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When digital meets physical – Agile Innovation of Mechatronic Systems

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FOREWORD BY THE SUPERVISOR

Problem Statement

Until recently developing new products was a haphazard affair, based on a combination of past performance, existing knowledge and good instinct. The significant impact of digitization is a limited effectiveness in forecasting the future. Shortened technological cycles, especially for electronics and software products, increases the uncertainty about problem and solution space. The dynamic of innovation is boosted by new technologies enabling new business models that emerge at breathtaking pace and overturn whole industries. Established companies experience a rapidly changing environment, volatile markets, and face the challenge of how to capture value through innovation. The challenge of innovation is getting technology to market more quickly to compete with startups that are geared for rapid execution.

Strategies to cope digitization is being responsive and adaptive to changes. However, large companies often lack the adaptation and implementation speed needed to address this challenge. They usually operate in a culture driven towards efficiency rather than creativity. Companies are migrating from “Waterfall” to “Agile” to become faster. Agile principles introduce short and time-boxed development cycles (“Sprints”) with a limited scope. However, agile development of mechatronic systems is not studied extensively and only a few examples exist.

While long-range strategic planning may still be relevant to some degree, the frequency of evaluating these strategic plans becomes a relevant factor. In today's dynamic business environments, organizations need to break old habits of practicing planning as ceremonial processes that are conducted periodically. It is proposed to acquire feedback from users constantly and make late changes cost-efficient by implementing adaptability and changeability within system architectures. Being responsive and adaptive to changes must be understood as a major practice for developing successful systems.

Objectives

The aim of this research is to explore agile development of physical products. It is assumed that there are certain agile enablers (or agility providers) that support the development of agile capabilities. For agile projects, collaboration, for example, is more important than following a specific process. In general, agile thinking is more close-ended and addresses the so-called “fuzzy front-end of innovation” that is characterized by high uncertainty. It is to find out, how a “just do it” mentality can enable quick and flexible decisions leading to improved quality. The prototyping roadmap of interdisciplinary teams is examined to understand the agile process model for physical systems. Thus, several development sprints of mechatronic products are analyzed to derive a framework that balances “trial-and-error” and systematic approaches.

Results

Main outcome of this research study is the Makeathon-format "Think.Make.Start." ("TMS"). TMS is inspired by the theory of learning (e.g. Design Thinking), the avoidance of non-value-added activities (e.g. Lean Development), short time periods of working (e.g. Scrum), and traditional development methods (e.g. VDI 2221). The applied 5 – 10 days development sprint unites highly skilled talents from various disciplines to develop mechatronic systems in a minimum of time. The format fosters self-organization, rapid prototyping activities and a close interaction with the user. The development is done in small development cycles with limited functionality being incrementally developed. The development process is facilitated by the creation of several prototypes that is supported by a high-tech workshop ("Makerspace"). Based on the agile project paths an agile framework, "TAF", is derived to allow continuous integration for mechatronic systems while balancing agile and traditional methods. It represents a shortened and flexible development process, a closer collaboration and the integration of users or other relevant stakeholder (non-technical disciplines).

Contribution to academia

This work has given rise to the understanding of "agile" in the context of physical product development. "TMS" allows to design innovative mechatronic systems supported by an intensive collaboration between engineers and other domains. It is shown how rapid prototyping and continuous integration improves the product development in two ways: First, they improve the interaction between developers and users by continuous feedback. Second, prototypes improve the specification and communication of product properties across multiple teams in project-based organizations. Participants understand how other disciplines think, work and develop skills required to work in an interdisciplinary team ("t-shaped persons"). Thus, a new understanding on how to treat the product, the process and the team, as one single system is developed and consolidated in "TAF".

Implications for industry

The challenge for established corporates is to get to market more quickly. This research provides various starting points to allow agile product innovation in rigid structures. Dynamic resource distribution promotes flexibility in scope while keeping the budget. Cross-functional collaboration in innovation projects increases the development speed to stay competitive in today`s dynamic business environment. Team autonomy leads to faster decision-making in the face of changes or new requirements. A Makerspace enables the employees to respond to new ideas and test them directly in an accelerated process. TMS fosters rapid execution, teamwork and promotes collaboration across divisions. Internal contradictions are solved by embracing open innovation, less hierarchical management and integration of entrepreneurial behaviors.

Garching, February 2018

Prof. Dr.-Ing. Udo Lindemann

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[1] http://blog.aichriedler.de/index.php/2015/10/18/the-best-course-you-can-choose-at-tu-munich/

“Be Stubborn on Vision, but Flexible on Journey. – Jeff Bezos”

THE FOLLOWING PUBLICATIONS ARE PART OF THE WORK PRESENTED IN THIS DISSERTATION:

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CONTENT

1. Introduction

This chapter gives an overview of the overall thesis. Based on a short introduction the objective of this research study is outlined. The focus of the research is described while touching upon relevant areas of the state of the art and research. The chapter concludes with a presentation of the author`s practical experience and the structure of the research work.

1.1 Initial Situation and Motivation

For the development of **mechatronics systems,** one must take into consideration that electronics and software represent an ever-increasing part of the final product (Eigner, 2014, p. 15). Traditional mechanical engineering, electrical/electronic and software methods cannot just be coordinated, but common interdisciplinary design approaches must be proposed. To **design innovative** and multidisciplinary products traditional development processes need to be rethought in terms of trends such as agile design methods, servitization of products and increasing demand for mass-personalized products (Gürtler and Lindemann, 2016, p. 485). Especially, the early phases of product development are characterized by **uncertainty** due to rapid technology change and continuously changing user needs. Corporates seek for a higher level of **responsiveness** and **adaptiveness**. Hence, user-centered, quick and flexible approaches increase the capability of being adaptive and responsive to changes.

The term "**agility**" has been used increasingly in the context of product development since the turn of the millennium. It is largely synonymous in English “agile” and in German “agil” and means active, flexible, nimble, versatile or spirited (Haberfellner *et al.*, 2015, p. 46). In the context of product development, "agile" can be interpreted differently, with two different facets being expressed (Haberfellner and Weck, 2005). If the term "agile" refers to the **result**, the developed product should be mobile in the sense of changeable, and subsequently, configurable (Haberfellner *et al.*, 2015, p. 47). If "agile" is related to the design or development **process**, then it should be flexible and adaptable to accommodate and implement new or modified requirements during development (Haberfellner *et al.*, 2015, p. 47). An agile **organization** is a way to handle complexity by a change in management (Mollbach and Bergstein, 2014). Agile products as well as agile processes become an important and meaningful concern in a rapidly changing world with increased frequency of change and product innovation as well as shortened development and product life cycles (Blockus, 2010, p. 34).

