, et al., 1998). New automotive trends emerge almost on a daily basis. In 1998, Wolters, et al., explained that future vehicles will be connected via modern communication technology to the global web and exchange information about the current traffic situation or signal maintenance intervals. Today, such things no longer belong to visions of the future: rather, built-in navigation systems providing real-time information on the current traffic or alternative routes are quite common. Naturally, some inventions predicted in the past are still a thing of the future even today: for example the reduction of CO_2 emission (Wolters, et al., (1998); Ebel & Hofer, (2014)), globalization (Wolters, et al., (1998); Wolters & Hocke, (1999); Diez, (2015)) or shortening the product development process (Wolters, et al., (1998), Weber, (2009); Hirz, et al., (2013)). Generally, there exists various information (in literature, scientific papers and others) on the automotive industry, which is due to its great importance. Currently, the automotive industry generates a revenue of USD 3.5 billion worldwide. Thus, the present discusses current trends in the automotive industry.

The global automotive industry is facing major technological and structural upheavals at the moment. Kaas, et al.'s, (2016) study reveals the following four disruptive technology[2] trends which will affect the automotive industry until 2030: *diverse mobility*, *connectivity*, *electrification* and *autonomous driving*, which is supported by other literature as well (Kalmbach, et al., (2011), Ebel & Hofer, (2014), Winterhoff, et al., (2015)). In the next sections, these disruptive trends are briefly discussed and, in the end, their role in the present automotive industry is investigated.

---

[2] Christensen, (2011) defines a disruptive innovation as a product or service which is designed for a new set of customers. He argues that disruptive innovations can successfully damage companies that are well managed, have excellent R&D and are reliable towards their customers. "*Generally, disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches. They offered less of what customers in established markets wanted and so could rarely be initially employed there. They offered a different package of attributes valued only in emerging markets remote from, and unimportant to, the mainstream*" (Christensen, 2011)

3.1 Diverse Mobility

The increased demand for mobility is a worldwide issue. Until 2020, the global population will increase by further 800 million to a total of 7.7 billion people (Stricker, et al., 2011). Stricker et al.'s, (2011) survey shows that 90% of this increase will happen in Asia and Africa, and they assume that each person's travelled kilometer will increase likewise. This results in increased car traffic which already presents a huge problem in almost all big cities, e.g. daily traffic jams and constant reduction of parking spaces (Bratzel, 2014). Kaas, et al. (2016) believe that this will result in a huge burden for car owners. In addition, Bratzel (2014) illustrates that the mobility behavior of younger generations has already changed towards the trend that having a car is not important any longer.

In line with this, Stricker et al., (2011) present car sharing as a possible solution for the increased demand in mobility and the consequently altered mobility behavior. In 2011, the first business models using car sharing emerged (e.g. *Car2Go, DriveNow*). Today there exist numerous car sharing and mobility provider business models that provide solutions for almost every problem. Often named in connection with this is the business *Uber*, a relatively new provider that allows its customers to make trip requests via their smartphone in order to contact Uber drivers who use their own cars to provide taxi-services (Uber Technologies Inc., 2016). Uber is currently valued at USD 62.5 billion (Newcomer, 2015) and is pushing the development of self-driving cars (Kalanick, 2016). The aim is to prevent the development of self-driving taxis that can be requested via smartphones and that would lead to high unemployment rates among taxi drivers. Kaas, et al., (2016) summarize that stricter regulations, technical innovations and consumer preferences will add to the fundamental shift in mobility behavior until 2030 as shared mobility provides consumers with optimal solutions for almost every problem.

3.2 Connectivity

In modern countries, mobile providers achieved a comprehensive, fast and stable mobile coverage. Besides being able to use one's phone almost everywhere, the internet connection allows to connect cars which, in turn, makes possible an exchange of information between the car and its environment. This connection between the vehicle and the internet is provided either by a built-in transmitter and receiver, an own SIM card or an external system such as a smartphone. This has several advantages for stakeholders, customers, automotive manufacturers and states. Automotive manufacturers are directly connected to their customer and can thus present new mobility and business models. The driver can be assisted with intelligent information systems providing real-time traffic or personalized routing information. This results in more comfortable driving and higher safety. Moreover, traffic could be actively monitored and influenced which allows for increased safety. Johanning & Mildner, (2015) summarize their findings in three main fields: safety, efficiency/economy and infotainment. These enable a merging of the automotive and mobile industries which has a market potential of more than one billon vehicles, making possible numerous new business models to meet this rapidly growing market (Johanning & Mildner, 2015).

Siebenpfeiffer, (2014) and Johanning & Mildner, (2015) illustrate several cases, requirements, implementations and challenges of connected car systems. Kaas, et al., 2016 believe that the connectivity "*will increasingly allow the car to become a platform for drivers and passengers to use their transit time for personal activities, which could include the use of novel forms of media and services*".

3.3 Electrification

Electric vehicles (EVs) are almost as old as vehicles with internal combustion engines: the first EVs were introduced in the late 19th century, where they were as popular as vehicles using other driving technologies. Due to their many weaknesses (short cruise range, low speed and short-lived batteries) and the increased development as well as the many advantages (especially concerning higher speeds and the ability to cover longer distances) of vehicles with internal combustion engines, the latter stayed on the automotive market. In the decades to follow, EVs will be a mere peripheral phenomenon and – despite the climate change and the oil crisis pushed EV technologies – their many disadvantages could not yet have been solved sufficiently (Thomas, et al., 2013).

In the last years, the issue of *electro mobility* increasingly gained media attention due to the problems of diminishing natural resources and environmental pollution. Conventional combustion engines will not solve these problems, which is why EVs can function as a possible solution (Thomas, et al., 2013). Especially in the last years, EVs were met with new enthusiasm due to high oil prices, improved battery technologies[3] and expanded recharging infrastructure (Dijk, et al., 2013), and new business models emerged (Bohnsack, et al., 2014). Chen & Perez, (2015) additionally found out that the development of the EV industry can be further pushed by innovations with regard to the battery and infrastructure system. Moreover, new business models will focus on being service-oriented (Kley, et al., 2011). Already, it seems that traditional and new OEMs focus on developing EVs (see chapter 5.2.2). Traditional OEMs also follow these trends, e.g. with the BMW i-series vehicles or the BMW *ChargeNow* service that allows charging of EVs (Bayrische Motoren Werke AG, 2013). Further information on requirements, limitations and opportunities of electric mobility is presented by Kampker, et al., (2013).
In the last year, the number of sold EVs has grown rapidly, rising from 45,000 EVs sold in 2011 to more than 300,000 in 2014. Furthermore, EVs increased their market share and accounted for 1% of new car sales in the Netherlands, Norway, Sweden and the United

[3] In this case, battery technologies can be either battery or fuel cell technologies (Hardman, et al., 2013).

States (EVI - Electric Vehicle Initiative, 2015). In comparison to the sales of vehicles with internal combustion engines, this is only a drop in the ocean, but Kaas, et al., (2016) emphasize that the share of EVs could be up to 50% in 2030. The strength of the EV market might be further enforced by stricter emission regulations, lower battery costs, widely available charging infrastructure and increased consumer acceptance (Kaas, et al., 2016). Figure 6 displays the cumulative sales targets which will continuously grow to 6 million sales in 2020.

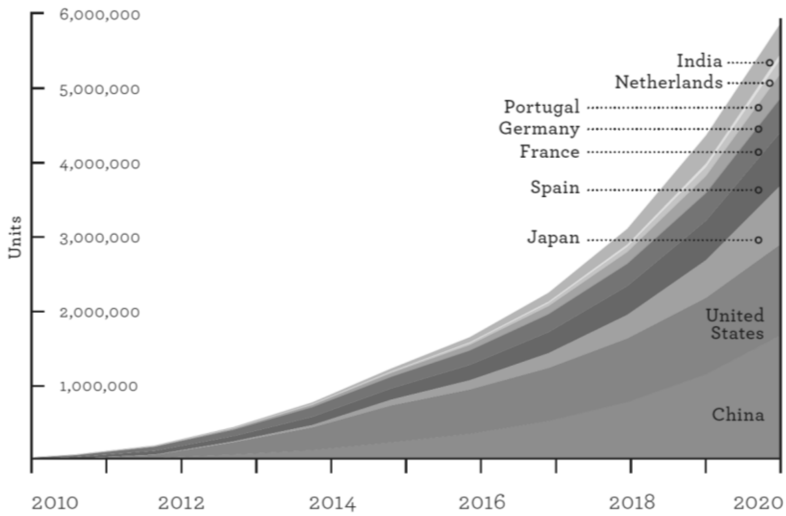


Figure 6 Sales targets of the most important EV countries (EVI - Electric Vehicles Initiative, 2013)

3.4 Autonomous Driving

Autonomous driving is the trend in the automotive industry that currently receives the most attention in the press, literature and scientific papers. Back in the 1980s, the self-driving *Pontiac Firebird Trans Am* “KITT” from the television series *Knight Rider* was a science-fiction scenario. Today, however, the autonomous car is no longer a vision; rather, it is considered the most disruptive technology that the automotive industry has ever seen. Today, advanced driver assistant systems ADAS and active safety systems are so comprehensively developed that the step to autonomous driving appears almost inescapable (Johanning & Mildner, 2015).

General ADAS play a significant role in preparing both regulators and consumers for autonomous driving (Kaas, et al., 2016). Advanced driver assistant systems that are already in use are for example *adaptive cruise control*, *lane keeping assistants*, *pre-crash systems*, *automated parking*, *traction control* or *anti-lock braking systems*. In order to realize a fully automated vehicle, further key systems have to be installed which provide smart cooperation with the already existing ADAS (Johanning & Mildner, 2015). Johanning & Mildner, (2015) describe several key systems and sensors which are necessary to achieve fully autonomous driving, e.g. *LIDAR* (Light Detection and Ranging), smart algorithms, car-to-car communication and car-to-infrastructure control. These mechatronics systems allow interactions that result in a complex system (Johanning & Mildner, 2015).

The term *fully autonomous driving* should be explained before discussing it further. In January 2014, SAE International issued their J3016 standard which provides a common taxonomy and definition of automated driving. SAE (2014) lists six levels of driving automation from no to full automation (see Figure 7)

SAE level	Name	Steering and acceleration	Monitoring of driving	Fallback performance	System capability
		Human driver monitors the driving environment			
0	**No automation**	Human driver	Human driver	Human driver	n/a
1	**Driver assistance**	Human driver and system	Human driver	Human Driver	Some driving modes
2	**Partial automation**	System	Human driver	Human driver	Some driving modes
		Legal issues			
		Automated driving system (“system”) monitors the driving environment			
3	**Conditional automation**	System	System	Human driver	Some driving modes
4	**High automation**	System	System	System	Some driving modes
5	**Full automation**	System	System	System	All driving modes

Figure 7 SAE Levels of driving automation (adopted from SAE International, 2014)

SAE defines these levels as follows:

- <u>No automation:</u> “*the full-time performance by the human driver of all aspects of the fallback performance, even when enhanced by warning or intervention systems*”
- <u>Driver assistance</u>: *“the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the fallback performance of dynamic driving task*”
- <u>Partial automation:</u> *“the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the fallback performance of dynamic driving task”*
- <u>Conditional automation:</u> *“the driving mode-specific performance by an automated driving system of all aspects of the fallback performance of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene”*

- High automation: *“the driving mode-specific performance by an automated driving system of all aspects of the fallback performance of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene”*
- Full automation: *“the full-time performance by an automated driving system of all aspects of the fallback performance of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver”*

Furthermore, SAE J3016 describes the key definitions as follows:

- Fallback performance of the dynamic driving tasks includes “*the operational (steering, braking, accelerating, monitoring the vehicle and roadway) and tactical (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the strategic (determining destinations and waypoints) aspect of the driving task.*”
- System capability (driving modes) is a type “*of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, closed-campus operations, etc.)*”

A major distinction is made between level 2, where the driver is the fallback performance, and level 3, where the automated systems perform the entire fallback performance. Furthermore, SAE (2014) explains that these levels are “*descriptive rather than normative and technical rather than legal*” and they “*imply no particular order of market introduction. Elements indicate minimum rather than maximum system capabilities for each level. A particular vehicle may have multiple driving automation features such that it could operate at different levels depending upon the feature(s) that are engaged*”.

Experts believe that the main advantage of autonomous driving is the increased traffic safety. In fact, speeding, ignoring traffic rules and not keeping the distance to other vehicles are the main reasons for accidents with personal injuries (Johanning & Mildner, 2015). Also, autonomous vehicles cannot be driven drunk. However, several legal issues have to be solved, especially concerning machine ethics, i.e. the factor of which option the system should select: A (drive into a group of children) or B (drive into a wall and hurt the passenger). This and other ethical issues have to be solved or else automated vehicles (even sophisticated ones) will continue to fail crash tests (Goodall, 2014).

All these unresolved technical, legal and social issues are the last hurdle that stands between autonomous driving and its realization on today’s streets (Johanning & Mildner, 2015). In the last months, several states dealt with the legal problems of autonomous driving because current traffic regulations are still based on the *Vienna Convention on Road Traffic* signed back in 1968 (UN Secretary-General, 1968). Thus, first states have already taken action to enable the development of autonomous driving (cf. BMVI, (2015); NCSL US, (2016)). Based on its advantages, it is only a matter of time until autonomous driving will be fully implemented (Johanning & Mildner, 2015). Kaas, et al., (2016) believe that once all legal restrictions and technological issues are resolved, up to 15% of new cars could be fully autonomous by 2030.

3.5 Impacts on the automotive landscape

The presented disruptive innovations have major impacts on the automotive industry – both on established and new players. Several years ago, established OEMs (henceforth called "traditional OEMs") merely interacted with established suppliers and competed with other traditional OEMs. In early 2000, new OEMs emerged mainly in China, for example *BYD, Great Wall* or *Geely* (Diez, 2015). In recent years, further new OEMs such as *Tesla, Faraday Future* or *NextEV* emerged and are now competing – together with tech giants such as *Google* or *Apple*, and mobility providers such as *Uber* and *Zipcar* – against traditional OEMS. Figure 8 illustrates the resulting complex automotive landscape, showing that traditional OEMs now fight on multiple fronts (Kaas, et al., 2016). In fact, this is also visible in other industries, where new products and customer needs have big impacts on the existing industrial landscape (e.g. Apple's smartphone and *Nokia*) (Winterhoff, et al., 2015). Nevertheless, some traditional OEMs have successfully managed to refocus and adapt to current changes.

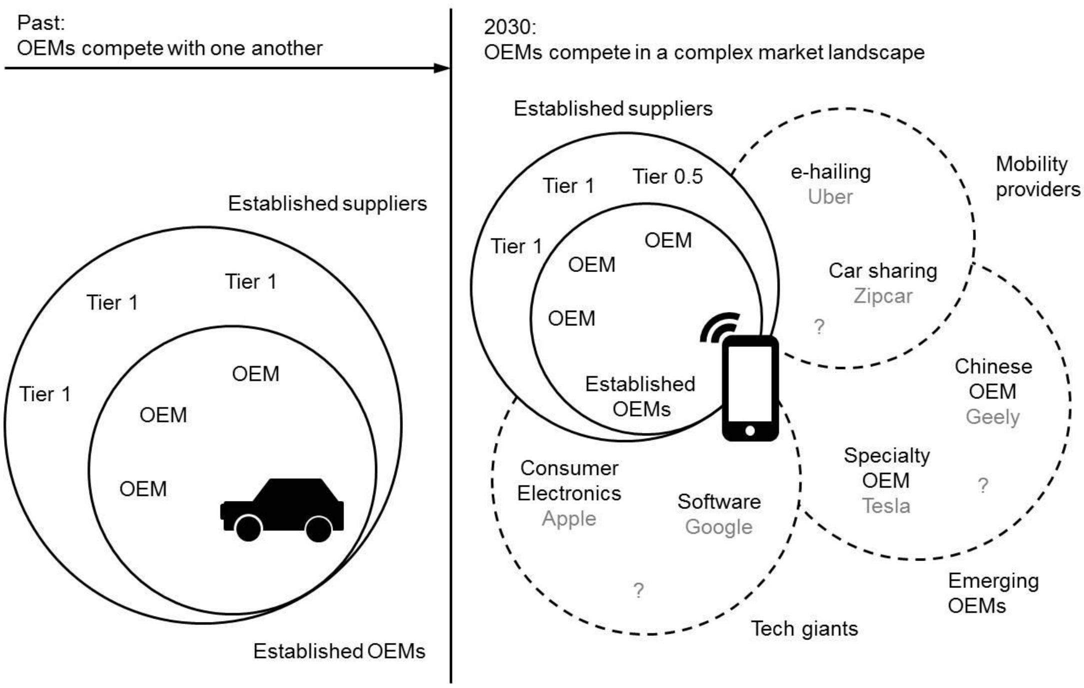


Figure 8 Competitive Landscape in 2030 adopted from Kaas, et al., (2016)

Emerging OEMs now target only specific economically attractive segments and activities along the value chain before exploring further potential fields (Kaas, et al., 2016). As shown in in Figure 9, Kaas et al. display that emerging OEMs focus on design, software development and sales. In fact, software is the factor that makes current trends in the automotive industry possible in the first place. Therefore, hardware development of sub-systems is not that important for emerging OEMs. Rather, established suppliers will increase the share of the vehicles' total value (Kaas, et al., 2016). In recent years, the proportion of vehicles from OEMs decreased from 30% to 20% of the total vehicle value (Diez, 2015). Established suppliers provide complete vehicle systems and sub-systems to the OEMs. Here, strategic alliances and partnerships across technologies help to successfully develop a car and further reduce its costs.

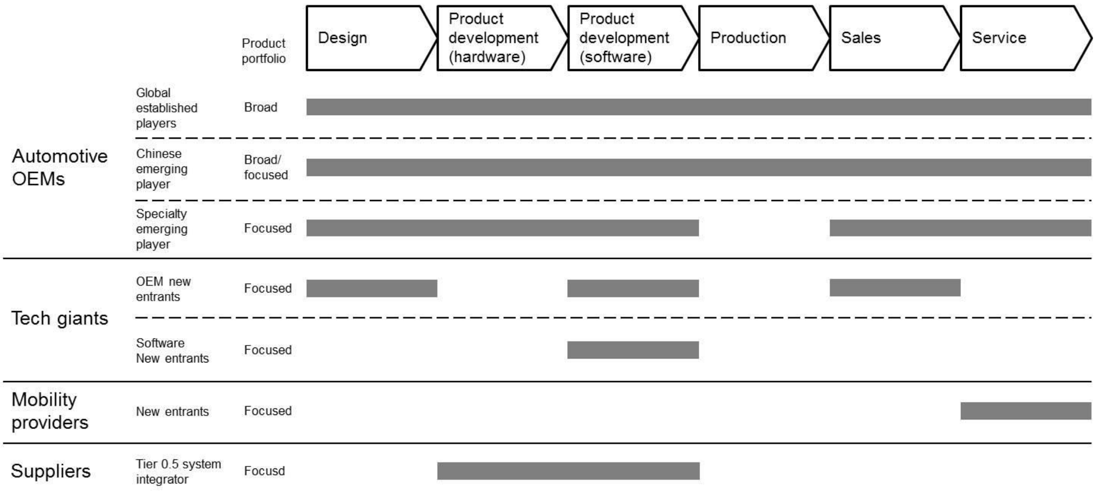


Figure 9 New entrants are focusing on selected product and processes along the value chain adopted from Kaas, et al., (2016)

Especially emerging OEMs try to facilitate their growth with strategic alliances and frontloading development which allows fast production (Aggeri, et al., 2008). As a result, strategic alliances have increased dramatically and also changed the competitive paradigm. Nowadays, international markets show alliance-based, network-to-network competition as compared to former firm-to-firm competition (Lorenzoni & Baden-Fuller, 1995). The aim for many companies is to identify, improve and ensure their competitive advantages and develop new strategies (Dyer, et al., 2001). Alliances create knowledge and change the customer value proposition. Furthermore, they can be seen as a tool for effective firm learning, especially with regard to radical technology development with a high degree of uncertainty (Aggeri, et al., 2008). This can be seen in the field of hybrid and plug-in hybrid/electric vehicles (Holmberg, 2011). Other industries related to the automotive industry are also affected by current changes (Bertoncello & Wee, 2015), e.g. due to the introduction of autonomous driving. Bertoncello & Wee, (2015) display that car insurances, for example, changed their business models because accidents and insurance in general will decrease in the future – however, they now focus on insuring the automotive manufacturers against "liabilities to technical failure" of their AVs.

As shown, new trends have impacts on the automotive industry by giving rise to new, changing existing and eliminating current business models. Thereby, the automotive industry landscape will become increasingly complex and provide suppliers with a stronger basis by preventing finished and pre-produced systems.

4 Systems Engineering

In the modern economy and science, the complexity of products and projects steadily increases. In order to develop such products or investigate such complex[4] systems, a structural and systemic approach is required.

Systems engineering is an interdisciplinary and methodological approach which seeks to successfully manage and design highly complex systems. In the early 1940s, the term *systems engineering* was first used by *Bell Telephone Laboratories* (Schlager, 1956). In the following years, the evolution of SE with the aim to develop complex and highly technical systems was driven forward by different institutions, for example *Military Systems* by the US Department of Defense, or *Space Systems* by the National Aeronautics and Space Administration (NASA).

The literature provides several descriptions and different views of the term systems engineering:

- <u>For the NASA (1995), systems engineering is…</u>
  "*…a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals*."
- <u>For the Department of Defense (2001), Systems Engineering…</u>
  "*…consists of two significant disciplines: the technical knowledge domain in which the systems engineer operates, and systems engineering management.*"
  The Department of Defense puts the focus on the process of systems engineering management and defines it as…
  "*…an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs*"*.*
- <u>For INCOSE, (2006), systems engineering is…</u>
  "*…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, and then proceeding with design synthesis and system validation while considering the complete problem.*

[4] The terms *complexity* and *complicated* are widely used and often refer to the same systems. Ulrich and Probst distinguish between *complexity* and *complicated*, and understand complexity as a system feature where the degree depends on the number of elements; their interconnectedness and the number of different system states, on the other hand, is complicated. (Ulrich & Probst, 1995)

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."

Overall, SE can be summarized as a structured interdisciplinary management approach which has the objective to successfully solve complex problems in the most *cost-effective*[5] way by *considering performance, cost, schedule and risk* (NASA, 1995).

SE emerged as an effective approach which manages complexity and reduces possible risks. The increased complexity of a product has direct impacts on the life cycle because of longer developing times. In order to provide an overview of complex systems, action and thinking models may be of help (Winzer, 2013).

With all projects and/or products, the cost/benefit-factor is always very important. This needs a systematic approach as SE covers the entire project life-cycle because it is employed from the pre-concept phase onwards. If a problem is detected at the beginning of the project, this results in less costs than if it was detected in a later project phase. If fixing a problem costs one Euro in the requirement phase, it might cost 40 Euro in the test phase and 250 Euro in the operation phase. Due to the higher effort in the early phases, SE enables to act and influence these events. INCOSE (2006) explain that 20% of the average project costs can be reduced by using SE.

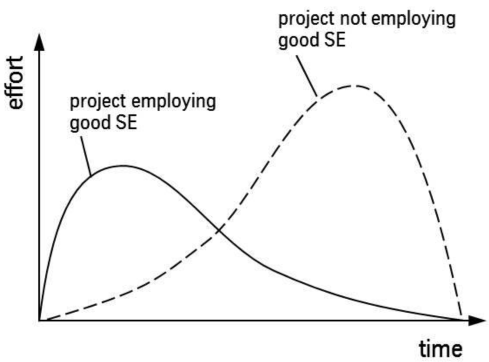


Figure 10 Total effort (therefore total cost) of solving a problem is less when done early in the project lifecycle (adopted from INCOSE Uk ltd., 2009)

Systems thinking and *action models* are necessary parts of the SE philosophy in order to find methods to solve the problem. Systems thinking is a way of thinking which is used to address uncertain and complex real world problems. According to INCOSE (2006),

[5] "*A cost effective system must provide a particular kind of balance between effectiveness and cost: the system must provide the most effectiveness for the resources expended or, equivalently, it must be the least expensive for the effectiveness it provides. This condition is a weak one because there are usually many designs that meet the condition. Think of each possible design as a point in the tradeoff space between effectiveness and cost*." (NASA, 1995)

systems thinking "*recognizes that the world is a set of highly interconnected technical and social entities which are hierarchically organized producing emergent behavior*".

The procedure or action model is a structured holistic process for handling projects. Thus, the model supports the developer and defines when logical steps and tasks have to be taken. There exist procedure models for micro and macro levels. (Lindemann, 2005)

Furthermore, several systems engineering approaches can be found in the literature. In this thesis, the SE approaches "*SE according to Hall-ETH*" (Haberfellner, et al., 2015) and "*Design methodology for mechatronic systems*" (VDI 2206, 2004) are discussed. Other approaches are the "*SIMILAR Process*" according to Bahill & Gissing, (1998) and the "*Munich Procedural Model – MPM*" according to Lindemann, (2005).

4.1 System Theory

The interdisciplinary science system theory aims at the comparative study of systems. Ludwig von Bertalanffy[6] is considered as the founder and one of the principal authors of the "General system theory". His publications "*The Theory of Open Systems in Physics and Biology*" (1949) and "*General System theory: Foundations, Development, Applications*" (1976) describe new ways of thinking at their time of publishing.

Bertalanffy, (1976) defines systems as "*sets of elements standing in interrelation*". In fact, a system is not just made up of its components, but it is the relations, i.e. how they interact, which are important. "*You cannot sum up the behavior of the whole from the isolated parts, and you have to take into account the relations between the various subordinate systems which are super-ordinated to them in order to understand the behavior of the parts*". (von Bertalanffy, 1976) Furthermore, he describes the terms *complexity, open,* and *dynamic systems* and tries to mathematically describe these systems.

According to Weckowicz, (1989) "*Ludwig von Bertalanffy … occupies an important position in the intellectual history of the twentieth century. His contributions went beyond biology, and extended into cybernetics, education, history, philosophy, psychiatry, psychology and sociology. Some of his admirers even believe that this theory will one day provide a conceptual framework for all these disciplines*".

The general system theory and the theory of cybernetics as well as their combination form the basis for all further modern system theory approaches. Some examples are listed in the following:

- Game Theory: "*the study of mathematical models of conflict and cooperation between intelligent rational decision-makers*". (Myerson, 1991) The concept of game theory is to provide a language to structure, formulate, analyze, and understand strategic situations. A strategic situation (or strategic game) involves two or more individual interacting players which face a set of actions with given rules of playing. Each action results in gain or loss, depending on what the other players choose to do or not to do. (Myerson, 1991)
- Chaos Theory: formally defined as "*the study of a-periodic behavior in nonlinear dynamic systems*." Chaos theory investigates insights into non-linear dynamics, uncertainties, and unpredictable system behaviors. In this context, the butterfly effect is popularly referred to: it describes a meteorologist concept that the flapping of a butterfly's wings in one part of the world can result in a huge storm on the other side of the world weeks later. (Cambel, 1993)

[6] Biologist, human and system scientist; born in September 19, 1901 in Atzgersdorf, Austria and died in June 12, 1972 in Buffalo, NC, USA

4.1.1 Definition

The term *system* is generally and widely used, for example in *IT system, transport system, solar system, economic or education system*. Generally, systems can be products (hard- and software), processes, persons or organizations. As there exist numerous meanings, the term shall be described first. The literature gives several definitions, according to which a system is:

1. *"a set of objects, together with relationships between the objects and between their attributes"* (Hall & Fagen, 1956)
2. *"a set or arrangement of elements and processes that are related and whose behavior satisfies customer/operational needs and provides for life cycle sustainment of the products"* (IEEE STD 1220, 1998)
3. "*a combination of interacting elements organized to achieve one or more stated purposes*" NASA, (1995) and INCOSE, (2006)
4. *"a set of connected things or devices that operate together"* (Cambridge Dictionary, 2016)

In summary, a system consists of elements and relations which form a unified entity. However, these two aspects are not enough to completely describe a system because it lacks explanations on how the system is limited, which characteristics and relations its elements show, and what the purpose of the system is. The system as a whole and its related components are displayed in Figure 11.

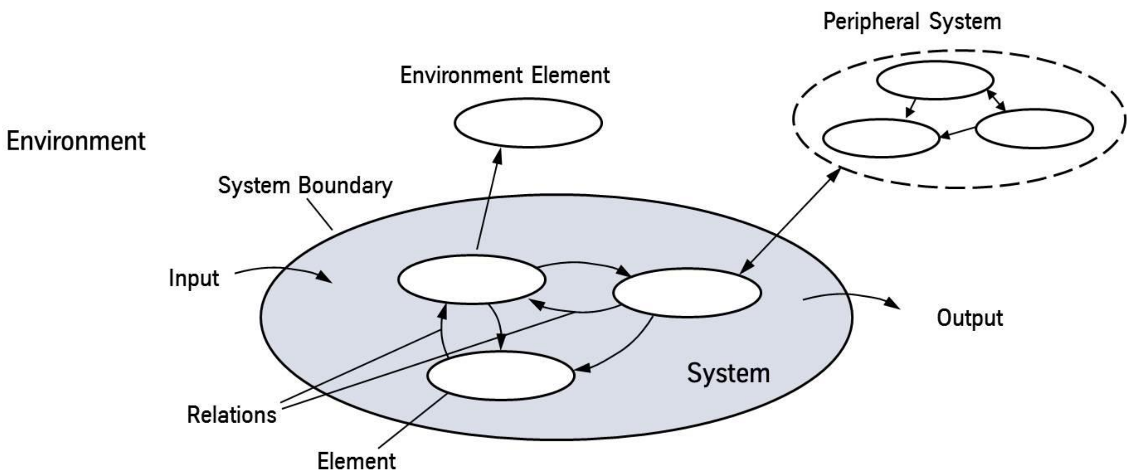


Figure 11 System and its environments (adopted from Haberfellner, et al., 2015)

Haberfellner, et al., (2015) describe a system and its components as follows:

- Systems: consist of related elements.
- Elements: have properties and functions which can be expressed by qualitative and quantitative parameters. Elements interact with others within and beyond systems. These interactions can be related to information, energy or material.
- System boundary: this boundary is a more or less arbitrary line drawn to separate the system from its environment. System boundaries need not be physical boundaries. Within the boundary, the elements' relations are stronger (i.e. more important, higher amount) compared to those between the system and its environment.
- Environment: the area beyond the system boundary.
- Subsystem: if an element is a system itself, the element/system can be subdivided into elements on a lower level.
- Supersystem: each system can be displayed in a higher level as a supersystem by summarizing several systems on the same level.
- System of systems: this describes a system which consists of several individual systems and has two features: it does not depend on the supersystem but works independently and can be acquired separately.

System hierarchy:

The subdivision of a system into several levels results in a hierarchic system setup or system hierarchy. If a system cannot be divided any further, the resulting unit is called element, which is depicted as a Blackbox. (Haberfellner, et al., 2015)

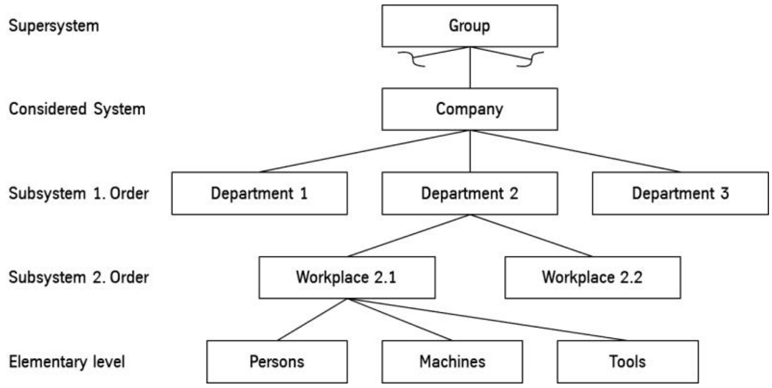


Figure 12 System hierarchy (adopted from Haberfellner, et al., 2015)

Blackbox, Greybox and Whitebox:

The term *Blackbox* is used for systems which can be viewed in terms of their input and output, without having any knowledge of their internal processing.

Figure 13 Blackbox with input and output (adopted from Haberfellner, et al., 2015)

In comparison to the Blackbox, the inner components or logic of a *Whitebox* system are available and known. A *Greybox* system is either grossly (low degree of detail) or partially (degree of detail is different within the depiction) structured. (Haberfellner, et al., 2015)

Furthermore, a system and its interaction with its environment can be described using three different system types (based on the literature):

- Open systems: Open systems interact with their environment, whereby energy and material have to be exchanged. Generally, all real systems are open systems.
- Closed systems: These systems only energetically interact with their environment. They can have several inputs and outputs, but need at least one input and one output.
- Completed (isolated) systems: these idealized systems have no relation with their environment and occur especially in the field of thermodynamics.

Ulrich & Probst, (1995) describe that the interaction of the system elements and relations can be displayed in four basic system types.

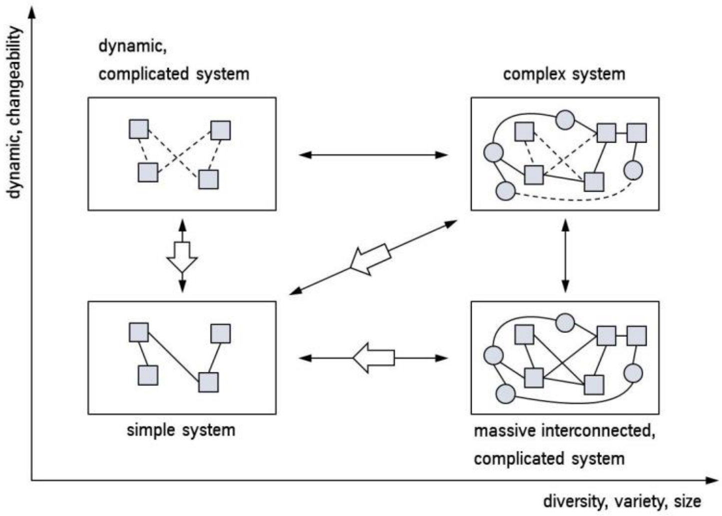


Figure 14 System types (adopted from Ulrich & Probst, 1995)

Figure 14 displays the four basic system types based on their system feature (Ulrich & Probst, 1995):

- Simple systems: simple systems consist of few fixed elements which are constantly related to each other. Due to the simple relations, these systems can be described analytically (in specific cases also mathematically).
- Massive interconnected, complicated systems: these systems are characterized by the large number of elements and a great variety without any dynamic relation. Due to large numbers of factors, it is often difficult to describe such systems.
- Dynamic, complicated systems: these are systems with less variety and with low dynamic interactions. It is difficult to quantitatively describe these systems because of their dynamic character.

- Complex systems: they have a large number of elements which are dynamically related and often show system-wide interactions. Therefore, it is more difficult to describe these systems in a quantitative way.

4.1.2 Cybernetics

In 1948, Norbert Wiener[7] defined the term cybernetics as "*the scientific study of control and communication in the animal and the machine*" in his publication "*Cybernetics: Or Control and Communication in the Animal and the Machine*". Cybernetics is relevant to the study of several systems such as mechanical, physical, biological, cognitive, and social systems. Importantly, Norbert Wiener pointed out that effective action requires communication.

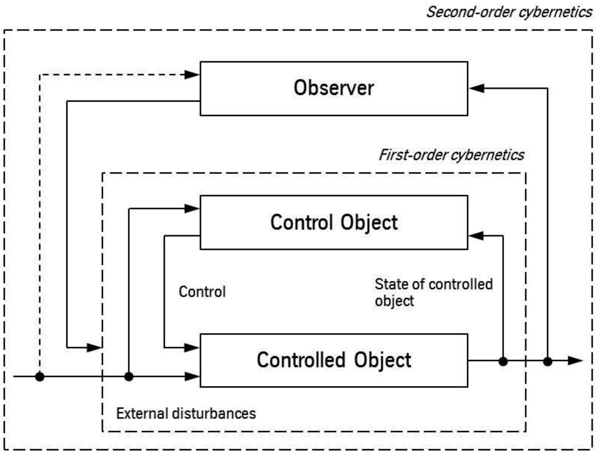


Figure 15 First- and second-order cybernetics (adopted from Novikov, 2016)

The term cybernetics stems from Greek κυβερνητική (kybernetike) which refers to the steersman of a ship and also forms the etymological root of the word "governor".

Since its first usage, several different types of cybernetics came into being (Novikov, 2016). In this thesis, the "*first and second-order cybernetics*" are briefly discussed.

The cybernetics established by Norbert Wiener is often referred to as "first-order cybernetics" in the literature. The primary objective of first-order cybernetics is the analysis and engineering implementation of goal-directed behavior. One typical example of the principles of cybernetics is a room thermostat. This thermostat compares the current temperature (provided by the heat sensor) to the target value set to a desired temperature. The difference between these values causes the controller of the thermostat to regulate the heating system so that the desired temperature will eventually be reached. The state of equilibrium should be reached via feedback loops in accordance with the deviation analysis. Wiener's cybernetics moreover include the following terms: control,

---

[7] Mathematician and philosopher; born on 26 November 1984 in Columbia, Missouri, U.S., died on 18 March 1964 in Stockholm, Sweden

communication, information, system, feedback, black box, variety, homeostat. (Novikov, 2016)

The "*second-order cybernetics*" were described by Heinz von Foerster[8] as the cybernetics of cybernetics. Foerster, (2003) explained that "*a brain is required to write a theory of a brain. From this follows that a theory of the brain, that has any aspirations for completeness, has to account for the writing of this theory. And even more fascinating, the writer of this theory has to account for her or himself. Translated into the domain of cybernetics; the cybernetician, by entering his own domain, has to account for his or her own activity. Cybernetics then becomes cybernetics of cybernetics, or second-order cybernetics.*" Therefore Novikov, (2016) notes that the central concept of second-order cybernetics *"is an observer as a subject refining the subject from the object*" (displayed in Figure 15).

4.1.3 **Systems Thinking**

The perspective of system engineering is based on systems thinking and is an approach to display complex systems in models. For INCOSE, (2006) „*Systems thinking occurs through discovery, learning, diagnosis, and dialog that lead to sensing, modeling, and talking about the real-world to better understand, define, and work with systems*". Moreover, it "*recognizes circular causation, where a variable is both the cause and the effect of another and recognizes the primacy of interrelationships and non-linear and organic thinking — a way of thinking where the primacy of the whole is acknowledged."*

Senge, (2006) defines systems thinking in his book: "*it is a framework for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It is a set of general principles spanning fields as diverse as physical and social sciences, engineering and management".* Systems thinkers think in feedbacks and circular causation (Figure 17), as compared to traditional linear thinking (Figure 16).