The environment in which products are invented, specified and constructed is changing. The systems are becoming more **complex** and the speed at which requirements and expectations are changing is rapidly increasing. **Individualization** is omnipresent and **time to market** may mean the difference between a successful product launch or a financial failure (Boehm and Turner, 2006, p. 2). Traditional development is characterized by **extensive upfront planning** and **process optimization**. These **plan-driven methods** concentrate on the product quality as well as the predictability and improvement of the specified processes (Boehm and Turner, 2006, p. 2). In the late 1990s a counter-movement against the existing, **rigid** and restrictive development concepts arose in software development (Haberfellner *et al.*, 2015, p. 104). The so-called **Agile Manifesto** plays an essential role in this context, written by the supporters that summarizes the key messages or values (Beck *et al.*, 2001):

"Individuals and interactions over processes and tools"

"Working software over comprehensive documentation"

"Customer collaboration over contract negotiation"

„Responding to change over following a plan"

The right side of the sentences above is not considered unimportant, but the left side is more important. Agile Methods leave behind heavyweight processes, to accept change and to promote agility. Particularly helpful are methods that have **short cycle times** that involve **customers** and focus more on **adaptation** than prediction (Boehm and Turner, 2006, p. 4). An increasing number of companies have integrated agile methods into their development efforts, with the goal of developing products with minimal documentation in a rapidly changing environment leading to high customer satisfaction (Boehm and Turner, 2006, p. 4). Unfortunately, plan-driven and result-driven approaches are often perceived as opposites and not as **valuable complements** (Boehm and Turner, 2006, p. 4 ff.). In this research study it is argued that both have their legitimacy under certain conditions of use (Haberfellner *et al.*, 2015, p. 123). Synergy effects in the context of product complexity are to be found balancing traditional, **plan-driven** and more agile, **result-driven** approaches.

The basic idea of agile approaches is not only to master complexity, but also to deal with it in an interdisciplinary team. **Digital technologies** lead to new customer requirements and uncertainty within the innovation process. Technology change results in short product life cycles and continuously changing markets, accompanied by reduced market penetration. Volatile markets lead to limited effectiveness in forecasting the future. Early product specification is becoming less meaningful in advance, and companies face the challenge of traditional value-adding activities and new digital business models.

Large corporates often lack the ability to adapt and respond to changes rapidly and flexibly. Knowledge silos create barriers to effective communication and collaboration. **Digitization** of a company is a critical driver in breaking down silos and fostering enhanced collaboration resulting in benefits from a common knowledge basis. Globalization shifts from cross-border flows of goods and capital to enormous data and information flow. Partnerships become more important as the number of cross-industry and new business innovations become higher than groundbreaking technical inventions. Digital technologies lower entry barriers for new competitors, providing access to global ideas, technologies and innovations. The competition is not the other enterprise, but startups that are geared for rapid execution (Böhmer and Lindemann, 2015, p. 917). **Startups** bring the necessary **spirit** of innovation that has all too often disappeared in large companies.

Information technology and technology merge in the **mechatronic system**. New interdisciplinary approaches are needed to efficiently handle different technology cycles during development and over product life cycles. Thus, companies must handle the conflicting goals of both the exploitation of existing business models and the exploration of new digital businesses. **Agility** allows one to handle the increasing **complexity** and changing environments of **volatile markets**.

1.2 Objective of the Work

The aim of this research is to derive strategies to integrate the concept of "agile" into the innovation and product development process of complex mechatronic systems in order to increase the innovation capability. The work is limited to the early phase of product innovation and separated into two main parts (see Figure 1-1). First, agile development of physical products is explored for interdisciplinary teams and mechatronic products. Second, a strategy is derived to integrate agile approaches into the complex context of an OEM in order to increase the innovation capability, while fostering digital transformation.

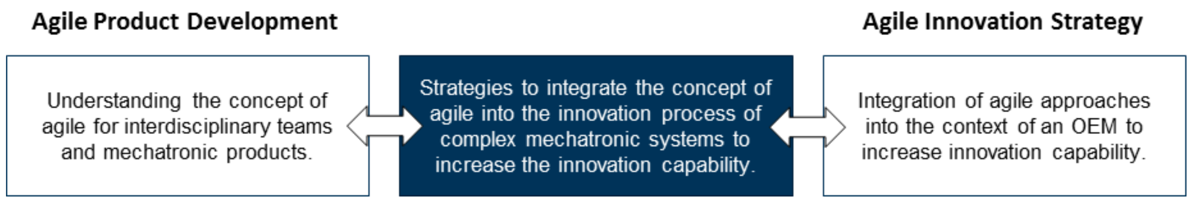

Figure 1-1: Objective of the work.

Agile methods are explored in the context of mechatronic product development. The Agile Manifesto is iteratively transferred into the context of product development by the creation of the format: Think.Make.Start. (TMS). The Makeathon provides an ideal setting for agile product development. Students focus on a fast and flexible way to explore product ideas with high technical and market uncertainties. The role of prototyping is examined by translating traditional plan-driven approaches to agile result-driven approaches.

According to the understanding of "agile" being more of a team competency, the objective of TMS is to experience agile, and simultaneously, to develop the necessary skills. All participants are briefly introduced to human-centered design to emphasize with the user and find problems worth solving. While getting to know the others, random teams brainstorm on various ways to solve these. Based on personal skills and interest, interdisciplinary teams are formed autonomously. Starting with an initial "problem-solution-fit", teams are guided by agile coaches, as well as technology and business experts from the initial idea to the final prototype. The idea is to empower the participants, who themselves compete in teams but collaborate on the coursework.

The best practices of "agile" within the mechatronic context, found during 7 batches of TMS at Technical University of Munich, were captured in an agile prototyping framework ("TAF"). It comprises agile values and principles as well as traditional methods and helps the teams to remain focused during a highly iterative and flexible development. The main aspect is to give priority to the innovation object, shifting from plan-driven to result-driven development. Instead of optimizing the process (e.g. Lean) or rather defining context-based process models (e.g. Open Innovation), the agile framework promotes the creation of various prototypes, while focusing on the necessary characteristics of the prototypes. Starting with just a vision, a minimum feature set is derived in order to build the first prototypes. Different types of prototypes are used to evaluate user-, engineering- or business-driven hypotheses. Complex questions are broken down into “doable” increments, so that they can be answered with minimum time and resources. Finally, the prototypes show the progress towards a product vision that is driven by both results and evaluated hypotheses.

Industry faces the challenge of limited effectiveness in forecasting the future. **Time to market** is reduced by actively involving the user during the development process. Product development is planned roughly in the long-term, but more accurately in the short-term. **Product specification** is evaluated and tested iteratively with the user. The creation of various prototypes improves the **quality** in means of meeting the users` needs. Resources are allocated dynamically to create the maximum value for limited time and resources. Budgeting and planning options are kept open until the last responsible moment to allow for late changes. Such flexible investment speeds up projects and optimizes the developmental approach at levels above teams and projects.

To make use of the full potential of “agile” in product development a **special setting** is required to decouple agile teams from traditional management. Dynamic reallocation of resources and budgets across value streams is essential. **Cross-functional** teams must be given the autarky to develop a mechatronic subsystem with minimum time and resources. A clear separation of responsibility, for example, within the development of the whole system is to be defined. Thus, existing strategies from the field of entrepreneurship are examined to transfer “agile” in the context of corporate innovation. An **entrepreneurial short-sight** is fostered to unleash the innovation potential by allowing flexible and quick implementation of ideas. A variant of TMS is introduced at a corporate in order to evaluate the format in a more complex context and to allow iterative development cycles for fully dedicated teams.

An agile group benefits from its **learning organization** that has the capability to be responsive and adaptive to changes. Instead of cultivating knowledge silos, employees collaborate in **innovation cells** that create prototypes to learn and to acquire user feedback. This internal flexibility is enriched by external partners. Startups become a partner by investment, acquisition, incubation or cooperation. Corporate executives involved with startups attest the advantages of being immersed in the **startup culture**. **Intrapreneurs** help to absorb the innovation culture and apply what they have learnt back into day-to-day jobs. Positive side effects are better networking (“knowledge exchange”), high collaboration (“user-centered” / “entrepreneurial”), and self-organization of several key stakeholders (“collective intelligence”). Startups benefit from the greater infrastructure and the efficient processes of a corporate. **Agile partnerships** make technology and trend radars more important in the short-term. Agile teams integrate the latest technology even late in the development process thereby increasing the innovativeness of a product. Hence, the whole system that can be adapted rapidly, becomes extremely flexible.

1.3 Thematic Analysis and Focus of the Study

Until recently, developing new products was about past performance, specifying the offer, assembling a team, and going into stealth mode for designing, building, and manufacturing. It has been identified that a certain degree of flexibility for the **innovation processes** is of great advantage (Herstatt and Verworn, 2001, p. 11). The scientific discourse on innovation management is characterized by a **strong phase** and **context orientation** (Vetter, 2011, p. 35). New linear models have been designed, comprising softer overlapping phase transitions. The latest models tend to be more flexible and involve agile frameworks (Link, 2014). The approach shifts from purely linear and sequential to iterative and collaborative (Böhmer *et al.*, 2016, p. 918).

Digitization is reshaping companies across industries; leaders must manage uncertainty better and establish more agility. Digital transformation puts a new set of pressures on organizations, and traditional approaches struggle with the rapid testing, failing, learning, adapting, and iterating that **agile innovation** requires. Volatility, unpredictability, complexity and ambiguity are all synonyms for **uncertainty**, which is a major issue to be tackled in the digital age. Companies must simultaneously run the business and hit regular performance goals, while exploring new business opportunities. To perform in the digital age, complexity must be handled by adequate systems engineering and the inclusion of more disciplines, where traditional and agile capabilities are essential.

Mechatronic products become more **complex** and will have more computing power and network connectivity. This leads to extended design challenges in understanding the difficulties of complex systems where **agile methods** will be a key technology for mastering these. The term „agile" is found in many research fields, like manufacturing, software development, organization theory, requirements and change management as well as supply-chain and human resource management. Cognate subjects are User-Centered Design, Lean Development and Corporate Entrepreneurship.

This work is based on the assumption that agile practices have a positive impact on innovation capability. However, certain preconditions are necessary to enable agile development. The various aspects of **agility** are explained in a framework by (Förster and Wendler, 2012, p. 14). Agile drivers are external factors that necessitate the adoption of agile methods. In response to this, agile capabilities are developed to deal with these drivers. Agile enablers (also known as agility providers) are factors that support the development of agile capabilities (Sharifi and Zhang, 1999, p. 7). There are no sufficient strategies to integrate agile approaches into the innovation and product development processes of complex mechatronic systems.

The aim of this research is to explore agility within the context of **mechatronic product development**. Aspects of product and process are considered and unified in **system** development. Engineering change management, agile project management and product architecture strategies are side issues partially investigated in this work. The focus is on **uncertainty** caused by (un)expected **change** and the resulting gain in **knowledge**. The construct of the **prototype** plays only a subordinate role from a traditional process viewpoint relating to effectiveness and efficiency aspects (Vetter, 2011, p. 6). **Agility** focuses on iterative prototyping in order to learn about and improve the product. It combines **flexibility** with **speed**, resulting in a fusion of product and process view (Smith, 2007, xii). According to (Vetter, 2011), the **innovation process** of startups is characterized by **object-specific** orientation. The emergent character of “agile” is manifested in highly individual prototyping roadmaps. The cost of prototyping is compensated by the rise of rapid prototyping technologies. Digital technologies, like virtual reality, facilitate the early validation of complex mechatronic systems. By specifying an agile innovation strategy for corporates, the potential of “agile” internally (an innovation process) and externally (a startup collaboration) is elaborated. Outlining an Open Innovation Ecosystem, Makerspaces, startup collaborations and internal strategies (e.g. skunk works) are described.

1.4 Research Approach and Practical Experience

A qualitative research approach is applied as it is rich in detail and enables recognizing nuances (Ingle, 2013, p. 19). It is important to deeply understand the perspective of design and design activities that are associated with agility (e.g. need finding or prototyping). Qualitative data deliver more *information* about interactions and situations, helping to understand the **context** of the projects (Guba, E. G., and Lincoln, Y. S., 2000, p. 106; Köppen and Meinel, 2015). For this research, interviews, project reports, and observations represent the qualitative data collection that is used to develop a project-specific understanding.

A case study design, frequently used in industrial network research, is used to explore the research topic presented in this thesis. The approach in this research is based on “systematic combining” grounded in an “abductive” logic, to answer “how” or “why” questions. Case studies are appropriate when researchers have little control over events, and when phenomena are studied within a real-life context (Yin, 2003, p. 1). The flexible research procedure allows one to react to unanticipated and emerging events, being especially beneficial for projects that are studied in an *iterative* process and are embedded in an ambiguous setting (Simons, 2009, p. 26). The research deals with single case research aiming at theory development from case studies as suggested by Eisenhardt (1989) (Dubois and Gadde, 2002). This type of case study is especially suitable for new topic areas (Eisenhardt, 1989, p. 532; Skogstad and Leifer, 2011; Schmiedgen *et al.*, 2016; Schindlholzer *et al.*, 2011). The case is evolving during the study and through systematic combination **patterns becomes clearer** with every effort (Dubois and Gadde, 2002). However, there will surely be pieces left out, which fit **other research efforts** (Dubois and Gadde, 2002).

The “Design Research Methodology” suggested by (Blessing and Chakrabarti, 2009) serves as an **overall structure** for this study. It includes a four-stage process as illustrated in Figure 1-2. The theoretical background is gained through a literature analysis and supports the formulation of the research design and goal. To assess the current state in research and practice, available literature and data are reviewed, and informal qualitative discussions with customers, employees, management staff members and competitors are conducted.