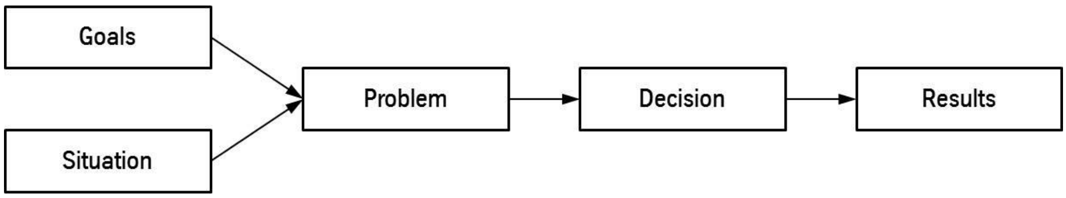


Figure 16 Linear (event oriented) thinking (adopted from Sterman, 2000)

[8] Physicist and philosopher; born on 13 November 1911 in Vienna, Austria and died on 2 October 2002 in Pescadero, California, USA

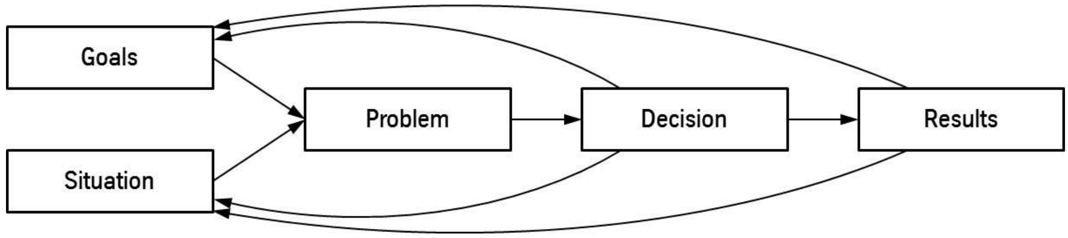


Figure 17 Feedback view (adopted from Sterman, 2000)

Furthermore, Haberfellner, et al., 2015 present several ways of thinking in systems:

- Environmental oriented view
  In the environmental oriented view, the focus is on the environment of the system and the relations between them. The system itself is not considered. Examples are customers, competitors, stakeholders etc.
- Effect oriented view or Blackbox view
  In the effect oriented view, the impacts or inputs from the environment together with possible system behaviors and the resulting effects or outputs are considered. A possible example is the energy balance of a company, i.e. its emissions.
- Structure oriented view
  In this view, the system's elements and their relations are considered, especially with regard to the dynamic effect and processes. The structure oriented view helps to understand how input and output are created. An example could be the material flow of a production facility.

Overall, systems thinking can be summarized as a way of thinking which enables better understanding (and engineering) of complex systems (Haberfellner, et al., 2015).

4.2 SE Approach According to *Hall-ETH*

Figure 18 displays the system engineering philosophy according to *Hall-ETH*. The top level of the *Hall-ETH* approach shows the SE philosophy with system thinking and the action model.

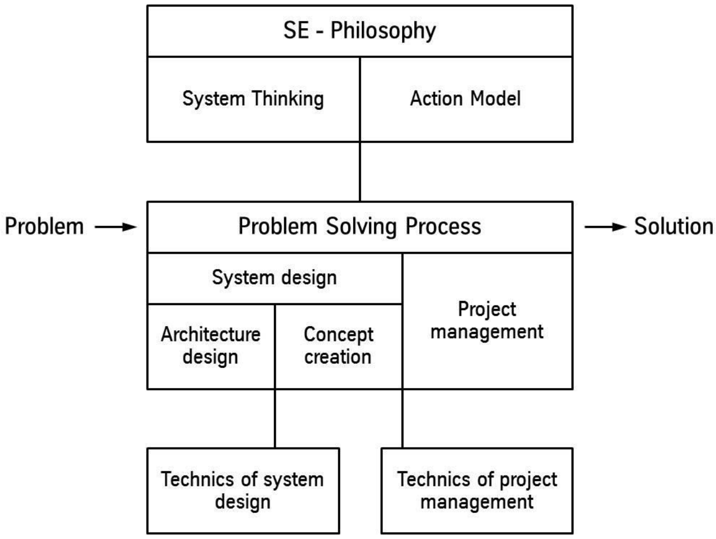


Figure 18 Systems engineering concept (adopted from Haberfellner, et al., 2015)

Haberfellner, et al., 2015 see their problem solving process as the action model in systems engineering. Therefore, it is located at the center of the graphic. The system design includes tasks such as architecture design and concept creation and deals with content-related questions and solutions. Compared to other SE approaches, Haberfellner locates project management next to the system design as a part of the problem-solving process. Project management is the sum of all necessary organizational and available actions for planning, guiding, controlling and managing a project in a content-, time- and cost-related manner.

The methods, technics and tools for system design as well as for project management are the fundaments of this SE approach. Proven methods help to make the right decisions and, consequently, minimize possible risks. In addition to valuation and decision making techniques, verification and validation methods are presented. Compared to other SE approaches, these methods do not have a special focus but support as an assistance tool. They cannot – and should not – make decisions but *facilitate* decision making.

Like other SE approaches, the *Hall-ETH* problem-solving process is based on the thoughts of system theory. Several system design and system thinking methods help to display a problem and its relations as a whole system (see chapter 4.1.1). For modeling, the graphical methods “Bubble Chart” and “Matrix Notation” are used to support this process. Thereby, the system should be viewed from different aspects (different “glasses”), which results in a better understanding of the system or problem.

In their action model (displayed in Figure 19), Haberfellner, et al., (2015) present four basic ideas which characterize the model and which should be regarded as components that can be usefully combined:

- Top down
  "*Proceeding from the general to the particular way and not the opposite way*"
- Development of variants
  "*Looking consequently for alternative solutions, the first or only a single solution is not satisfying*"
- Project phases
  "*Dividing the process of system development and system implementation into project phases*"
- Problem solving cycles
  "*… a kind of working- and thinking logic no matter what kind of problem it is and in which phase it appears*"

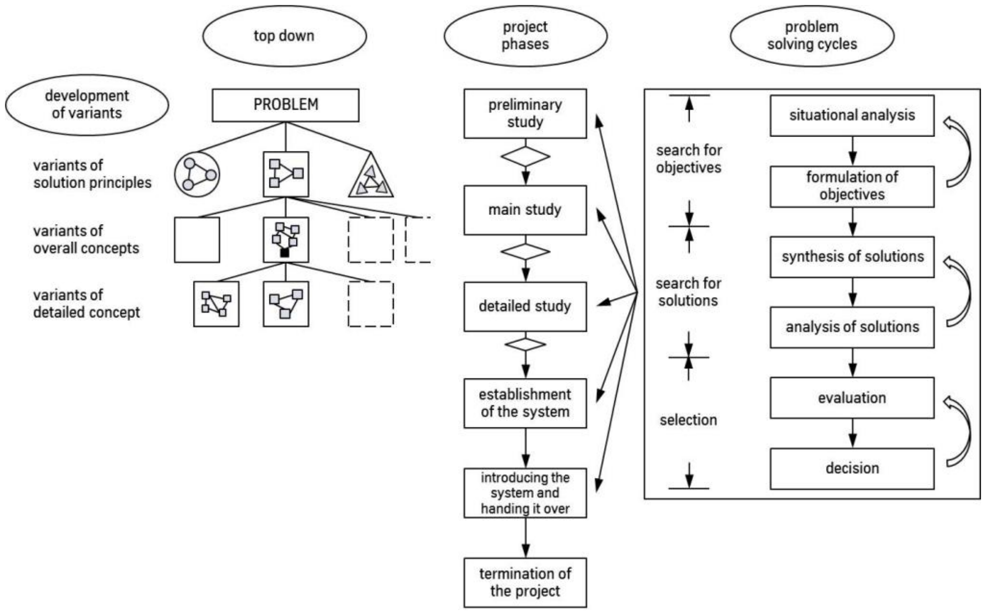


Figure 19 Action model (adopted from Haberfellner, et al., 2015)

In the following section, these four basic approaches are briefly discussed.

4.2.1 Top down approach

The basic idea of the top down approach is the systematic procedure of solving a problem, beginning at the top and proceeding to the next level (Figure 20). This resembles the observation view which should be broad at first and is then restricted step by step. This applies to the investigation of the problem, the starting situation and the solution. The design of the objectives should also be general at first and should then transform into more detailed objectives as the project progresses. Due to this, premature and detailed decisions should be prevented, which often cause prolonged projects and increased costs.

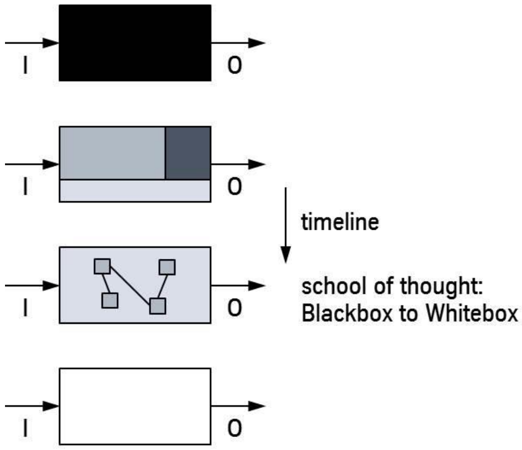


Figure 20 Top down approach (adopted from Haberfellner, et al., 2015)

4.2.2 Developing variants

An important factor in systems engineering is the approach of developing different variants. The use of the first solution is hardly always the best and, therefore, all possibilities should be taken into account (Figure 21). At this point, an understanding of the basic problem is necessary so as to develop different alternatives. In this context, there exist different variants with regard to a basic idea as well as specific design variants that are based on the same basic idea but essentially differ in their details.

By not implementing this approach, possible yet vital solutions to a problem may be ignored. In the further development, the problem-fixing needs time and creates additional costs. By using different valuation methods, one solution is selected and the next level is reached. Haberfellner et al, (2015) present several methods for valuation and decision making, e.g. analytic-hierarchy-process, cost-benefit-calculation, value benefit analysis, or the decision tree.

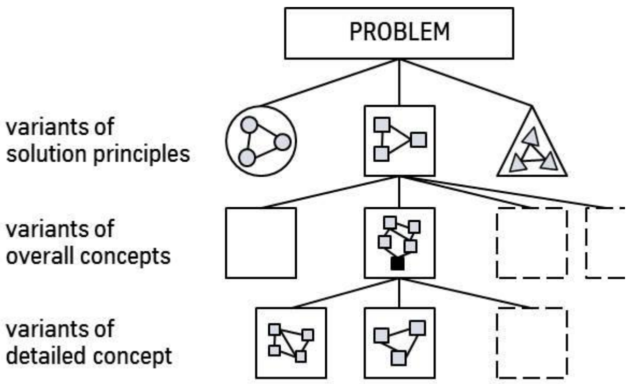


Figure 21 Successive development of variants and elimination (adopted from Haberfellner, et al., 2015)

4.2.3 **Project Phases**

Systems engineering distinguishes project phases for the macro and micro logic (level). In this section, the phases of the macro level are discussed. The idea is to divide the project into phases and thereby structure it into manageable stages. This enables a stepwise planning, decision and realization process with predefined gates at which the project can be temporarily paused or entirely cancelled (displayed in Figure 22 The information provided in the following paragraphs is taken from Haberfellner, et al. 2015.

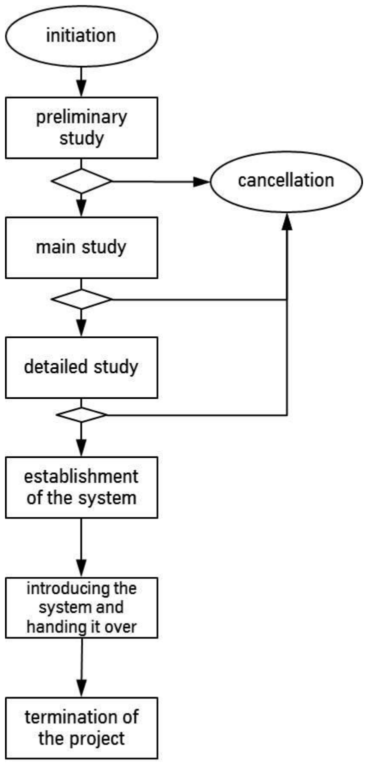


Figure 22 Project phases (adopted from Haberfellner, et al., 2015)

Each phase has a defined input and output and is logically and timely separated from the other phases. In principle, this approach is an ascertainment and extension of the *top down* and *developing variants* approaches. The results at the end of each phase are the assessment basis for further procedures. At this point, a decision-making panel is consulted which ensures a constant exchange between the project team and the client. The predefined gates allow changes, possible improvements and the cancellation of the project. The ability for changes decreases with increased progress. The amount of phases varies depending on the project and its size.

<u>Initiation:</u>

A customer request, an idea or a problem are possible initiating factors for a project. In this phase, one attempts to create enough *problem awareness* and give the client an opportunity for a solution, which should then result in the start of the preliminary study. This phase is rather short if problem awareness (psychological stress) and opportunity awareness are high and if suitable personnel and enough resources exist for the preliminary study.

Preliminary study:

In this study, the feasibility[9] of the project is to be proven with justifiable efforts. In the preliminary study, the surveyed area is broadly and consciously defined in order to ensure that the solution works in the end. Therefore, an analysis of the current state is conducted. Furthermore, the problem is defined in this phase in order to determine which requirements the solution should have. In addition, fundamental variants for the possible solutions, goals and the design area are created and defined. At the end of the preliminary study, a decision is made whether the project is continued or cancelled.

Main study:

The goal of the main study is to determine the structure of the total system on the basis of the solution selected in the preliminary study. The tasks of this study are the creation of a master plan for the next phases as well as their priorities, the definition of the team member and the assignment of the tasks to these team members. Additionally, an investment calculation should be conducted in order to ensure the economic efficiency of the project. In the end of this study, a decision is again made whether the entire system is still feasible and continued or whether the project should be cancelled.

Detailed study:

The detailed study includes objects from subsystems and system aspects and serves to define detailed solutions and make decisions about the design variants. Moreover, the discussion of sub-problems which occur in the detailed concepts should be treated in the respective detailed phase. In the end, it is verified whether the detailed concepts meet the requirements and could be integrated into the solution. This is the last gate at which the project/product can be cancelled before it is executed.

Establishment:

In this phase, the project or product is realized and tested and the establishment phase is thus a production phase for the project and product, as opposed to other conceptual phases. Besides production, this phase includes testing (individual and integration testing) of the project/product, creating the associated documentation and manuals, defining maintenance, etc. The system should be completed so that it can be used afterwards.

[9] Technical, economic, social, organizational and political feasibility

Introduction:

It is vital to know that only small and simple solutions can be introduced as a whole. Large and complex systems have to be introduced step by step because of the high number of non-calculable side effects and their risks. The objectives, requirements and warranty have to be checked by the client before he takes over the system. Additionally, the system has to be explained to the user and the operator. The formal handover from the creators normally ends with a farewell party.

Termination:

A project ends with the proper acceptance of the solutions by the client. Now, several final tasks have to be initiated such as billing, lessons learned or the dissolution of the team. Afterwards, the usage, maintenance or revision take place until the system is eliminated or replaced.

4.2.4 Problem-solving cycle (PLC)

The problem-solving cycle is used on the micro level (logic) in order to support the developer with the solving of a problem. The PLC can be applied at any project phase and is based on Dewey's logic of problem-solving. The process focuses on the steps *Search for objectives*, *Search for solutions* and *Selection* (as shown in Figure 23). The current project phase has a major impact on the content and degree of detail in the individual steps. Additionally, information is gathered and important results are documented. These two processes are conducted simultaneously over the whole PLC (Haberfellner, et al., 2015).

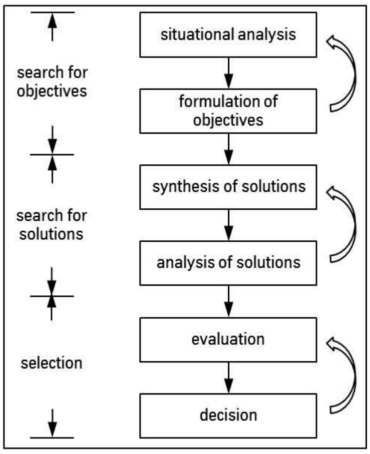


Figure 23 Problem-solving cycle (adopted from Haberfellner, et al., 2015)

Haberfellner, et al., (2015) describe the including steps of the problem-solving process includes as follows:

Initiation:

This step initiates the process of problem-solving. This initiation of the PLC in a project phase might be the result of a previous phase.

Situational analysis:

The objective of this step is the analysis of the initial situation and the assignments in order to understand them. On this basis, the goals are defined. Depending on the current project phase, the design of this step may differ: in the preliminary study, this step is used to find and analyze the symptoms of the problems, while, at a later stage, the objective of this step is to deal with the specific staring point (e.g. which overall concept has been decided on?). Here, Haberfellner, et al., (2015) present different point of views which support the user:

- The *system-oriented view* (from system thinking) which supports the structure of the system functions.
- The *cause-oriented view* which investigates the symptoms of the current situation.
- The *solution-oriented view* displays possible solutions and interventions.
- The *future or time-oriented view* aims at estimating future developments. Here, possible changes are discussed with regard to how the system will behave in short-, middle- and long-term development if no action is taken.

The result of the situational analysis is qualitative and quantitative information for a better overall view of the problem. Due to the analysis, it may be necessary to change the previously defined goals. (Haberfellner, et al., 2015)

Formulation of objectives:

On the basis of the results and information gathered in the situational analysis, the decision is made of which objectives should be pursued. It is often difficult to make such decisions – especially at an early stage – because the ideas and expectations are mostly based on inaccurate information. Therefore, the formulation of objectives is usually situated at the end of the *search of objective* phase. The latter's aim is a systematical summary of the objectives in order to build a basis for the search of a solution. Therefore, users need to observe four basic rules: *solution-neutral* (function and effect), *complete*, *operational* (precise and clear) and *realistic*. The objectives can be separated into *must*, *could* and *target* criteria. Finally, the objective decision or authorization is formed and documented. (Haberfellner, et al., 2015)

Synthesis of solutions:

The synthesis of solutions is the constructive and creative step of the problem-solving cycle. It aims at creating solutions based on the results and information of the situational analysis. These solutions need to meet the defined requirements and should be well specified so that they can be objectively compared to each other. They can be first drafts, concepts, designs or specifications for a possible realization. To create solutions, different creativity techniques are applied (e.g. morphological scheme, TRIZ, brain-storming, or the 6-3-5 method). (Haberfellner, et al., 2015)

Analysis of the solutions:

The analysis of the solutions is a critical and analytical-destructive step of the problem-solving process. It seeks to verify whether the solutions or concepts created meet the requirements or whether there are any major weaknesses. Such weaknesses are easier to eliminate with fictitious concepts (i.e. those existing only on paper) than with concepts that already progressed to concretization phase. As solutions become more and more specific, the analysis needs more time and is more specific and detailed. The main objective of this steps is to determine, whether

- formal aspects (must criteria) are fulfilled
- the individual solutions comply with the current phase and the right ascertainment level
- the solution is useful for integration
- the functions of the solutions are recognizable and can be evaluated
- questions can be answered in relation to the operation’s reliability (safety, reliability, usability, etc.)
- requirements and consequences can be evaluated in an economic, technical, personal, or social manner. (Haberfellner, et al., 2015)

Evaluation:

The aim of this step is to evaluate all valid alternatives and to select those which fulfill the requirements. These requirements are the same that were already used during development and pre-selection. Only those variants fulfilling the must criteria are approved in the end. Often, objective evaluations are not possible, which makes the use of several evaluation methods necessary. Such methods and techniques for valuation and decision making are presented by Haberfellner et al, (2015) and are listed in the following: argumentative balance, cost-benefit-calculation, value benefit analysis, and decision tree. These methods make the decision more transparent and thus comprehensible, but do not replace the decision itself. This reduces arbitrariness and irrationality of decisions and increases their quality. (Haberfellner, et al., 2015)

Decision:

Based on the results of the evaluation step, an alternative is chosen. Thereby, it is not always necessary to choose the alternative with the best results in the evaluation. It is even possible that none of the alternatives fits the requirements and the project needs to be cancelled or reviewed. In this case, new objectives have to be defined or revised or the concept needs to be changed. The result of the decision should be a satisfying solution that can serve as an impulse for the following phase.

4.3 Mechatronic Systems Engineering VDI 2206

To display an additional model, the *Mechatronic Systems Engineering* approach according to VDI 2206 is briefly discussed in this chapter. The VDI 2206 approach combines the *top down* and *bottom up* approaches which results in a V-shaped model (shown in Figure 24). The approach is methodical, integrated and well-established in the domain of software engineering and for developing mechatronic products. It serves as a fundamental approach for the communication and cooperation of experts across different sectors. The top down approach investigates the requirements and specifications of the requested total systems (and in the following the sub-systems and concepts), while the bottom up approach implements a permanent verification[10] and validation[11] between the requirements (left side) and the actual system (right side). In the end, the total system has to be validated with regard to whether the initial objectives were met. (VDI 2206, 2004)

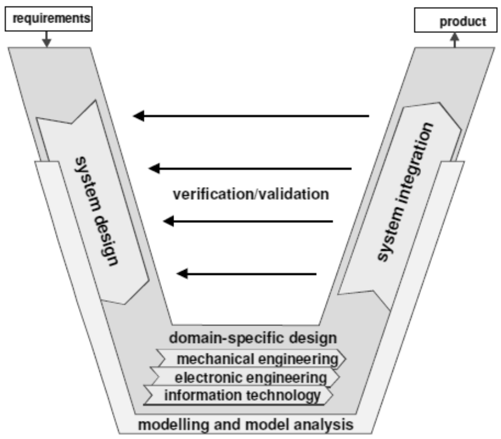


Figure 24 V-model (adopted from VDI 2206, 2004)

VDI 2206 (2004) describes the V-model methodology as a flexible approach which includes the following three core competences:

- *General problem-solving cycle on the micro level*
- *V-model on the micro level*
- *Predefined process modules for handling recurrent working steps in the development of mechatronic systems*"

<u>Problem-solving cycle as a micro-cycle:</u>

The problem-solving cycle used is based on the general SE problem-solving cycle as presented in chapter 4.2.4. It supports developers in the work process and with predictable tasks and, as a result, reduces sudden and unpredictable problems. Figure 25 displays the problem-solving cycle of VDI which slightly modifies the cycle from Haberfellner et al. (2015).

---

[10] VDI 2206, (2004) describes verification as "…a *correct* product being developed?"
[11] VDI 2206, (2004) describes validation as "…the *right* product being developed?"

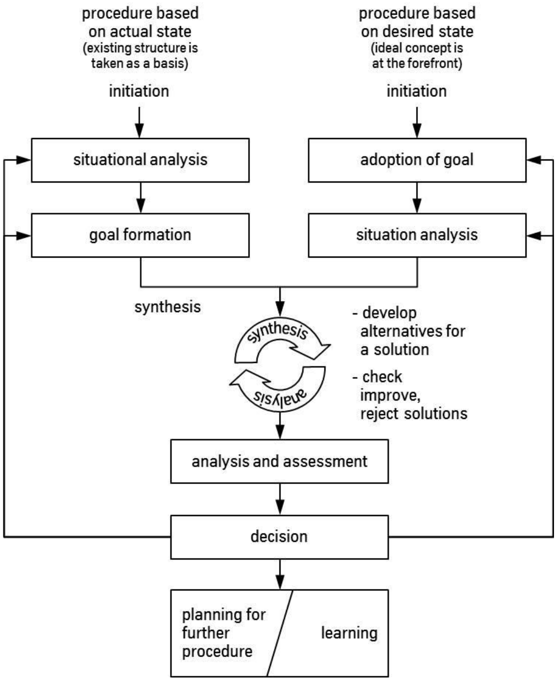


Figure 25 Problem-solving cycle as a micro cycle (adopted from VDI 2206, 2004)

<u>V-model as a macro cycle:</u>

Figure 24 displays the V-model as the generic procedure for the development of mechatronics systems. Similarly to the project phases in chapter 4.2.3, this procedure differs from project to project. VDI 2206, (2004) describes the procedure steps as follows:

- <u>Requirements:</u>
  In the beginning, the objectives and requirements of the product are described in more detail.
- <u>System design:</u>
  The aim is to describe the main physical and logical operating specifications of the solution and the overall function of the system is broken down into relevant sub-functions.
- <u>Domain specific design:</u>
  Here, further detailing and calculation take place so as to ensure the performance of the function.
- <u>System integration:</u>
  The results from the individual subsystems are assembled into an overall system in order to be able to investigate the interactions of these subsystems.
- <u>Assurance of properties</u>
  The progress of the solution / design must be continuously checked by comparing it to the concept requirements.
- <u>Modeling and model analysis:</u>
  The system's properties are investigated by using simulation, models and computer-aided tools.

- Product:
  The end of the continuous macro-cycle is the product. In this case, the product can be a prototype, functional test unit or pilot – the product does not have to be elaborate or complete.

The macro cycle can be run several times depending on design, complexity and progress made. The number of macro-cycles depends on the specific development task, i.e.: in a first cycle, a prototype can be developed which, in the next cycles, can be adapted to fit serial or mass production. In the second run, the product is further concretized (e.g. by fine dimensioning or behavior simulation). (VDI 2206, 2004)

Process modules for recurrent working steps:

Some steps and sub-steps occur more often, which is why they are partly predefined process modules. Such modules are for example *system design*, *modeling and model analysis*, *domain-specific design*, *system integration* and *assurance of properties*. Due to the increased importance of informatics in mechatronics (see chapter 2), it can be assumed that increased *assurance of properties* is required. The fact that the other modules are quite similar to those already explained in the previous chapter 4.2 accounts for why the following section only focuses on this module. (VDI 2206, 2004)

After each phase (system design, domain-specific design and system integration) it is necessary to valuate systems and their properties on the basis of the requirements. This step is called *verification* and *validation*. There exist several methods to support the assessment of complex products and their functions and they can be carried out in a real experiment, a virtual experiment or in a combination of these two. Virtual experiments can be investigated with the aid of model-in-the-loop simulations, while the combination of real and virtual experiments can be investigated in a hardware-in-the-loop environment (VDI 2206, 2004). VDI 2206, (2004) explains the system as follows:

- Hardware-in-the-Loop (HIL):¨
  "…is the integration of real components and system models in a common simulation environment. The HIL replication (simulation) of dynamic systems by physical and mathematical models must in this case take place in real time and with the physical loads replicated. An example is the simulation of an entire vehicle of a computer with the connection of a real control device and the actor technology for functional control to provide vehicle stability. A decisive advantage of HIL is the function test of the control device under real conditions while at the same time saving on time- and cost-intensive driving maneuvers".

- Software-in-the-Loop (SIL):
  "*…is the integration of system models in a common simulation environment with the modeled process (controlled system); both the function to be developed and the process (controlled system) on which the function acts are modeled. The SIL replication (simulation) of dynamic systems by mathematical modes do not have to take place in real time. A decisive advantage of SIL is the function test under simulated conditions while at the same time saving on time- and cost-intensive experiments (for example driving maneuvers). In this basis of an SIL environment, either the function, the process or both parts can be physically realized and analyzed with regard to their behavior in a closed loop*."

5 Case Study

In the automotive industry, the trends *connectivity*, *electrification* and *autonomous driving* have direct and indirect impacts on the current automotive landscape. New OEMs that do not come from the classical engineering sector penetrate the market with different business models, fast time-to-market strategies and new technologies. This results in an increasingly complex automotive industry landscape. In this new landscape, current and long-term automotive suppliers alike are faced with new situations and challenges. One of these automotive suppliers is TKS, a company that is already dealing with the new situation in the automotive industry. The objective of this case study is to evaluate and investigate the impacts of recent developments on TKS. In order to examine this complex case, the study uses the approach of *systems engineering* according to Hall-ETH (cf. chapter 4.2). In order to provide a clear overview, the case study is structured into separate chapters, which are Introduction to the *Case Study*, *Investigation of OEMs*, *Steering Systems* and *Impacts on the Manufacturing Engineering Process*.

The chapter *Introduction to the Case Study* introduces TKS and its environment as well as problems and objectives of the present case study. Moreover, it is explained which systems will be more closely investigated by providing a brief introduction of internal processes. The latter can be separated into two possible views, the *PrestaWorld* process and the mechatronics product lifecycle process. This chapter corresponds to the preliminary study of the SE project phases.

The next chapter investigates selected OEMs by placing the focus on new OEMs and their business models. However, a traditional OEM is investigated as well so as to be able to display differences between new and traditional OEMs. In the end, the investigated OEMs are compared and important findings and impacts related to TKS are highlighted. This chapter corresponds to the first main study of the project phases.

The chapter *Steering Systems* presents the second main study of this case study. First, steering systems and their evolution are explained in detail and a current system that is still in development is presented. Afterwards, it is attempted to create concepts for an innovative steering system based on current automotive trends. Here, the creativity method *morphological scheme* is used to support the process of inventing such a system. Subsequently, the concepts are compared and evaluated. In the end, the findings of these concepts are shown and discussed. This main study serves as the basis for the following detailed study *Impacts on the Manufacturing Engineering Process.*

The last chapter treats the impacts on the manufacturing engineering process with regard to the concepts created. First, the conceptualized steering systems will be transferred to realistic products. Afterwards, the manufacturing procedures for all concepts are defined in order to determine the required machinery. On the basis of the machinery, the amount of employees, the investments and the needed real estate area are calculated. Finally, the concepts are compared and the findings are analyzed and discussed.

5.1 Introduction to the Case Study

At the beginning, the partner TKS is introduced and afterwards, an overview of TKS's environment is given. Based on the current problem statement of the company, a decision needs to be made which environmental systems are worth analyzing in more detail. In the end, the internal processes and sub-processes are displayed in two different depictions.

5.1.1 ThyssenKrupp Steering

The company "Press- und Stanzwerke AG" (engl. pressing and stamping plant) was founded as a subsidiary of the Swiss Group Oerlikon in Eschen, Liechtstein, in 1941. In 1991, German ThyssenKrupp AG acquired Press- und Stanzwerke AG and was henceforth named ThyssenKrupp Presta AG. In late 2015, ThyssenKrupp updated their brand image and renamed ThyssenKrupp Presta into ThyssenKrupp Steering (in the following referred to as TKS). TKS is part of the business consortium "Components Technology" of ThyssenKrupp. Components Technology TKS specializes in cold forging and the development and production of steering systems for the automotive industry. Towards their customers, TKS presents itself as a supplier of steering systems, but it also provides individual parts for these systems. The main customers of TKS are traditional OEMs such as Volkswagen Group, Daimler, Ford and BMW. The last months saw the emergence of new OEMs with new business models and innovative products.

5.1.2 TKS systems

TKS operates in a complex environment which includes customers, suppliers and competitors. On the basis of system thinking, TKS can be described from different angles. The environmental factors that influence TKS are complex - as are the effects they have on the company. Mostly, customers influence which technologies and products make it to the market; however, this also works the other way round since it is often the case that technology in the end is the decisive factor of whether a customer decides for a TKS system. Furthermore, technologies in automotive industries can be determined by statutory regulations and specific laws. In this thesis, TKS is displayed in the center of these influencing factors and it interacts with its environment (see Figure 26). Due to mutual and strong linkages between the environment's sub-systems, interrelations and feedback are not displayed.

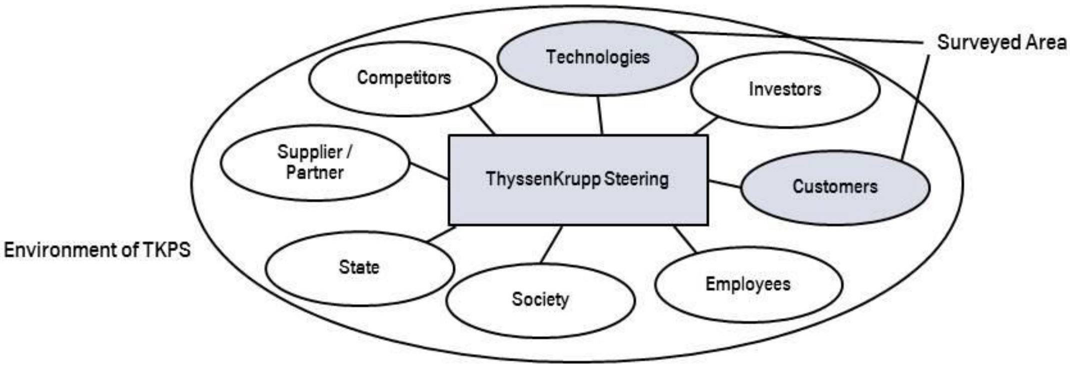


Figure 26 Economic environment of TKS with surveyed areas highlighted in gray (own illustration)

The displayed environment systems include (adapted from Certo & Certo, 2005):

- <u>Technologies</u>
  Current and future steering technologies.
- <u>Investors</u>
  ThyssenKrupp AG is the parent company of TKS and thus an investor.
- <u>Customers</u>
  All customers across all industries. Main customers are automotive OEMs.
- <u>Employees</u>
  Employees working at TKS and their interest in their salary.
- <u>Society</u>
  Society may be concerned about employment possibilities and/or the protection of the environment.
- <u>State:</u>
  Laws, regulations and taxation.
- <u>Supplier / Partner:</u>
  Suppliers providing TKS with products, raw material and technologies.
- <u>Competitors:</u>
  They operate in the same environment, which affects TKS in several ways.

5.1.2.1 Problem statement and Decision

The current trends *diverse mobility, connectivity, electrification* and *autonomous driving* in the automotive industry significantly change the automotive landscape (see chapter 3). According to the analysis, the emerging of new OEMs and new steering technologies has major impacts on TKS. New OEMs (henceforth called "emerging OEMs") are automotive manufacturers that try to enter the market with new business models and new vehicle technologies. They often come from software development and not from the mechanical engineering sector and support the development of new innovative steering technologies. Both the emerging OEMs as well as new innovative steering technologies are analyzed and resulting impacts on TKS are explained in the following.
Together with TKS, the following questions were compiled in order to find answers to them in the following main and detailed studies:

- How do emerging OEMs behave in regard to their development process and requirements compared to traditional OEMs?
- What are the impacts of emerging OEMs on current processes at PrestaWorld?
- What could conceptualized innovative steering systems look like?
- What impacts do these innovative steering systems have on operation processes?

Based on these questions, the focus in further investigations will be on the environmental factors “Technologies” and “Customers” (cf. Figure 26). A main study is conducted for each of these two factors. The first main study analyzes emerging and traditional OEMs, the focus being on emerging OEMs. Afterwards, the selected OEMs are compared and differences are highlighted and, finally, impacts on TKS are summarized and findings are shown. The second main study discusses steering systems and their evolution. For this, a potential innovative steering system is used to deduct several possible steering concepts that can afterwards be evaluated and compared. In the end, one potential innovative steering concept is selected.

Both systems focus on processes and procedures used at TKS. The Mechatronic Product LifeCycle MPLC process is used for new customers and their request of products as the MPLC uses several processes of PrestaWorld processes that include all sub-processes used ad TKS. In order to provide necessary background knowledge, these processes are briefly explained and one sub-process each is treated in more detail. With regard to PrestaWorld, the core process of *manufacturing engineering* is considered in detail because it includes the procedures of manufacturing and investment planning as well as investment purchasing. With regard to the MPLC, the *quotation phase* is displayed as it shows a shorter request phase for emerging OEMs.

5.1.3 **TKS Processes**

The selected systems and the main studies investigate the internal processes of TKS. Therefore, these processes are introduced briefly. The internal processes at TKS can be separated into two different areas. The first is the PrestaWorld process which includes all existing processes of TKS and has the objective to fulfill the customer goal. The second process is the MPLC that has access to the six core business processes of the PrestaWorld process and which realizes the product requested by the customer.

5.1.3.1 PrestaWorld Process

The PrestaWorld process displays all processes of TKS and has the aim to fulfill the customer goal within the company. It includes three different types of processes: management, business and supporting.

The management process is responsible for the target achievement of TKS (cf. Figure 27, orange fields). Business processes are those processes which directly create value for the customers and their use of know-how creates a competitive advantage (blue fields). Supporting processes symbolize internal services (green fields). The PrestaWorld process is implemented within the entire company, with slight modifications depending on the individual departments, i.e. local processes are only used at a specific site – either for the entire site or its individual departments. The processes can be separated into main, sub- and elementary processes.

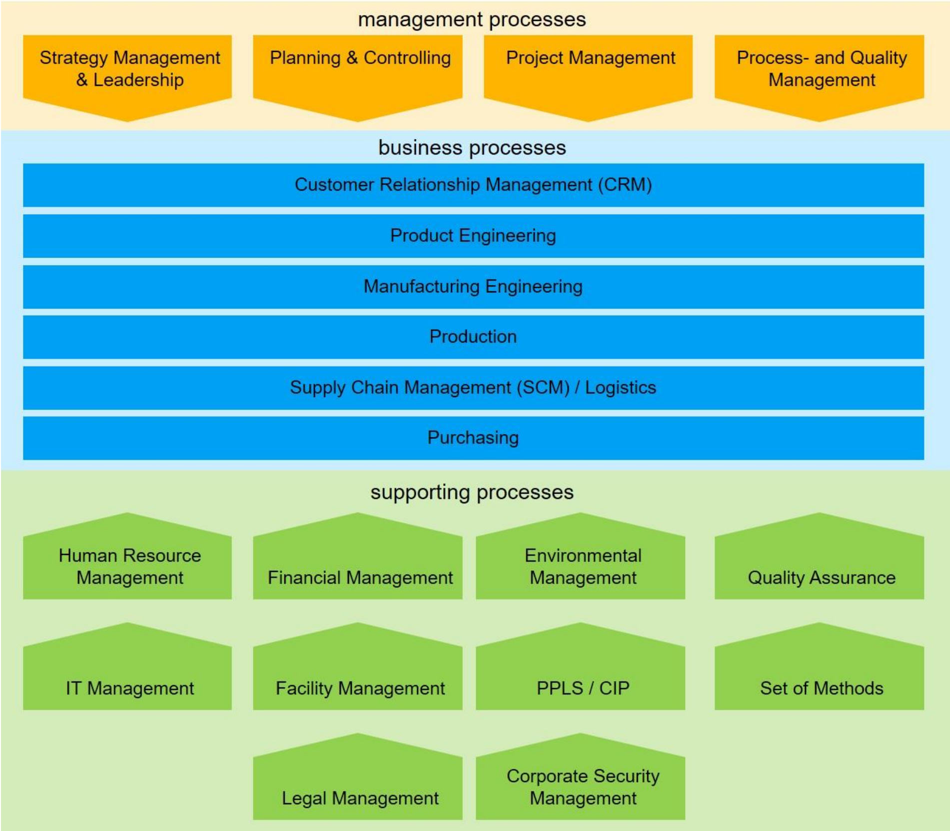


Figure 27 PrestaWorld process (company document)

The six core business processes are:

- Customer Relationship Management (CRM)
  - describes all activities concerning the handling of customer-related topics.
- Product Engineering
  - contains all engineering processes and supporting processes related to engineering.
- Manufacturing Engineering
  - plans and develops all activities relevant to processing or production that are necessary for the manufacturing of the product.
- Production
  - e.g. of deliverable products, taking into account factors such as material, man power, energy and resources.

- Supply Chain Management (SCM) / Logistics
  - plans, executes and supports the supply chain activities throughout the value-chain, from suppliers to final customers. Based on customer requirements, the aim of SCM is to coordinate and optimize the flow of material, financial means and information between the company and partners of the supply chain.
- Purchasing
  - includes all purchasing activities from purchase strategies, via procurement and supplier control up to purchasing material.

It is assumed that all PrestaWorld processes are affected by the impacts. The process of manufacturing engineering is treated in more detail here because of the currently high number of orders, the resulting expansion of TKS and the thus resulting increased investment into production facilities and machinery.