The case study, in which data (reports and interviews) are collected and analyzed, is conducted as part of the “Descriptive Study I”. As **hardware-related** agility and the application thereof in large corporations has not yet been studied extensively, this research begins with an **explorative study** of seven separate practical lecture courses (“Think.Make.Start”) at the Technical University of Munich (TUM). The courses took place once per semester from

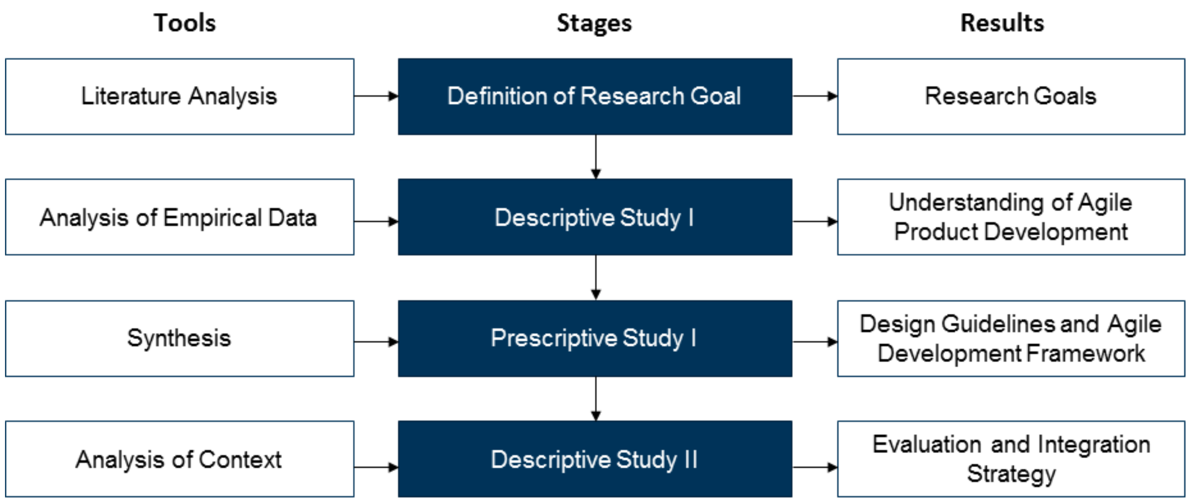

Figure 1-2: Design Research Methodology, adapted from (Blessing and Chakrabarti, 2009, p. 15).

summer semester 2015 to summer semester 2018 and were held on 10 consecutive working days. The student projects that emerged in each course are used as cases for a case study research. The results provided a comprehensive understanding of the cases, which, in turn, are used as a basis for the development of design guidelines in the "Prescriptive Study I". An evaluation of the guidelines is part of the "Descriptive Study II". The resulting insights are then elaborated on in a **conductive case study** research by conducting interviews, and hypothesis-based analysis of six innovation projects at an OEM. Based on the analysis, the format "Think.Make.Start." (TMS) is evaluated at an OEM.

In order to achieve the aims of this thesis, outlined in Chapter 1.2, four research questions are derived for the two objectives of this research. First, it must be revealed how to **define** an "agile" development approach for mechatronic products. Second, it must be understood how to **integrate** this agile development approach into the complex context of an OEM, thereby unleashing the innovation capability. The logic for (I) how to define an agile product development model is derived from the student projects and the "lessons learned" during TMS at TUM. The following two research questions are examined:

RQ1: Which **elements** are relevant for agile development of mechatronic systems?

RQ2: How to define a **result-driven** development approach for physical products?

A mixed-method research design, called embedded design, was used to understand the prototyping experience, including their thinking and learning processes while prototyping. Quantitative data were collected to support and provide additional information to the primary qualitative data set (Borrego *et al.*, 2009, pp. 58–59; Creswell, 2012, pp. 544–546). The aim of this research is based on developing interpretive understanding and gaining meaning from experiences, thinking and learning process while prototyping. The primary data of this thesis is qualitative data. Quantitative data collected via surveys was used to support and provide additional information to the qualitative data (Creswell, 2012, p. 545). The mixed method research design, embedded design, combines the advantages of both quantitative and qualitative data to allow for a better understanding of the research problem and question (Creswell, 2012, p. 535).

Strategies on how to (II) integrate the concept of “agile” in order to unleash the innovation capability, are expressed in two research questions:

RQ3: Which factors influence the **innovation capability** and how to measure it?

RQ4: How to **integrate** agile elements into the **complex context** of an OEM?

Appropriate cases are selected to answer the proposed research questions. To gain different perspectives, innovation projects address business model innovation, new technologies and highly interdivisional projects. The innovation projects at the OEM provide a deep understanding on the complex process of product development with all the influences and challenges involved. They are especially valuable enabling one to answer the research questions three and four, providing great insights into different aspects, relevant within a large corporate. Successful and unsuccessful cases are analyzed from the innovation projects as recommended by (Eisenhardt, 1989, p. 537) and (Yin, 2003, p. 52) with the aim of building theories from success and failure scenarios (see Chapter 6.4).

A typical qualitative data collection method for case study research is used, comprising interviews, observations, and project archival (Eisenhardt, 1989, p. 537; Yin, 2003, p. 83; Stake, 1995). Interviews and observations are used to collect data from the innovation projects, and documentation is analyzed to understand the context and origin of the projects. Multiple data collection methods allowed a triangulation of data, which provides a stronger validity and strengthens the grounding of the developed theory (Yin, 2003, 46, 99; Eisenhardt, 1989, p. 538). Following the strategy by (Eisenhardt, 1989), an analysis was conducted within and across cases.

Practical Experience

The work is based on the experiences of several student projects in diverse contexts. The projects ranged from a lost-and-found station for the elderly (“Flink”), an electric sharing E-skateboard (“EC-Board”), a massage system (“Massageboy”) to new ideas to individualize a digital interior for today`s cars (“MyMINI”). A collaboration with the startup Motius[2] resulted in a bread baking machine for Omani bread (“Khubz”). Student society projects include the development of the second generation of the humanoid robot “Roboy[3]” and the development of “TUM Hyperloop[4]” at Technical University of Munich (TUM). The variety of projects allows a holistic view of agile`s potential and limitations in the context of product development. The research is enriched by the development of a user-innovated Frappuccino machine (“Casper”) in the context of the research project “InnoCyFer[5]” (see (Niehues, 2016)). The deepened understanding of agility within product development, however, is mainly based on

[2] https://www.motius.de/de/

[3] https://roboy.org/

[4] https://tumhyperloop.de

[5] www.goo.gl/jEsjZc

seven generations of “Think.Make.Start.”[6] (TMS). This interdisciplinary lab. course (Module MW2245) was founded at Technical University of Munich and performed in close cooperation with UnternehmerTUM GmbH[7], the center for innovation and business creation at TUM. Over ~389 students from eight different departments participated in the intense Makeathon format. Elements of the Think.Make.Start. format have been elaborated with Plansee and Siemens. The comprised agile development framework is partly applied to Roboy 2.0 and to some extent evaluated with Merck and Comeau. A research cooperation with the design education lab and d.school at Stanford University provided the in-depth focus on human-centered design. Student research projects at Massachusetts Institute of Technology gained valuable insights into systems engineering.

The evaluation study bases on a close collaboration between BMW Group and TUM. The semi-weekly research practice allowed a deep dive into the challenges and opportunities in the automotive industry. The project work involved an intensive exchange with respective experts at the following BMW departments: the department for total vehicle lower series and MINI, the department for product line BMW i and the department for research, new technologies, and innovations. The research practice comprised six innovation projects aiming to constantly reflect the derived hypotheses for an agile innovation strategy. The implications for industry are conducted by a successful implementation of a TMS-Makeathon at the BMW Group (P&G, 2017, p. 3). The format has been elaborated nine times with ~325 employees from various divisions at BMW Group.

1.5 Structure of the Work

The structure of the research work is aligned with the previously outlined research questions and its implicit structure. Figure 1-3 illustrates the building blocks of the work. The main part of the research is divided into three chapters. First, the **Agile Product Development** is developed iteratively from seven Makeathons at Technical University of Munich (Chapter 5). Second, the context of digital transformation of an OEM is examined in terms of innovation capability (Chapter 6). Third, the Agile Product Development is evaluated in the automotive context and an **Agile Innovation Strategy** is derived aiming for a sustainable adoption (Chapter 7).

Chapter 1 outlines the initial situation and motivation for this research. Based on the objective of the work, the focus of the study is described. The research approach is presented in detail, resulting in the exact structure of the work.

Chapter 2 briefly introduces agility in the context of product development. Three focus areas are described in more detail, framing the focus of the work. Future challenges of mechatronic systems are outlined, going into detail in terms of innovation dynamics and the resulting complexity. The potential of collaborative innovation and the impact of Makerspaces are outlined for startups and large corporations.

[6] https://www.thinkmakestart.com/

[7] https://www.unternehmertum.de/

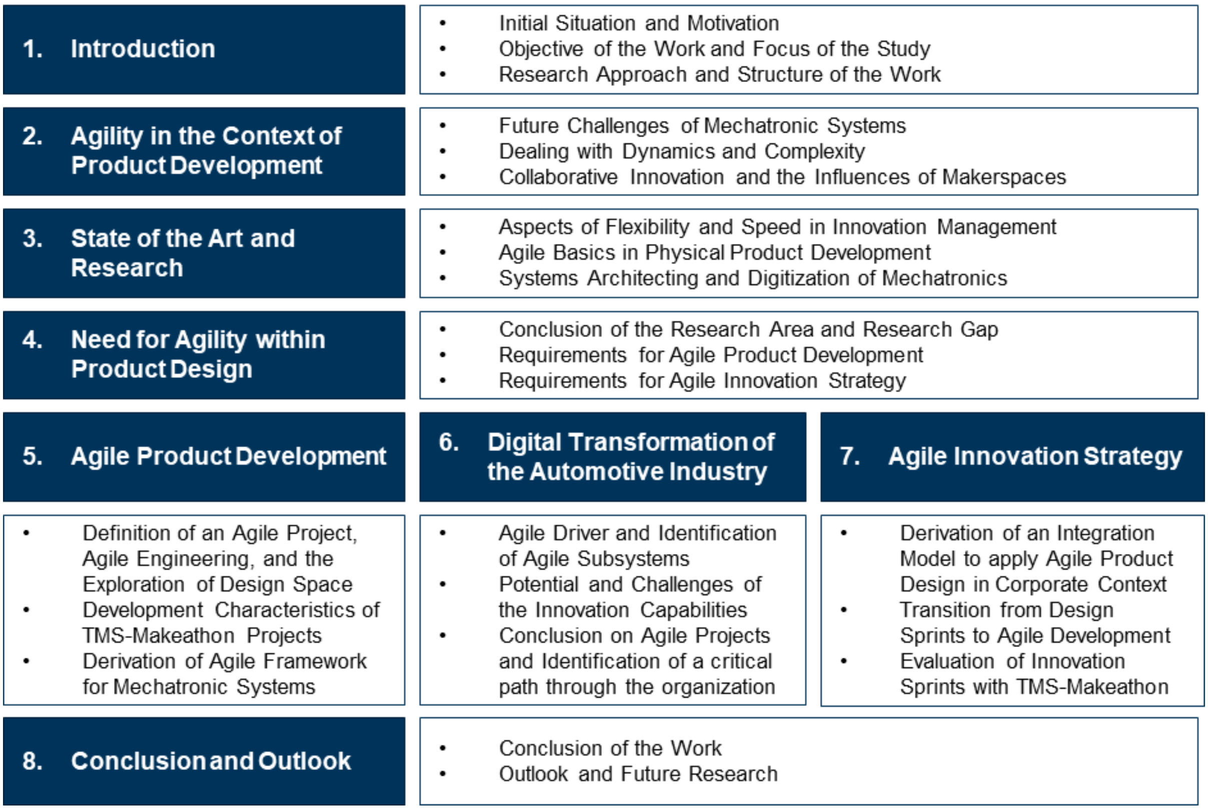

Figure 1-3: Structure of the work.

Chapter 3 outlines the art and research, relevant for the objective of this work. First, aspects of innovation management are elaborated. Different innovation types and strategies aiming to increase flexibility and speed in innovation processes are examined. Second, agile basics in development and project management are exemplified for physical products. Third, systems architecting and the effect of digitization on mechatronic systems is outlined. Changeable architectures and correlating development strategies are introduced to deal with uncertainty in the context of mechatronic systems.

Chapter 4 aggregates promising aspects of the state of the art and research and highlights the research gap of missing strategies to integrate the concept of "agile" in the context of mechatronic systems. The need for agility in product design is summarized, and requirements for an Agile Product Development are defined. For evaluation purposes, requirements for an Agile Innovation Strategy are gathered to successfully integrate Agile Product Development.

Chapter 5 summarizes the findings of seven Makeathons in terms of Agile Product Development. Based on the definition of an agile project, agile engineering and the exploration of the design space is described. Characteristics of the Makeathon projects are explained focusing on product development. From the 75 mechatronic products a prototyping framework is derived, thereby balancing agility with stability in terms of systems design.

Chapter 6 introduces agile driver and correlating agile subsystems of an OEM. The innovation capability is analyzed and the impact of digital transformation on the organization is elaborated. Based on the examination of six innovation projects at the OEM, a critical path to complete projects on time by focusing on key task is derived. The chapter concludes with preconditions for agile projects in a corporate structure.

Chapter 7 combines the Agile Product Development of Chapter 5 with the insights gained in Chapter 6. An integration model is outlined summarizing relevant organizational aspects which the Agile Innovation Strategy must address. The transition phase from idea to concept and from concept to product is explained by the concept of systematic agility. Product development is divided into design sprints and agile development, whereby the first phase is evaluated by the application of the TMS-Makeathon at the OEM. Management strategies are outlined to overcome the lasting ambidexter of startup agility and corporate quality.

Chapter 8 summarizes the research and outlines future research questions of interest.

2. Agility in the Context of Product Development

This chapter briefly introduces agility in the context of (physical) product development and outlines four focus areas. First, future challenges of mechatronic systems are described. Second, companies face the challenge of an increasing speed of development due to rapid changes in markets, technologies or political conditions. At the same time, product complexity and customer requirements increase significantly. Third, the potential of collaborative innovation of startups and large companies is outlined. Digitization is a huge driver of innovation; Startups that earned millions within a few years and are disrupting entire industries in a short time prove the huge innovation potential. Fourth, the rise of the Maker Movement is outlined. Makerspaces help a community to think, imagine and collaboratively create new products. Startups benefit from these facilities as they facilitate prototyping practices with less resources, providing valuable user insights early in the development process.

2.1 Future Challenges of Mechatronics

"Fortune 500 firms in 1955 v. 2015; Only 12% remain, thanks to the creative destruction that fuels economic prosperity" – Mark J. Perry

Innovations are, to a certain extent, something new that breaks into the market (Ehrlenspiel and Meerkamm, 2013, p. 371). Innovations are a significant increase in performance, an increased number of product features or a replacement of previous technologies with new solutions. The future can only be predicted to a certain extent, which limits planning activities of innovation projects and any call for flexibility to react and adapt to changes. A business's long-term sustainability is determined by its ability to address a constantly changing market and the economic environment.