Manufacturing Engineering

The manufacturing engineering process (internally also known as operation process) is one of the six PrestaWorld core processes. It is located at the department *ZOD* and within the operation teams for manufacturing and investment planning as well as investment purchasing. The manufacturing process plans and develops all processes or production-relevant activities that are necessary for the manufacturing of the product.

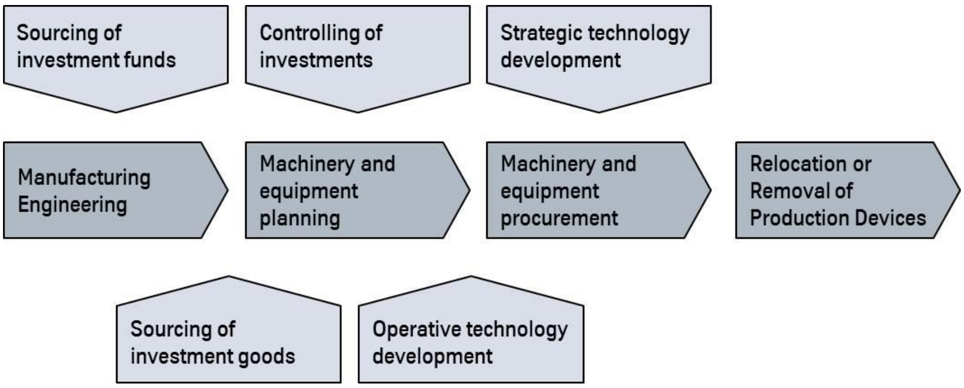


Figure 28 Manufacturing engineering process (company document)

As a process of PrestaWorld, the manufacturing engineering process is composed of operation and supporting processes.

First, operation processes and their tasks can be described as follows:

- Manufacturing Engineering:
  Determination and evaluation of variants for the production process with regard to machinery and locations. This includes the following selected operation tasks:
  - feasibility study concerning assembly and manufacturing technique
  - rating and affecting the product design concerning assembly and manufacturing aspects

  - choose, rate and develop manufacturing methods
  - analysis of capacity, alignment with capacity, choice of location
  - rating of clock cycle, OEE, shift plan, amortization period
  - determine labor demand and capital expenditure requirements
  - establish manufacturing calculation
  - roughly describe the workflow
- Machinery and equipment planning:
  Elaboration of target specifications and catalogs of requirements for machines and systems based on the actual manufacturing concepts.
- Machinery and equipment procurement:
  Update the target specifications and readjust the catalogs of requirements for machines and systems based on the actual manufacturing concepts.
- Relocation or removal of production devices
  The process ensures that production devices are removed or relocated correctly.

Second, supporting processes can be described as follows:

- Sourcing of investment funds
  Timely provision of account assignment order numbers and calculation of cashout for investments.
- Controlling of investments
  The main activities of this process are controlling the budget requests, purchase requisitioning and updating the project investment budget.
- Strategic technology development
  This includes processes for controlling of all strategic innovation and technology developments (production processes and technologies).
- Sourcing of investment goods
  Cost-effective and timely provision of machines and equipment, which includes supplier requests and analyses as well as “investment goods”.
- Operative technology development
  A process for the development of production technologies.

It should be noted that the above described processes evolved over time and do thus not reflect all current processes or the arrangement of departments. As a matter of fact, these processes are currently evaluated and will be revised in the course of internal restructurings within the next months.

5.1.3.2 Mechatronic Product Life Cycle MPLC

As stated above, the PrestaWorld process includes the Mechatronic Product Life Cycle (MPLC) which assesses all six business processes. It covers all processes beginning with a customer requests, via product development and serial production of the steering systems, up to the delivery of spare parts. The aim of the MPLC is to achieve and implement the target defined, all the while taking into account qualitative, temporal and cost requirements. Figure 29 shows the MPLC with its six product phases.

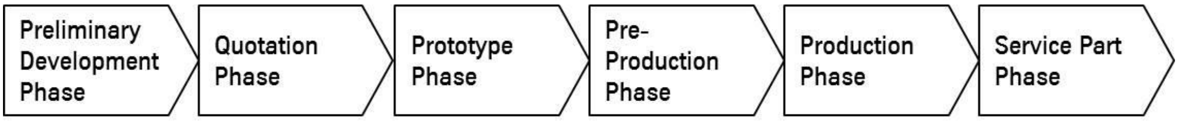


Figure 29 Phases of the mechatronic product life cycle (company document)

Furthermore, the MPLC can be displayed with regard to required reviews, customer milestones and MPLC-specific processes (see Figure 30). The nine PRESTA reviews (i.e. quality gates) are project milestones, where the project's status is assessed with the help of a checklist. The participants of the process shown below consists of the extended project team with at least one division manager. The reviews have to be held at the dates specified in the project schedule which was created in Review 0. Moreover, the Review meetings are project-specific and treat all salable products. Even though not all components are treated individually, the respective steps for each component, assembly or salable product are the same. Based on the MPLC, items have to be included or excluded from the series.

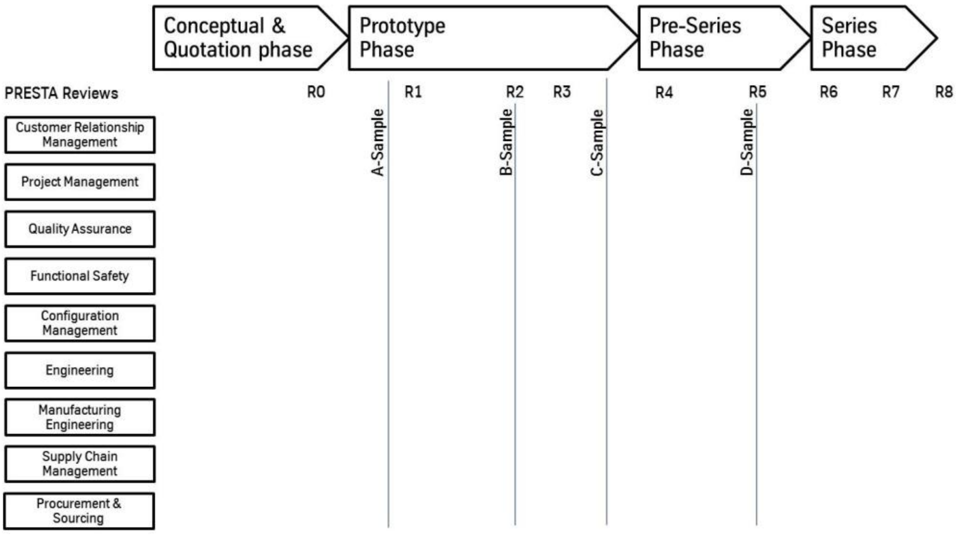


Figure 30 MPLC as synchro process (company document)

In the following, the quotation phase is described in more detail because it is strongly related to emerging OEMs that currently request innovative products.

<u>Quotation phase</u>

The quotation phase includes all actions that need to be taken in order for a company to be awarded a contract after bidding on a tender and ends with Review 0.

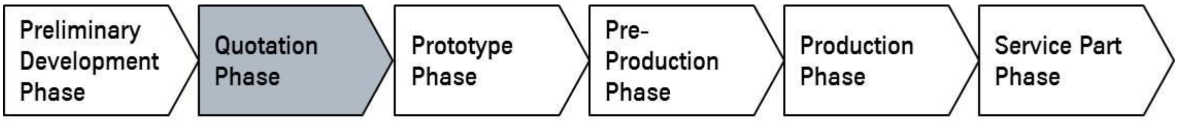


Figure 31 Quotation phase as a part of the MPLC (company document)

In general, the product manager needs a close relationship with the company's actual and potential customers. His goal is to convince customers or potential customers of the technology, reliability as well as the technical and economic advantages of TKS's products. Specific requests need to be handled by an experienced development team. As soon as the customer requirements are understood completely, a product and production concept is created in collaboration with the departments production, logistics, purchasing and product development. A contract represents a further crucial factor, which is why it has to be examined by legal advisers. This step also needs to be considered in the planning. Finally, with the overall concept and the corresponding calculation of costs having been fixed, an offer can be submitted to the customer. Upon approval by the customer, a project team is put together and the project schedule is drawn up. The individual steps of the quotation phase, which usually lasts between one or two months, are shown in Figure 32.

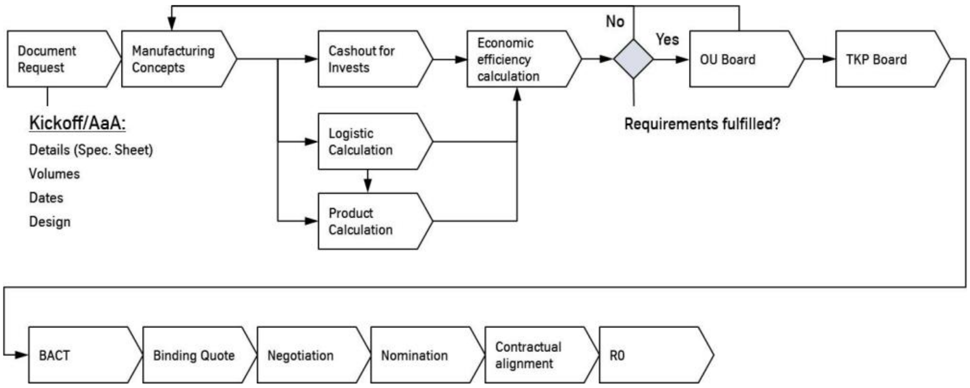


Figure 32 Steps of the quotation phase (own illustration)

This thesis uses parts of these processes in order to calculate possible outcomes.

5.2 Investigation of OEMs

In the first main study, current customers of TKS are investigated. In addition to the emerging OEMs mentioned in chapter *New trends in the automotive industry,* even more OEMs are expected within the next years. The emerging OEMs focus on few specific yet economically attractive segments of the value chain. In the last months, they requested steering systems of TKS for the first time. Their behavior was entirely new to TKS and led to some difficulties. To be able to understand these OEMs and to prepare for future requests[12], TKS initiated an analysis of the emerging OEMs with the aim of answering the following two key questions:

1. How do emerging OEMs behave in regard to their development process and requirements compared to traditional OEMs?
2. What are the impacts of emerging OEMs on current processes at PrestaWorld?

The customers of TKS can be separated into the following groups: traditional OEMs (Volkswagen Group, BMW Group, FIAT, etc.), emerging OEMs (whereby it is not distinguished between Chinese and special OEMs), and other industries (e.g. trucks, brakes, etc.)

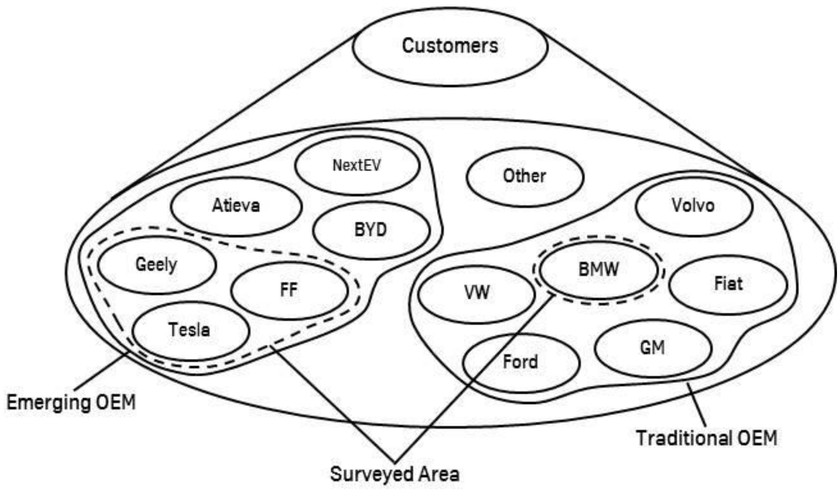


Figure 33 Selected customers of TKS that will be surveyed (own illustration)

Figure 33 displays a variety of current customers of TKS. Furthermore, the groups are separated from each other in order to provide a more detailed overview. It should be noted, however, that the figure does not display all customers of TKS.

The following chapter is divided into four subchapters. The chapter *Selection* specifies the OEMs which are going to be investigated. Furthermore, the procedure and topics which are to be answered are explained. The following chapter *Investigation of selected OEMs* deals with the four selected OEMs and their special characteristics. In the next chapter

[12] Kaas, et al., (2016) divide the future landscape into established and emerging OEMs, tech giants and mobility providers. Currently, only traditional and emerging OEMs are customers of TKS.

Comparison, emerging and traditional OEMs are compared with highlighting their differences. Moreover, this chapter answers the first key question. The last chapter *Summary and Findings* summarizes all findings and, based on the information gained, recommendations for future processes are made.

5.2.1 **Selection**

In order to be able to make precise statement in the end, a selection of customers has to be made. Therefore and in accordance to the limited purpose of the present thesis, the scope of investigation is restricted to four surveyed OEMs. Their selection was performed together with a group of company experts, who also determined that the focus would be on emerging OEMs. Therefore, three of four investigated OEMs should be emerging OEMs. To better display differences between emerging and traditional OEMs, an additional traditional OEM would have been required, but the limited time schedule only allowed for one traditional OEM in total. Thus, more traditional OEMs would be necessary to make the results of this thesis universally valid.
It was decided that the OEMs need to meet the following conditions to be selected:

- OEM is a current customer of TKS
- OEM focuses on innovative technologies and current trends
- Information (internal or external) has to be available and may be used.

Based on this, the following OEMs were selected:

- *Tesla Motors Inc.*: one of the first OEMs focusing on new trends
- *Faraday Future Inc.*: emerging OEM which recently placed an order of products and also focuses on new trends
- *Zhejiang Geely*: representative of Chinese emerging OEMs
- *BMW Group*[13]: one of the oldest and biggest traditional OEMs

The following section introduces the selected OEMs. As each OEM has specific characteristic, a systematical procedure of the analysis is necessary because this allows to objectively compare the different OEMs. Also, it minimizes the risks of an uncontrolled and thus prolonged analysis. For each OEM, the following topics have to be analyzed:

- <u>Short overview</u> – general information about the OEM
- <u>Business strategy</u> – what is the business strategy of the OEM? What does the company focus on?
- <u>Product development process</u> – what does the product development process look like? How long is the timeline of the process?
- <u>Platform strategy</u> – is a platform strategy applied?

[13] There exist numerous traditional OEMs; together with company experts, the decision was made to investigate BMW Group.

- Manufacturing plan – what is the manufacturing plan of the vehicles? Are there own facilities or a contract manufacturer?
- Marketing and distribution – how are the vehicles distributed?
- Strategic partnerships – which partnerships are unique and interesting?
- SWOT Analysis – SWOT analysis of available information
- TKS Relation – what does the interaction between the OEM and TKS look like?

In the end of each subchapter, a short summary of the OEM and the findings is provided.

Different sources of information were used to analyze the OEMs: external (web, newspapers, literature and company information) as well as internal (interviews) sources. It should be noted that the financial risks and backgrounds of the OEMs are not considered in this thesis.

5.2.2 **Investigation of selected OEMs**

5.2.2.1 Tesla Motors Inc.

Tesla Motors Inc. (referred to as *Tesla* in the following) is an American company with the aim to develop, produce and provide electric vehicles for the mass market. Tesla was founded in 2003 by engineers Martin Eberhard and Marc Tarpenning and is situated in Silicon Valley, Palo Alto, U.S. The founders' plan was to build an electric vehicle that would be superior to any gasoline-powered car. It soon became the mission of Tesla to accelerate the world's transition to sustainable energy (Tesla Motors Inc., 2016a). In February 2004, Elon Musk – a South African entrepreneur and engineer, and one of the company's first investors – was made Chairman of the Board. He is well known due to previous and current projects, including the company *PayPal* that specifies in electronic payment, or the spacecraft company *SpaceX* (Gregersen, 2014).

Figure 34 Tesla Motors factory in Fremont, California (The Tesla Motors Team, 2014)

Business strategy:

Chen and Perez (2015) investigated the overall business strategy of Tesla and extracted the following information in comparison to traditional OEM:

1) Enter the market with a high-end product and move to the mass market
2) Installation of a high performance supercharger station network to reduce range anxiety
3) High level of integration of information technology, advanced in-car service and digital distribute channel
4) New value configuration due to vertical integration from EVs manufacturing

From its very beginning, Tesla had a clear strategy for its products in mind (see Figure 35). On 19 July 2006, the company officially became a car manufacturer by presenting the *Tesla Roadster* to the market. The car was produced from 2008 to 2012 by Lotus Car in a small series and was an expensive high class sports car. The next step was thus to develop a next generation of cars, which was done with *Model S*, a sedan both average in price and volume. Model S was financed by the money earned in the sales of Tesla Roadster. In June 2008, Model S was announced in a press release and it was presented to the public in March of the following year. Tesla Model S is a full-sized battery-driven electric sedan whose production began in 2012 at the former *NUMMI* factory, now called *Tesla Factory* (Klermasch, 2010). The company changed the original concept of different generations of cars and developed only minor differences between generation 2 and 3. *Model X* – a small SUV – was presented in late 2015 and in March 2016, *Model 3*, an affordable sedan, was announced. This model is currently being developed and shall be sold on the mass market at an estimated price of 35,000 USD. The actual production of Model 3 is scheduled for late 2017 (Tesla Motors Inc., 2016b).

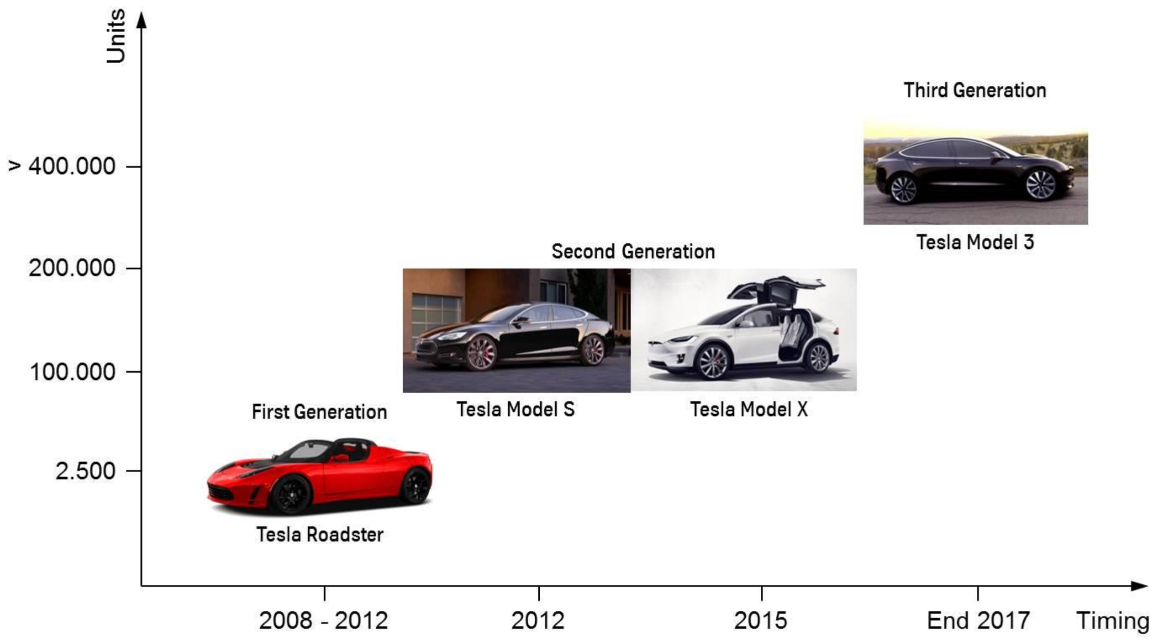


Figure 35 Market strategy of Tesla Motors (company document)

Tesla already has a reservation list for Model 3 which is available online or directly at the dealers and which functions according to the first come, first served principle. In order to make a reservation, customers have to pay a deposit of 1000 USD. This concept of paying a deposit for a car one has only seen once and never actually driven is entirely new to the automotive business. Still, only the first day saw an amazing 250,000 reservations that generated over 250 million USD for Tesla Motors (Randall, 2016).

On the same date, Tesla announced the extension of their supercharger station network. This includes the extension of availability and is especially important for future sales. Besides all current information technology and in-car services, the most important factor for buying a battery-driven car is the availability of charging possibilities. If customers decide on which car they will buy, they will certainly pick the company with the best infrastructure when it comes to charging. At a supercharger station, car owners can plug in for free (or in combination with an option package), which allows them to drive another 270 km with just 30 minutes of charging (Tesla Motors Inc., 2016c).

On 20 July 2016, Elon Musk announced yet another master plan (Musk, 2016), and explained that he intends to combine Tesla and the recently acquired company *SolarCity*. Furthermore, he disclosed the next strategy points for Tesla Motors:

- Expand the electric vehicle product line
- Develop self-driving
- Car sharing

In 2017, two new vehicles will be unveiled: the heavy-duty truck *Tesla Semi* and an urban transporter with capacity for a large number of passengers – both with the vision of autonomous driving. Regarding autonomous driving, Musk explained that Tesla is currently extending the development of autonomous driving via deploying fleet learning. Tesla believes that genuine self-driving will be allowed by law worldwide, if their fleet manages to cover 10 billion km. As soon as statutory regulations accept autonomous driving, Tesla customers shall have the option of sharing their vehicles. Currently, a car owner uses his car between 5 and 10% and car sharing would allow to make money if the own car is not used. As Tesla's plan has not yet been achieved completely, it seems they will stick with their second master plan.

<u>Product development process:</u>

Detailed information about Tesla's product development process is not available – neither in the web nor the literature. Thus, the following section is based on information from internal sources. Tesla planned to work with a short product development process, which is reflected by a short acquisition process and quick feedback from customers. However, the reality is different due to the changing of the start of production dates and other delays. Furthermore, envisaged volumes were never reached. Therefore, it seems that

Tesla expanded the process for the current Model 3 project with the aim of reducing possible failures and risks that might occur when being the first to enter the mass-market with a new product (internal interview).

Tesla architecture:

Model S and Model X are built on the Tesla platform and it is assumed that Model 3 will also built on this platform (Tesla Motors Inc., 2016e). In an internal presentation, Tesla displayed the parts which they will reuse from Model S to build Model 3. However, there is no detailed information about the platform strategy, neither internal nor external.

Manufacturing plan:

As already mentioned, Tesla's first car was produced by Lotus. In 2011, Tesla acquired the former NUMMI plant in Fremont, California and, in the same year, parts of the facility were modified and manufacturing equipment was installed. More than 160 special robots make the manufacturing process highly automatic. Additionally, Tesla opened an assembly facility in Tilburg, Netherlands in 2013, which serves as a distribution point and final assembly station for Model S vehicles sold in Europe. The aim is to deliver the vehicles faster to the important European market (Tesla Motors Inc., 2013a). Further information about future manufacturing facilities and the manufacturing plan are currently not available even though detailed research with the aid of internal and external sources was done.

Marketing and distribution:

Tesla owns the complete sales and re-sales channel of their vehicles. Compared to other OEMs that sell through franchised dealers, Tesla sells directly via the internet or company-owned showrooms. On the internet, customers can easily customize their vehicle, obtain sale or financing prices and in the end purchase the vehicle. At the showrooms or galleries, customers only deal with Tesla-employed specialists for sales, service and engineering. This creates a valuable buying experience for the customer. Furthermore, Tesla believes that a close communication between customer and specialists is an advantage when it comes to the speed of its product development (Tesla Motors Inc., 2013b). Including all showrooms, service centers and galleries, Tesla owns more than 370 locations around the world (Tesla Motors Inc., 2016f).

Strategic partnerships:

Similar to other car manufacturers, Tesla focuses on the development and production of cars, covering everything from vehicle (chassis) and powertrain engineering (battery, motor and gear box) to software engineering (battery management, motor control). (Evanson, 2014) In the beginning, the company had no expertise in producing cars, which is why they entered strategic partnerships with other major companies like Lotus, Panasonic, or Daimler. These partnerships provided valuable information for Tesla with regard to product and process innovation.

The way Tesla provides access to all their patents and follows an open innovation strategy is unique in the automotive industry (Karamitsios, 2013). Generally, the automotive industry tries to secure intellectual property with patents. However, in comparison to other OEMs, Tesla tries to actively use important factors for success by displaying great flexibility and adaptability, besides relying on traditional elements such as costs, quality and time. (Moritz, et al., 2015). Therefore, Tesla can faster adapt to market changes compared to traditional OEMs, which creates a huge competitive advantage.

<u>SWOT analysis:</u>

Moritz, et al. (2015) conducted a SWOT analysis[14] of the overall strategic situation of Tesla (shown in Figure 36). The strengths of Tesla Motors are that they are a technology leader and innovative tech pioneer and have a strong brand image. In comparison to other OEMs, Tesla has gained immense knowledge with regard to developing and producing electric vehicles. The mentioned strong brand image is reflected by its customers: over 300.000 customers ordered an electric vehicle upon having seen it at its presentation. Model 3 has not yet been driven and there exists only some basic information about it. Nonetheless, customers were willing to pay a deposit of 1000 USD for a car they did not even know – let alone when they will get it. Additionally, they are willing to overlook the re-scheduling of deliver dates. Their Autopilot system which was presented in 2015 accounts for Tesla being a leader in modern technology: this kind of advanced driver assistant system is currently one of the most advanced systems on the market. In addition, Tesla made a commitment to developing and refining technologies for pushing and enabling self-driving (Tesla Motors Inc., 2015).

One of the company's major weaknesses is that they have never produced a vehicle in mass production. Tesla plans to enter the mass-market with Model 3 in 2017. On the one hand, this might lift them to the position of a "big player" in the automotive industry but, on the other hand, several serious problems could arise, including product recalls because of unfinished or faulty vehicles. Delivering unfinished vehicles and the resulting recalls could result in a financial disaster and damage the currently strong brand image (one only has to be reminded of the famous "*dieselgate*" of Volkswagen Group[15]).

[14] SWOT is an acronym for strengths, weaknesses, opportunities, and threats. Typically, a SWOT analysis is conducted to develop businesses or products as it helps to identify internal and external factors (favorable and unfavorable) to achieve the planned objective (Schawel & Billing, 2014). In this thesis, the SWOT analysis is used to display the strengths, weaknesses, opportunities and threats of Tesla Motors Inc.

[15] Volkswagen equipped its vehicles with a software that cheated in emission tests (Gates, et al., 2016). Consequently, customers sued Volkswagen and the company agreed to pay up to 14.7 billion USD to settle the claims (Tabuchi & Ewing, 2016).

Currently, Tesla’s biggest opportunity is the pushing of electric mobility with regard to political and statutory regulations. Governments and politicians alike push electric mobility with subsidies and tax benefits (e.g. in the US or Germany). This could reduce the prices of electric vehicles and make them more affordable for new customers.

The following threats have the highest impact on the business model of Tesla: “*Major breakthrough in competing technologies*” and “*Crowing out by market entry of big or new players with high resource base*”. Electric battery-driven vehicles are only an intermediate step on the way to vehicles driven by fuel cells (Thomas, 2009; O’Hayre, et al., 2016). Indeed, Tesla takes great risks by building the so-called “Gigafactory”. The Gigafactory is a huge facility constructed for the production of batteries for Tesla vehicles and their Powerwall battery. Nonetheless, Tesla aims at reducing the costs of the battery with this factory. However, Tesla will have invested for nothing if fuel cells have a major breakthrough in the next years. Also, there emerge new OEMs with similar business models. In the next years, these OEMs try to penetrate the market with electric and highly automated vehicles. In addition, traditional OEMs are beginning to focus on these new technologies too. In contrast to emerging OEMs, they have a lot of experience in developing and producing cars and know how to react to new situations.

The following figure shows a SWOT analysis of Tesla:

Strengths:	Weaknesses:
• *Technology leader in the EV sector* • *Unique business model and product concepts* • *Innovative tech pioneer* • *First mover advantage* • *Strong brand image and reputation* • *Advantages of a niche marketer* • *Partnership with* Panasonic	• *Low brand awareness in the mass market* • *Highly dependent on single-source suppliers* • *Prohibition of direct sales in some states in the US* • *High cost structure, low economies of scale* • *Production delay, long waiting times for customers* • *Low experience in car production* • *Problems with the global extension of the sales network*
Opportunities:	**Threats:**
• *Political and social demand for electric mobility* • *Governmental initiatives and grants to boost the breakthrough of EVs* • *Growing global demand for mobility* • *High entry barriers* • *Peak-oil- barriers* • *Cost reduction by advancement of battery technology*	• *Major breakthrough in competing technologies* • *Crowding out by market entry of big players* • *New market players with high resource base (e.g.* Google*)* • *Permanent low oil prices reduce attractiveness of EVs*

Figure 36 SWOT analysis of Tesla (adopted from Moritz, et al., 2015)

Tesla as TKS customer:

In 2014, Tesla approached TKS with regard to the carryover of products for their vehicles (specifically a steering column from Daimler). Model S was already in production and Model X in development. Due to a short acquisition phase[16], TKS proposed a carryover steering column with some minor design modifications as well as another steering column from another Daimler model. The main reason for this was the high volume and low cost of the vehicle Model 3. By using an existing and already developed product, both the development time and price could be reduced significantly.

Due to the short development process, Tesla expects quick feedback within days when it comes to the feasibility of different design options and the related product price. In return, Tesla is good at providing quick feedback and making fast decisions too. However, the

[16] In this thesis the acquisition phase includes roughly the following tasks: lobbying, pre-development activities, product concept, product calculation, process concept, economic calculation, binding quotation and nomination by the customer.

company often changes the product and/or its design from one day to another. This challenging behavior results in a significantly higher workload for TKS and thus reduces the efficiency of the project.

In the projects Model X/S, the acquisition phase took around three months from the request of information to the nomination by the customer[17]. The planned start of production (SOP) was February 2015, but Tesla re-set the SOP to October 2015 (information is not available). Moreover, for the Tesla project Model 3, the duration of the acquisition phase was expanded to eight months and the planned SOP is announced to be July 2017. Furthermore, there is a major gap between the forecast and actual requested volumes as, in general, no information on the theoretical Tesla product development process is available. The TKS sales department estimates that the Tesla product development process will take between two and three years from the project kickoff to the SOP.

Currently, TKS supplies electrically or mechanically adjustable steering columns for the current Model X/S project. Tesla is also interested in a complete wheel-to-wheel solution (steering column, i-shaft and steering gear). TKS made a quote for i-shafts, but did not receive a nomination. Tesla requested a steering gear with a variable ratio and an internal Failure in Time[18] rate of $1x10^{-9}$ for the failure of assistance and software to support the external command for autonomous driving. The TKS steering gear did not meet the necessary requirements, which is why no quote was submitted. Electromechanical products for autonomous driving need a low FIT-rate for safety and legal issues (internal source). TKS thus lost this steering gear project to a competitor.

<u>Summary:</u>

Tesla was one of the first car manufacturers that focused on electric vehicles, innovative technologies and a different business model. Other OEMs (e.g. the BMW i-series, Nissan Leaf) followed Tesla by adding electric vehicles to their product portfolio. In the last years, Tesla successfully sold vehicles at the well contested luxury market (Tesla Motors Inc., 2016). Due to this, other OEMs with similar business models soon entered the market.

Overall, Tesla works with a self-imposed short development process and pushes innovative technologies. The current shows that they increased the development time. However, additional research would be useful to fully understand Tesla’s development process and whether or not Tesla will stick to it.

[17] Calculated with the deposited dates from the internal business database
[18] The FIT-rate is used to measure failure rates of devices in operation. $1x10^{-9}$ corresponds to one failure expected in one billion operating hours.

From time to time, Tesla adds newly developed technologies to current products, e.g. the dual motor and the autopilot were unveiled in 2014, two years after presenting Model S to the market. The autopilot could be inexpensively installed in already delivered vehicles. Recently, Tesla added a HEPA filter and bioweapon defense mode against air pollution and bacteria to the product portfolio (Tesla Motors Inc., 2016d). Traditional OEMs usually wait to update vehicles until the facelift, which allows them to perform minor changes to the design, material or production, without completely redesigning the vehicle. A facelift is normally done five years after the SOP – by continuously bringing improved products to the market, Tesla is thus able to react to current technology trends.

5.2.2.2 Faraday Future Inc.

Faraday Future Inc. (in the following referred to as Faraday) is an American company that focuses on the development of intelligent electric vehicles and mobility solutions. Faraday was founded in 2014 in Gardena, California by Chinese technology billionaire Jia Yueting. Jia Yueting is the founder and CEO of *Leshi Internet Information & Technology* – also known as LeEco (formally LeTV). LeEco is a Chinese technology company which provides a wide range of businesses, from Internet TV, video production and smartphones to e-commerce.

Faraday is publically represented by Nick Sampson, Senior Vice President of R&D and Engineering, and former director of Vehicle and Chassis Engineering at Tesla Motors. He created the entire concept for the vehicle architecture of Tesla Model S (Faraday Future Inc., 2016a). Faraday headhunted for their employees all over the world and along all industry sectors to put together a diverse team. Thus, members of the current executive team one worked for automotive companies like Tesla and the BMW Group, as well as untypical automotive companies like *Picarro Inc*. and *Hawaiian Airlines* (Faraday Future Inc., 2016b; Biedrzycki, 2016). From the very beginning, Faradays' mission is to provide premium electric vehicles with a high level of connected technology, safety and automation (internal sources).

Figure 37 Manufacturing facility of Faraday in North Las Vegas, Nevada (Faraday Future Inc., 2016c)

Faraday announced that they plan to launch a new, state-of-the-art automotive manufacturing plant in December 2015. The plant is located in North Las Vegas, Nevada and production will start two years later (Faraday Future Inc., 2015). Faraday will invest 1 billion USD in the three million square-feet big location and its final expansion which will create 4500 jobs. After legislative approval of the project, grounding of the facility took place in April 2016 (Faraday Future Inc., 2016c). In contrast to Tesla, Faraday will build their first car entirely on their own[19].

Business strategy:

The vision and mission of Faraday are to

1. build a brand by globally providing and selling a premium electric vehicle, and
2. expand to a full range of electric vehicles.

To achieve these ambitious goals, Faraday employs the following operative strategies:

1. Short product development process
2. Detailed manufacturing plan
3. Apply internet business marketing and distribution models to conventional vehicles.

On 4 January 2016, Faraday unveiled their "car of concepts" *FFZero1* at the Consumer Electronics Show[20] in Las Vegas. The aim of the concept car FFZero1 is to show and investigate potentials for future car development. Furthermore, Faraday presented some technical data about the FFZero1: 1000 horsepower, 0-60 mph under three seconds and a top speed over 320 km/h (Tilley, 2016). The FFZero1 is built on the newly developed Variable Platform Architecture which will be used for all future vehicles (Faraday Future Inc., 2016d).

Figure 38 Variable Platform Architecture used for all vehicles (Faraday Future Inc., 2016d)

Faraday has an overall market strategy that is similar to Tesla Motors Inc. It starts with a low volume of vehicles that will be expanded to the mass-market over the next years.

[19] The Tesla Roadster was produced by Lotus, see 5.2.2.

[20] An annual trade show held in Las Vegas, Nevada. The event typically features presentations of new products and technologies in the consumer electronics industry. For more information see www.ces.tech.

Faraday's first electric vehicle will be an SUV – in contrast to Tesla and their sports car Roadster. The SUV will be manufactured in the new facility in Nevada and the scheduled SOP is mid-2017. Their current market strategy plans that a new vehicle shall enter different markets each year (Figure 39). However, until today, Faraday did not unveil any electric vehicles and it is therefore unclear whether the company will stick to its product strategy or not. Future investigations will be necessary to determine this.

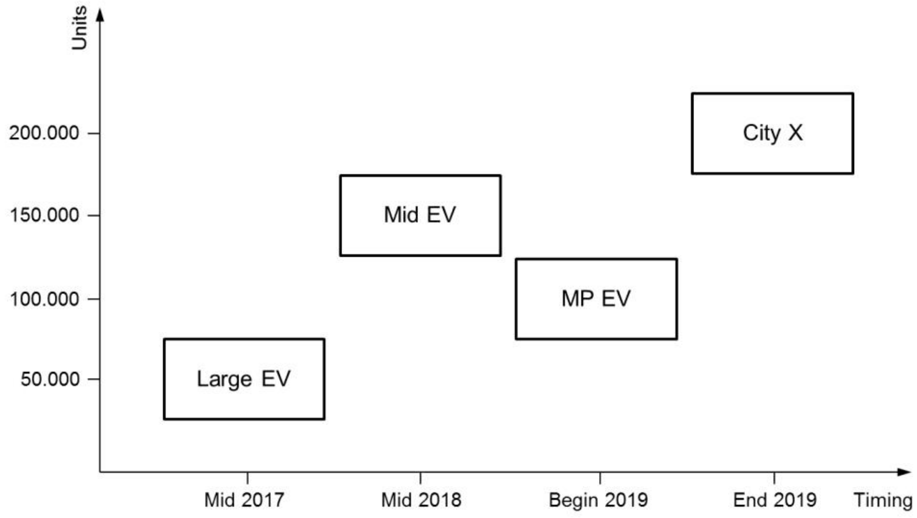


Figure 39 Market strategy of Faraday Future (company document)

Faraday does a lot of research in autonomous driving, which forms a key part of the company's identity (Faraday Future Inc., 2016e).

<u>Product development process:</u>

Compared to other emerging OEMs, Faraday attempts to penetrate the mass market in a short time with a wide range of vehicle types and configurations in different markets. This is supported by a shorter development strategy: by using simultaneous engineering and advanced development technologies, Faraday expects a 20 month saving compared to the traditional linear product development process. Figure 40 displays Faraday's development process with an expected development time of 3.5 years. Faraday will use their simultaneous process for all future projects.

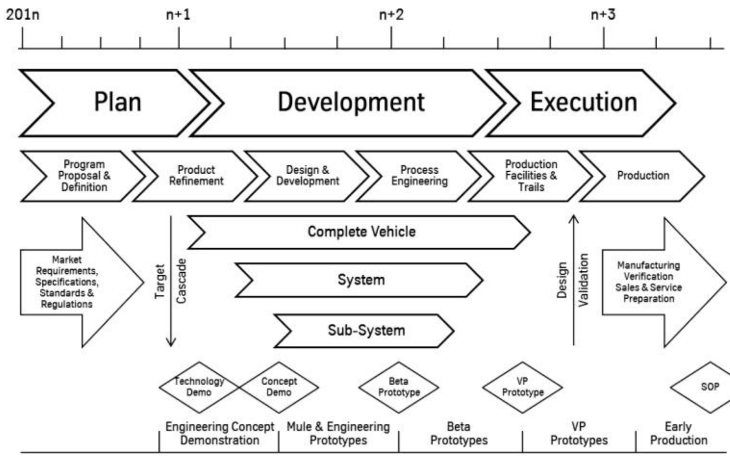


Figure 40 Faraday product development process timeline (company document)

Furthermore, the company re-uses existing and already developed systems and parts. This enables to save time and costs. In contrast to Tesla, Faraday ordered a 100% carryover part without any design changes.

Variable Platform Architecture:

As mentioned above, Faraday uses a variable platform architecture for all future vehicles. In the long run, platform strategies encourage the reduction of the overall development time as it provides an adaptable powertrain and battery architecture. Depending on the project needs, modular powertrains and batteries can be easily adapted to new requirements: an extra battery column could be inserted for vehicles with a large wheelbase, which increases the battery storage (see Figure 41). The cruising range of an electric vehicle depends on the battery storage and it can be extended by increasing the latter. A variable platform allows a flexible production of different vehicle models on a single assembly line. Further advantages are cost reduction, limited proliferation of parts and reduction of throughput times (Muffatto, 1999).