In the course of **digital transformation**, traditional product development, focusing on hardware (sales of vehicles), shifts towards product service systems (sales according to the number of miles) with new innovative business models (Lindemann, 2016, p. 483 ff.). To cope with technological and market-related **uncertainties**, systematic innovation management is essential. "VUCA" is an acronym that describes volatile markets, an unpredictable future, complex systems, and ambiguous situations (see Figure 2-1). As **product complexity** and the **rate of market change** have increased over the last years, companies face the challenge of

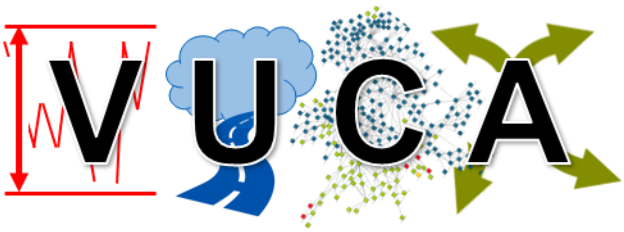

Figure 2-1: Illustration of "VUCA" (abbreviation for: Volatile, Uncertain, Complex, and Ambiguous).

forecasting the future and specifying product requirements upfront (Thomke and Reinertsen, 1998).

The term "**mechatronics**" is composed of the words "mechanics and electronics" (VDI-Richtlinie, 2004, p. 9). Over the past years software gained in importance and mechatronic systems evolved from discrete electrical and mechanical parts to integrated electronic–mechanical system (see Figure 2-2) (Eigner, 2014, p. 42; Isermann, 2008, p. 14). The concept of interdisciplinary system thinking is in the focus of product development (Janschek, 2010). Mechatronic products gain in importance as they offer far-reaching opportunities for **innovation** (Hellenbrand, 2013, p. 11; VDI-Richtlinie, 2004, p. 14; Luckel *et al.*, 2000, p. 25). The development and operation of mechatronic systems, however, became increasingly **complex**, due to digitization and Industry 4.0. Value-adding components have shifted strongly to the information technology by more than 40 percent. Forecasts see the trend continuing to rise (Hensel, 2011, p. 2). Bender quantifies the share of innovation in the machine-building sector, being in in the area of information technology, to 90 percent (Bender, 2005, p. 7).

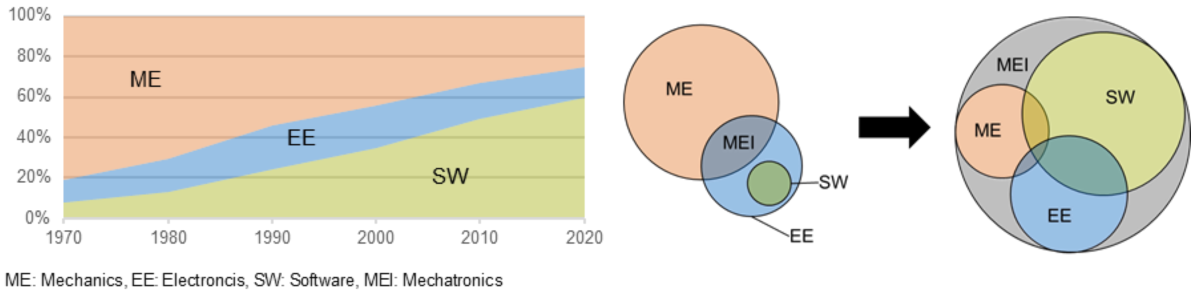

Figure 2-2: Transformation of the term "mechatronics", adapted from (Eigner, 2014, p. 43).

The increase in mechatronic products is accompanied by advantages and new challenges. Higher quality over product lifecycle is achieved, and product features are modified after start of production, by the adaptation of software, for example (Hellenbrand, 2013, 1, 11). New challenges arise as a result of the **interplay** between the **various disciplines** (Luckel *et al.*, 2000, p. 4). Developers are confronted with different ways of thinking (see Figure 2-3). Computer scientists and electrical engineers are more **function-oriented**, while mechanical engineers focus more on the **component** and think of longer innovation and product life cycles (Hellenbrand, 2013, p. 18 ff.). As software and hardware merges to mechatronic systems, numerous dependencies call for **interdisciplinary development**.

The fast pace of electronics and software is an increasing challenge for future products (Eigner, 2014). To design **innovative** and **multidisciplinary products**, the traditional development process needs to be adapted (Bricogne *et al.*, 2016, p. 75). Interdisciplinary environments require cross-domain communication and collaboration between the disciplines involved to gain a common understanding of the future product (VDI-Richtlinie, 2004, p. 4). Usually, the development team has different conceptual worlds and thought patterns, which is why they speak "different languages" (Kruse, 1996, p. 18). Jung (2006) outlines that requirements of mechatronic products are mainly implicit. Taking a non-technical discipline to the traditional

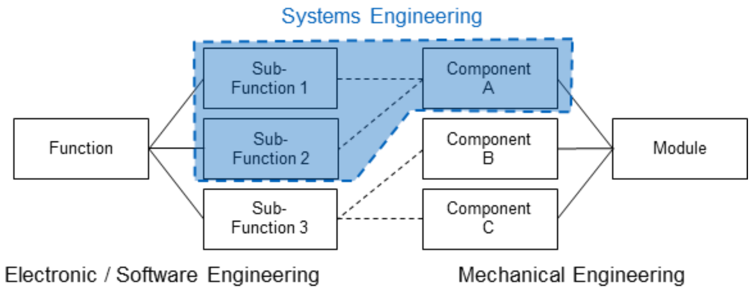

Figure 2-3: Disciplines in mechatronics think differently, adapted from (Hellenbrand, 2013, p. 18).

mechatronics disciplines creates a new dimension of **interdisciplinary collaboration** (Jung, 2006, p. 3).

Agile methods rely on common **interdisciplinary design** approaches to react more flexibly to dynamic conditions (Douglass, 2016b, p. 29). They are characterized by adaptiveness and responsiveness to deal with different **technology cycles** during product development and the over product lifecycle. Complex mechatronic systems are characterized by a long-running development process of more than 3 years. The challenge for companies is to shorten and flexibilize the development process, so that the product is not outdated when hitting the market. Likewise, companies face lower **market penetration** because of reduced product life cycles. New strategies are needed to counter outdated software or electronics subsystems, while mechanical subsystems are designed for more than 10 years. Companies can react by offering **updates** and **upgrades** to increase the product lifecycle of mechatronic systems, for example.

2.2 Dealing with Dynamics and Complexity

The term **innovation dynamics** is widely used in literature, characterized by the number of renewals of innovation objects per time unit (Ramsauer, 1997, p. 66). Primarily products, processes, structures and human areas are considered as innovation objects (Ramsauer, 1997, p. 60). System theory classifies the dynamics into external and internal dynamics (Padulo and Arbib, 1974, v). External dynamics are described as environment dynamics and internal dynamics as corporate dynamics. **Digitization** leads to accelerated technology cycles and the challenge of innovation is getting technology to market more quickly (Böhmer and Lindemann, 2015). Companies experience volatile markets with very short product life cycles due to rapid technological innovation (Aytac and Wu, 2013).

(Schumpeter, 2013, p. 100) describes innovation as a dynamic element and "implementation of new combinations". (Mensch, 1975, pp. 54–58) describes stagnation as a lack of significant innovations. The dynamics of innovation are **result-oriented**, and the process is defined as a black box (Mensch, 1975, p. 37). The term "frontloading" is used to indicate the efforts in the early development phases to assure high quality and stability of the process. With increasing innovation dynamics, a complicated, but stable system becomes complex (Ulrich and Probst, 1991, p. 57). In **turbulent environments** relations are no longer transparent and companies must adapt to continuous change, which is why **corporate dynamics** have been gaining in importance (Ramsauer, 1997, p. 57). (Schuh, 2005, p. 8) outlines internal and external **complexity drivers** ranging from company size, diversification of business area, number of organizational units as well as number of external stakeholders (e.g. suppliers). To handle this complexity, agile methods are used within the innovation process (Link, 2014). Operations are simplified whenever possible, a mindset based on speed and flexibility is promoted and the strategy shifts to "*glocal*" (= think global, act local).

Figure 2-4 illustrates the “fuzzy front end” of the early phase of an innovation process. Innovation projects are characterized by experimental approaches to reduce risk and optimize the innovation potential. With increasing information and knowledge, the impact on an innovation project decreases and the cost for change increases rapidly. A high number of **prototypes** for the early phase allow gaining knowledge more quickly (Thomke and Reinertsen, 1998). Flexible technologies and a modular product architecture limit the cost of change even in late stages (“smart functional partitioning”). On the **engineering side**, uncertainty is reduced to a technical design problem as the focus of the product development **problem** often lies on the solution process of a **pre-defined problem** (Lorenz, 2008, p. 11).

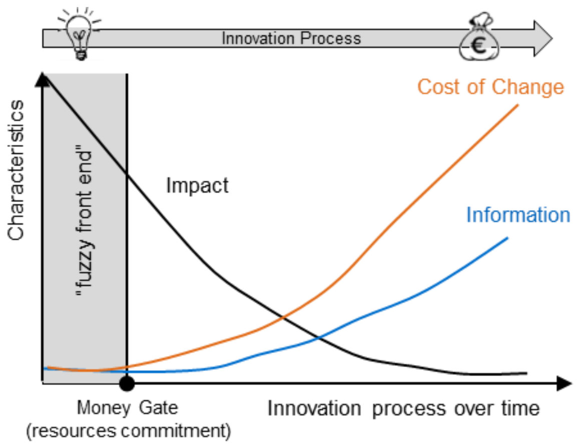

Figure 2-4: Cost of change over innovation process (Herstatt and Verworn, 2007, p. 114).

Innovations embedded in the company, require new requirements for **transversal communication** between all participants from different disciplines, engineering activity and cultures (Gürtler and Lindemann, 2016, 484,486). Cross-departmental collaboration and an “error culture” that positively deals with failures, are essential to develop innovations. The motivation and granted freedom of the employees are a central success factor for innovations.

2.3 Collaborative Innovation

“The greatest danger in times of turbulence is not the turbulence. It is to act with yesterday`s logic.” –P. F. Drucker

Shorter innovation cycles involve a lower market penetration and the need for companies to innovate more frequently. **Digital technologies** lower the barriers for startups and increase the metabolism of the economy. Globalization is entering a new era, defined by flows of data and information, increasing the rate of innovation, “being a function of the number of people connected and exchanging ideas." (Singularity, 2014). An **innovation culture** must prevail in companies as the basis for ensuring their continuing existence by fostering the constant creation of innovations (Gassmann and Sutter, 2013, p. 1). Only 10 percent of all development projects lead to sustainable success, and past success leads to a lack of changeability (Wildemann, 2004, p. 383). The development of **future-oriented products** must remain a top priority, and the **customer factor** continues to gain in importance.

Innovations cannot be planned in a deterministic way, luck and coincidence are a constant companion for innovations (Gassmann and Sutter, 2013, p. 2). For certain types of innovations there is always an associated risk and high costs (Wedeniwski, 2015, p. 113). Incremental innovations, for example, are less risky than the focus on disruptive innovation (Gassmann and Sutter, 2013, p. 9). Innovation management instruments and innovation processes try to focus on promising innovations. Companies can choose between three different strategies with regard to innovation. On the one hand, the goal can be pursued as a **pioneer** in the market by entering the market first with an innovative idea. In this way, a high level of innovation can be built, and higher prices can be demanded. But pioneers are also at greater risk and have higher development and marketing costs (Jones and Bouncken, 2008, p. 815). Alternatively, the role of an **early follower** or a **late imitator** may be appropriate. Innovations are optimized and brought onto the market with less risk and lower costs, because the pioneer's inputs are profitable and the market can be reliably estimated (Wentz, 2008, p. 68). On the importance of the pioneering attitude opinions diverge strongly in the literature. While (Cooper, 2011, p. 304) emphasizes that **speed** is everything, (Gassmann and Sutter, 2013, p. 57) are convinced that in most industries it is not worthwhile to act as market pioneers. They attribute much greater chances of success to the "early follower".

According to (Cross, 2012), companies usually operate in a culture driven towards efficiency rather than creativity. As companies get bigger things slow down, and they lose the ability to take risks, because they have so many systems, structures and processes. Established companies are successful in specialized market segments and with incremental innovations, while startups and small businesses have better capabilities to capture a new market in a minimum of time (Christensen, 1997). A survey of 1245 European companies conducted by Forbes in 2011 reveals the **key barriers** that prevent the implementation of corporate ideas in the company (Forbes, 2011). Figure 2-5 shows that the main barriers are internal. For entrepreneurial projects, the main barriers are a lack of resources to implement and pursue the project. Two

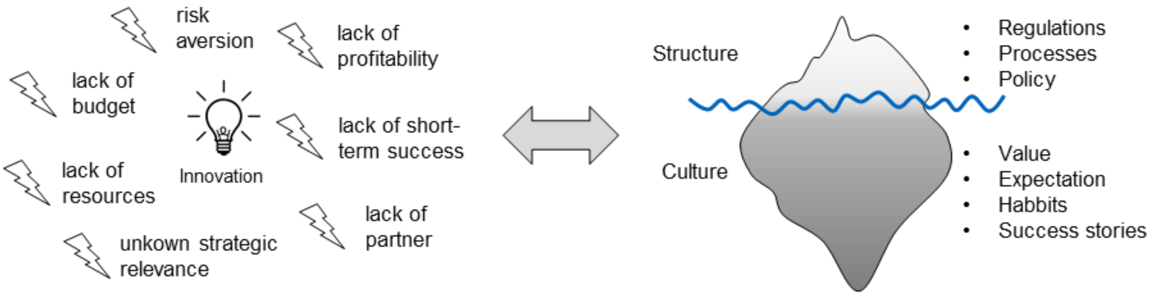

Figure 2-5: Reasons why innovations are not implemented, based on the organizational iceberg (according to (French and Bell, 1994; Rüegg-Stürm, 2005; Engelen et al., 2015, p. 24; Forbes, 2011).

barriers are of immediate top management relevance: risk-averse top management blocks corporate activities because they do not lead to profits fast enough or no potential for profits is seen at all. Other internal barriers are missing resources (e.g. partners or expertise), lack of cooperation of other divisions, existing internal rules or unknown alignment with corporate strategy. (Engelen *et al.*, 2015, p. 24)

Because of maturing technologies and aging product portfolios, companies must create, develop, and sustain innovative new businesses. However, creating new businesses is challenging after years of **downsizing** and **cost cutting** their way to success. Companies must grow rapidly by partnering with startups and look in two directions at once: exploitation of existing and exploration of the new. However, most **corporate entrepreneurship** activities face various barriers, and research shows that most of them fail. Independent innovation hubs rarely work for well-established systems, processes, and cultures.