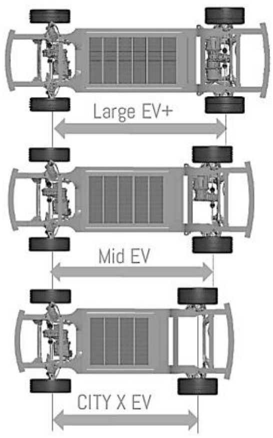


Figure 41 Adjustable variable platform (company document)

Manufacturing plan:

Faraday divides their manufacturing plan into two phases and two countries. For each country, i.e. US and China, they planned Phase 1 and 2: Phase 1 for the US is a greenfield project currently in progress by building the first plant in Nevada. The first stage of the plant shall be finished in late 2017 and will include the production of the SUV. For Phase 1 in China, a contract manufacturer will produce the Mid EV for Faraday. In the long run, Faraday plans their own manufacturing facility in China. In Phase 2, Faraday plans to produce their high volume models (*MPV* and *City X*). By 2019, a green- or brownfield facility shall be available for production. Again, Faraday has ambitious goals for their manufacturing plan, and it remains open whether they will achieve their manufacturing goals.

Marketing and distribution:

Faraday views cars as a hardware platform or "extended mobile phone". Their vehicles are to represent premium cars sold at an affordable price. The plan is thus to provide customers access to autonomous vehicles of different types depending on their needs. Customers should be able to request a cargo vehicle and, the next day, change their mind for a sporty sedan. All vehicles will have comprehensive integrated internet functions because the company believes that customers want to be connected all the time. Their vehicles should know the way and highlight places along this way that might be interesting for the passengers (Warren, 2015). Faraday has further interest in providing a high value after sale service. Thus, a full entertainment system could provide passengers with their favorite TV series or if the car is stuck in traffic, passengers could shop in different online stores. Faraday benefits from their mother company LeEco's expertise when it comes to content and entertainment technology. Furthermore, Faraday will sell their cars via the internet, just like Tesla Motors. This reduces the costs for marketing and advertising.

Strategic partnerships:

Recently, *Aston Martin* and Faraday Future announced a partnership as Faraday will help to bring the electric *Aston Martin RapidE* to the market. Additionally, Aston Martin and LeEco entered into a partnership, with LeEco providing a new infotainment system for Aston Martin vehicles. Like Tesla, Faraday uses this partnership to accelerate the learning effect for product and process development as LeEco has the advantage of being able to sell their infotainment system to other vehicles and other OEMs.

SWOT analysis:

To summarize all findings, a SWOT analysis was conducted (see Figure 42). The strength of Faraday Future is definitely the unique business model and the partnership with LeEco. While the focus is still on the hardware (i.e. chassis, engine, etc.), in the future, the software and the available applications will get more attention. This is ascribed to the boom in smartphone technology. Compared to other emerging OEMs, Faraday has no existing production and no moving vehicle has been presented so far. This obvious weaknesses will be eliminated over the next months and years, by presenting a moving car and finishing the production facility in Nevada. A clear opportunity for Faraday is the change of the overall vehicle business model. Additional revenue due to the high value of after sale services or advertising could change the automotive industry. The biggest threats to Faraday Future are new market players like *Apple*[21] or Google[22], which have both a financial background and the know-how when it comes to building an operation software.

Strengths:	Weaknesses:
• Unique business model and product concept • Platform strategy from the very beginning • Advantages of a niche marketer • Partnership with LeEco	• No moving car presented • High cost structure • No existing production • Low/no experience in car production • No existing sales network
Opportunities:	**Threats:**
• Hardware platform • Infotainment system • Advertisement • Growing global demand for mobility • Political and social demand for electric mobility • Governmental initiatives and grants to boost the breakthrough of EVs	• Will not meet scheduled start of production • New market players with high resource base (e.g. Google) • Crowding out by market entry of big players

Figure 42 SWOT analysis of Faraday Future

Faraday Future as TKS customer:

At the end of July 2015, TKS was contacted by Faraday concerning a wheel-to-wheel solution[23] for their vehicles. At the beginning of September, TKS submitted a non-binding quote with a price estimation and a carryover of a current BMW project. After two weeks, Faraday nominated TKS for a complete wheel-to-wheel solution of their first vehicle *DF91*. As explained, Faraday supports the concept of re-using existing and developed products as this allows a significant reduction of the overall development time. This would allow the company to reach the SOP in 2017, which makes fast development necessary. Faraday did not provide TKS with a specification sheet or product requirements. They rather asked what the existing product's possibilities and specifications are.

[21] There are rumors about Apple's *iCar* project, but no clear information has yet been released.
[22] https://www.google.com/selfdrivingcar/ accessed on August 24, 2016
[23] Wheel-to-wheel solution includes the components steering column, i-Shaft and steering gear

By using an existing product, TKS had to verify the legal and property rights of the product design and manufacturing tools. Typically, the machines are owned by TKS, but – depending on the costumer – the rights of the product design and manufacturing tools are owned by them. It thus has to be verified whether TKS is allowed to sell the existing product to another customer or not.

Summary:

Like other emerging OEMs, Faraday pursues ambitious goals. The next months and years will be decisive for Faraday Future as they will show whether they reach their objectives. Currently, the information on Faraday's business model and their products is based on non-qualitative sources such as expert interviews, presentations, or the web.

There are a lot of similarities between Faraday Future and Tesla Motors: Faraday has a big financial investor with a clear vision and mission for the company. Also, the current product strategy is structured in the same way as Tesla's. However, Faraday focuses on the software and the provided applications, develops an own electric vehicle called *LeSEE* and also owns another emerging OEM called *Atieva*.

To be able to make more precise statements, further investigation needs to be done.

5.2.2.3 Zhejiang Geely Holding Group Co., Ltd

Zhejiang Geely Holding Group (in the following referred to as Geely) is a Chinese multinational automotive manufacturing company. Originally, Shufu Li founded Geely as a refrigerator manufacturer in Taizhou in 1986. In 1997, Geely started specializing in the automotive industry, primarily producing motorcycles, scooters, and engines (Alon, et al., 2008). Geely was first officially registered as an automotive company in 2001 and soon became the first private Chinese enterprise building passenger cars. Today, Geely is headquartered in Hangzhou, Zhejiang as one of the largest independent private automobile manufactures in China besides *BYD*, *Great Wall* and *Chery*. The holding includes the brands Geely and *Emgrand*, *London Taxi Company* and *Volvo Car Cooperation*. Geely mainly manufactures in China and has currently over 18,000 employees – including 2,300 engineers and technicians worldwide. The product portfolio of Geely Holding consists of more than 30 complete vehicle models, mainly powered by internal combustion engines (Zhejiang Geely Holding Group, 2014). Today, Geely is one of China's top ten automobile manufacturers (Fetscherin, 2011).

Figure 43 Official logo of Zhejiang Geely (www.geely.com)

<u>Business strategy:</u>

In the beginning, Geely had the vision of producing a vehicle from scratch by simply combining capital, technological and human resources. Wang and Kimble (2013) report that Geely's first vehicles were poorly designed and eventually unfit to use in practice. Therefore, the company changed its strategy to the imitation of existing vehicles and started to reverse-engineer and copy components. However, Geely deliberately modified the copied products to achieve a more open and modular product architecture, all the while aiming at an interface which allows a mix-and-match of high-level components from different sources[24] in a flexible and efficient way (Wang & Kimble, 2013).
According to Zentes, et al., (2011), the technology- and performance-competent strategy is built on the following key foundations:

- Focus on new product development
- Focus on new technology
- Focus on quality
- Expansion by broadening the sales volume
- Expansion of production capacity
- Expansion by additional mergers and acquisitions

In the recent years, Geely changed their business strategy "…from technological imitation to innovation" (Xu & Li, 2014). The transformation process began in May 2007 and was accomplished after three phases in 2015 (von Bismarck & Zheng, 2016). This Geely achieved by making significant investments in manufacturing capacity, product development, technological research, sales network (Fetscherin, 2011) and the education of their employees (von Bismarck & Zheng, 2016).

At the beginning, only few vehicles were actually sold and they increased their market share very slowly. By focusing on new products and a multi-brand strategy, sales

[24] An engine produced by Geely fits into the chassis of several different manufacturers. Additionally, a wide range of engines from the open market fit into Geely vehicles (Wang & Kimble, (2010); Wang & Kimble, (2013)).

increased up to 500.000 units per year (excluding Volvo). After having established the company at the Chinese market, Geely started to enter the North America and Europe markets. However, the quality and names of the models were not competitive enough to hold their ground against multinational competitors. Due to the high investments in quality and R&D and the knowledge from Volvo, Geely began manufacturing models with a good qualitative standard[25] and a low price. This makes Geely a real alternative for Western costumers (von Bismarck & Zheng, 2016).

At the *Beijing Auto Show* 2014, Geely unveiled the plug-in-hybrid concept car *Emgrand Cross* and announced the increased R&D with regard to new energy vehicles (Geely, 2014). On 18 November 2015 the Emgrand EV was launched, presenting a fully electric vehicle. It is the first car of *Blue Geely Initiative* and will be their new brand strategy. The company announced that they will change to a new energy vehicle manufacturer in the next years (Joseph, 2015). This reflects the "go with the trend"-philosophy and the targeted adaption to new requirements (von Bismarck & Zheng, 2016). The new energy strategy includes the following bullet points (Geely, 2016):

- Affordable PHEVs at prices of traditional cars
- New Energy Vehicles should make up 90% of the total sales volume (65% PHEV / HEV; 35% EV)
- Successful development of hydrogen/metal fuel battery vehicles
- Leading new energy, Smart Car and light weight technologies

Product development process:

There is currently no detailed information about Geely's product development process available on the web or in the literature. However, internal sources estimate the development cycle at three to four years.

Product architecture:

As mentioned before, Geely moved towards a modular and more open product architecture. Through the acquisition of Volvo, Geely has complete access to Volvo's technology[26]. Sun Xiaodong (the Vice President of Zhejiang Geely Holding Group) announced "The One Geely" strategy, which follows a "platformisation" and "universilation" of products. The result is a unified platform for all brands: Geely will use the compact modular architecture (CMA) platform (Geely, 2014). The CMA platform was developed in cooperation between Geely and Volvo (Volvo Car Group, 2015). The first cars using the highly-innovative CMA platform are expected in 2017 in Volvo's *40*-product line models (Volvo Car Group, 2015) and in 2018 by Geely (company documents). The

[25] Emgrand EC7 became the first of Geely's vehicles that obtained a four star rating in the European safety test (von Bismarck & Zheng, 2016).
[26] Volvo signed an agreement for transferring their technologies to Geely (AutoTech Review, 2013).

CMA platform was simultaneously developed with the Scalable Product Architecture (SPA) platform, which is already on the market (XC90). In the future, the complete fleet of Geely and Volvo will be built on these platforms.

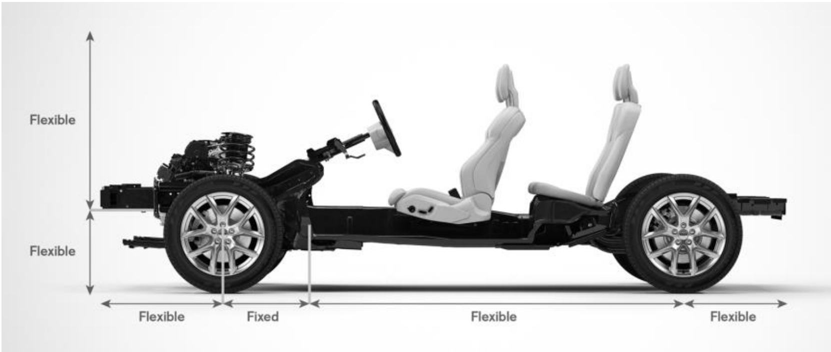


Figure 44 Compact Modular Architecture CMA (Volvo Car Group, 2015)

CMA and SPA share their technology, including powertrain, infotainment, climate and safety systems. This offers Geely and the subsidiary a high degree of modulation for their future cars (Volvo Car Group, 2015).

Manufacturing plan:

In the last years, Geely continuously increased its production capacity to 670.000 units per year (excluding Volvo). The production facilities are located all over China[27] and their capacity varies between 50.000 and 250.000 units per year (Geely Automobile Holding, 2014). It seems that Geely will expand their production volumes in the next years (requested volumes, company documents). There is no detailed information about Geely's manufacturing plan, both considering online and literature sources.

Marketing and distribution:

In China, Geely restructures their distribution from a multiple dealer network to a one dealer network. In April 2016, Geely counts 685 dealers in China and 464 sales and service outlets in 31 oversea countries, with the number of dealers having been reduced from a total of 1068. As already mentioned, Geely focuses on exporting their vehicles to the North American and European markets. In 2015, only 5% of the vehicles were exported[28] (Geely, 2016). Geely was the first Chinese automobile manufacturer to establish an around-the-clock after-sales service information (Zentes, et al., 2011). The company still sells their vehicles via the classic way of dealers.

Strategic partnerships:

[27] Chengdu, Jinan, Lanzhou, Linhai, Luqiao, Ningbo/Cixi, Shanghai and Xiangtan (Geely Automobile Holding, 2014). Moreover, two joint venture plants in Belarus and Uruguay (Geely, 2016).
[28] In 2013, the export quote was about 25%.

Geely made two interesting acquisitions with London Taxi Company in 2006 and in 2010. In addition, it entered into strategic partnerships and joint ventures with other companies (von Bismarck & Zheng, 2016). In 2013, *Kandi Electric Vehicles Group* and Geely signed an agreement for a joint venture. Kandi Electric's core business is the manufacturing of electric vehicles (Zhejiang Geely Holding Group, 2014). It is assumed that Kandi Electric contributed to the development of Emgrand EV. In the following section, the acquisition of Volvo is briefly discussed.

In 2010, Geely bought the Swedish automotive manufacturer Volvo from *Ford Motor Company* for $1.8 billion. With this acquisition Geely obtained access to developed and highly advanced technology from Volvo – especially the complete product development process (Wang, 2011). In 2012, the two companies agreed to transfer developed technology from Volvo to Geely (AutoTech Review, 2013). Thus, Geely was able to develop a car using already existing technologies (e.g. the mid-size platform, safety innovations and heating, ventilation and air condition). Geely and Volvo also developed their current CMA platform in cooperation.

A summary of the beneficial effects of this acquisition was displayed by Wang (2011) and Gao (2015):

- Geely has access to Volvo's core technology
- Brand enhancement of Geely
- A high-end car brand which is profitable again
- High growing possibility for Volvo in the Chinese market

SWOT analysis:

All findings of Geely are summarized[29] in the following SWOT analysis (see Figure 45). The strength of Geely is definitely the acquisitions of Volvo and London Taxi: they allow the company access to well-developed technology and well-known brands. Furthermore, Geely is a well-known brand in the Chinese automotive market which is currently the largest automobile market in the world (International Organization of Motor Vehicle Manufacturers, 2016). Another strength is the continuous adapting of their business strategy to be able to tackle new trends in the automotive industry. Compared to non-Chinese OEMs, Geely still has a low brand image in the global automotive market, despite the acquisition of Volvo. In 2009, the Chinese government started to subsidize electric vehicles and, currently, the Chinese EV market is a very promising one both for customers and manufacturers (Hua, et al., 2010). The ability to change their business strategy to fit new energy vehicle manufacturers increases Geely's potential for growth in the next years. The biggest threat to Geely are other competitors in the automotive sector, which currently or in the future operate in the Chinese market (Ebel & Hofer, 2014).

[29] Condensed information from the sources: Wang, (2011); Fetscherin, (2011); Huihui, (2012); Wang & Kimble, (2013); Geely Automobile Holding, (2014); von Bismarck & Zheng, (2016)

Strengths:	Weaknesses:
• Acquisition of Volvo • Well-known Chinese manufacturer • Reduced labor costs • Skilled workforce • Emphasis on R&D and Quality • Established sales and distribution networks • High profits • Ability to adapt business strategy to new market situations	• Integration of Volvo • Relatively low brand image • Competitive market
Opportunities: • Chinese market is growing • Growing global demand for mobility • New products and services • New acquisitions • Political and social demand for electric mobility • Governmental initiatives and grants to boost the breakthrough of EVs	Threats: • Growing competition • Technological problems • Increasing costs • Tax changes

Figure 45 SWOT analysis of Geely

Geely as TKS Customer:

There is no clear information about the first contact between Geely and TKS. Currently, there are several projects for Geely, mostly concerning wheel-to-wheel solutions[30] including all TKS products. There is currently one project on the CMA platform that will be produced for Geely and Volvo. Some parts and components thereof were used from an already existing product, while some parameters were adjusted. For the newest project, Geely requested a 100% carryover product from another active project. The customer's planned SOP is 2017. Additional information or specification sheets of the process were not available.

Summary:

Geely produces vehicles in concordance with the requirements of its customers. At the very beginning, the majority of Chinese people wanted a cheap vehicle – the quality was not important. However, people soon began to wish for safe and high-quality vehicles. Geely thus changed their business strategy and started to produce vehicles with better technology and high quality standards. They invested in their research base and built educational organizations to train their own engineers. Geely's philosophy can be

[30] Wheel-to-wheel solution includes the components steering column, i-shaft and steering gear.

described as “*go with the trend and survive with changes*” (von Bismarck & Zheng, 2016). Currently, Geely is again adapting their product and brand strategy to new trends in energy vehicles. The company has high goals as can be seen by the planned manufacture of two million vehicles in 2015 (von Bismarck & Zheng, 2016). However, only some 500.000 units were produced which is only 25% of the planned volume. Thus, for the year 2016, Geely plans to sell 600.000 vehicles (Geely, 2016). It would be interesting to know which volumes are planned for the next five to ten years.

For more precise statements, further research and investigation have to be done: one could, for example, do additional research on other Chinese emerging OEMs in order to to get a broader insight into the Chinese automotive market and their participants.

5.2.2.4 BMW Group

Bayrische Motoren Werke Aktiengesellschaft (in the following referred to as BMW) is a German high-end automotive manufacturing company. BMW was founded in 1916 as an aero-engine manufacturing company in Bavaria, South Germany. In 1928, it presented their first automobile called *DIXI*[31]. In 1952, BMW presented their first car, the *501*. In the next years, BMW’s volume of vehicles increased and several production facilities were constructed all around the world. In 1986, BMW united all research and development work under one roof in the *FIZ* Munich. It was the first time that an automotive manufacturer established such an institution and BMW is generally considered a pioneer in emerging technologies, including turbocharging and advanced vehicle electronics. Today, BMW is headquartered in Munich, Germany as one of the largest independent private automobile manufacturers worldwide. The BMW Group contains the premium brands BMW, *Mini* and *Rolls-Royce Motor Cars*. BMW mainly produces in Germany, China and the US and currently has over 122,000 employees. In 2015, 2,279,503[32] vehicles were produced (Bayrische Motoren Werke AG, 2016a). BMW produces their vehicles using a customer- and order-specific approach and make-to-order (BMW Group Media Information, 2014b).

Figure 46 BMW emblem (www.bmwgroup.com)

[31] Dixi, an Austin 7, was built with a license from the Austin Motor Company.
[32] BMW – 1,905,234 #; Mini – 338,446 #; Rolls-Royce – 3,785 #.

Business strategy:

This thesis focuses on the strategies 2008 “Number One” and 2016 “Number One > Next”. In late September 2007, BMW presented their future business strategy “Number One”. The objective was to position BMW as a leading provider of premium products and services for individual mobility. The aim was to realize this vision with the House of Strategy in 2020 (cf. Figure 47). The four pillars represent BMW Group’s particular strengths and distinctive features. Innovations due to projects are located in the pillars “Shaping the Future” and “Access to Technologies and Customers”. Building on these pillars, BMW announced that they will launch a dynamic and efficient hybrid car in 2009. The entirely new vehicle would be equipped with a new driving system. Furthermore, they presented BMW’s *ConnectedDrive*, a virtual co-pilot that connects the vehicle to its environment and the general traffic (Bayrische Motoren Werke AG, 2008). One year later, *Mini E*[33]*,* an electric concept car, was presented. The know-how of the Mini E-project was used for the *BMWi*-project launched in late 2007 (Bayrische Motoren Werke AG, 2009).

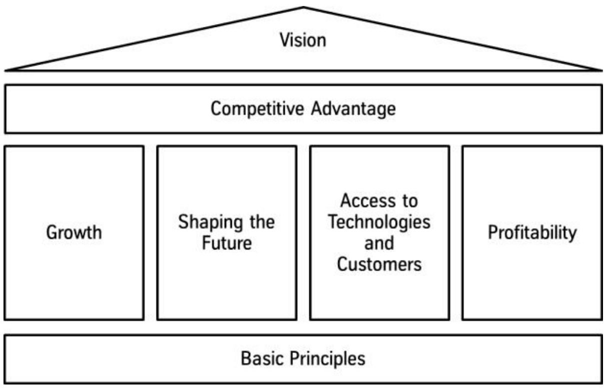


Figure 47 House of Strategy Number One modeled acc. to Bayrische Motoren Werke AG, (2008)

The strategic objectives of the BMWi-project stem from the corporate strategy Number One: the project was created to generate growth through new target groups, products and services. With the i-project, BMW started to provide a 360° electric mobility service for their customers comprising the following services (Bayrische Motoren Werke AG, 2013):

- *DriveNow*: car sharing platform, www.drive-now.com
- *ChargeNow*: public charging stations, www.chargenow.com
- *ParkNow*: parking app, www.park-now.com

The results of the BMWi-project are the cars *BMW i3* and *BMW i8*. BMW i3 is available as a battery-driven electric vehicle, BEV, or as a plug-in hybrid vehicle, PHEV, and it was unveiled in 2013 (BMW Group Media Information, 2013a). One year later, BMW i8 was presented to the public as a plug-in hybrid sports car (BMW Group Media Information, 2014a). BMW sold 29.513 cars of the i-series worldwide, which is an increase of 65.9%

[33] Mini E was presented at the *Los Angeles Auto Show* as a fully electrical vehicle with 156 mile range (BMWBlog, 2008). The Mini E was available via leasing for private customers (Bayrische Motoren Werke AG, 2009).

compared to 2014, and thus the highest increase in sales of all BMW series (Bayrische Motoren Werke AG, 2016a).

In 2015, BMW presented an adapted and updated strategy called “Number One > Next”. The House of Strategy was reduced and adapted to the following points:

- Vision
- Competitive advantage
- Strategic approach
- Corporate culture

BMW transferred their technologies to their core brand series, which was henceforth named *iPerformance*. The first models of this new strategy were introduced to the market in 2016: *225xe*, *330e*, *740e* and *M760Li xDrive* are plug-in hybrid vehicles with a maximum cruise range of 40km (BMWBlog, 2016). BMW’s iPerformance focuses on PHEVs and *iDivision* on BEVs. In the next years, new vehicles will be developed and the i-series portfolio will be extended. Furthermore, BMW announced that they will place an additional focus on new powertrain technologies (e.g.: hydrogen) and digitalization (connectivity, artificial intelligence and autonomous driving) (BMW Media Information, (2016); Bayrische Motoren Werke AG, (2016b).

Platform architecture:

BMW follows different platform strategies for different vehicle models. Current strategies are *UKL*, *35up* and *LifeDrive Architecture*. LifeDrive Architecture was developed especially for electrical vehicles and it includes two independent modules: the Life Module (passenger compartment) and the Drive Module (chassis, driveline technology and battery). The passenger compartment is made of carbon fiber, which is both light and provides the necessary strength, while the Drive Module is made of aluminum. This construction setup enables a modular development of future EVs (BMW.de, 2016).

Figure 48 LifeDrive Architecture (BMW.de, 2016)

Product development process:

The product development process of BMW is called Product Evolution Process (PEP) or time-to-market process. It summarizes all activities necessary for the design and testing of products as well as the set-up of production processes required for the manufacturing of the product. All phases and milestones of the PEP are documented and well defined (BMW Group, 2008). The timeline of the PEP is estimated at four to five years (48 to 60 months)[34]. Figure 49 displays the phases of the product development process[35]. Furthermore, BMW has an extended technology phase (advance and preparation phase) for the first 24 months. In this project phase, BMW develops a new technology or component for a vehicle together with the supplier (company information). Further information on the general product development process are provided by several sources[36]. A detailed process of BMW was not available for this thesis and the process is thus investigated no further.

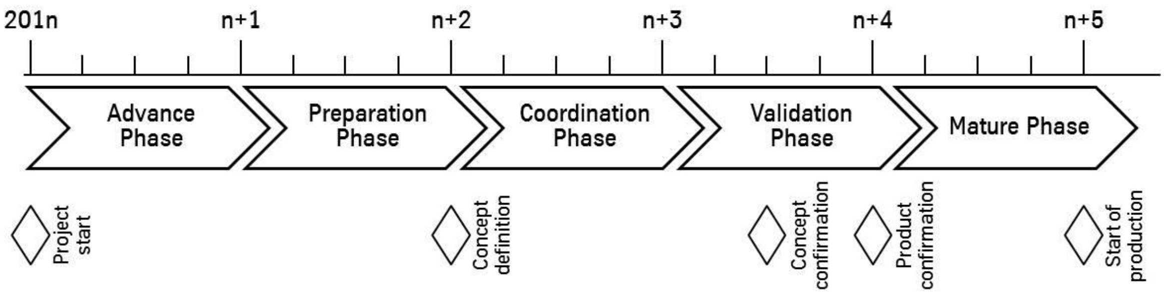


Figure 49 Product development process (PEP) (modified and summarized from Hirz, et al., (2013); BMW Group, (2008); company documents)

Manufacturing plan:

BMW produces their components and vehicles all around the world and currently operates 30 production locations in 14 countries. Most production facilities are located in Germany, others in Austria, South Africa, the United States and China. An extension of existing facilities as well as the building of new facilities are currently under development (Bayrische Motoren Werke AG, 2016a). BMW aims to achieve a balanced growth on all continents and markets. To launch products even faster and gain a competitive edge, the company uses additional capacities from external production partners (e.g. *Magna Steyr* in Graz, Austria). BMW forces their strategy to fit a more flexible and faster production in order to be economical and efficient and to deliver faster (BMW Group Media Information, 2014b).

34 BMW calculates with Months before SOP (MvS - Monate vor Serie)
35 This merely shows the sequence of basic processes. The time span of each process depends on the project and was thus not investigated.
36 Hirz, et al., (2013); VDA, (2009); Sörenson, (2006).

Marketing and distribution:

BMW Group acts in more than 150 countries and the sales network includes 3,310 BMW sales partners (Bayrische Motoren Werke AG, 2016a). BMW only sells their new vehicles via sales partners – buying a BMW via the internet is currently not possible.

Strategic partnerships:

In recent years, BMW entered into several strategic partnerships, for example with Magna Steyr, *Intel*, *ParkNow* or *HereMaps*. Magna Steyr is a contract manufacturer that produces complete vehicles for BMW (BMW Group Media Information, 2014b). ParkNow is a mobile parking service which allows its users to book a parking space in advance depending on price and location (BMW Group Media Information, 2013b). In July 2016, Intel, BMW and *MobileEye* revealed their strategic partnership for developing self-driving vehicles and future mobility concepts. The aim of this collaboration is to build fully automated vehicles in serial production by 2021 (Intel Corporation, 2016). An interesting acquisition of BMW was HereMaps from *Nokia* in December 2015: this acquisition was done in cooperation with BMW's competitors *Mercedes Benz* and *Audi*. HereMaps is one of the major companies in the mapping business besides *TomTom* and *Google* (Hucko, 2016). It delivers high-definition maps combined with real-time location information. In fact, real-time traffic information and high-definition maps are essential for the development of self-driving vehicles. The shareholders ensured that HereMaps remained independent and open to all its customers (Here, 2015).

SWOT analysis:

To summarize all findings, a SWOT analysis of BMW was conducted (see Figure 50). Valued at $26 billion, BMW is the second most valuable brand in the automotive industry. Another strength of BMW is the continuous development of products and innovations. BMW is also known for their high quality of products which is reflected in the low recall rate (statista.com, 2015). A weakness of BMW is the high cost structure that comes with producing high quality cars and hiring skilled employees. As a result, the premium vehicles have higher prices compared to other cars. The growing demand for mobility is an opportunity for BMW and its current products DriveNow and iDivision. BMW has the potential to grow by extending the current portfolio: especially concerning the EV sector where BMW still sells less vehicles compared to other OEMs[37]. The biggest threats to BMW are the growing competition, increasing costs and governmental initiatives with regard to EVs. In 2015, Germany announced buying grants for electric and hybrid vehicles, which means that a customer will get a reward of EUR 4,000 for buying an electric vehicle (von Erichsen, 2016). With this reward, the acquisition costs of an EV can be reduced and sales volumes shall increase. Furthermore, the production costs of BMW increased over the last years (Bayrische Motoren Werke AG, 2016a).

[37] http://insideevs.com/monthly-plug-in-sales-scorecard/, consulted online on 20 July, 2016.

Strengths:	Weaknesses:
• Strong brand image • Product innovation • Quality • Strong R&D capabilities • Skilled employees • High employee productivity	• High cost structure • High prices • Brand portfolio? • Strategic alliances
Opportunities: • Expand brand portfolio • Growing global demand for mobility	**Threats:** • Growing competition • Increasing costs • Governmental initiatives and grants to boost the breakthrough of EVs

Figure 50 SWOT analysis of BMW

BMW as a TKS customer:

There exists no clear information about the first contacts between BMW and TKS. Currently, several projects for BMW are active, including wheel-to-wheel solutions[38] and all products of TKS. TKS supplies a steering system for BMW i8 with a low number of units. In this case, an already developed steering system was adapted to the new vehicle's specifications. For the newest project, BMW requested a completely new steering gear for a vehicle with the SOP in 2021. BMW provided TKS with a detailed specification sheet with all requirements, dates and milestones.

Summary:

BMW is one of the oldest car manufacturers in the world that focuses on premium and luxury vehicles. In this thesis, BMW was used as an example for traditional OEMs.

In general, BMW always tried to meet customer requirements and presented new innovative technologies. Nevertheless, the company concentrates on its core competencies and its slogan "Freude am Fahren" (the pleasure of driving). BMW is an OEM that presents finished products of high quality and life cycle, which originate in the long development process. The strategies "Number One" and "Number One – Next" indicate that BMW is ready to face the new automotive trends connectivity, electrification and autonomously.

It should be noted that further investigation of more traditional OEMs has to be done in order to provide more accurate statements of this group of OEMs.

[38] Wheel-to-wheel solutions include the components steering column, i-shaft and steering gear.

5.2.3 **Comparison**

The prior chapters examined business models, development processes and core competences of emerging and traditional OEMs. In the following chapter, the main findings are compared and discussed. Further information of all analyzed OEMs is displayed in Table 1 below.

Table 1 Summarized information of investigated OEMs

	Tesla Motors	Faraday Future	Geely	BMW Group
Webpage	www.tesla.com	www.ff.com	www.geely.com	www.bmw.com
Founding year	2003	2014	1986	1916
Business background	Software	Software	Mechanical Engineering	Mechanical Engineering
Current CEO	Elon Musk	Nick Sampson	Li Shufu	Harald Krüger
CEO background	Engineer and entrepreneur	Mechanical engineer	Mechanical engineering	Mechanical engineering
Turnover	USD 4,000 million	N/A	USD 3,300 million	USD 80,000 million
Number of employees	13,000	750	19,000	122,000
Vehicles sold in 2015	50,000	N/A	500,000	1,900,000
Electric vehicles sold in 2015	50,000	N/A	N/A	30,000
Focus on	EV	EV	ICE, PHEV, EV	ICE, PHEV, EV
Product request	Carryover product	Carryover product	Carryover product	New development
Timeline of development cycle (kickoff – SOP)	2-3 years	3-4 years	3-4 years	4-5 years
Requested response time	4 weeks	2 weeks	4-6 weeks	4-6 weeks
Timeline between request and nomination	3 & 8 months	2 months	6 months	24 months
Timeline between nomination and SOP	17 months	21 months	27 months	36 months
Autonomous driving	Yes	Yes	Yes	Yes

New OEMs focus on selected vehicle types along the value chain. The main focus of the present thesis is on the current automotive trends electrification, connectivity and autonomy. These have a high market potential and promise high profits (Kaas, et al., 2016). Therefore, it is important to have a fast time-to-market strategy because products are outdated quickly. Software companies with the right product at the right time often started a disruptive change in technology and in the end became market leaders[39]. This is important when taking into account that all CEOs and founders of the analyzed emerging OEMs have a background in the software industry[40]. Thus, the CEOs have experience in the software industry and therefore try to quickly react to the future automotive market[41].

Traditional OEMs possess the necessary background (both technically and financially) to simultaneously develop cars for several markets. Therefore, they are positioned more broadly compared to emerging OEMs. To enter the new market, the emerging OEMs have to reveal the right products at the right time (Kim & Mauborgne, 2004). This requires a fast time-to-market which can be achieved by short development processes. An emerging OEM’s development process is already much shorter than that of a traditional OEM.

To save time during the development process, emerging OEMs order already developed products (carryover products). By using already existing technology, they save a lot of time and due to the fact that the products are already being used, initial technical difficulties were found and corrected, i.e. the products are tried and tested. However, the developing of a vehicle with carryover products only bears the risk that the end result is not perfect: badly defined interfaces and makeshift solutions may have negative effects on the end product. Geely made this experience in the beginning of their history, consequently changed their philosophy and optimized the adaption of existing products by defining their interface.

In recent years, traditional OEMs realized the change in the automotive industry and started new business and product strategies in order to face new automotive players (Freitag, 2016). In fact, it seems they have been adapting successfully for years. Over the years, traditional OEMs continuously improved their products and reduced the development time[42] from the maximum of six to a maximum of five years. In addition, traditional OEMs are continuously involved in product development processes, which provides them with detailed and specific requirements of steering systems (visible in the detailed specification sheets). Traditional OEMs have long-time experiences in developing vehicles and the changing of the market landscape.

To sum up, emerging OEMs focus on their core competences and selected parts along the value chain. For new players, it is crucial to quickly gain basic knowledge and competencies. This can be done via external sources, strategic partnerships and joint

---

[39] Apple’s iPhone, Google’s search engine or Facebooks social network are popular examples (Viardot, 2013).
[40] Tesla Motors – Elon Musk (PayPal), Faraday Future – Jia Yueting (LeeECO); NextEV – William Li (Bitauto.com).
[41] Blue Ocean Strategy (Kim & Mauborgne, 2004).
[42] Development process timeline of a traditional OEM: 1993 – 5 to 6 years; 2007 – 4 to 5 years.

ventures (Moritz, et al., 2015). New OEMs often position themselves as technology leaders with innovative ideas at an early stage (Ebel & Hofer, 2014). Currently emerging OEM focus on "bringing the vehicle to the market next year".

5.2.4 Summary and Findings

The two main impacts on TKS which stand out from Table 1 are the short product development process and the use of carryover products.

In fact, the short product development process has a strong impact on TKS and its processes. The current Mechatronic Product Life Cycle (MPLC) was introduced to develop a mechatronic steering system together with a traditional OEM. The requirements of the products and the timeline are known and adjusted to the OEM processes. For years, many projects have been successfully completed with this process. However, the emerging of new OEMs and their short development process gave rise to several process limitations. The current process – especially the acquisition phase – have to adapt in order to be able to react to these new development processes. Based on the limited scope of the master thesis, only a briefly investigation of the acquisition process is provided.

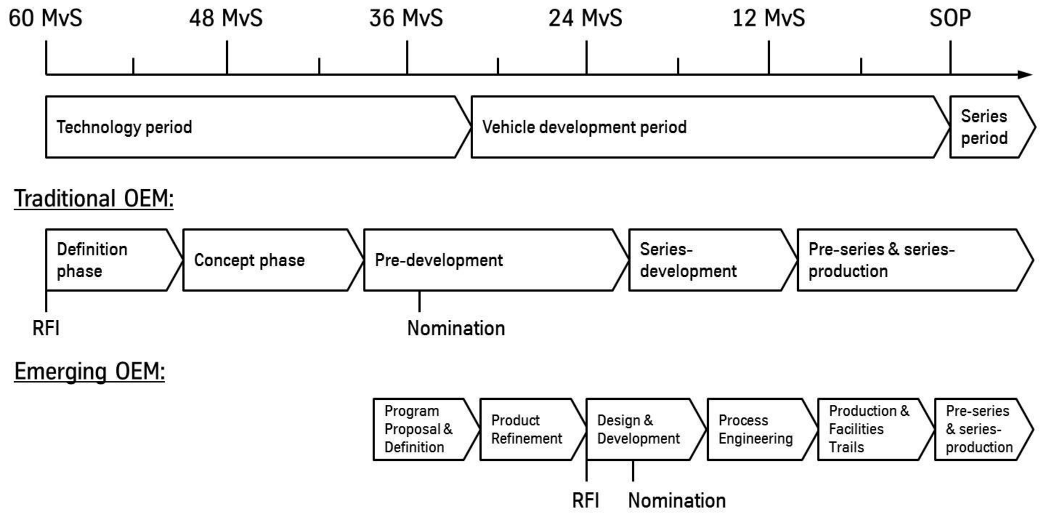


Figure 51 Compared product development process and RFI and nomination points (own illustration)

For a traditional OEM, the acquisition phase takes between one and two years (from the request of information to the nomination). This has the advantage that a business partnership is created with the customer and potential volumes can be forecasted. In the case of an emerging OEM, the acquisition phase is usually very short and takes around two months. However, the problem is that emerging OEMs effected the nomination before TKS had made an official quote. This resulted in the first product price only being an estimation that could not be efficiently calculated, which led to minor problems.

Another influencing factor are currently offered products. As already explained, emerging OEMs order already developed products from existing projects. These products are usually linked to a specific customer (e.g. his tools or designs). In the automotive industry, standardization is used to reduce developing and production costs (e.g. each presented OEM has its own platform strategy). Based on this, TKS should develop its own standardized steering systems platform strategy. With this, several steering systems could be provided for different customers. Furthermore, OEMs focus on selected parts along the value chain and TKS has the opportunity to appear as a system supplier.

In addition, emerging OEMs focus on autonomous driving, for which the steering system has to fulfill several requirements (e.g. FIT-rate, be fail-safe, etc.). Here, projects were lanced in order to further investigate this topic.

A more thorough investigation of the impacts on the acquisition process has already been started by several departments and experts investigating this problem. However, TKS is interested in finding out how standard innovative steering systems impact the current manufacturing process. Therefore, the next main study investigates steering systems and their evolution in more detail.

5.3 Steering Systems

In the second main study, innovative steering systems are investigated to answer the third key question of "*What could conceptualized innovative steering systems look like?".*

The first vehicles in history already needed steering systems. Over the years, they were further shaped and developed due to technological progress. The first steering system was a purely mechanical product, which was improved in the subsequent years until the creation of the first power-assisted steering systems. At the beginning, the power assistant was hydraulic, but it changed over time to an electrical assistant that had several advantages. Figure 52 hierarchically divides "Technologies" into separate sub-systems of *existing technologies* (i.e. mechanical or electrical steering systems) and those *under development*.

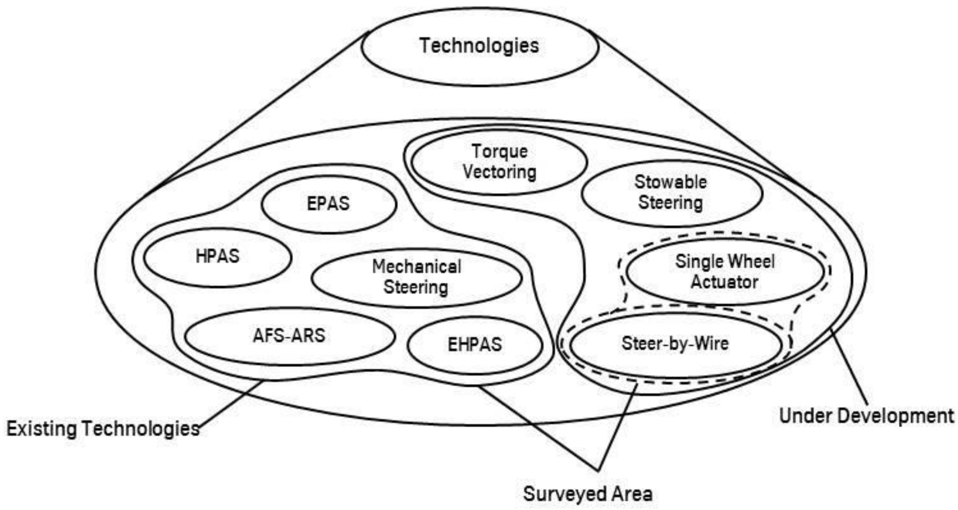


Figure 52 Steering technologies (own illustration)

In the following sections, the evolution of steering systems is treated in more detail. The current trend of autonomous driving is seen as one of the main factors for innovative steering systems, which is why selected steering systems under development are also investigated, e.g. SbW systems. Based on the assumption that the SbW concept is the next step in the evolution of steering systems, there are several ways in which the concept can be put into practice: SE, for example, offers creative methods such as the morphological scheme, which was used in the present thesis to quickly develop different variants of steering systems.. The created concepts are evaluated using another SE method. Finally, the concepts are compared and findings are discussed. The overall method of the following chapter is the problem life cycle according to the Hall-ETH approach.

5.3.1 **Steering Technologies**

A steering system enables the driver to control the lateral dynamics of the vehicle and thus the direction of driving. Figure 53 displays the main components of a steering system: the steering wheel, the steering column with an intermediate shaft (i-shaft), the steering gear and tie rods. The steering system transfers the rotation of the steering wheel via the steering column and i-shaft to the steering gear. The steering gear then transforms this rotation to a linear movement. Via the tie rod, the linear movement is transferred to an offset of the steering axis of the wheel carrier. Due to the lever at the steering axis, the linear movement is transformed back to a rotational movement. With the skew of the wheel, lateral forces are created which lead to the yawing moment that causes the vehicle to be able to drive in a circle (Pfeffer & Harrer, 2013).

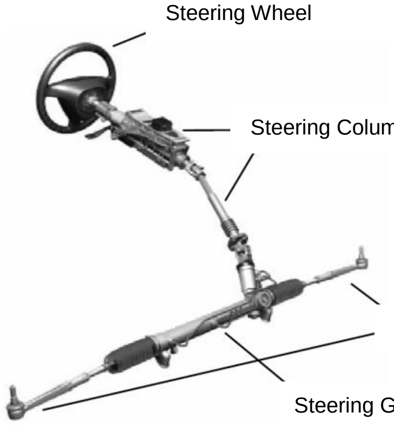


Figure 53 Steering system of Porsche 997 *(Pfeffer & Harrer, 2013)*

Functionality and objectives:
Generally, a steering system has to fulfill two superordinate tasks: first, to transmit the input from the driver to the wheels and, second, to provide feedback[43] about the current vehicle situation. The steering system is a very important safety part of the vehicle and it is crucial that it precisely maintains the desired driving course of the vehicle. Therefore, different and often contrary requirements of the steering system arise: on the one hand, the torque effort of the steering wheel has to be sufficiently low to enable steering without signs of fatigue, and, on the other hand, a high torque effort has to be provided to prevent unintended steering inputs (Pfeffer & Harrer, 2013).

[43] The feedback about the road contact and force between the surface and tire is provided by the steering wheel. This information is important for the driver and can be divided into two categories: content and disturbance information. The first is necessary to reliably control the vehicle. If the friction force between wheel and surface decreases (called understeering), the steering wheel torque drops. This behavior has to be transmitted via the steering wheel in order to inform the driver that grip limits are reached (Pfeffer & Harrer, 2013).

Requirements:

Current steering systems should fulfill the following requirements (Pfeffer & Harrer, 2013):

- Low steering wheel torque
- Accuracy, directness, predictable response, free movement
- Feedback information about the road condition between wheel and road
- Automated and controlled returning of the steering wheel
- Good Noise, Vibration, Harshness performance
- Low steering wheel angles during parking situations
- Low energy consumption
- Compact packaging and low weight

All these requirements influence the design of the steering system. Additionally, the requirements are supplemented by the following factors:

- Cost
- Packaging
- Production
- Maintenance etc.

The steering system is a safety-relevant component and therefore subject to strict controls and requirements. Their purpose is to ensure that the vehicle is steerable under all operating conditions. The legislative requirements can be found in relevant directives. (Pfeffer & Harrer, 2013)

Each OEM has different requirements concerning the steering systems for different vehicle classes: if the OEM and its vehicle are located in the high price segment, for example, the effort and requirements are higher. In general, it is important to understand the needs and requirements of the customer. Moreover, to develop an appropriate steering system, it is important to understand vehicles (internal sources), as they are a complex system with sub-systems that influence each other. Additionally, the engine's design influences the design of the steering system.

The evolution of steering systems:

Since the introduction of vehicles, different kinds of steering systems have been developed. Figure 54 provides an overview of the evolution of the steering system as well as current and possible future trends. Similar to other industries, the trend towards mechatronic solutions also took place with steering systems. Over the years, steering systems evolved from purely mechanical products, via hydraulic power systems to mechatronic electric power steering systems. Compared to mechanical steering systems which do not have additional features, electric power assisted steering is able to fulfill additional tasks such as handling dynamics occurring because of crosswind. The systems of the future will be fault-tolerant SbW systems.

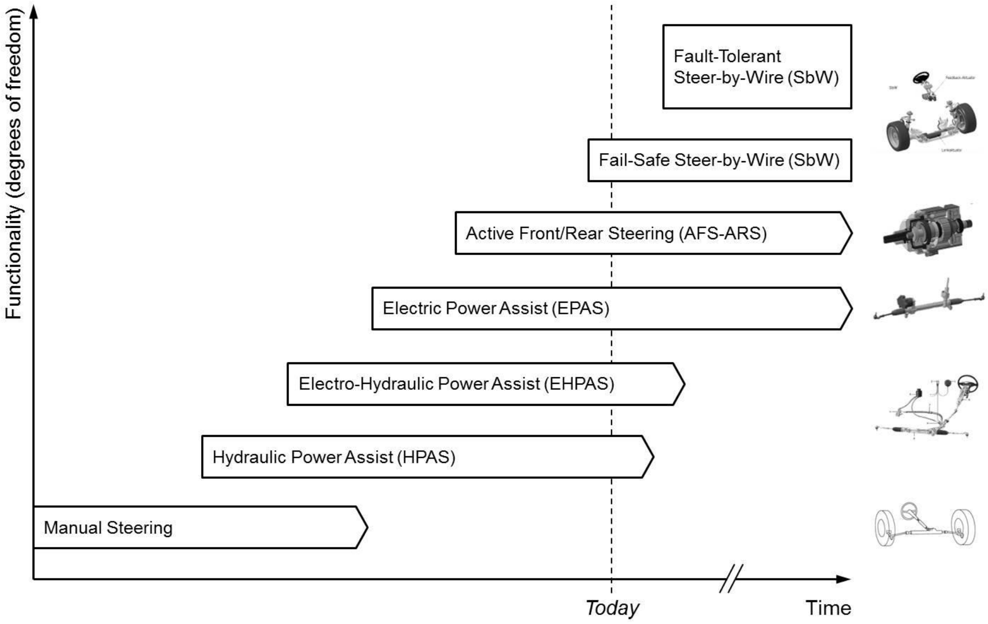


Figure 54 The development of steering systems (company document)

5.3.1.1 Manual Steering

A manual or mechanical steering system is a steering system that does not offer the driver support through an external force (see Figure 53). This results in systems with low costs[44] and a low weight. Additionally, the driver receives good feedback. In order to reduce the workload for the driver, the overall steering ratio needs to be very high. The steering effort is high and exhausting for the driver, especially cornering and parking demand huge efforts. Due to the ever increasing weights of vehicles – especially when it comes to heavy goods vehicles – an external power assisted steering system is required and mechanical steering systems were no longer used in Europe after around 1980 (Pfeffer & Harrer, 2013).

[44] Cost of manual steering compared to EPS.

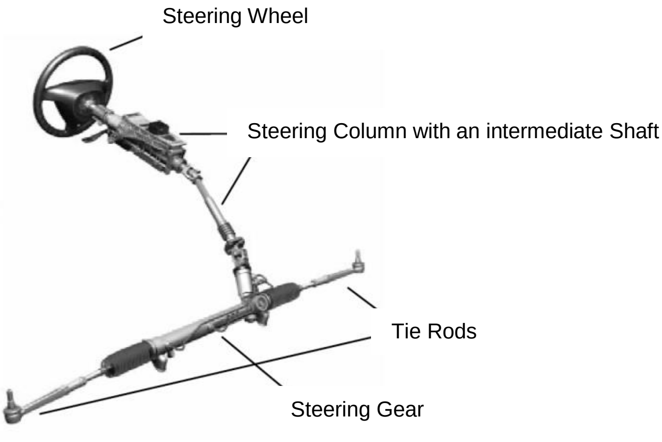


Figure 55 Manuel steering (Pfeffer & Harrer, 2013)

5.3.1.2 Hydraulic Power Assisted Steering (HPAS)

The first hydraulic power assisted steering systems (HPAS) were installed by Chrysler in the models *Imperial* and *New Yorker* in 1951. HPAS systems were the first power assisted steering systems on the market when they entered it in late 1970. Vehicles from European OEMs were generally lighter compared to US vehicles and thus, a power assisted steering system was not required. HPAS systems help the driver with additional torque at the required torque and thereby reduce the steering effort. For several years, HPAS systems were state-of-the-art when it came to steering systems in the automotive industry. (Pfeffer & Harrer, 2013)

<u>Functionality:</u>

A torsion bar is installed at the lower end of the column shaft and controls a valve. By turning the steering wheel, the torsion bar is twisted slightly – as is the valve. Basically, the valve determines the difference of the pressure at the hydraulic actuator. As a result, an additional force assists the driver (Pfeffer & Harrer, 2013).

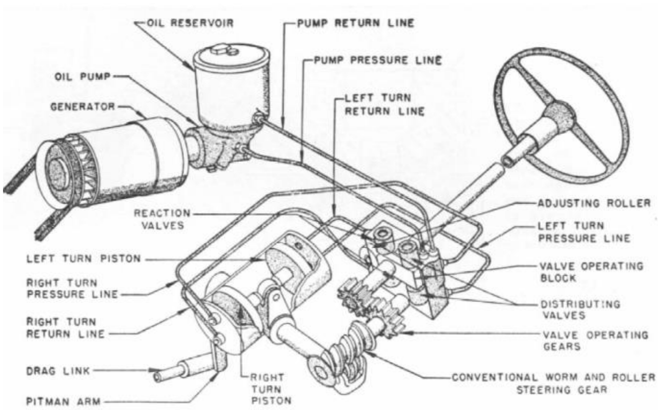


Figure 56 Hydraulic power assisted steering system principle by Gemmer (Pfeffer & Harrer, 2013)

The hydraulic pump is directly connected to the combustion engine by a belt and continuously used. Due to this, it consumes energy from the engine even though no steering support is given. This leads to increased fuel consumption, which is one of the main disadvantages of HPAS systems. Thus, they were further developed and the pump drive is now no longer powered by the combustion engine but an additional electric motor. These systems are referred as electro-hydraulic power steering (EHPS) (Pfeffer & Harrer, 2013).

5.3.1.3 Electric Power Assisted Steering (EPAS)

Electric power assisted steering (EPAS or EPS) soon replaced the hydraulic power steering system and today is one of the most commonly used systems. A sensor measures the torque on the column and sends a signal to the electronic control unit (ECU) that provides assisting torque. The ECU calculates the amount of assisting torque required and controls the electric motor to generate the necessary torque. There are three different places to install the electric motor into a steering system:

- Steering column: between the steering wheel and the i-shaft (column EPS)
- Pinion: between i-shaft and steering gear (pinion EPS)
- Rack: between the pinion and the tie rod (rack or dual pinion)

If the motor is installed between the steering wheel and the i-shaft (see Figure 57), the torque generated by the motor and the one from the driver have to be transmitted through the i-shaft. The latter is limited by its plastic deformation, which is why column EPS is mainly used for compact and mid-size vehicles. Heavier vehicles require higher assisting forces, which can be achieved by installing the motor directly at the rack, i.e. parallel to the driver input (see Figure 58). Depending on the forces and installation space, different solutions are possible (Pfeffer & Harrer, 2013).

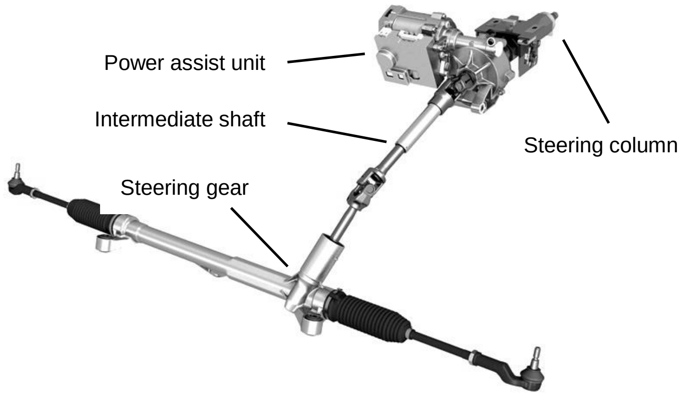


Figure 57 Layout of a column EPS system (ThyssenKrupp InCar plus, 2014)

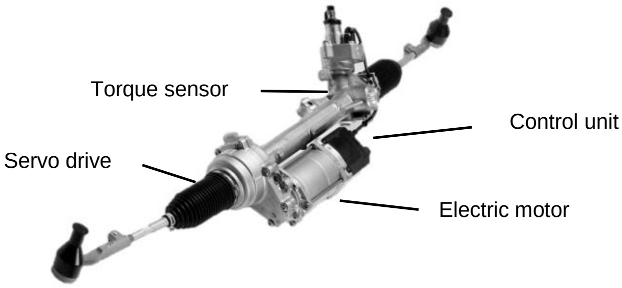


Figure 58 Rack EPS (company document)

Compared to the hydraulic power assisted steering systems, the energy consumption is significantly lower with EPS systems. Depending on the demand, the electric motor generates the required torque: e.g. for parking, a higher degree of support is necessary than for driving on a highway where additional torque is not required and the engine is not running. Additionally, strong electric power assisted systems can steer the vehicle without any additional force from the driver. This is a big advantage for automated driving. Currently, such systems are used for advanced driving assistant functions, like automated parking or lane keeping. Possible disadvantages are a higher inertia, additional friction and lower feedback (Pfeffer & Harrer, 2013).

5.3.1.4 Active Front/Rear Steering (AFS-ARS)

The previous chapters described steering systems working with assisting torque or force. Active steering does not change the required hand wheel torque, but supports the steering wheel angle with an additional steering angle. A superposition gearbox (typically mounted at the column or directly at the gearbox input shaft) enables a superposition of angles. The big advantage of active steering system is that the steering ratio is variable. Depending on the driving mode (e.g. vehicle velocity) the required angle is adjusted: at low speeds (e.g. parking), the ratio can be minimized and thus the maneuverability is increased, while at high speeds, the ratio is decreased which increases the stability of the high speed driving (Pfeffer & Harrer, 2013).

In an active rear steering system, the rear wheels steer in small angles dependent on the steering angle and the vehicle velocity. In case the rear wheels steer in the opposite direction, it is possible to reduce the turning radius. To stabilize the vehicle in high speed situations, the rear wheels steer in the same direction. As Pfeffer & Harrer, (2013) explain, the use of superimposed steering systems is an important step for future innovative steering systems as the connection of AFS/-ASR with SbW enables to develop new steering functions (Pfeffer & Harrer, 2013).

5.3.1.5 Steer-by-Wire

Steer-by-Wire (SbW) is a steering system without a mechanical linkage between the steering wheel and the road wheels. The driver input is transmitted via the cables of an

ECU to the actuators, which control the steering rack movement. Due to the lack of a mechanical link, no direct feedback about the road condition is available. Therefore, an additional feedback actuator at the steering column is required to generate haptic feedback for the driver, which is done by an independent software. The first vehicles using SbW have already been built as special- and prototype vehicles (e.g. the mules *Infiniti Q50* or *TKS InCar®plus*), but so far, no complete SbW system has achieved a breakthrough in the automotive industry due to legal restrictions, safety issues and high costs.

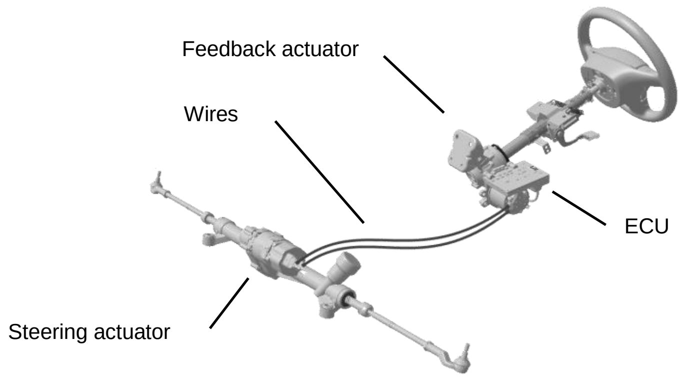


Figure 59 SbW principle (company document)

Safety and regulations:

As conventional steering systems still have a mechanical linkage, the loss of steering control due to failures is usually not considered. Based on present legal standards and the manufacturers' experiences, mechanical steering systems are designed with sufficient safety margins. (Frede, et al., 2010) In SbW steering systems where there is no mechanical linkage and hence no mechanical fallback system, an additional safety system is necessary. Such safety requirements could be achieved either by a fault-tolerant or a fail-safe system. Figure 60 displays an overview of the possible architectures and redundancies of such systems.

The factor of fail-safety relies on a mechanical backup system, which could be a clutch as a linkage. Changing the mechanical shaft to a mechanical clutch does not offer any advantage for a steering system and is thus not interesting for the market. The fault tolerant system is achieved by doubling all components involved in the steering process, especially the ECU (Pfeffer & Harrer, 2013). New mechatronic products have to be at least as safe as conventional steering systems. In their survey, Frede, et al. (2010) describe that redundancy can be designed for all different product levels but is mainly limited due to costs, installation space and weight issues. Isermann (2016) provides a deeper insight into fault-tolerant components for automobiles. In this thesis, it is assumed that SbW systems will have a fault-tolerant system that meets legal and redundancy requirements.

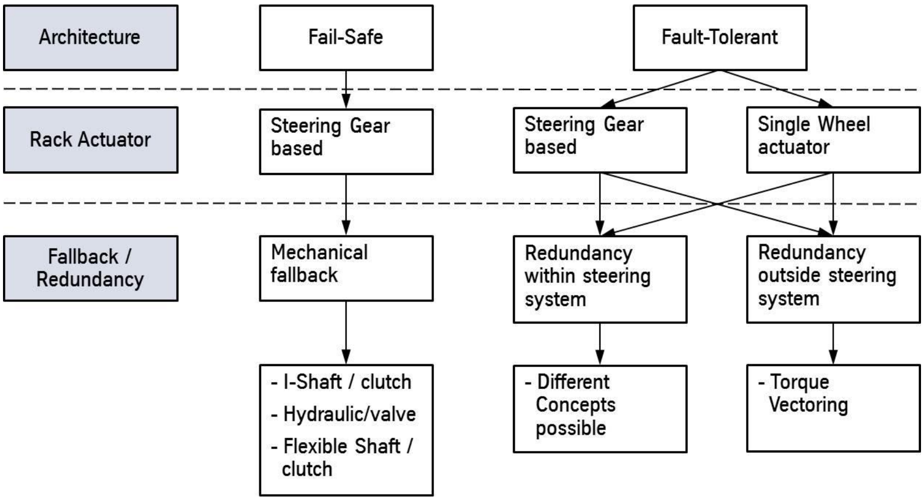


Figure 60 System architectures (according to Polmans, 2014))

<u>Advantages and disadvantages:</u>

Table 2 shows the main advantages and disadvantages of SbW systems.

Table 2 Advantages and disadvantages of SbW systems (according to Pfeffer & Harrer, 2013)

Advantages	Disadvantages
• Modularity • Packaging space • Passive safety • Reduction of variants • Simpler axle geometry • Specific feedback • New interface for steering possible • Enables driver assistance systems	• Higher costs • No feedback • Complexity • Safety system

SbW systems with a fault-tolerant safety system offer multiple advantages compared to conventional steering systems, especially when it comes to the flexibility of design. More space is available in the engine compartment and there exist no restrictions for other components. Also, the weight can be reduced because of the missing mechanical linkage between steering column and gear. In addition, an SbW is modular and enables an easier adaption to right/left-hand driving equipment. Due to its flexibility, different platforms could share the same hardware parts, which results in advantages concerning production and planning. Moreover, the steering's design can be changed to other interfaces such as, for example, a joystick. Further advantages are a variable steering ratio (adapted to vehicle speed and steering wheel angle) and the implementation of an advanced driver assistant system. Current SbW systems are more expensive compared to conventional steering systems because of redundancy[45].Therefore, automotive OEMs do currently not use SbW systems (Pfeffer & Harrer, 2013). If an SbW would enter the mass market, its price might drop and the economy of scale and the mentioned advantages would promote the market penetration of SbW systems. Due to the attention automated driving received in recent years, it is only a question of time when SbWs will start to replace current steering systems.

As mentioned, drivers require haptic feedback in order to drive a car. The missing mechanical linkage between the wheels necessitates a feedback actuator that generates the required haptic feedback for the driver. An electric motor is used to generate the feedback and is placed directly at the steering column. However, this generates additional weight and costs and needs space. These are clear disadvantages. Still, an electric motor is able to create different feedback depending on different situations (Sigilló, et al., 2015). Internal tests revealed that SbW systems can generate an even better steering experience (internal sources).

According to Polmans & Stracke, (2014), SbW is only the next logical step in the development of new steering systems. The costs and technical challenges of these systems are still too high compared to the final customer benefits. However, autonomous driving has a huge influence on SbW systems as the required redundancy for autonomous driving enables redundant SbW systems (Polmans, 2015). Therefore, it can be assumed that SbW systems are just the next evolutionary step in the history of steering systems as they will finally be enabled by autonomous driving.

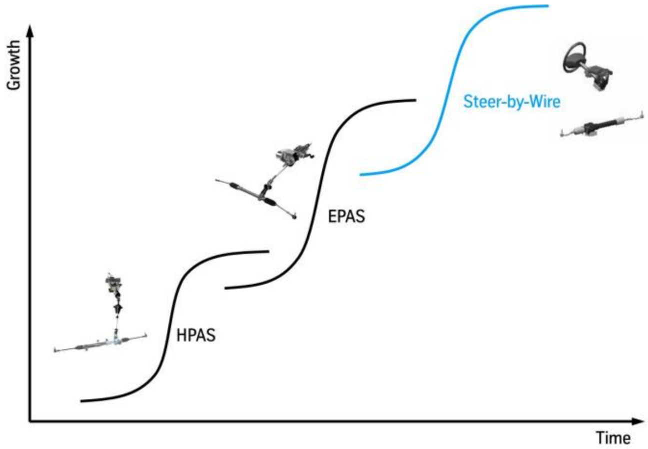


Figure 61 SbW is the next evolutionary step (adopted from Christensen, 2011)

5.3.1.6 Steering systems in development

The following steering systems and sub-systems are currently being developed at TKS and a brief introduction into *single-wheel actuators* and *torque vectoring* is thus provided.

[45] The bachelor thesis presented a rough cost estimation and price difference between a redundant SbW and a redundant EPS system. (Vincent Börger, Bachelor Thesis, RWTH Aachen, July 2015)

Single-wheel actuator

The SbW technology can be introduced in several ways. An alternative to conventional steering gears could be the use of single-wheel actuators. In this chapter, the focus is on front axle steering with two single-wheel actuators as rear axle steering has already been discussed in chapter 5.3.1.4 (internal source). By using individual wheel steering, a steering angle up to 90° can be achieved. Therefore, the vehicle has very high maneuverability, for example when being parked (cf. Figure 62).

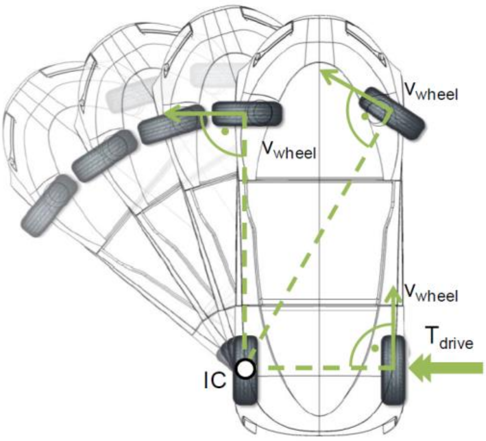


Figure 62 Maximum steering angle (Hesse, et al., 2013)

An advantage is that the ideal steering angle can be processed for each driving situation, which results in a full utilization of the lateral force potential of the front axle and increased driving safety (Hesse, et al., 2013). In addition, Pfeffer & Harrer, (2013) name immanent redundancy and space saving as further benefits. Disadvantages could be higher costs and strong forces required at the steering actuators (Pfeffer & Harrer, 2013).

Figure 63 displays one design solution of a Single-Wheel Actuator from the research vehicle *SpeedE,* in which the electric motor is integrated directly into the upper control arm. Due to the axis rotation of the motor, the steering angle is processed. This design allows steering angles of up to 90° (Hesse, et al., 2013).

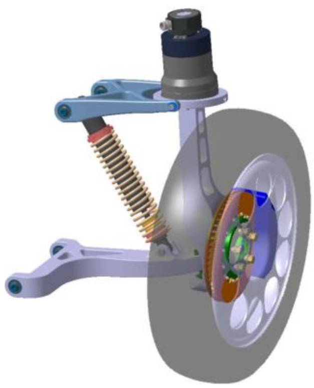


Figure 63 Example of an independent single-wheel steering solution (Hesse, et al., 2013)

Another design solution of a single-wheel steering system is evident in the patent of Polmans & Hirschmann, (2014) displayed in Figure 64. In this solution, the single-wheel is processed with tie rods as in steering gears.

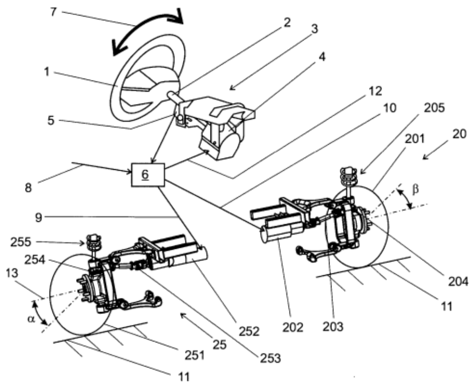


Figure 64 Concept of a SbW system with two front single-wheel actuators (Polmans & Hirschmann, 2014)

<u>Torque vectoring:</u>

As discussed in chapter 5.3.1.5, a fallback solution is required for the case of a system failure in SbW steering systems. For electronic stability control systems, torque vectoring is already commonly used in vehicles (in the form of wheel individual brake interventions). (Polmans & Stracke, 2014)

Torque vectoring is the controlled distribution of brake and drive torque on the individual wheels. Different torques at the wheels create a yaw moment at the vertical axis of the vehicle, as displayed in Figure 65. The results of an additional system are improved vehicle safety and vehicle dynamics performance (Folke, et al., 2010). The idea of TKS is to use this yaw moment to steer the vehicle in a conventional way (internal source).

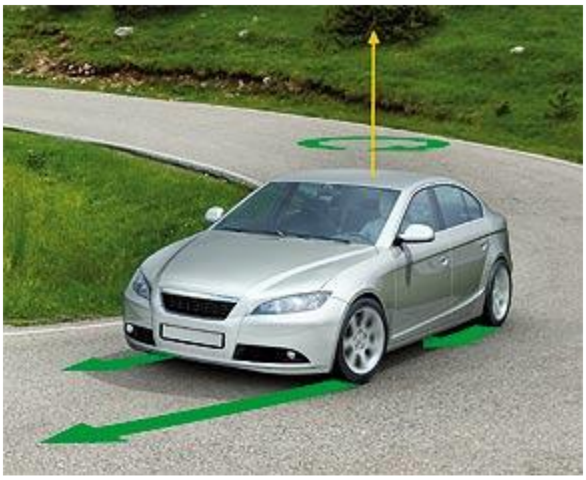


Figure 65 Principle of torque vectoring (Folke, et al., 2010)

Currently, no information is available on using torque vectoring as a satisfying alternative to conventional steering system. TKS views torque vectoring as promising redundancy technology, which is why it is currently investigated. (Polmans & Stracke, 2014)

5.3.2 Conceptualized steering systems

This chapter deals with the conceptualization of modular and flexible SbW steering systems that can be integrated into different car platforms. The aims are to present possible innovative steering systems and display their impacts on the manufacturing engineering. Moreover, the following requirements are to be met: the steering systems need to be small in size, lightweight, composed of simple hardware parts and they shall not contain a complex software interface. With regard to autonomous driving, the steering concepts shall be either highly or fully automated[46]. The steering column is not important for present purposes. For the sake of comparison, the first concept shows an already existing steering system.

The concept must meet the following requirements that were developed together with experts of TKS:

- High quality
- Low complexity
- Flexible, innovative solutions
- Be highly automated

In the best case, it would also meet the two criteria listed below:

- Steering column
- Fully automated

The three criteria of price, safety and redundancy were deliberately omitted as, in the present case, price is unimportant because this thesis merely focuses on the steering system's functionality. Also, it is assumed that it meets the required standards concerning safety and redundancy as well as all legal requirements. Naturally, in future projects, these criteria have to be included and evaluated.

The concept creation follows a morphological scheme: the creativity tool, i.e. the morphological scheme, helps to find analytically and systematically possible variants of solutions (Haberfellner, et al., 2015). Thinking in systems, sub-systems and elements helps to create the morphological scheme of the steering system: in fact, it can be separated into the sub-systems Steering column, i-shaft and Steering gear (Figure 66). Each of this sub-systems has a variety of alternatives that again include additional entities.

[46]Further information about the SAE levels are provided in chapter 3.

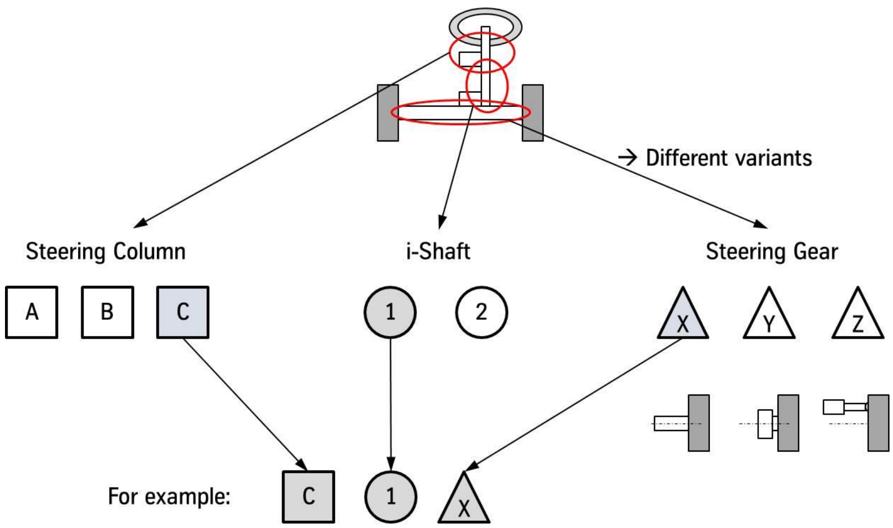


Figure 66 Basic sub-systems of the steering system (own illustration)

The input for steering the vehicle can be given either by a human or a system[47]. The steering wheel itself also shows alternatives concerning the control type as it can vary between a joystick, tablet computer, game controller or no steering type at all. The connection type between the input and the steering column could be rigid, stowable or removable (as with Formula 1 cars). The steering column usually is rigid or 2D-mechanically/electronically adjustable (adjusted upward/downward and in length). New vehicle concepts show that the steering wheel can also be 3D-adjustable, e.g. as a steering wheel that is suitable both for left and right hand driving[48]. The connection between the steering could either be a standard i-shaft, or it could be replaced by a by-wire system or a mechanical clutch. The inputs steering torque or steering angle can be transferred or supported via different power assisted steering gears (see chapter 5.3.1) or via torque vectoring directly onto the wheels. Furthermore, there exist different options of transferring information to the road: via classical trapezoid, four-wheel or single-wheel actuators.

Morphological scheme:

The aim of the following morphological scheme is to find as many innovative steering systems as possible. The generated morphological scheme is displayed in Figure 67 and allows to create 16.200 different concepts. However, not all variants are useful or realistic for the automotive industry. In order to reach an accurate statement which innovative steering systems could be used in reality, an adequate number of variants needs to be determined. In this case, four innovative steering concepts were decided on. As mentioned above, an additional existing steering system is created for the sake of comparison.

[47] In the present case, a system is defined as an external software or robot which is able to steer the vehicle either highly or fully automated.
[48] https://www.bmwgroup.com/en/next100/markenvisionen.html; accessed on 8 August 2016.

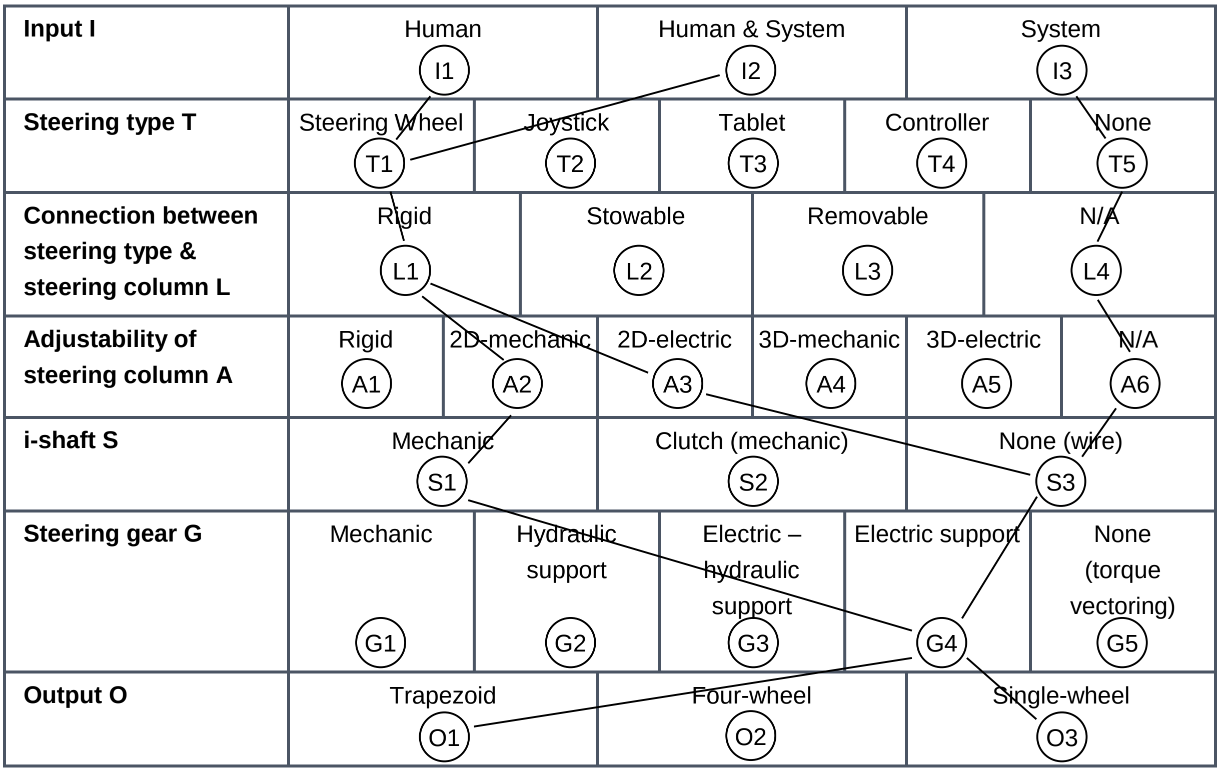


Figure 67 Morphological scheme of the conceptualized steering system (own illustration)

The following concepts were created together with experts and they will be further analyzed in the next step:

- Concept 1: I1 – T1 – L1 – A2 – S1 – G4 – O1
- Concept 2: I2 – T1 – L1 – A3 – S3 – G4 – O1
- Concept 3: I2 – T1 – L1 – A3 – S3 – G4 – O3
- Concept 4: I3 – T5 – L4 – A6 – S3 – G4 – O1
- Concept 5: I3 – T5 – L4 – A6 – S3 – G4 – O3

Figure 68 shows different concepts and the possible evolution of steering systems in the future. These concepts represent basic principles of steering systems.

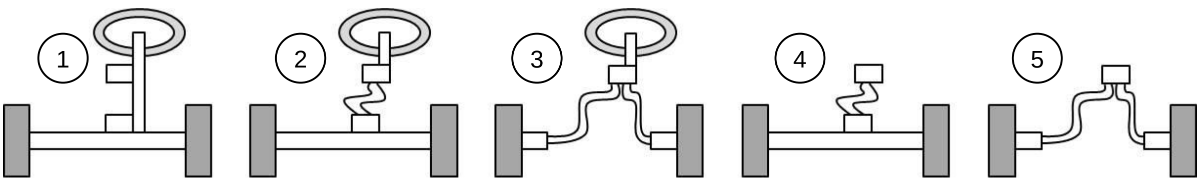


Figure 68 Evolution of future steering systems (own illustration)

1. Current steering system with rack-EPS
2. SbW system with rack-EPS
3. SbW system with two front single-wheel actuators
4. SbW system without a steering column and with rack-EPS
5. SbW system without a steering column and with two front single-wheel actuators

Concept 1

This concept refers to a currently used steering system and thus serves a referential purpose. The input is provided by a human driver but it could also come from an external system. In the present case, however, it is assumed that it is a human that creates the input. The steering wheel is rigidly connected to the steering column, the latter being 2D-mechanically adjustable and mechanically linked to the electric power assisted steering gear (rack-EPS). The weight of the complete steering system is approximately 19.5 kg (internal source).

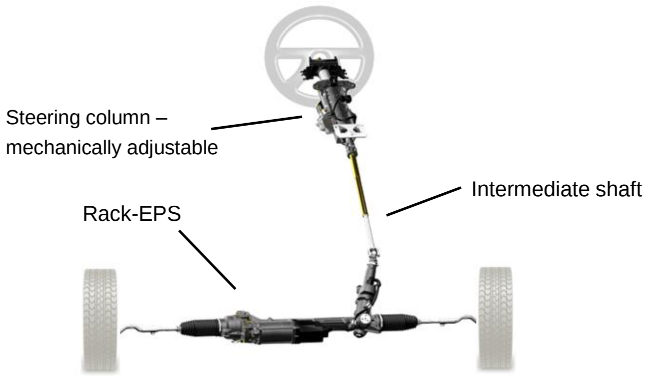


Figure 69 MVLS steering column with i-shaft and rack-EPS (company document)

Concept 2

Concept 2 is a SbW system which is currently being developed. A driver or external system provide input for the steering system. The steering wheel is rigidly connected to the steering column, which is 2D-electrically adjustable. The steering information is processed by the ECU and transmitted by wire to the electric power assisted steering gear (rack-EPS). The weight of this system is estimated at 22 kg (internal source).

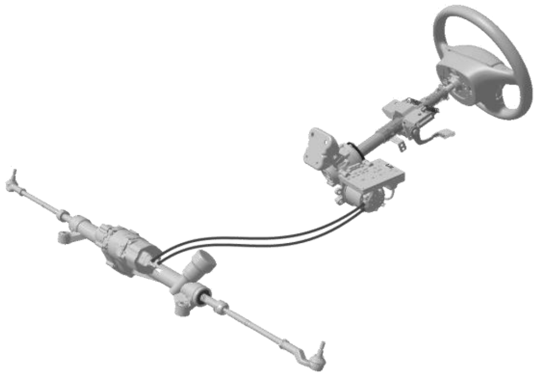


Figure 70 SbW with EVLS steering column and rack-EPS, currently being developed (company document)

Concept 3

This concept assumes that the steering input stems from a driver or a highly automated external system which is able to steer the vehicle. The steering wheel is rigidly connected to the steering column, and is 2D-electrically adjustable. The steering information is transmitted by wire to the two front single-wheel units. The front wheels work independently from each other and adjust the necessary steering angle. The steering system's weight is approx. 24-26 kg (internal source).

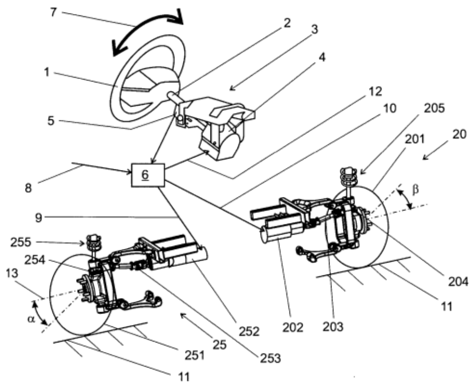


Figure 71 Concept of a SbW system with two front single-wheel actuators (Polmans & Hirschmann, 2014)

<u>Concept 4</u>

Concept 4 presents a steering system for a fully automated vehicle without a steering wheel or a steering column. The vehicle is steered by a fully autonomous external system that the ECU, which in turn controls the electric power assisted steering gear. The weight of the ECU and the R-EPS is approx. 14 kg (internal source).

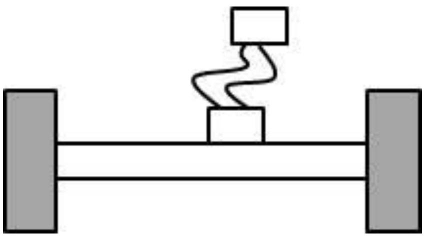


Figure 72 Concept of a SbW system with rack-EPS and without a steering column (own illustration)

<u>Concept 5</u>

This concept is similar to concept 4 as it presents a SbW system without a steering wheel and steering column. The vehicle is steered by a fully autonomous external system which again triggers the ECU that controls each of the two front single-wheel actuators. The weight of the ECU plus the two single-wheel actuators is around 18 kg (internal source).

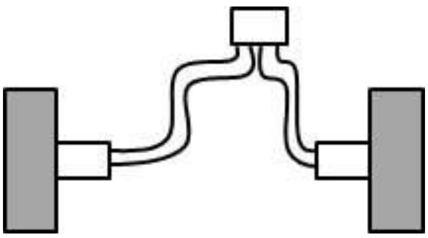


Figure 73 Concept of a SbW system with two front single-wheel actuators and without a steering column (own illustration)

5.3.3 **Comparison and Evaluation**

The above mentioned concepts now need to be compared and evaluated with the help of supporting tools. This aims at reducing the risk of subjectivity (e.g. by selecting a personal favorite) and makes the decision process more transparent. The result of the evaluation ideally is a steering system which fulfills the previously defined requirements.

The value benefit analysis is used for the comparison and evaluation as it provides a qualitative validation method for systematically solving complex problems. The latter are divided into smaller sub-problems that are easier to solve as a possible emotional involvement or subjective preferences towards one or more desired solutions are excluded. The resulting solutions can rationally be verified, especially if the scope of the desired overall solution is not yet clear. The aim of the value benefit analysis is to select, prioritize and order alternatives, rather than dealing with problems or questions such as tendencies or gradual decisions (e.g. “How much money should be invested?”). (Kühnapfel, 2014)

The value benefit analysis is executed with seven experts of different TKS departments in order to obtain a well-reasoned statements: one expert comes from R&D, two from sales (EU and US), three from operation services (one division head, team leader and project manager) and I, the author of this thesis, function as a moderator. The result of this value benefit analysis shall be a prioritization of the above mentioned concepts and the concept with the highest score is to be used for further investigations. The number of alternatives has already been limited to four and all concepts presented above will be evaluated.

5.3.3.1 Decision Criteria

Table 3 lists the criteria which were discussed and selected in two meetings with the R&D employee.

Table 3 Criteria catalogue

Criterion	Short	Description
Modularity/Flexibility	Crit. A	How modular and flexible is the steering system in its interchangeability? E.g.: Easy to use for different platforms, etc.
Product Space	Crit. B	How much space does the product need? Smaller products are preferred.
Degree of Automation	Crit. C	Which degree of automation is possible and aimed at, based on the SAE level of automation?
Weight	Crit. D	Is the product heavy? Due to the EV trend, lighter parts are preferred.
Simplicity of Hardware	Crit. E	How complex are the mechanical parts? E.g.: Easy to install, manufacture,… etc.
Simplicity of Software	Crit. F	How complex is the software? E.g.: Effort for adaption customer request, etc.
Haptic Feedback	Crit. G	Is the haptic feedback for the driver good? Haptic feedback is an important input for the driver.

In a first step, the R&D employee and the author of this thesis discussed and decided a first weighting (see Table 3). This helps to obtain a quick overview and first results. A fundamental problem in this weighting of decision criteria is the personal involvement of the creator.

Table 4 Weighted criteria

Criteria	Short	Weight
Modularity/Flexibility	Crit. A	25.0%
Product Space	Crit. B	25.0%
Degree of Automation	Crit. C	15.0%
Weight	Crit. D	15.0%
Simplicity		10.0%
- Hardware	Crit. E	5.0%
- Software	Crit. F	5.0%
Haptic Feedback	Crit. G	10.0%
Sum		100.0%

For this complex problem, the pairwise comparison method was used in order to prioritize the individual criteria. It is a commonly used tool in connection with other validation methods (Saaty, 2012). The pairwise comparison approach is easy to use and systematical and allows to make a “more objective”[49] decision. Ideally, it should be done by several persons to minimize a potential standard deviation. There exist numerous forms of the validation method; however, in the present case, the scheme follows Pfeifer’s (1996) approach.

As a start, each team member compared the criteria and decided on which is more important by entering the values into a matrix. The following values were available:

- 2 = Criteria A (horizontal) is more important than criteria B (vertical)
- 0 = Criteria A (horizontal) is less important than criteria B (vertical)
- 1 = Criteria A (horizontal) is as important as criteria B (vertical)

For example, if one employee ranks *modularity/flexibility* more important than *product space*, the cell is filled with the number 2. The main diagonal of the matrix is reciprocal and to complete it, the inverse value has to be filled in. In this case, *product space* would be less important, which means that the cell is filled with 0.

The criteria *simplicity of soft- and hardware* were considered together because both are equally important with regard to the system. The principal diagonal can thus be filled with 1 because the criteria have the same importance. The results of the fields are added up by line and then standardized. The highest number indicates the most important criterion of all criteria compared. Table 5 illustrates a pairwise comparison done by the operation service team member.

[49] A truly objective method does not exist (Haberfellner, et al., 2015).

Table 5 Decision matrix with pairwise compared criteria (operation service 1 – 10 June 2016)

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	2	1	1	2	2	9	25.0	1
Product Space	0	1	1	0	1	0	3	8.3	6
Automation Grade	1	1	1	1	2	1	7	19.4	3
Weight	1	2	1	1	2	2	9	25.0	1
Simplicity	0	1	0	0	1	2	4	11.1	4
Haptic Feedback	0	2	1	0	0	1	4	11.1	4
						Total	36		

The result of the above decision matrix is that the criteria *modularity/flexibility* and *weight* have the highest priority with 25%. The criterion *product space* shows the lowest importance with only 8.3%.

This decision matrix was done with all the team members and can be found in appendix A.1. The values of all fields were summed up by line again and then standardized. The final result is a priority of the criteria and the associated percentage weight (illustrated in Table 5). Compared to Table 4, the criteria ranking and weighting changed: now, the most important criterion is *automation grade*, followed by *weight* and *modularity/flexibility*. The criterion *simplicity* is still the least important even though the weighting increased by 7%. In general, the weight of the criteria is closer to the average line.

Table 6 Decision matrix with all values

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	7	9	8	4	9	8	45	17.9	2
Product Space	5	7	7	7	10	7	43	17.1	4
Automation Grade	6	7	7	11	13	13	57	22.6	1
Weight	10	7	3	7	8	10	45	17.9	2
Simplicity	5	4	1	6	7	7	30	11.9	6
Haptic Feedback	6	7	1	4	7	7	32	12.7	5
						Total	252		

In Figure 74, the calculated values of the criteria and the associated standard deviation are presented. It is obvious that the standard deviation of the first four criteria is almost equal. The criterion *simplicity* shows the lowest standard deviation, while *haptic feedback* has the highest. For more accurate results, the number of participates would have to be higher.

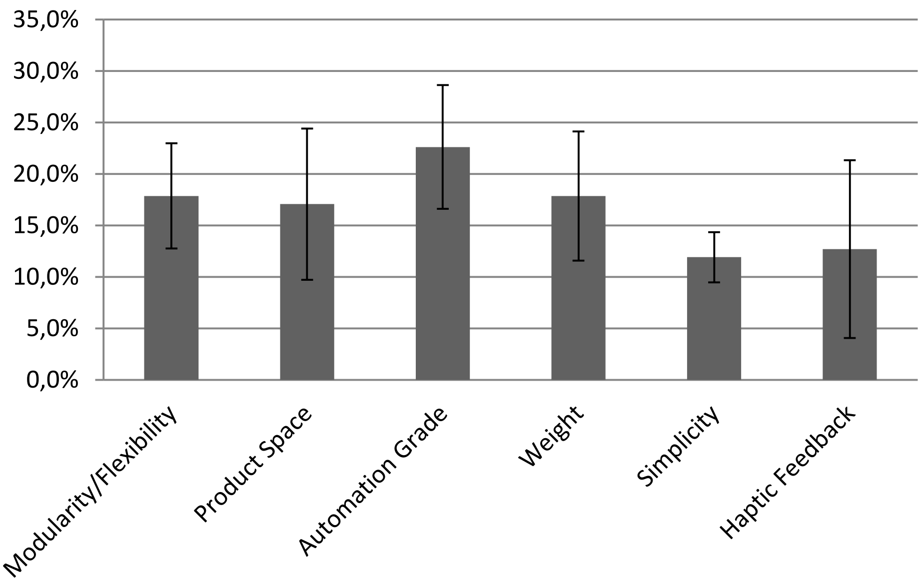


Figure 74 Criteria with weight and standard deviation

In the following validation and calculation, the deviation is not taken into account. For the sensitivity analysis, it indicates which of the criteria's weighing could change.

The pairwise comparison allows fast validation of criteria with minimal effort. Also, the method is objective and allows the evaluation of complex relationships. However, the displayed percentages do not represent absolute or universal values as the evaluation was built on subjective rankings.

5.3.3.2 Validation and calculation

In a next step, the concepts were validated and calculated. For the validation, a grading scale was developed (cf. Table 7) together with the expert from R&D. Most of the criteria cannot be objectively calculated or validated, which is why a grading system ranking from 0 (worst, N/A) to 4 (very good) was chosen. For the weight of the criteria, a range was introduced because only approximate values were available. Based on the SAE levels, the grade for *degree of automation* has been set accordingly. Level 3 was omitted because the experts believe that it will be skipped in the final development. The grade of the criterion *simplicity* ranges from very complex to very simple, whereby very simple is good and thus obtains grade 4. The same applies to *haptic feedback* as this is necessary for the driver to drive safely and in a controlled manner.

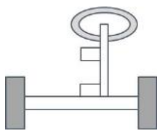
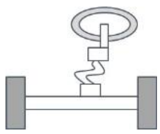
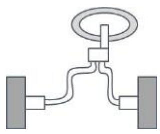
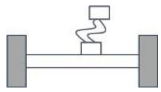
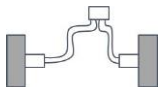
Table 7 Grading matrix

Grade / Criteria	0	1	2	3	4
Modularity/Flexibility	Very low	Low	Average	Good	High
Product Space	Very high	High	Average	Low	Very low
Weight	> 26 kg	25.9-22.0	21.9-18.0	17.9-13.0	12.9 kg <
Degree of Automation[50]	No Automation (Level 0)	Driver Assistance (Level 1)	Partial Automation (Level 2)	Highly Automation (Level 4)	Full Automation (Level 5)
Simplicity	Very complex	Complex	Average	Less Simple	Simple
Haptic Feedback	N/A	Poor	Average	Good	Very good

Next, the value benefit analysis was conducted and each concept was validated. The value benefit analysis was done together with expert from R&D and one member from operation service. Each criteria and the associated grade were discussed, whereby the R&D employee's arguments were more important. The results of the analysis are displayed in Table 8 below.

[50] As indicated above, based on the SAE level, the team discussed Level 3 and came to the conclusion that it will be omitted in the development process.

Table 8 Value benefit analysis of the steering system concepts

		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
											
Criteria	Weighted	Grade	Weighted	Grade	Weighted	Grade	Weighted	Grade	Weighted	Grade	Weighted
Modularity/ Flexibility	17.9	1	17.9	3	53.6	4	71.4	3	53.6	4	71.4
Product Space	17.1	1	17.1	2	34.1	3	51.2	3	51.2	4	68.3
Degree of Automation	22.6	3	67.9	3	67.9	3	67.9	4	90.5	4	90.5
Weight	17.9	2	53.6	1	17.9	1	17.9	3	53.6	2	35.7
Simplicity	11.9										
- Hardware	6.0	2	11.9	3	17.9	3	17.9	3	17.9	3	17.9
- Software	6.0	3	17.9	2	11.9	2	11.9	1	6.0	1	6.0
Haptic Feedback	12.7	3	38.1	2	25.4	2	25.4	0	0.0	0	0.0
Sum	**100**		**206.3**		**228.6**		**263.5**		**272.6**		**289.7**

It appears that concept 1 has the lowest grade in *modularity/flexibility* because of several restrictions concerning design and mechanics (e.g. engine, bulkhead throughput, etc.). In contrast to that, the SbW steering gears or wheels can be placed as needed. The same applies to *product space*: the concepts using a single-wheel actuator need the least amount of space. All steering systems can be used in a fully autonomous vehicle, but concepts 4 and 5 do not possess a steering column. Therefore, they have to be used with a fully autonomous driving system. Concept 2 has the lowest ranking concerning weight as weight is reduced by eliminating the i-shaft but simultaneously increased due to the required feedback actuator. The concept with the lowest weight is concept 4 because of the reduction of the steering column and the optimized R-EPS. Each of the single-wheels (left and right) requires an ECU for positioning, which results in an increased weight. Moreover, the effort and complexity of the software are higher. Therefore, the grading is lower than with concept 1. It is assumed that the software for fully autonomous driving is more complex, thus the lowest grading is given to concepts 4 and 5. Due to the fact that they do not have a steering column, *haptic feedback* is ranked with 0. The feedback of concept 1 was graded highest because of the long-time experience. It is assumed that

SbW systems are able to generate better haptic feedback but in this case, concepts 2 and 3 are ranked lower.

The final result is that concept 5 displays the highest ranking, followed by concepts 4 and 3 even though the criterion *haptic feedback* was ranked with 0 and the linked weight was only average. The high ranking is due to *modularity, flexibility* and *product space*.

The developed concepts can be divided between highly autonomous (concept 2 and 3) and fully autonomous systems (concept 4 and 5). Steering systems with single-wheel actuators show higher results compared to R-EPS concepts. Possible reasons for this are a higher degree in *modularity/flexibility* and less *product space* required. The author assumes that as soon as legal regulations of autonomous driving are enforced, SbW will enter the market. It should be noted that the results of the present value benefit analysis are not empirically validated and thus not universally valid.

Sensitivity analysis

The sensitivity analysis detects differences and changes in the value benefit analysis by applying a review of the *weighting* and *grading*.

With the spreadsheet program Microsoft Excel, the weights and the grades were changed on a trial basis. There are small changes in the calculation of concepts 3, 4 and 5, for example: the grading of the criterion *automation degree* (highest weight) was applied to concepts with the highest grade. Still, concept 5 shows the highest ranking but the gap between the others has now become very small. Nonetheless, the steering concepts with single-wheel actuators still show higher ratings. Other changes to the values did not have any noteworthy effects, which supports the assumption that SbW systems are preferred.

5.3.4 Summary and Findings

The result of the value benefit analysis displays that fail-safe SbW steering systems will be developed based on the advantages compared to current steering systems – all assuming that the problem of legal issues concerning fully autonomous driving will be solved. Based on the value benefit analysis, concept 5 seems to best meet the requirements. Especially the SbW steering systems with single-wheel actuators show huge advantages compared to systems with R-EPS (cf. Table 9). Haberfellner, et al.'s, (2015) "argumentative balance" is another method for evaluation as it provides an overview of decision situations.

Table 9 Argumentative balance of SbW steering systems (internal source)

	R-EPS	Single-Wheel Actuator
Advantages	• Established • Increased redundancy compared to single-wheel (wheels are connected, mechanically redundant) • Weight	• Ideal steering angle in all driving situations • Minimum tire wear, maximum grip level • Increases maneuvering capability • Steering angles up to 90° possible • Packaging freedom
Disadvantages	• Steering angle is limited • Packaging freedom compared to single-wheel	• Not established • More complex • High functional safety requirements

Based on this overview, single-wheel steering systems show more technical advantages compared to R-EPS steering systems. TKS is already developing single-wheel actuator steering systems, which is in line with the present evaluation.

In a next step, an additional problem-solving cycle would have to be executed in accordance with Haberfellner, et al., (2015). In the first step, the problem would be analyzed and objectives determined. By applying system thinking, the steering system would then be separated into different sub-systems and, using a top-down approach, subsequently analyzed (steering column, i-shaft, steering gear). In a next step, the individual sub-systems would be investigated more closely. One could use the principle of building variants to determine possible alternatives, e.g. with regard to the steering input. The morphological scheme also poses a useful tool to easily and quickly create different concepts – this step corresponds to the synthesis of solutions. As a last step of the problem-solving cycle, the created concepts would be evaluated with the value benefit analysis and, based on the requirements, one innovative steering system could then be selected.

As a matter of fact, the problem-solving cycle approach is often used unconsciously in practice. In the present case, however, the controlled use of the approach allows to analyze and solve the given problem more quickly. A detailed study of the selected innovative steering system can again use the problem-solving cycle and looks as follows:

- Search for objectives:
  More detailed requirements from the customer: product space, weight, FIT-rate, electrical supply, ECU linkage, number of products, etc.
  The result would be a formulation of the goals.

- Synthesis of solutions:
  Developing different solutions; see Figure 75 for examples
- Evaluation and selection of solutions:
  Audit of all solutions with regard to their practicality and basic validity. Selection of one solution by a validation.

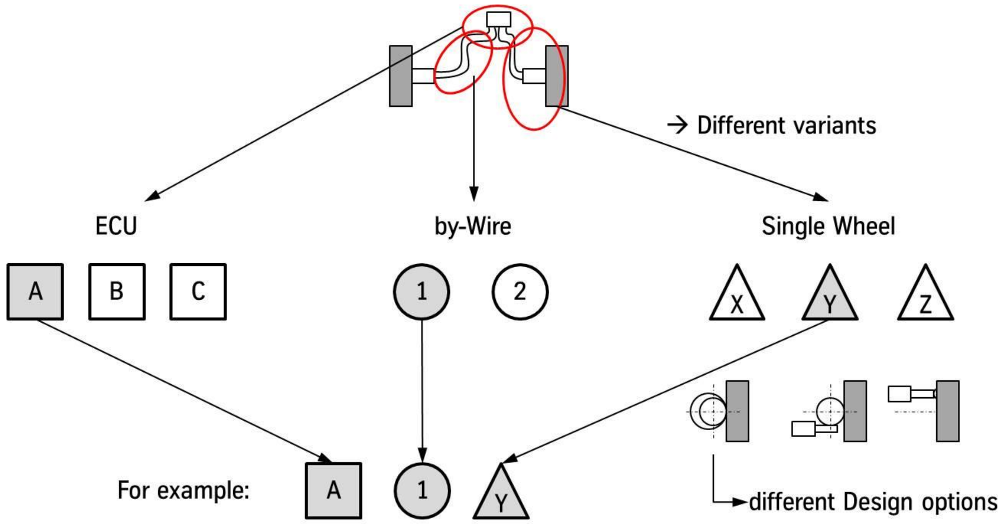


Figure 75 Building variants of a selected concept (based on Haberfellner, et al., 2015)

Each module, i.e. ECU, by-Wire and single-wheel, requires an own problem-solving cycle that has to be conducted to fulfill the overall requirements of the steering system. Thus, it is important to mention that the perfect module does not necessarily have to be the best solution for the whole system. In this case, several repetitions would be required which takes a lot of time and work.

In the next study, the impacts of the mentioned innovative steering systems on operation processes are investigated. Due to the electrification in the steering systems, parts and manufacturing procedures will be omitted but the concepts are transformed to realistic products. Afterwards, these product concepts will pass several procedures which provides detailed information about the necessary amount of machinery, employees and real estate area.

5.4 Impacts on the Manufacturing Engineering Process

The present chapter analyzes the impact of the above introduced innovative steering systems on the manufacturing engineering procedures. In order to achieve consistent results, several limitations as well as an intermediate step are necessary. First, the conceptualized steering systems have to be transformed to realistic products, i.e. they need to be designed in such a way, that mass-production is possible. This step was done in cooperation with experts by taking into account existing manufacturing procedures. Based on these and the information gained (mostly internal sources), and again relying on concepts already in use, rough layouts for plant can be created. The information gained can be used for investment planning and the calculation of the capital expenses CAPEX[51] that become relevant in chapter 5.4.3. In the last chapter, a summary with the findings and their impacts is provided.

The manufacturing engineering process plans and develops all processes and production-relevant activities that are necessary for product industrialization. Further information about the process is provided in chapter 5.1.3. In order to answer the key question, the processes "Manufacturing Engineering" and "Sourcing of investment funds" need to be executed (see Figure 76). This is done by the "manufacturing planning" and "investment planning" teams.

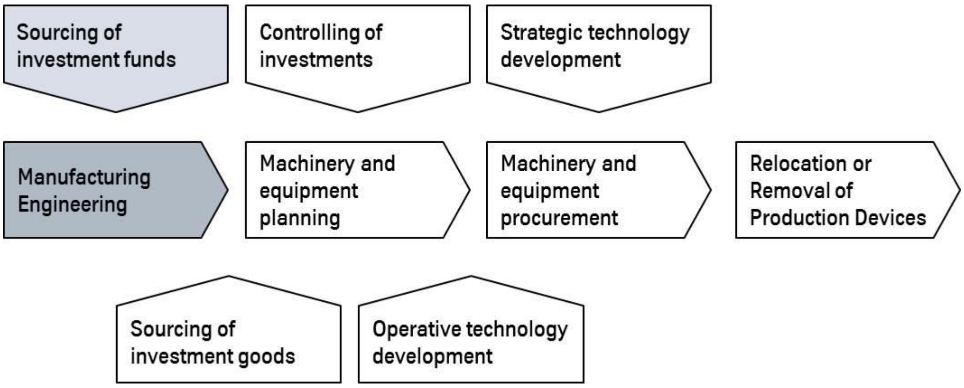


Figure 76 Sub-processes displayed in the manufacturing engineering process (company document)

Furthermore, the procedures "Manufacturing Engineering" and "Sourcing of investment funds" are also part of the quotation process (see Figure 77). In the latter, they are titled "manufacturing concepts" and "cashout for investments" and mark checkpoints that every developed concepts has to pass.

[51] Capital expenditures are long term assets, e.g. property, plant and equipment.

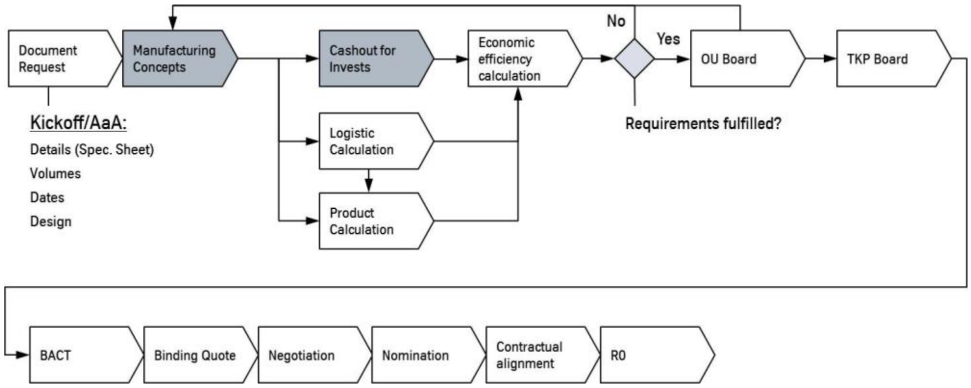


Figure 77 Selected processes displayed in the quotation process (company document)

Each steering system should be produced for seven years within a volume of 1,000,000 units per year. All required machines and test benches are new acquisitions – as is the plant that is located in North America[52]. Based on the information from the first main study, the products are carryover products. The cost of R&D, logistics, material and buy parts is not discussed in the present case as these are difficult to quantify. Moreover, the aim of the present thesis is to display the change of the manufacturing procedures, which is why production costs are also not discussed further.

5.4.1 Transformation from Concept to Product

The conceptualized steering systems have to be transferred to realistic products in order to be able to describe the manufacturing process. For each concept, a make-or-buy-decision was made in cooperation with experts while focusing on the core competences[53] of TKS. Therefore, all assemblies and parts are tagged as buy-parts which are currently not being produced at TKS. Furthermore, the decision had to be made of whether TKS should assemble all necessary parts on their own or whether the company should commission another Tier 1 with the steering systems. This is especially important with regard to single-wheel steering systems. It was decided to produce the steering parts and assemble the further suspension parts because, generally, the goal is to use as much carryover products as possible. Due to reasons of confidentiality, no detailed drawings can be provided.

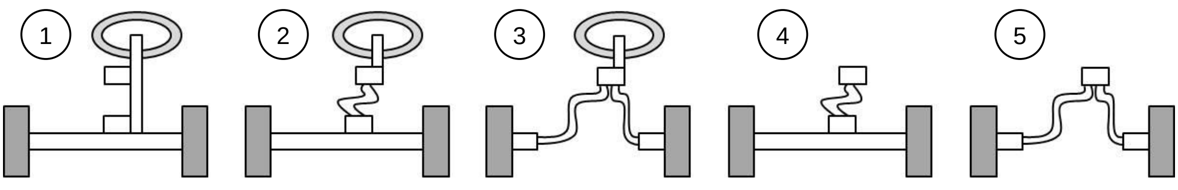


Figure 78 Concepts of steering systems (own illustration)

[52] Expert requirements. Normally, a location evaluation has to be done.
[53] The core competence of TKS is to enable steering.

Concept 1

In concept 1, the complete steering system was taken from a current customer project (EVLS steering column, i-shaft and R-EPS). The selected steering system is state-of-the-art and meets all necessary requirements. As all information and processes are available, this concept serves as a reference steering system for other concepts.

Concept 2

In concept 2, the i-shaft was eliminated, which necessitated several adjustments to the steering system's subsystems. At the steering column, some parts were removed and a feedback actuator was added. For this, an existing ColPAS system is used which already has a motor that can theoretically function as a feedback motor. Thus, the manufacturing procedures are quite familiar. The required safety and legal regulations have to be ensured with regard to the steering gear by adding a second Powerpack[54]. Also, those parts and elements were eliminated which are no longer necessary. The by-wire system is a buy-product and sourced from a supplier.

Concept 3

In concept 3, the R-EPS (steering gear) and the i-shaft were eliminated. The steering gear was replaced with a single-wheel steering and the adjusted steering column (with the feedback actuator) is similar to the one in concept 2. To obtain a realistic single-wheel steering system, a current patent[55] of the company was used. For the single-wheel steering system, the make-or-buy-decision was made together with experts: each individual part was evaluated, discussed and the make-or-buy decision was made. In the end, the core products, i.e. only a few parts and assemblies, remained that will still be produced in the future; all relevant parts and the by-wire system are sourced from a supplier. The realistic single-wheel system was verified and validated by an expert[56].

Concept 4

Concept 4 no longer possesses a steering column or an i-shaft. Thus, it can only be used for fully autonomous vehicles because no steering is possible. The input for steering is provided by an external ECU which is not produced by TKS. The steering gear solution from concept 2 is used.

[54] This is one possible option to offer a fault-tolerant steering system.
[55] For the preparation of the master thesis, the patent was opened and could therefore be accessed.
[56] Safety and legal regulations were discussed. Attempts were made to meet the required conditions.

Concept 5

As in concept 4, the steering column and the i-shaft do not exist in this concept and this steering system, too can only be used for fully autonomous vehicles as steering is not possible. The input for steering is provided by an external ECU which is not produced by TKS and the single-wheel solution from concept 3 is used.

As a result of the concept transformation, only the following three subsystems are necessary to realize concepts 2 to 4:

- Adjusted steering column with feedback actuator
- SbW R-EPS
- SbW single-wheel system

Due to the fact that the realistic steering systems were presented, the manufacturing concepts can now be discussed in more detail.

5.4.2 Manufacturing Planning

The manufacturing concepts are created together with the department "Manufacturing Planning". By having established realistic steering system concepts, the manufacturing planning can now determine the necessary manufacturing procedures. The concepts are then used to deduce information about the investment planning. The results of the manufacturing concepts are:

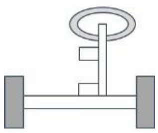
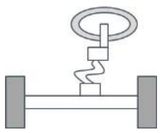
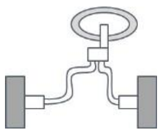
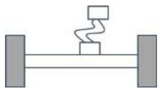
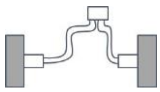
- Used machines and processes
- Approximate investments for the machines
- Amount of direct employees
- Overall Equipment Effectiveness OEE[57]
- Cycle time
- … and more

Again, existing and already developed manufacturing concepts were reused. The manufacturing concept of concept 1 is already available and thus serves as a reference. Together with experts, the evaluation of the manufacturing procedures for the other concepts was done. As a result of the transformation, only the manufacturing processes of the subsystems (adjusted steering column with feedback actuator, SbW R-EPS and the SbW single-wheel system) need to be created. The manufacturing concepts for the steering column and the SbW R-EPS could be prepared quickly because of already existing expertise and information.

[57] The OEE is a factor that evaluates how effectively a manufacturing operation is utilized. It is calculated my multiplying three OEE factors: availability, performance and quality (Erlach, 2013).

The manufacturing concept of the single-wheel steering systems needed several revisions because the design of the system needed to be suitable for mass production. Together with experts, each production step and the used production technology were closely investigated. The initial thought that the i-shaft production is no longer necessary proved wrong: in fact, by using a single-wheel steering concept that possesses an i-shaft to manipulate the angle, the production of said i-shaft is still necessary. Other manufacturing processes are added, e.g. the link production and the assembly of the gear unit. The production volume of the single-wheel steering systems is 2,000,000 units per year because a left and a right steering system is needed. In the end, a manufacturing concept was made for each steering concept (see overview in Table 10).

Table 10 Overview of all necessary manufacturing procedures

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
					
Steering Column					
Production Steering Shaft	X	X	X		
Production Steering Spindle	X	X	X		
Production Steering Column	X	X	X		
Feedback actuator		X	X		
i-Shaft					
Production Steering Shaft	X		X		X
Pre-Assembly	X		X		X
Steering Gear					
Production Input Shaft	X				
Production Sensor Pinion	X	X		X	
Assembly Sensor Shaft	X	X		X	
Production Ball Screw Spindle	X	X		X	
Production Ball Screw Nut	X	X		X	
Assembly Ball Screw	X	X		X	
Production Gear			X		X
Assembly Gear			X		X
Assembly Powerpack	X	X	X	X	X
Final Assembly	X	X	X	X	X

If steering systems without a steering column (fully autonomous vehicles) are requested, the manufacturing procedures of the steering column will no longer be needed. However, the i-shaft manufacturing procedure might still be necessary, as this depends on the single-wheel steering solution. If this single-wheel solution is ordered, the i-shaft production will still be needed. It should be noted that only one single-wheel solution was investigated in the present case and other single-wheel solutions might thus need different manufacturing procedures.

The same applies to the steering gear production: according to customer preferences and the product market penetration, different manufacturing procedures are possible and required. In all concepts, the manufacturing procedure “Assembly Powerpack” and “Final Assembly” are available. According to company experts, these will thus have higher priority in the future.

5.4.3 Investment Planning

The aim of the *cashout for investments* (CFI) process is the calculation of the capital expenditures CAPEX. This was done in cooperation with experts from the investment department as the CFI process needs information from different departments of TKS. The calculation is provided for all concepts, the results of which are summarized at the end of this chapter.

The CFI calculation includes the following sub-calculations:

- Manufacturing machining
- Logistics
- Test field
- Software development
- Cold forging
- Infrastructure
- Building
- Protoshop
- Tooling
- Lump sum payments
- Calculatory interest payments
- Manufacturing planning
- Subsidies and incentives

Since these sub-processes are complex and time-consuming for TKS departments, a selection of procedures was done in cooperation with the experts, which are discussed in more detail in the following section.

The CFI focused on the following procedures:

- Manufacturing machining:
  The investment for required machines and tools is listed in the sub-section "Manufacturing Machining". Input is provided by the manufacturing concept itself. The section includes CAPEX for the purchasing of new machines, tools, transport systems, rebuilding of existing machines, machine packaging, shipping, customs duty, installation and commissioning. Moreover, the machines schedule, order dates and cash outs are planned in this section.

- Test field:
  The required investment for all test field activities is planned in the sub-section "Test Field", with input coming from the head of the global test field himself. The section includes CAPEX for the purchasing of new test benches, climate chambers, measuring equipment, measuring and control software, updates or rebuilding of existing test benches, machine packaging, shipping, customs duty, installation and commissioning. Also, the machine project schedule with order dates and cash outs is planned in this section.

- Building:
  The required investment for buildings and production plants is planned in the sub-section "Building". The input is provided by the head of the global production plant coordination. The section includes CAPEX for the purchasing of real estate, the construction or expansion of buildings, warehouses, office buildings and production and logistic areas, as well as building and office infrastructure. Furthermore, a rough schedule of the construction phase, providing milestones, and cash outs are planned in this section.

- Calculatory interest payments:
  The section "Calculatory Interest" includes all calculatory interest payments for investments larger than five million EUR. Due to internal regulations, the amount needed to be capitalized.

- Manufacturing planning
  In the section "Manufacturing Planning", all working hours of internal machine project managers are calculated. Due to internal regulations, this amount had to be capitalized as well. Hours and hourly rates are calculated depending on the size of a machine project with the help of an internal algorithm. Moreover, planning services are a significant part of the total CAPEX of a machine and can account for up to 30% of the total volume.

5.4.3.1 Manufacturing Machining

The investments for each machine are provided by the manufacturing concepts and were calculated and integrated into the CFI. Furthermore, the machine schedule, order dates and cash outs were planned; however, they are not relevant for this case. Table 11 lists the total investments of the manufacturing machines.

Table 11 Manufacturing machining investments (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Manufacturing machining [TEUR]	106,818	98,651	66,084	70,441	37,874

In addition, the employees needed to operate the machines for one work shift can be deduced from the manufacturing concept (see Table 12).

Table 12 Required employees (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Required employees [#]	121	143	149	65	71

5.4.3.2 Test Field

The *Test Field* department provided a list of the required test benches for each concept. It was already pointed out that test benches for serial production only are necessary and that they have to be new acquisitions. For concept 1, a list of necessary test benches is available. First, however, a list for all necessary test benches was created. For concepts 2 to 5, the three subsystems steering column with feedback actuator, R-EPS and single-wheel system were jointly evaluated with test field experts. Afterwards, for each of the subsystems, a list of necessary test benches was created. Thereby, it emerged that the new steering concepts need more test benches than re currently being used[58]. The reasons are stricter safety and legal regulations. In addition to the higher number of test benches, an increased amount of investment was assumed. In the end, the values were integrated into the CFI and the total test field investments are illustrated in Table 13.

Table 13 Test field investments (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Test field [TEUR]	2,582	4,379	8,851	1,267	5,739

[58] A higher number of test benches is necessary for new mechatronic systems (Lamberg & Wältermann, 2000).

5.4.3.3 Building

For each concept, a manufacturing layout was created together with the *Factory Planning* department. Thereby, an existing building layout from a current project was used as a basis.

The investment of buildings are based on the area needed. In the calculation, the following areas are distinguished: assembly, production, logistic and warehouse, test field and support, and office. The assembly area is provided by the machine space[59]. The assembly area includes the machine space plus the needed logistic space for all machines. The logistic area is calculated by a factor of the machine space – as is the logistic and warehouse space. The test field and support area is composed of the number of test benches. In this case, the calculation of the required space is not linear as the required space per test bench decreases based on the overall amount of test benches. The required office space is calculated gradually. Since test field and support are located in an office building, the required space can be deducted. Finally, the real estate is the sum of all areas, including greenfield ratio, parking lots and street connection.

The plant layout for concept 1 was done first because this concept requires the most machine space and one standard building does not suffice. Therefore, the building layout was mirrored. Next, the needed machines were added[60] one-by-one, taking into account the respective area, i.e. assembly machines were assigned to the assembly area, production machines to the production area, and so on. This procedure was repeated for each concept so as to ensure comparability and illustrate the variations of the required machine and warehouse space. Figure 79 shows the building layouts for all concepts.

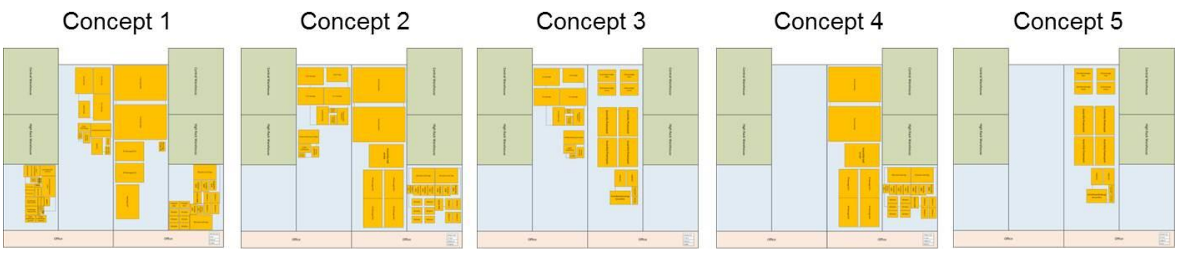


Figure 79 Overview of all plant layouts (own illustration)

[59] Information about the estimated machine space is provided in the manufacturing concept.
[60] A realistic workflow is considered but not validated as it is not relevant for the present case.

All calculated areas were crucial for the CFI and are displayed in Table 14.

Table 14 Overview of the calculated areas (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Machine space [m^2]	9,701	9,253	5,297	7,084	3,128
Production area [m^2]	16,165	15,130	8,475	11,660	5,004
Logistic & warehouse [m^2]	9,701	9,253	5,297	7,084	3,128
Test field & support [m^2]	420	570	1,020	200	690
Office area [m^2]	5,580	5,430	3,480	2,800	2,700
Real estate area [m^2]	**86,040**	**82,035**	**49,335**	**58,708**	**31,112**

To calculate the total investments of the building factor, each building area was multiplied by its own standard price per square meter, which is determined by a price per square meter used in a current project. The total investments are listed in Table 15.

Table 15 Building investments (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Building investments [TEUR]	24,795	23,710	14,482	16,127	9,042

5.4.3.4 Calculatory Interest Payments

The present section includes all calculatory interest payments for investments larger than 5 million EUR. As stated, the amount has to be capitalized due to internal regulations. A standard interest rate factor is used to calculate the payments (see Table 16).

Table 16 Calculatory interest payments (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Calculatory interest payments [TEUR]	644	616	376	419	235

5.4.3.5 Manufacturing Planning

Manufacturing planning includes investments for all working hours of internal machine project managers. The planning investments are calculated with the standard percentage of machine investments and displayed in Table 17.

Table 17 Manufacturing planning (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Manufacturing planning [TEUR]	17,495	17,456	13,994	11,607	8,144

5.4.3.6 Total CAPEX

To finish the CFI, all received and calculated investments are summarized in the CFI, resulting in the total capital expenses. An overview of the total CAPEX and the investments is given in Table 18 below.

Table 18 Total CAPEX of all concepts (internal source)

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Manufacturing machining [TEUR]	106,818	98,651	66,084	70,441	37,874
Test field [TEUR]	2,582	4,379	8,851	1,267	5,739
Building investments [TEUR]	24,795	23,710	14,482	16,127	9,042
Calculatory interest payments [TEUR]	644	616	376	419	235
Manufacturing planning [TEUR]	17,495	17,456	13,994	11,607	8,144
Total CAPEX [TEUR]	**152,333**	**144,812**	**103,787**	**99,860**	**61,034**

Already, first tendencies and impacts are visible. Their connection to TKS is going to be discussed in detail in the last chapter.

5.4.4 Summary and Findings

All information gathered was thoroughly analyzed and summarized in diagrams (see Appendices A.2, A.3 and A.4). Based on these diagrams, the innovative steering systems show impacts on the building area, the amount of machinery, the test field and the resulting investments. In the following section, these impacts are discussed.

5.4.4.1 Building Area

The required machine and real estate areas will be significantly reduced (see Figure 80 and Figure 81) due to focusing on the core competences. Moreover, production machines were reduced, while the number of assembly lines was increased. The space reduction between concepts 1 and 2 is relatively small as only the production of the i-shaft was eliminated. However, the required machine space is reduced by 45% from concept 1 to 3 and by 68% from concept 1 to 5. In concept 4, more space is required compared to concept 3, where almost all parts and elements of the steering gear R-EPS are produced. In the single-wheel steering concepts, there are more buy-products, which is why part production is reduced and shifted to assembly machines.

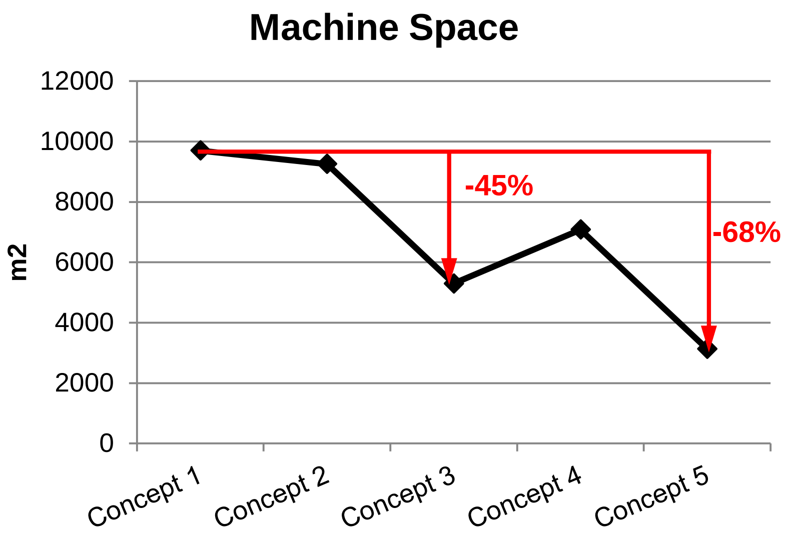


Figure 80 Reduction of the machine space from concept to concept (own illustration)

Due to the low need for machines, future production plants could be built smaller. The percentage of the reduction for the total real estate behaves similar with regard to machine space. By needing only 30% of the initial area, smaller plants can be built, which allows for example to build a decentralized production network. A higher product variety and the smaller lot size result in an increased effort of the centralized production control (Spath, et al., 2013). The requirement of small, flexible and scalable manufacturing results in a complex control which can be fulfilled with a decentralized production network (Matt, et al., 2014). With small production facilities, TKS is able to build such a decentralized network. In addition, small facilities can be built closer to TKS customers, which results in shorter delivery distances and, thus, delivery times, which in turn positively affects delivery reliability[61] (Zsidisin, 2003).

[61] Delivery reliability may be expressed as the percentage of orders that are delivered concerning the right quantity at the promised time to the right location (Zsidisin, 2003).

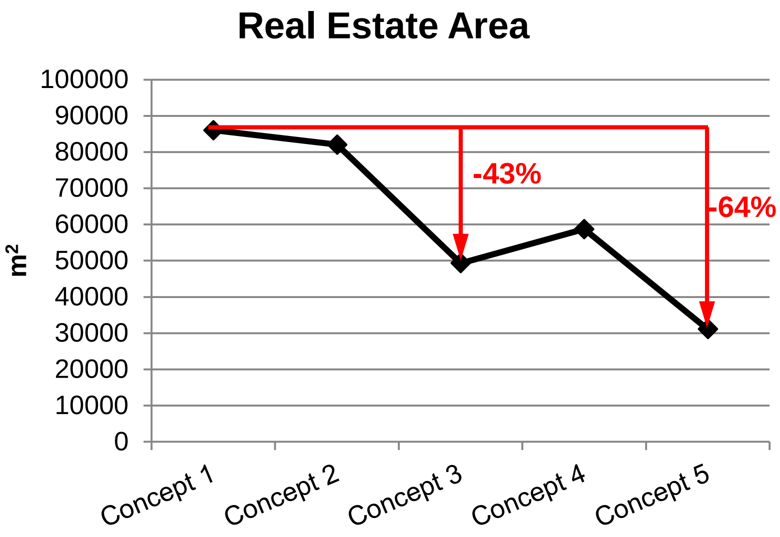


Figure 81 Reduction of the real estate area from concept to concept (own illustration)

Smaller production facilities also influence the needed investments (see 5.4.4.3), which both affect the workload of the projects. Consequently, less project planning and controlling is needed which has an effect on the number of project managers.

5.4.4.2 Employees

Depending on the concept, the amount of directly (production) or indirectly involved employees (project & investment planning managers, etc.) varies.

Depending on the concept, more or less production employees are required (see Figure 82). For concepts 2 and 3, more employees for one shift will be required, than in concepts 4 and 5. The additionally required employees of concept 2 result from the additional Powerpack and the assembly of the feedback actuator for the steering system. For concept 3, two million single-wheel steering systems have to be produced (left and right), which effects the amount of employees. Concepts 4 and 5 show that the number of employees required will decrease by 56% and 41%, respectively. This is caused by the elimination of the steering column and the missing i-shaft production. This means that the production of the steering column requires a lot of personnel. In general, few production employees in smaller facilities might lead to the assumption that employees are no longer important, which could allow to relocate production facilities back into high labor cost countries (e.g.: US, EU).

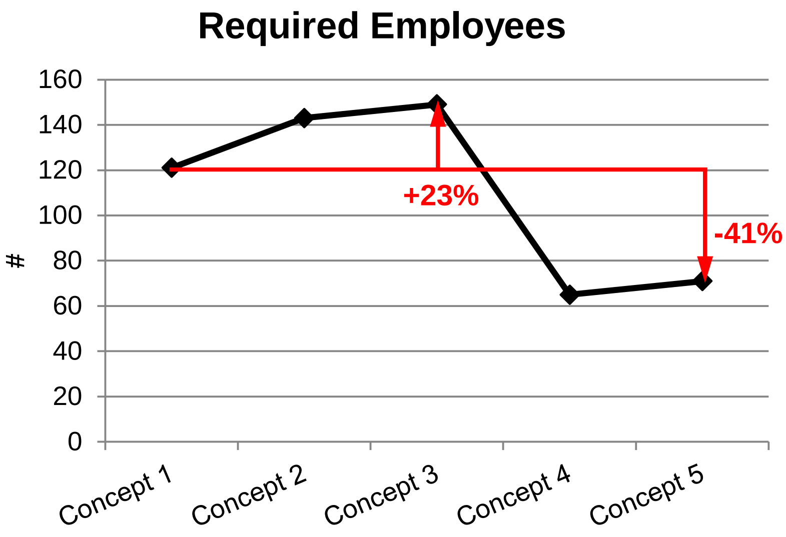


Figure 82 Number of required employees for one shift (own illustration)

If the developed concepts are viewed from an evolutionary angle, employees have to be hired to fulfill the required work. Afterwards, they will no longer be needed and they have to be reduced, which is why an employee strategy is recommended[62]. Necessary additional employees could be compensated with extended automation and smart robotics. In addition, the opportunity to involve the *Industry 4.0* approach for future production systems was internally presented as strategic opportunity, but is not further investigated in this thesis.

Contrary to the reduction for directly involved production employees, the behavior of indirectly involved employees is different: e.g. more engineers will be required for the test field because of the high number of test benches (see chapter 5.4.3.2). Especially concepts 3 and 5 (single-wheel solutions) show a high number of test benches. This comes from the production of two million single-wheel systems (both for the left and right side). Furthermore, these systems are very complex and need a high degree of reliability; all parts (mechanical, electrical and software) must thus be carefully designed and thoroughly tested. A reduction of the testing costs could be achieved by using virtual testing (see chapter 4.3 – Hardware-in-the-Loop HiL). Due to this, more engineers will be required for serial production (Albarello, et al., 2016). However, the number of required employees cannot be deduced from the sum of investments (see Figure 83).

[62] For example educating current employees for additional tasks.

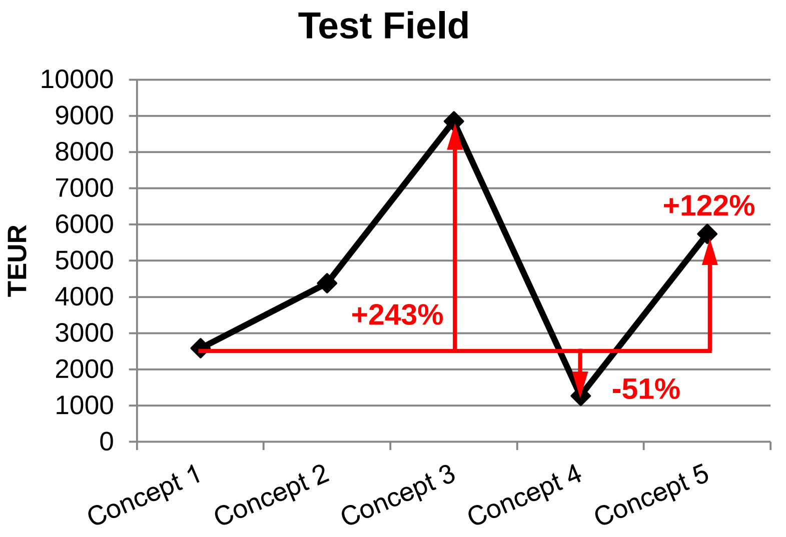


Figure 83 Test field investments for each concept (own illustration)

Manufacturing planning managers are also indirectly involved as their workload is reduced due to the reduction of the number of manufacturing machines. This results in the fact that less managers will be required to handle projects. Figure 84 displays how investments for manufacturing planning linearly decrease from concept 3 to 5 (with a maximum of 53% for concept 5).

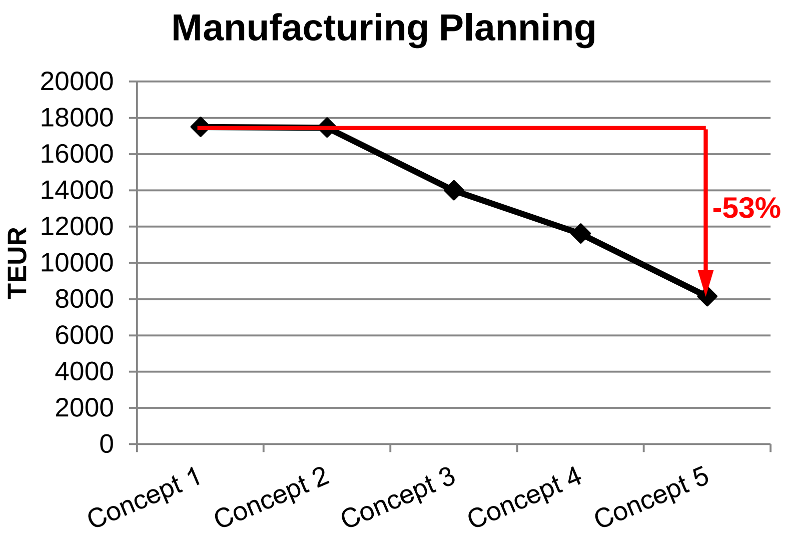


Figure 84 Investments of the manufacturing planning (own illustration)

5.4.4.3 CAPEX

The concepts have the biggest impact on the total CAPEX. The reduction of machining and thus of the buildings result in decreased CAPEX (see Figure 85). From concept 1 to 3, the CAPEX are reduced by 32% and to concept 5 by 60%. The reduction of the CAPEX has the following impacts:

- The reduced CAPEX result in less needed loans from banks or the *ThyssenKrupp AG*. The negation phase with the latter will also be reduced due to the lower loan capital.
- Due to the reduction of the CAPEX, TKS can take greater risks when building new facilities. TKS would, for example, not accept high risk projects for 150 million USD, given the fact that a 60 million USD project bears comparatively small risks.
- A reduction of the CAPEX results in less projects and thus less workload for the manufacturing and investment planning team. However, more projects could be acquired with the same amount of investment.

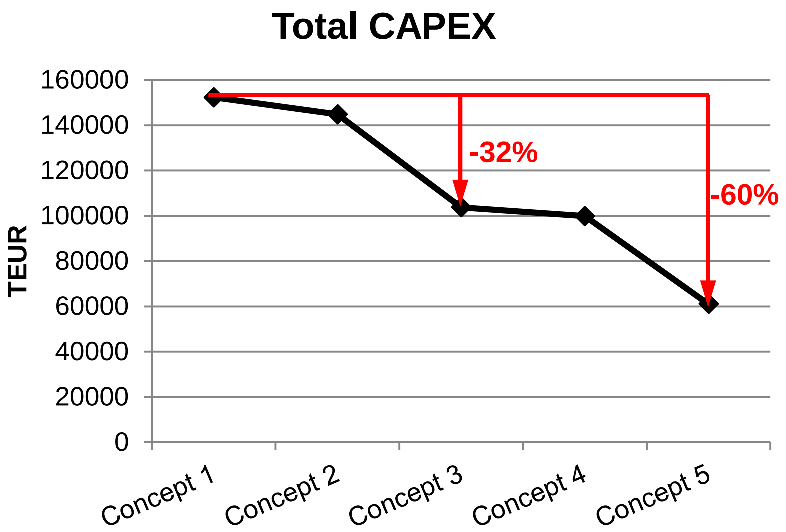


Figure 85 Total CAPEX of all concepts (own illustration)

6 Discussion and outlook

The aim of this thesis was to display the impacts of new OEM business models and innovative steering systems on selected processes of the automotive industry. It emerged that current trends in the automotive industry such as electrification, connectivity and autonomous driving encourage new OEMs to enter the automotive sector with new business models. This results in a more complex automotive landscape where traditional suppliers face new challenges such as shorter development processes or the use of carryover products. Furthermore, autonomous driving enables innovative steering technologies that significantly change the suppliers' value chain. The use of the systems engineering approach according to HALL-ETH allowed a systematical and controlled procedure with regard to dealing with this complex issue.

In the preliminary study *Introduction to the Case Study,* the current situation of ThyssenKrupp Presta Steering AG was analyzed. In addition, the environment of TKS was illustrated in systems. Based on the current situation and the new automotive trends, the problem statement and the objectives were formulated in four key questions that were answered in the present thesis. Based on that, the surveyed areas were defined as systems which were investigated in more detail. It was decided to conduct two main studies, one for investigating the customers and one for investigating relevant technologies.

In the first main study *Investigation of OEMs,* the first two key questions "*How do emerging OEM's behave in regard to their development process and requirements compared to traditional OEM's?*" and "*What are the impacts of emerging OEMs on current processes at* PrestaWorld*?*" were discussed. At the beginning, three emerging and one traditional OEM were analyzed in more detail in order to, afterwards, illustrate their differences. Emerging OEMs focus on current automotive trends, especially on electrification and autonomous driving because these have a high market potential and promise high profits. Using their experience in software development, these emerging OEMs try to penetrate the market with a fast time-to-market strategy. They know from their own experience that being the first on the market is crucial. Each of the investigated OEMs has their SOP in 2017, which is to be achieved with a short development process. Due to the short development process, the OEMs work with a short acquisition process and they generally request already developed carryover products. In general, emerging OEMs differ from traditional ones with regard to requesting, developing and ordering. They affect the TKS PrestaWorld processes and sub-processes which have so far been used by for traditional OEMs. Currently, the short development acquisition and the carryover products have a major impact on the acquisition process. Therefore, several departments and experts started investigating this impact, which is why it was not further pursued in the main study.

In the second main study *Steering Systems,* the evolution of the steering system was outlined and new innovative steering systems were presented. In accordance with SE, the problem life cycle was executed in this study. At the beginning, the current situation as well as an evaluation of steering systems was provided. Afterwards, the aim of the study was formulated in a third key question: "*What could conceptualized innovative steering systems look like?*" The focus was placed on SbW steering systems because of the current trend of autonomous driving since the latter is regarded to enable SbW technology. However, fault-tolerant SbW steering systems will only be developed if underlying legal issues of fault-tolerant autonomous driving have been solved. Therefore, four SbW steering concepts were created with the help of the morphological scheme as creativity technique because it allows fast and easy development of steering concepts. Afterwards, the created concepts were analyzed and a decision was made with regard to which conceptual steering systems should be used. For this, another SE method was used to support the decision: the value benefit analysis allowed to make a transparent decision. The evaluation of the concepts showed that SbW steering systems with single-wheel actuators have a higher potential than SbW systems with R-EPS because they provide ideal steering angles for all driving situations. Furthermore, the maneuvering capability is higher and they provide more installation space compared to systems with Rack-EPS. Nonetheless, it unclear if and which steering system will prevail in the future. This study presented that TKS has made good decisions by developing both SbW with R-EPS and with single-wheel actuators. Based on this, the operation processes were investigated in a detailed study of the presented innovative steering systems.

The last key question "What impacts do these innovative steering systems have on the operation processes?" was answered in the chapter *Impacts on the Manufacturing Engineering Process*. No single concept was selected as it was unclear which steering system would prevail in the future. However, all conceptualized steering systems were transferred to realistic products, for which already existing products were used which show a high degree of compliance with the concepts. Together with experts, a rough production procedure was defined for the products that are currently being developed. For the single-wheel actuator, a current patent was used. Those elements of the steering system that do not match the core competences of TKS were defined as buy products. Due to this decision, the production procedures of the different steering systems could be displayed. Based on these manufacturing procedures, the facility layout, investment calculation and required employee processes were calculated. The have impacts on the operation process because, due to less required machinery, smaller real estate areas and a reduced investment capital, it can be assumed that the workload of the projects is also smaller. However, TKS has strategic opportunities to increase the workload of the operation service, some of which were also presented in the present thesis. Due to the smaller facilities, TKS has the opportunity to build them closer to their customers and thereby reduce the supply chain's distances and increase its reliability. Another strategic opportunity for TKS is to handle more projects due to the decreased CAPEX. These results show that innovative steering systems have major impacts on the operation processes.

Systems engineering approach:

All in all, the project was successfully completed with all desired key questions of TKS having been answered. With the information gathered, TKS, and especially the operation service department, are now capable of proactively preparing several strategies to increase the reduction of value and workload for the individual departments. It can be concluded that TKS is already on a good way. However, in order to ensure the best possible preparation as well as appropriate reactions, it is recommended that TKS develops further strategies.

As already mentioned, the SE philosophy allows a systematical and controlled procedure for complex projects. Thinking in and defining systems, elements and system boundaries allow to reduce the complexity of a project. In the present case, some procedures needed several repetitions and discussions with experts in order to be able to make more precise statements and gain an understanding of how the investigated systems influence each other. An example are the relations between autonomous driving, SbW and governmental regulations. (A) currently, autonomous driving is not commercially allowed except for special conditions, e.g. if vehicles are still under development. (B) Musk, (2016) explains that Tesla expands its development of autonomous driving by deploying fleet learning; he believes that genuine self-driving will be allowed by law worldwide, if their fleet manages to cover 10 billion km. This highlights the influence of autonomous driving on governmental regulations. (C) Polmans, (2015) claims that allowing fault tolerant autonomous driving may close the gap to SbW. It becomes obvious that the system *autonomous driving* directly influences the system SbW via the system *governmental regulations*. (D) In addition, the system SbW allows new interfaces for steering, a simpler axle geometry and new car designs which also influence autonomous driving (see Figure 86). In short: all named systems influence each other – if the system boundary is then extended, the entire system will become even more complex.

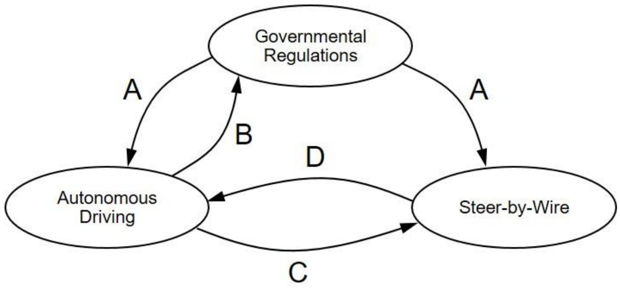


Figure 86 Influence on systems, draft (own illustration)

The action model from Haberfellner, et al., (2015) uses the four basic ideas of *top down*, d*evelopment of variants*, *project phases* and *problem-solving cycle*. The top down approach is often unconsciously used in practice while, in the present case, the deliberate decision to start with conceptualized and general steering systems enabled fast proceeding. In the following phase, the steering systems were transformed to realistic products which were not conceptualized in detail but sufficed in order to display changes of the manufacturing process. The development of variants was attempted but was not always possible: within the main study of steering systems, different variants were created, while this was not possible in the detailed study. This was due to time reasons and the fact that no decision was made for only on steering system. Nevertheless, the detailed study was implemented using various steering wheel concepts, even though not every concept used different variants.

The entire case study was divided into different project phases, which took some time since the individual phases were not clear at first. In the end, however, the division provided a more efficient and effective procedure. In each phase, the problem-solving cycle was used by defining the current situation and its objectives, which provides a goal that one can work towards. In the present case, small changes of the objectives were made because new information was continuously added to the project. In a final step, solutions were created and analyzed either with the help of a method (e.g. the value benefit analysis) or a group of experts (e.g. acquisition process). The SE approach from HALL-ETH has advantages and disadvantages but, in summary, it is a useful method to solve complex projects.

Concluding, this thesis showed that the area of steering systems is still one that is worth exploring in more depth. The future will show which steering systems will enter the market, since this still hugely depends on the direction that trends such as autonomous driving and electrification will take. This will hugely be influenced by statutory regulations, which is why no forecast can yet be provided on this topic. What is, however, certain, is that the influence of new technologies such as smart devices and autonomous driving has an ever increasing impact on the automotive industry, which opens up new possibilities and potentials with regard to innovative technologies in the area of steering systems.

List of References

Ackermann, C., Bechtloff, J. & Iserman, R., 2015. *Collision avoidance with combined braking and steering.* Wiesbaden, Springer Fachmedie.

Aggeri, F., Elmquist, M. & Pohl, H., 2008. *Managing learning in the automotive industry - the race for hybridisation.* Turin, Gerpisa 16th international conference.

Albarello, N., Arnold, A. & Budinger, M., 2016. Future Challenges in Mechatronics. In: P. Hehenberger & D. Bradley, eds. *Mechatronic Futures.* Toulouse France: Springer Internaional Publishing, pp. 25 - 39.

Alon, I., Fetscherin, M. & Sardy, M., 2008. Geely motors: a Chinese automaker enters international markets. *Int. Journal Chinese Culture and Management,* 1(4), pp. 489-498.

Associated Press , 2015. *The Washington Post.* [Online]
Available at: http://www.washingtontimes.com/news/2015/jan/13/a-look-at-the-5-biggest-chinese-automakers/
[Accessed 12 July 2016].

AutoTech Review, 2013. Agreement - Volvo to transfer technology to Geely. *AutoTech Review,* 2(1), p. 11.

Bahill, A. & Gissing, B., 1998. Re-evaluating Systems Engineering Concepts Using Systems Thinking. *IEEE Transactions on systems, man, and cybernetics - Part C: Application and Reviews,* 28(4), pp. 516-527.

Bayrische Motoren Werke AG, 2008. *Annual Report 2007,* Munich: Bayrische Motoren Werke AG.

Bayrische Motoren Werke AG, 2009. *Annual Report 2008,* Munich: Bayrische Motoren Werke AG.

Bayrische Motoren Werke AG, 2013. *BMW i Präsentation, London 10.Juni 2013,* London: Bayrische Motoren Werke AG.

Bayrische Motoren Werke AG, 2016a. *Geschäftsbericht 2015,* München: Bayrische Motoren Werke Aktiengesellschaft.

Bayrische Motoren Werke AG, 2016b. *Investor Factbook, July 2016,* Munich: Bayrische Motoren Werke AG.

Bertoncello, M. & Wee, D., 2015. *Ten ways autonomous driving redefine the automotive world,* Milan, Munich: McKinsey & Company.

Biedrzycki, P., 2016. *DuJour.* [Online]
Available at: http://dujour.com/lifestyle/faraday-future-founders-electric-cars-interview-pictures/
[Accessed 2nd May 2016].

BMVI, 2015. *Strategie automatisiertes und vernetztes Fahren,* Berlin: Bundesministerium für Verkehr und digitale Infrastruktur.

BMW Group Media Information, 2013a. *Press Kit - The BMW i3,* Munich: BMW Group Media Information.

BMW Group Media Information, 2013b. *Press Kit - BMW i announces strategic partnership with NOW! Innovations,* Munich: BMW Group Media Information.

BMW Group Media Information, 2014a. *Press Kit - The BMW i8,* Munich: BMW Group Media Information.

BMW Group Media Information, 2014b. *Press Kit - BMW Group Production,* Munich: BMW Group.

BMW Group Media Information, 2016. *Press Kit - BMW at the Consumer Electronics Show 2016 in Las Vegas,* Munich: BMW Media Information.

BMW Group, 2008. *Qualitätsmanagment Teile,* Munich: BMW Group.

BMW Group, 2016. *Sustainable Value Report 2015,* München: BMW Group.

BMW.de, 2016. *BMW.de.* [Online] Available at: http://www.bmw.de/de/neufahrzeuge/bmw-i/bmw-i/konzept.html [Accessed 18th July 2016].

BMWBlog, 2008. *BMWBlog.* [Online] Available at: http://www.bmwblog.com/2008/11/21/mini-e-test-drive/ [Accessed 18th July 2016].

BMWBlog, 2016. *BMWBlog.* [Online] Available at: http://www.bmwblog.com/2016/02/11/world-premiere-bmw-iperformance/ [Accessed 19th July 2016].

Bohnsack, R., Pinkse, J. & Kolk, A., 2014. Business models for sustainable technologies: Exploring business model evolution in the case of electric vehicles. *Research Policy,* Volume 43, pp. 284-300.

Bosch Automotive, 2016. *www.bosch.com.* [Online] Available at: http://aa-boschap-in.resource.bosch.com/media/parts/service_parts__auto_parts/brakes/bremsen_pias24_734x350_w734.jpg
[Accessed 30rd August 2016].

Bratzel, S., 2014. Die junge Generation und das Automobil - Die junge Generation und das Automobil der Zukunft?. In: B. Ebel & M. B. Hofer, eds. *Automotive Management.* Köln: Springer Gabler, pp. 93 - 108.

Brauck, M., Hawranek, D. & Schulz, T., 2016. Steuer frei. *Der Spiegel*, 27 February, pp. 13-20.

Breuer, B. & Bill, K. H., 2012. *Bremsenhandbuch - Grundlagen, Komponenten, Systeme, Fahrdynamik.* 4 ed. Wiesbaden: Springer Vieweg.

Briere, D., Favre, C. & Traverse, P., 2001. Electrical Flight Controls, From Airbus A320/330/340 to Future Military Transport Aircraft: A Family of Fault-Tolerant Systems. In: C. R. Sprither, ed. *The Avionics Handbook.* Williamsburg, Virginia: CRC Press.

Cambel, A. B., 1993. *Applied Chaos Theory - A paradigm for complexity.* 1 ed. s.l.:Academic Press Inc..

Cambridge Dictionary, 2016. *Camrbridge Dictionary.* [Online] Available at: http://dictionary.cambridge.org/dictionary/english/system [Accessed 10th August 2016].

Certo, S. C. & Certo, T. S., 2005. *Modern Management.* 10th ed. s.l.:Prentice Hall India.

Chen, Y. & Perez, Y., 2015. *Business Model Design: Lessons Learned from Tesla Motors.* ENS Cachan France, s.n.

Christensen, C. M., 2011. *The Innovator's Dilemma.* New York: Harper Business.

Collinson, R., 2011. Fly-by-Wire Flight Control. In: 3rd, ed. *Introduction to Avionics Systems.* Netherlands: Springer Science+Business Media B.V.,, pp. 179 - 253.

Czichos, H., 2015. *Mechatronik.* 3rd ed. Wiesbaden: Springer Fachmedien Wiesbaden.

Daimler AG, 2016. *www.daimler.com.* [Online] Available at: https://www.daimler.com/konzern/tradition/geschichte/1885-1886.html [Accessed 23rd August 2016].

Deperatment of Defense, 2001. *Systems Engineering Fundamentals,* FORT BELVOIR, VIRGINIA: DEFENSE ACQUISITION UNIVERSITY PRESS.

Diez, W., 2015. *Automobilmarketing - Erfolgreiche Strategien, praxisorientierte Konzepte, effektive Instrumente.* München: Franz Vahlen.

Dijk, M., Orsato, R. J. & Kemp, R., 2013. The emergence of an electric mobility trajectory. *Energy Policy,* Volume 52, pp. 135 - 145.

Dyer, J. H., Kale, P. & Singh, H., 2001. How To Make Strategic Alliances Work. *MIT Sloan Management Review,* 4(42), pp. Pages 37-43.

Ebel, B. & Hofer, M. B., 2014. *Automotive Management - Strategie und Marketing in der Automobilwirtschaft.* 2nd ed. Heidelberg: Springer Gabler.

Erlach, K., 2013. *Value Stream Design - The Way Towards a Lean Factory.* Heidelberg: Springer-Verlag Berlin Heidelberg.

Evanson, J., 2014. *Tesla Motors Investor Presentation,* s.l.: Tesla Motors.

EVI - Electric Vehicle Initiative, 2015. *Global EV Outlook 2015,* Paris: OECD/IEA/Clean Energy Ministerial .

EVI - Electric Vehicles Initiative, 2013. *Global EV Outlook - Understanding the Electric Vehicle Landscape to 2020,* Paris: IEA/OECD.

FAR/JAR 25, 2016. *Airworthiness Standards: Transport Category Airplanes.* [Online] Available at: http://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.list/parentTopicID/105
[Accessed 29th August 2016].

Faraday Future Inc., 2015. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/futuresight/faraday-future-looks-to-set-up-shop-in-north-las-vegas/
[Accessed 26 April 2016].

Faraday Future Inc., 2016a. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/futuresight/breaking-ground-on-a-ground-breaking-vision/
[Accessed 26 April 2016].

Faraday Future Inc., 2016b. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/team/
[Accessed 26 April 2016].

Faraday Future Inc., 2016c. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/assets/pdf/FF_Bio_NickSampson.pdf
[Accessed 26 April 2016].

Faraday Future Inc., 2016d. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/futuresight/ffzero1-a-car-of-concepts/
[Accessed 26 April 2016].

Faraday Future Inc., 2016e. *Faraday Future Inc..* [Online] Available at: http://www.ff.com/assets/pdf/Autonomous_Testing.pdf
[Accessed 01 July 2016].

Fetscherin, M., 2011. The Internationalisation of China's Geely Automobile: The Role and Importance of International Investments on Competitiveness. In: J. Zentes, B. Swoboda & D. Morschett, eds. *Fallstudien zum Internationalen Management.* Wiesbaden: Gabler Verlag, pp. 307 - 325.

Foerster, H., 2003. *Understanding Understanding: Essays on Cybernetics and Cognition.* s.l.:Springer.

Folke, R., Böker, R., Thomys, A. & König, L., 2010. Torque vectoring a new level of freedom for electric vehicles. *ATZ worldwide,* June, 112(6), pp. 8-12.

Frede, D., Khodabakhshian, M. & Malmquist, D., 2010. *A state-of-the-art survey on vehicular mechatronics focusing on by-wire systems,* Stockholm: KTH Royal Institute of Technology.

Freitag, M., 2016. Out! Of! Business?. *Manager Magazin*, April, pp. 48-54.

Gao, Z., 2015. The Enterprise Merger and Acquisition Effect on Firm Value - A Discussion on Geely's Acquisition of Volvo for Example. *Model Economy,* Volume 6, pp. 717-726.

Gates, G., Ewing, J., Russel, K. & Watkins, D., 2016. *New York Times.* [Online] Available at: http://www.nytimes.com/interactive/2015/business/international/vw-diesel-emissions-scandal-explained.html?_r=0
[Accessed 28 June 2016].

Geely Automobile Holding, 2014. *Geely - Annual Report 2014,* Hong Kong: Geely Automobile Holding.

Geely, 2014. *Geely.* [Online]
Available at: http://global.geely.com/news_info.php?33
[Accessed 12 July 2016].

Geely, 2016. *Geely.* [Online]
Available at: http://www.geelyauto.com.hk/core/files/presentation/sc/GeelyAuto-Presentation%20Apr2016.pdf
[Accessed 12 July 2015].

Goodall, N., 2014. Machine Ethics and Automated Vehicles. In: G. Meyer & S. Beiker, eds. *Road Vehicle Automation.* Switzerland: Springer International Publishing, pp. 93-102.

Gregersen, E., 2014. *Encyclopædia Britannica.* [Online]
Available at: http://www.britannica.com/print/article/1676437
[Accessed 21 April 2016].

Haberfellner, R., de Weck, O., Fricke, E. & Vössner, S., 2015. *Systems Engineering - Grundlagen und Anwendung.* 13., aktualisierte Auflage ed. Zürich: Orell Füssli Verlag.

Hall, A. D. & Fagen, R. E., 1956. Definition of system. *General Systems,* Volume 1, pp. 18-28.

Harashima, F., Tomizuka, M. & Fukuda, T., 1996. Mechatronics - 'what is it, why, and how?' An editoria. *IEEE/ASME Transactions on Mechatronics,* 1(1).

Hardman, S., Steinberger-Wilckens, R. & Van der Horst, D., 2013. Disruptive innovations: The case for hydrogen fuel cells and battery electric vehicles. *International Journal of Hydrogen Energy,* Volume 38, pp. 15438-15451.

Hehenberger, P. & Bradley, D., 2016. Mechatronic Futures. In: *Mechatronic Futures.* s.l.:Springer International Publishing, pp. 1 - 15.

Here, 2015. *Press Release - Backet by new shareholders, HERE to accerlerate deployment of real-time mps,* Berlin: Here.

Hesse, L., Schwarz, B., Klein, M. & Eckstein, L., 2013. *The Wheel-Individually Steerable Front Axle of the Research Vehicle SpeedE - 22nd Aachen Colloquium Automobile and Engine Technology.* Aachen, fka mbH.

Hirz, M., Wilhelm, D., Gfrerrer, A. & Lang, J., 2013. Chapter 1. Automotive Development Processes. In: *Integrated Computer-Aided Design in Automotive Development.* Berlin Heidelberg: Springer Berlin Heidelberg, pp. 1-23.

Holmberg, S., 2011. *Emerging Green-Technology Entrepreneurs: Entrepreneurial Pathwys to Growth in the Hybrid and Plug-In Hybrid/Electric Vehicle Space.* Stockholm, Sweden, ICSB World Conference Paper.

Hua, H. et al., 2010. Environmentla Implication of Electric Vehicles in China. *Environmental Science & Technology,* Volume 44, pp. 4856-4861.

Hucko, M., 2016. *Milliardeninvestition von BMW, Audi, Mercedes.* [Online] Available at: http://www.spiegel.de/auto/aktuell/bmw-audi-daimler-weshalb-der-kartendienst-here-so-wertvoll-ist-a-1085921.html
[Accessed 19th July 2016].

Huihui, Z., 2012. *Bachelor Thesis - China's Foreign Investment Analysis - Case Study of Geely Aquired Volvo,* Kuopio, Finnland: SAVONIA UNIVERSITY OF APPLIED SCIENCES.

IEEE STD 1220, 1998. *IEEE Standard for Application and Management of the Systems Engineering Process.* s.l.:IEEE.

INCOSE Uk ltd., 2009. *Z2 - Enabling Systems Engineering.* s.l.:INCOSE Uk lt..

INCOSE, 2006. *Systems Engineering Handbook v3.0 - A Guide for System Life Cylce Processes and Activities,* s.l.: International Council on Systems Engineering.

Intel Corporation, 2016. *intel.com.* [Online] Available at: https://newsroom.intel.com/news-releases/intel-bmw-group-mobileye-autonomous-driving/
[Accessed 19th July 2016].

International Organization of Motor Vehicle Manufacturers, 2016. *World Motor Vehicle Production by Country and Type 2014 - 2015,* http://www.oica.net/wp-content/uploads//Total-2015-Q4-March-16.pdf: OICA.net.

Isermann, R., 2008. *Mechatronische Systeme - Grundlagen.* 2. Auflage ed. Berlin: Springer Verlag.

Isermann, R., 2016. *Fault-tolerant components for automatic driving automobiles - some basic structures and examples.* Frankfurt, ATZ Fahrerassistenz Konferenz.

Johanning, V. & Mildner, R., 2015. *Car IT kompakt - Das Auto der Zukunft - Vernetzt und autonom fahren.* Wiesbaden: Springer Vieweg.

Joseph, N., 2015. *Autoblog.com.* [Online] Available at: http://www.autoblog.com/2015/11/18/geely-emgrand-ev-official/#slide-endcap
[Accessed 12 July 2016].

Kaas, H.-W.et al., 2016. *Automotive revolution - perspective towards 2030; How the convergence of disruptive technology-driven trends could transform the auto industry,* s.l.: McKinsey & Company.

Kalanick, T., 2016. *www.uber.com.* [Online] Available at: https://newsroom.uber.com/rethinking-transportation/
[Accessed 23rd August 2016].

Kalmbach, R., Bernhard, W., Kleinmann, P. G. & Hoffmann, M., 2011. *Automotive landscape 2025: Opportunities and challenges ahead,* Michigan, USA: Roland Berger Strategy Consultants.

Kampker, A., 2014. *Elektromobilproduktion.* Berlin Heidelberg: Springer Vieweg.

Kampker, A., Dirk, V. & Armin, S., 2013. *Elektromobilität - Grundlage einer Zukunftstechnologie.* Berlin Heidelberg: Springer - Verlag.

Karamitsios, A., 2013. *Open Innovation in EVs: A Case Study of Tesla Motors,* Stockholm, Sweden: KTH Industrial Engineering and Management.

Karaömer, A., 2013. *Master Thesis - The Relatoinship between The Brand Strategy and Business Strategy,* Stockholm: KTH Industria Engineering and Management.

Kim, C. W. & Mauborgne, R., 2004. Blue Ocean Strategy. *Harvard Busines Review,* Volume October, pp. 1-11.

Klermasch, C. M., 2010. *Tesla Motors - Eine Innovation von Martin Everhard and Marc Tarpenning zum Durchbruch des Elektroautos,* Norderstedt: Grin Verlag.

Kley, F., Lerch, C. & Dallinger, D., 2011. New business models for electric cars - A holistic approach. *Energy Policy vol 39*, 7 April, pp. 3392-3403.

Kühnapfel, J. B., 2014. *Nutzwertanalysen in Marketing und Vertrieb.* Wiesbaden: Springer Gabler.

Kühnl, C., 2010. Software gibt den Takt vor. *ME mechatronik ,* Volume 2, pp. 24-25.

Kyura, N. & Oho, H., 1996. Mechatronics - an industrial perspective. *IEEE/ASME Transaction on Mechatronics,* 1(1).

Lamberg, K. & Wältermann, P., 2000. *Using HIL Simulation to Test Mechatronic Components in Automotive Engineering.* Munich, dSpace GmbH.

Lindemann, U., 2005. *Methodische Entwicklung technischer Produkte - Methoden flexibel und situationsgerecht anwenden.* s.l.:Springer Berlin Heidelberg.

Lorenzoni, G. & Baden-Fuller, C., 1995. Creating a Strategic Center to Manage a Web of Partners. *California Management Review,* No. 3(Vol. 37), pp. 146-163.

Matt, D. T., Rauch, E. & Dallasega, P., 2014. *Trends towards Distributed Manufacturing Systems and modern forms for their design.* s.l., 9th CIRP Conference on Intelligent Computation in Manufacturing Engineering.

Merzouki, R., Samantaray, A. K., Pathak, P. M. & Bouamama, B. O., 2013. Vehicle Mechatronic Systems. In: *Intelligent Mechatronic Systems.* London: Springer London, pp. 437 - 575.

Mori, T., 1969. *Mechatronics - Yasakawa Internal Trademark Memo 21.131.01.* s.l.:s.n.

Moritz, M. et al., 2015. *Tesla Motors, Inc.: Pioneer towards a New Strategic Approach in the Automobile Industry along the Open Source Movement?.* Portland, OR - USA, s.n.

Muffatto, M., 1999. Introducing a plattform strategy in product development. *Int. J. Production Economics,* Issue 60-61, pp. 145-153.

Musk, E., 2016. *tesla.com.* [Online]
Available at: https://www.tesla.com/blog/master-plan-part-deux
[Accessed 21st July 2016].

Myerson, R. B., 1991. *Game Theory - Analysis of Conflict.* Cambridge, Massachusetts: Harvard University Press.

NASA, 1995. *Systems Engineering Handbook SP-610S,* s.l.: National Aeronatics and Space Administration.

NCSL US, 2016. *www.ncsl.org.* [Online]
Available at: http://www.ncsl.org/research/transportation/autonomous-vehicles-legislation.aspx
[Accessed 24th August 2016].

Newcomer, E., 2015. *Bloomberg Technology.* [Online]
Available at: http://www.bloomberg.com/news/articles/2015-12-03/uber-raises-funding-at-62-5-valuation
[Accessed 23rd August 2016].

Novikov, D., 2016. *Cybernetics - From Past to Future.* Switzerland: Springer International Publishing.

O'Hayre, R., Cha, S.-W., Colella, W. & Prinz, F. B., 2016. *Fuel Cell Fundamentals.* 3rd ed. Hoboken, New Jersey: Wiley.

oica.net, 2016. *OICA.net.* [Online]
Available at: http://www.oica.net/category/production-statistics/
[Accessed 5th August 2016].

Pfeffer, P. & Harrer, M., 2013. *Lenkungshandbuch.* Wiesbaden: Springer Vieweg.

Pfeifer, T., 1996. *Praxishandbuch Qualitätsmangement.* s.l.:Carl Hanser Verlag.

Polmans, K., 2014. *Development of an R&D Platform for SbW - Automotive Steering Technology Conference.* Berlin, s.n.

Polmans, K., 2015. Steer-by-Wire: Die Lenkungstechnologie der Zukunft?. *hitech - Das Magazin der Technik und Informatik,* Volume 1, pp. 10-11.

Polmans, K. & Hirschmann, R., 2014. *Steering system.* Germany, Patent No. DE102014004231 A1 .

Polmans, K. & Stracke, S., 2014. *Torque vectoring as redundant steering for automated driving or steer-by-wire; 5th International Munich Chassis Symposium 2014.* Wiesbaden, Springer Fachmedien.

Pomberger, G. & Blaschek, G., 1996. *Software Engineering.* 2nd ed. München, Wien: Hanser Fachbuch.

Pruckner, A., Stroph, R. & Pfeffer, P., 2012. Drive-by-Wire. In: A. Eskandarian , ed. *Handbook of Intelligent Vehicles.* London: Springer Verlag, pp. 237- 282.

Randall, T., 2016. *Bloomberg.* [Online]
Available at: http://www.bloomberg.com/news/articles/2016-04-01/tesla-s-model-3-lives-up-to-the-hype
[Accessed 21 April 2016].

Saaty, T. L., 2005. Making and validating complex decisions with the AHP/ANP. *Journal of System Science and Systems Engineering,* 14(1).

Saaty, T. L., 2012. *Decision Making for Leaders - Analytic Hierachy Process.* Third Edition ed. Pittsburgh: RWS Publications.

SAE International, 2014. *SAE J3016 - Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems,* s.l.: SAE International.

Schawel, C. & Billing, F., 2014. SWOT - Analyse. In: *Top 100 Management Tools.* 5th ed. Wiesbaden: Spring Gabler, pp. 246 - 248.

Schlager, K. J., 1956. Systems Engineering - Key to Modern Development. *IRE Transactions on Engineering Management,* 3(3), pp. 64-66.

Senge, P., 2006. *The Fifth Discipline.* 2nd ed. United States: Crown Business.

Siebenpfeiffer, W., 2014. *Vernetztes Automobil.* Stuttgart: Springer Vieweg.

Sigilló, M., Dold, M., Delmarco, C. & Polmans, K., 2015. *Implementation and testing of different control strategies on a steer-by-wire research platform; 6th International Munich Chassis Symposium 2015.* Wiesbaden, Springer Fachmedien.

Sörenson, D., 2006. *The Automotive Development Process - Doctoral Thesis.* 1st ed. Wiesbanden: Gabler Edition Wissenschaft.

Spath, D. et al., 2013. *Produktionsarbeit der Zukunft - Industrie 4.0. Studie des Fraunhofer-Institut für Arbeitswirtschaft und Organisation (IAO),* Stuttgart: Fraunhofer Press.

Spring, J., 2016. *Reuters.* [Online] Available at: http://www.reuters.com/article/us-autos-china-geely-idUSKCN0XA2QY [Accessed 12 July 2016].

statista.com, 2015. *statista.com.* [Online] Available at: http://www.statista.com/statistics/309639/vehicle-recalls-in-us-by-manufacturer/
[Accessed 22nd July 2016].

Sterman, J. D., 2000. *Business Dynamics.* s.l.:Mcgraw-Hill Education Ltd.

Stricker, K., Matthies, G. & Tsang, R., 2011. *Vom Automobilbauer zum Mobilitätsdienstleister,* Germany / Switzerland: Bain & Company.

Tabuchi, H. & Ewing, J., 2016. *New York Times.* [Online] Available at: http://www.nytimes.com/2016/06/28/business/volkswagen-settlement-diesel-scandal.html
[Accessed 28 June 2016].

Tesla Motors Inc., 2013a. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/blog/tesla-motors-opens-assembly-plant-tilburg-netherlands?redirect=no
[Accessed 27 June 2016].

Tesla Motors Inc., 2013b. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/blog/tesla-reinvents-car-buying-experience?redirect=no
[Accessed 27 June 2016].

Tesla Motors Inc., 2014. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/blog/factory-upgrade [Accessed 27 June 2016].

Tesla Motors Inc., 2015. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/blog/your-autopilot-has-arrived [Accessed 25th April 2016].

Tesla Motors Inc., 2016a. *Tesla Motors Inc.* [Online] Available at: https://www.teslamotors.com/about [Accessed 21 April 2016].

Tesla Motors Inc., 2016b. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/support/model-3-reservations-faq [Accessed 21 April 2016].

Tesla Motors Inc., 2016c. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/supercharger?redirect=no [Accessed 27 June 2016].

Tesla Motors Inc., 2016d. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/blog/putting-tesla-hepa-filter-and-bioweapon-defense-mode-to-the-test
[Accessed 28 June 2016].

Tesla Motors Inc., 2016e. *Tesla Motors Inc..* [Online] Available at: https://www.teslamotors.com/presskit [Accessed 28 June 2016].

Tesla Motors Inc., 2016f. *Tesla Motors Inc..* [Online] Available at: www.tesla.com/findus [Accessed 26th July 2016].

Tesla Motors Inc., 2016. *Letter: Tesla Fourth Quarter and Fulll Year2015 Update,* USA: Tesla Motors Inc..

The Tesla Motors Team, 2014. *Tesla Motors.* [Online] Available at: https://www.teslamotors.com/blog/factory-upgrade [Accessed 07 March 2016].

Thomas, C. E., 2009. Fuel cell and battery electric vehicles compared. *International Journal of Hydrogen Energy,* Issue 34, pp. 6005-6020.

Thomas, P. et al., 2013. Grundlagen. In: A. Kampker, D. Vallèe & A. Schnettler, eds. *Elektromobilität - Grundlagen einer Zukunftstechnologie.* Berlin Heidelberg: Springer Vieweg, pp. 5 - 57.

ThyssenKrupp InCar plus, 2014. Column EPS for compact and mid-size vehicles. *ATZ extra - The Project ThyssenKrupp InCar plus,* pp. 76-79.

Tilley, A., 2016. *Forbes.com.* [Online] Available at: http://www.forbes.com/sites/aarontilley/2016/01/05/faraday-future-were-going-to-move-a-lot-faster-than-tesla/#13bf13501f73
[Accessed 26 April 2016].

Traverse, P., Lacaze, I. & Souyris, J., 2004. Airbus Fly-by-Wire: A total approach to dependability. In: R. Jacquart, ed. *Building the Information Society.* Toulouse: Springer US, pp. 191-212.

Uber Technologies Inc., 2016. *www.uber.com.* [Online] Available at: https://www.uber.com/ [Accessed 23rd August 2016].

Ulrich, H. & Probst, G. J., 1995. *Anleitung zum ganzheitlichen Denken und Handel. Ein Brevier für Führungskräfte.* 4th ed. Bern: Paul Haupt Bern.

UN Secretary-General, 1968. *Vienna Convention on Road Traffic,* Vienna: United Nations.

VDA, 2009. *Das gemeinsame Qualitätsmanagement in der Lieferkette - Produktentsehung - Reifegradabsicherung für Neuteile.* 2nd ed. Frankfurt am Main: Verband der Automobilindustrie e.V..

VDI 2206, 2004. *Design methodology for mechatronic systems,* Germany: Verein Deutscher Ingenieure.

Verbeke, A., 2013. *International Business Strategy.* 2nd ed. Cambridge: Cambridge University Press.

Viardot, E., 2013. Achieving Market Leadership with Collaborative Innovation: The Case of Technology-Driven Companies. In: N. Pfeffermann, T. Minshall & L. Mortara, eds. *Strategy and Communication for Innovation.* Heidelberg: Springer Berlin Heidelberg, pp. 293 - 313.

Volvo Car Group, 2015. *Annual Report 2015,* Gothenburg, Sweden: Volvo Car Group.

von Bertalanffy, L., 1949. The Theory of Open Systems in Physics and Biology. *Science,* Volume 111, pp. 114-129.

von Bertalanffy, L., 1976. *General System theory: Foundations, Development, Applications.* New York: George Braziller.

von Bismarck, G. & Zheng, Y., 2016. Geely: A Case Study on the Trend Following Volvo-Owner. In: R. T. Segers, ed. *Multinational Management - A Caseook of Asia's Global Market Leaders.* Heidelberg: Springer International Publishing, pp. 33-54.

von Erichsen, F., 2016. *zeit.de.* [Online] Available at: http://www.zeit.de/politik/deutschland/2016-04/bundesregierung-elektroautos-subvention-kaufpraemie
[Accessed 20th July 2016].

Wallentowitz, H. & Leyers, J., 2014. Technologietrends in der Fahrzeugtechnik - Dimensionen, Verläufe und Interaktionen. In: B. Ebel & M. B. Hofer, eds. *Automotive Management.* Köln: Springer Gabler, pp. 29-55.

Wang, H. & Kimble, C., 2010. Low-cost strategy through product architecture: lessons from China. *Journal of Business Strategy,* 31(3), pp. 12-20.

Wang, H. & Kimble, C., 2013. Innovation and Leapfrogging in the Chinese Automobile. *Global Business and Organizational Excellence,* 6(32), pp. 6-17.

Wang, L., 2011. *A Case Study of the Acquisition of Swedish Volvo by Chines Geely, Master Thesis,* BTH - Blekinge Tekniska Högskola: School of Managment.

Warren, T., 2015. *www.theverge.com.* [Online] Available at: http://www.theverge.com/2015/11/19/9761852/faraday-future-car-company-

interview-tour-electric-tesla-competitor
[Accessed 21 March 2016].

Weber, J., 2009. *Automotive Development Processes.* Berlin Heidelberg: Springer.

Weber, M. & Weisbrod, J., 2002. Requirements Engineering in Automotive Development - Experiences and Challenges. *IEEE International Conference on Requirements Engineering,* pp. 331-340.

Weckowicz, T. E., 1989. *Ludwig von Bertalanffy - A Pioneer of General Systems Theory; CSR Working Paper No. 89-2,* Edmonton AB, Canada: Center for Systems Research Working Paper No. 89-2 Edmonton AB: University of Alberta.

Wiener, N., 1948. *Cybernetics: Or Control and Communication in the Animal and the Machine.* Cambridge, Massachusetts: MIT Press.

Winterhoff, M., Wendt, T. F. & Bernhard, W., 2015. *Think Act - Automotive 4.0 a disruption and new reality in the US?,* Michigan, USA: Roland Berger Strategy Consultants LL C.

Winzer, P., 2013. *Generic Systems Engineering - Ein methodischer Ansatz zur Komplexitätsbewältigung.* Berlin Heidelberg: Springer Vieweg.

Wolters, H. & Hocke, R., 1999. Auf den Weg zu Globaisierung - Chance and Risiken. In: I. Arthur D. Little Int., ed. *Die Zukunft der Automobilindustrie - Herausforderungen und Lösungsansätze für das 21. Jahrhundert.* Wiesbaden: Gabler, pp. 13-30.

Wolters, H., Landmann, R. H., Bernhart, W. & Karsten, H., 1998. *Die Zukunft der Automobilindustrie - Herausforderungen und Lösungsansätze für das 21. Jahrhundert.* Wiesbaden: Gabler.

Xu, K. & Li, X., 2014. Technological innovation from imitation in latecomer firms: evidence from China's auto firms. *Innovation and Development,* 4(1), pp. 161-173.

Zentes, J., Swoboda, B. & Morschett, D., 2011. The Internationalisation of China's Geely Automobile: The Role and Importance of International Investments on Competitiveness. In: M. Fetscherin, ed. *Fallstudien zum Internationalen Management.* Wiesbaden: Gabler Verlag, pp. 307 - 325.

Zhejiang Geely Holding Group, 2014. *Geely Group.* [Online] Available at: http://global.geely.com/geely_overview.php
[Accessed 4th May 2016].

Ziegler, C., 2016. *www.theverge.com.* [Online] Available at: http://www.theverge.com/2016/2/17/11031722/aston-martin-faraday-future-electric-car-rapide
[Accessed 23 March 2016].

Zsidisin, G. A., 2003. Managerial perceptions of supply risk. *Journal of Supply Chain Management;,* Volume 1, pp. 14 - 39.

List of Figures

List of Tables

Appendix

A.1

R&D – 31.05.2016:

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	2	0	0	1	0	4	11.1	4
Product Space	0	1	0	1	1	0	3	8.3	6
Automation Grade	2	2	1	2	2	2	11	30.6	1
Weight	2	1	0	1	1	0	5	13.9	3
Simplicity	1	1	0	1	1	0	4	11.1	4
Haptic Feedback	2	2	0	2	2	1	9	25.0	2
					Total		36		

Sales EU – 31.05.2016:

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	2	0	0	1	0	6	16.7	3
Product Space	0	1	0	1	1	0	6	16.7	3
Automation Grade	2	2	1	2	2	2	8	22.2	2
Weight	2	1	0	1	1	0	3	8.3	6
Simplicity	1	1	0	1	1	0	4	11.1	5
Haptic Feedback	2	2	0	2	2	1	9	25.0	1
					Total		36		

Sales US – 04.06.2016:

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	0	2	0	1	1	5	13.9	4
Product Space	2	1	2	0	1	1	7	19.4	2
Automation Grade	0	0	1	1	2	2	6	16.7	3
Weight	2	2	1	1	2	2	10	27.8	1
Simplicity	1	1	0	0	1	1	4	11.1	5
Haptic Feedback	1	1	0	0	1	1	4	11.1	5
					Total		36		

Author – 30.05.2016:

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	1	1	0	1	1	5	13.9	4
Product Space	1	1	1	1	2	2	8	22.2	2
Automation Grade	1	1	1	2	2	2	9	25.0	1
Weight	2	1	0	1	1	2	7	19.4	3
Simplicity	1	0	0	1	1	1	4	11.1	5
Haptic Feedback	1	0	0	0	1	1	3	8.3	6
					Total		36		

Operation Service 1 – 09.06.2016

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	2	1	1	2	2	9	25.0	1
Product Space	0	1	1	0	1	0	3	8.3	6
Automation Grade	1	1	1	1	2	1	7	19.4	3
Weight	1	2	1	1	2	2	9	25.0	1
Simplicity	0	1	0	0	1	1	3	8.3	4
Haptic Feedback	0	2	1	0	0	1	4	13.9	4
					Total		36		

Operation Service 2 – 10.06.2016

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	2	0	2	2	2	9	25.0	2
Product Space	0	1	0	1	1	2	5	13.9	3
Automation Grade	2	2	1	2	2	2	11	30.6	1
Weight	0	1	0	1	1	2	5	13.9	3
Simplicity	0	1	0	1	1	2	5	13.9	3
Haptic Feedback	0	0	0	0	0	1	1	2.8	6
					Total		36		

Operation Service 3 – 15.06.2016

	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	1	0	2	1	1	2	7	19.4	2
Product Space	2	1	2	2	2	2	11	36.6	1
Automation Grade	0	0	1	1	1	2	5	13.9	5
Weight	1	0	1	1	1	2	6	16.7	3
Simplicity	1	0	1	1	1	2	6	16.7	3
Haptic Feedback	0	0	0	0	0	1	1	2.8	6
					Total		36		

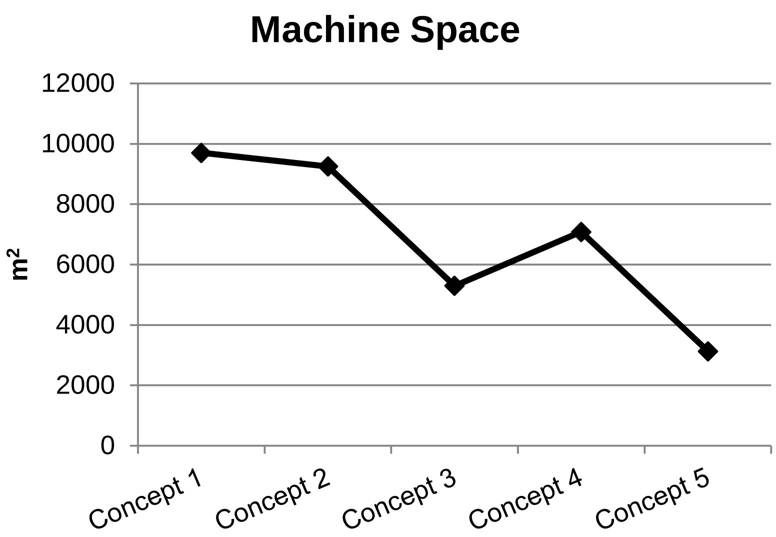
Accumulated matrices:

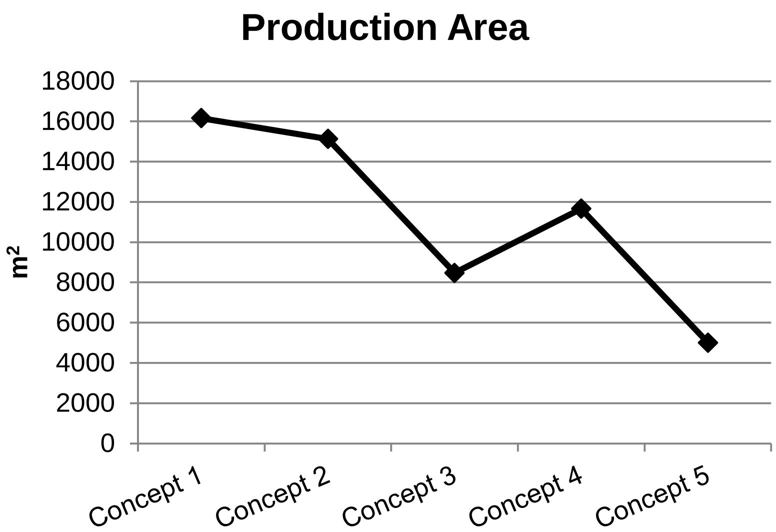
	Modularity/Flexibility	Product Space	Automation Grade	Weight	Simplicity	Haptic Feedback	Sum	%	Order of priority
Modularity/Flexibility	7	9	8	4	9	8	45	17.9	2
Product Space	5	7	7	7	10	7	43	17.1	4
Automation Grade	6	7	7	11	13	13	57	22.6	1
Weight	10	7	3	7	8	10	45	17.9	2
Simplicity	5	4	1	6	7	7	30	11.9	6
Haptic Feedback	6	7	1	4	7	7	32	12.7	5
					Total		252		

Average and standard deviation of the weighted criteria:

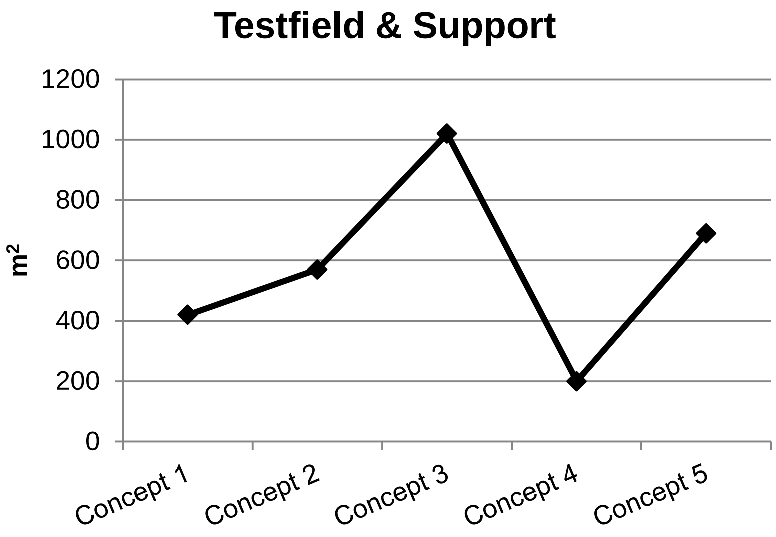
	R&D [%]	Sales EU [%]	Sales US [%]	Author [%]	Operation Service 1 [%]	Operation Service 2 [%]	Operation Service 3 [%]	Average [%]	Standard Deviation [%]
Modularity/Flexibility	11.1	16.7	13.9	16.7	25.0	25.0	19.4	17.9	5.1
Product Space	8.3	16.7	19.4	22.2	8.3	13.9	30.6	17.1	7.3
Automation Grade	30.6	22.2	16.7	22.2	19.4	30.6	13.9	22.6	6
Weight	13.9	8.3	27.8	19.4	25.0	13.9	16.7	17.9	6.3
Simplicity	11.1	11.1	11.1	11.1	8.3	13.9	16.7	11.9	2.4
Haptic Feedback	25.0	25.0	11.1	8.3	13.9	2.8	2.8	12.7	8.6

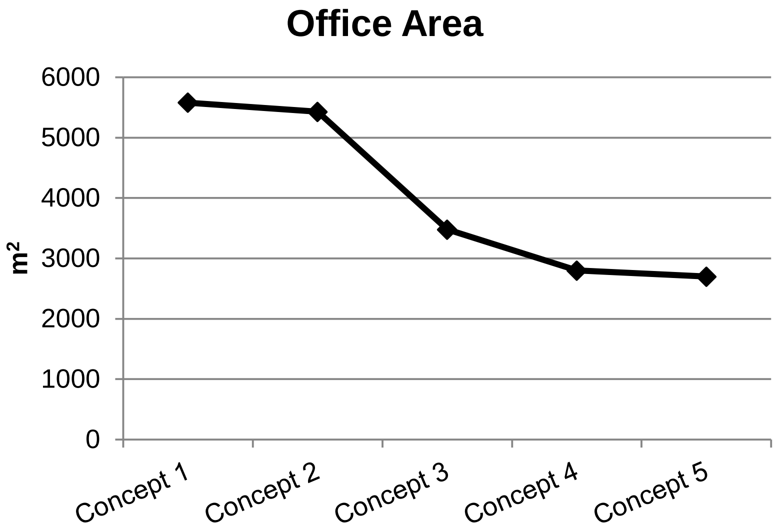
A.2

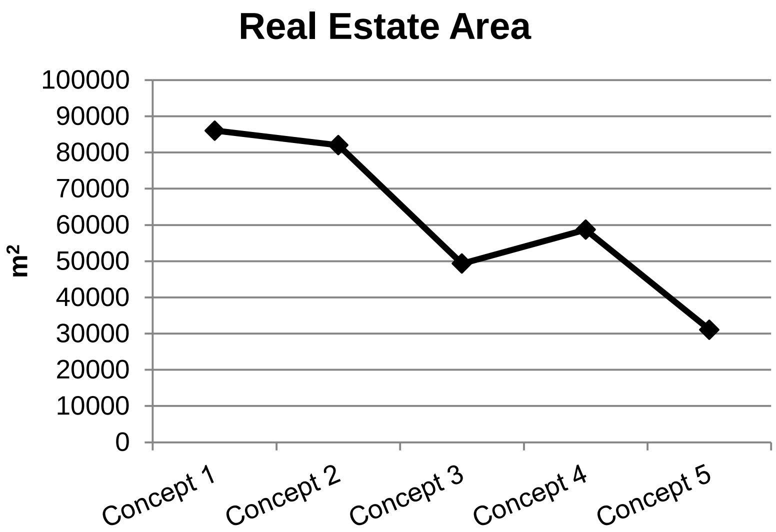

Machine Space
12000
10000
8000
6000
4000
2000
0
m²
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Production Area
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
m²
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5

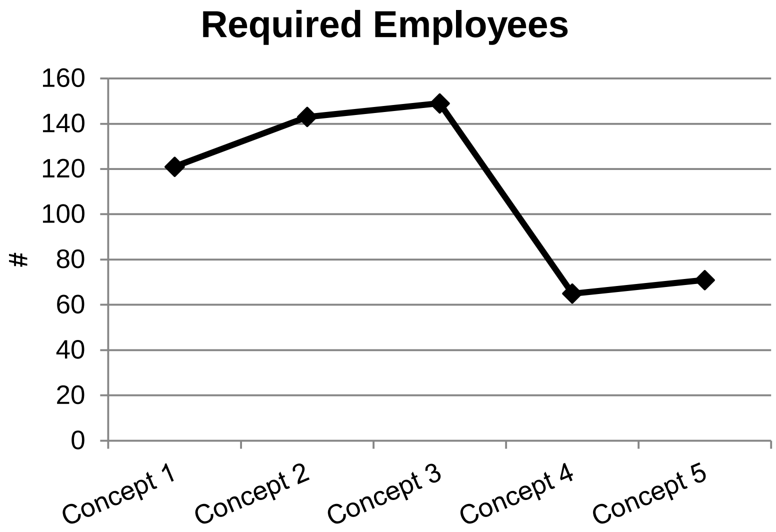

Logistic & Warehouse
12000
10000
8000
6000
4000
2000
0
m²
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Testfield & Support
m²
1200
1000
800
600
400
200
0
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5

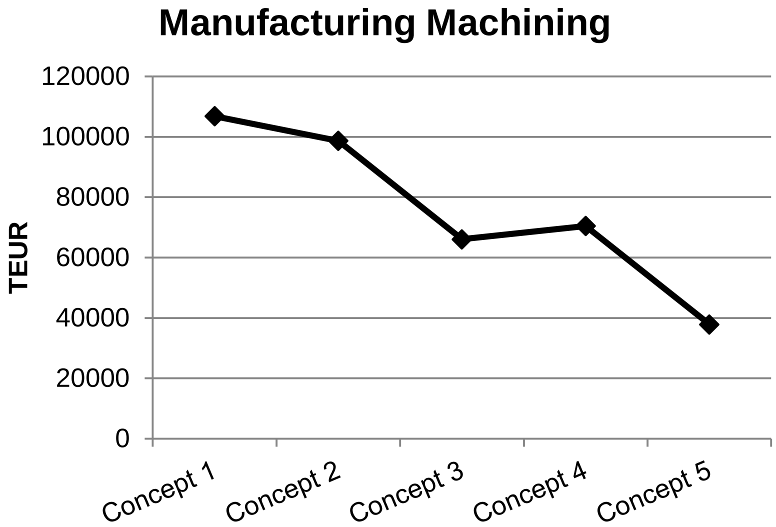

Office Area
m²
6000
5000
4000
3000
2000
1000
0
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5

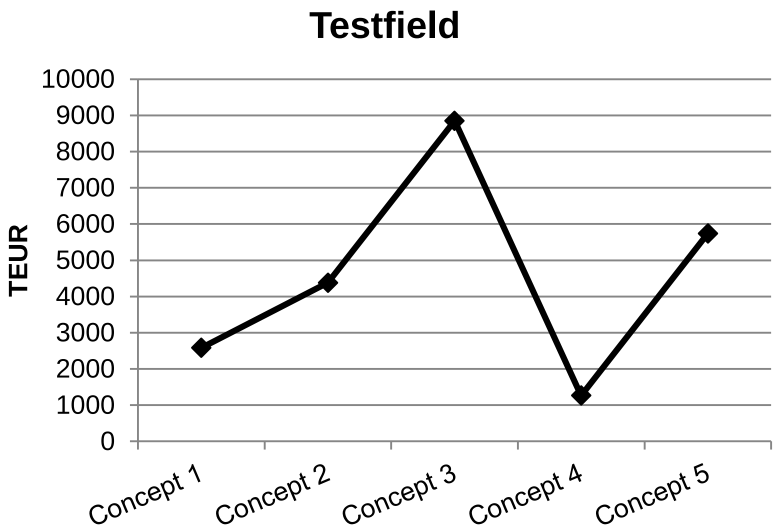

Real Estate Area
m²
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5

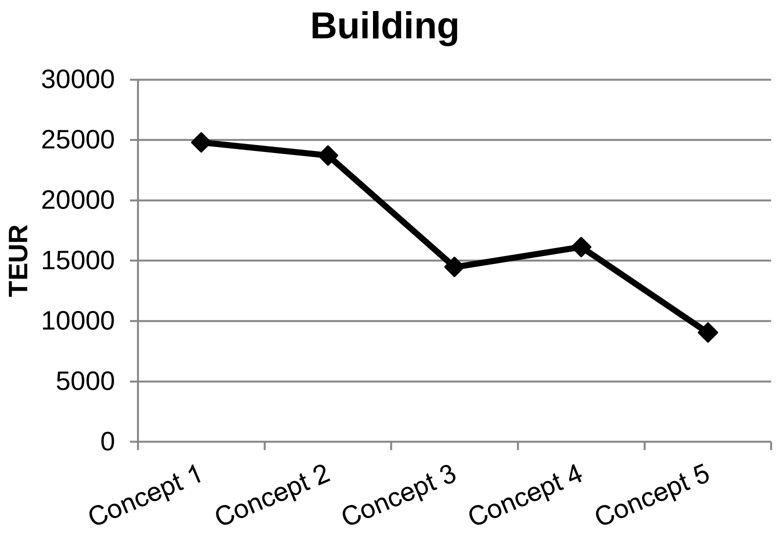
A.3:

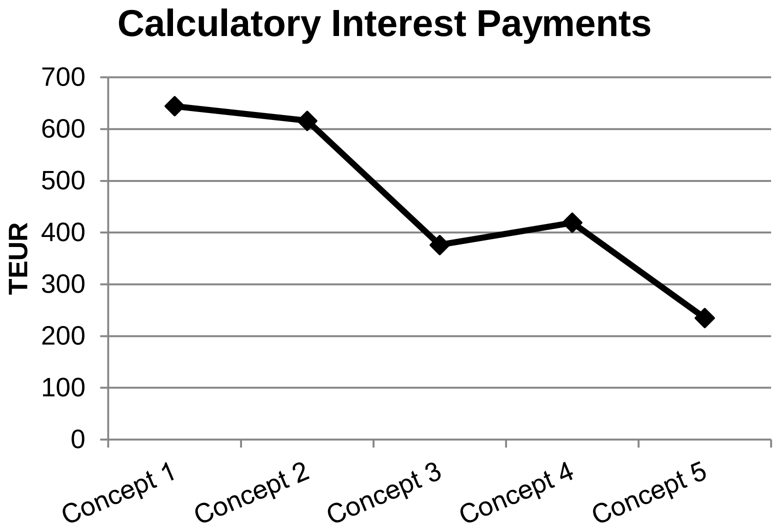

Required Employees
160
140
120
100
80
60
40
20
0
#
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5

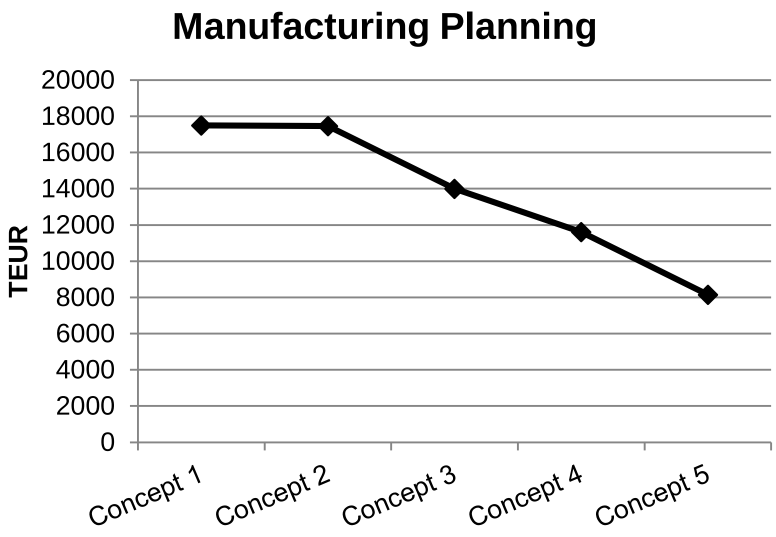
A.4:

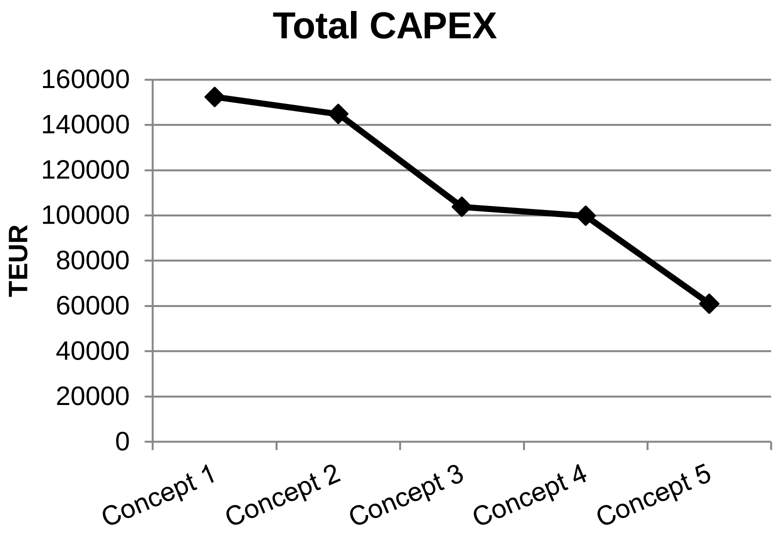

Manufacturing Machining
120000
100000
80000
60000
40000
20000
0
TEUR
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Testfield
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
TEUR
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Building
30000
25000
20000
15000
10000
5000
0
TEUR
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Calculatory Interest Payments
700
600
500
400
300
200
100
0
TEUR
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Manufacturing Planning
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
TEUR
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5


Total CAPEX
TEUR
160000
140000
120000
100000
80000
60000
40000
20000
0
Concept 1
Concept 2
Concept 3
Concept 4
Concept 5