The financial contracting, the technology and the organizational structure are the key characteristics of an **innovative startup**. The difference between an innovative startup and a large sophisticated corporation is based on internal financing and giving its employees low incentives in terms of organizational structure. The added value of (Gilson, 2010) "Innovative Plane" is to demonstrate the **gap** between innovative **startups** that pursue disruptive innovation and large established **companies** (see Figure 2-6). This gap cannot be easily overcome, since organizational structures and financial resources within the company have been established for a reason. Since startups can establish niche markets with low competition from established corporations, there has been an innovation boom of startups. (Bruse, 2016)

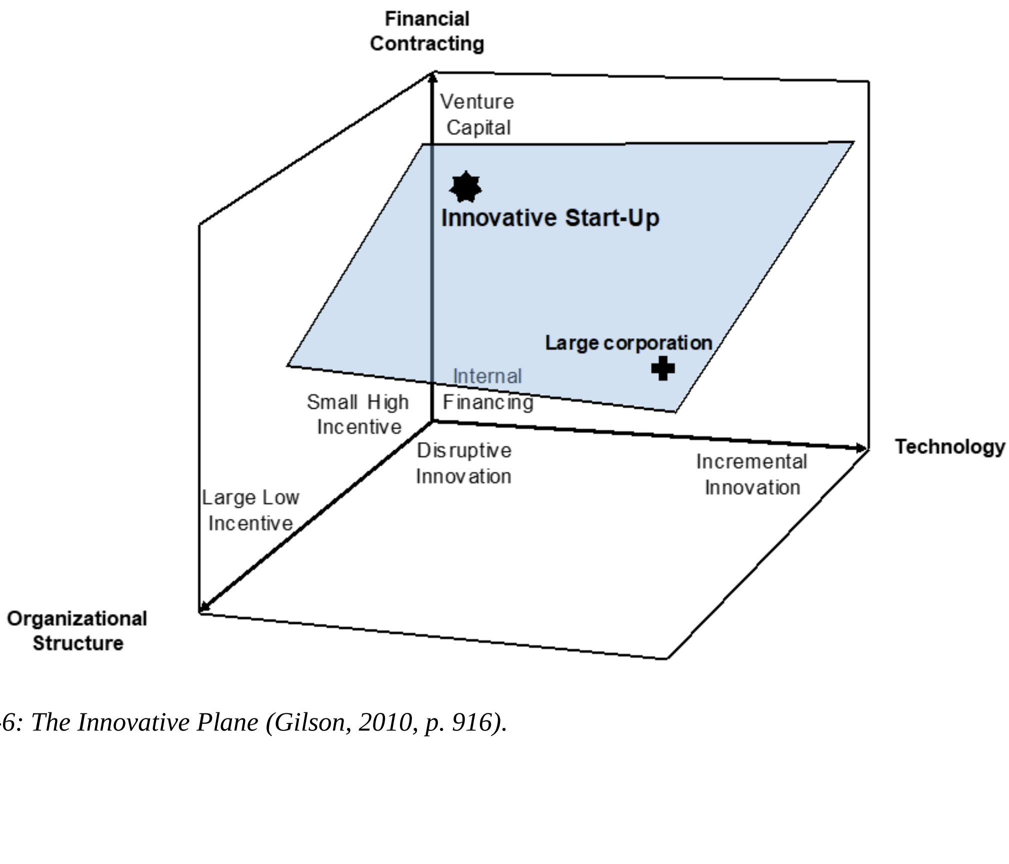

Figure 2-6: The Innovative Plane (Gilson, 2010, p. 916).

Despite the controversies, startups and established companies also work together on a regular basis. There are many examples highlighting existing models of cooperation and answering the question of how startups and established companies work together. The **relationship** of **startups** and **companies** is often referred to as "collaborative arrangements", "strategic alliances" or "coalitions" (Nieto and Santamaría, 2010). (Freeman and Engel, 2007, p. 94) describes corporate innovation in two ways: the “Corporate Model” and the “Entrepreneurship Model”. The **corporate model** is characterized by internal frictions that hinder innovation transfer and slow down dynamic resource allocation. Corporations try to separate the creative process from the commercialization process, by having the innovation take place in remote locations (e.g. Xerox Palo Alto Research Center). The **entrepreneurial model** represents the acquisition of innovative entrepreneurial startups (Freeman and Engel, 2007, p. 94). The characteristics of startups and corporates are completely opposed and differ in success factors or personality structures of managers, for example (Schoss, 2013, p. 57). Susanne Klatten, shareholder and chairman of the supervisory board of UnternehmerTUM GmbH, explains that cooperation is not always easy:

“The cooperation of startups and established companies strengthens the economic power and competitiveness of our country. But before a successful cooperation, there are usually a lot of hurdles. [...]” (UnternehmerTUM GmbH and Wissensfabrik – Unternehmen für Deutschland e.V., 2014, p. 2).

2.4 Makerspaces and Prototyping Activities

With the rise of "FabLabs", "TechShops" and other "Makerspaces", inventors, entrepreneurs and creative people have easy access to **high-tech** physical **workshops** to quickly realize product ideas. The term "Maker" describes individuals or groups that create objects as part of a do-it-yourself (DIY) culture (Ramsauer and Friessnig, 2016, p. 44). The "Maker Movement" is characterized by taking place in a collaborative and flexible environment whose supply does not need to be scaled given the existing type of demand (Lang, 2013). The reduction of the costs due to the increased availability of software (e.g. Autodesk tools) and affordable access to computer hardware (e.g. Arduino) have also prompted the higher sophistication of the DIY communities, cultures and projects (Kuznetsov and Paulos, 2010). The movement has sparked the formation of online communities that have become **learning platforms**. “Instructables[8] ®”, for example, founded in 2005 by MIT Media Lab graduates Eric Wilhelm and Saul Griffith provides instructions for DIY projects. “Shapeways[9] ®” assists Makers during the design and production, leaving the outsourcing of processes to others and connects Makers in networks.

The Maker Movement is also becoming increasingly important in industry. Company-owned incubators, accelerator programs, innovation rooms, creation centers, FabLabs, co-working spaces or academies are springing up all over the place. The increased innovation dynamic requires cooperation with agile partners. Future R&D practices are no longer taking place only internally but become more **open** and **collaborative**. The access to **Makerspaces**, allows

[8] https://www.instructables.com/about/

[9] https://www.shapeways.com/about

employees to test and implement ideas alongside conducting daily business and to communicate across-department silos or -company boundaries. Several examples, such as Microsoft “Building 87”, Amazon “Lab126” or Airbus’ “ProtoSpace” are facilities that provide a special environment and tools to develop disruptive concepts, and thereby, accelerate the pace of innovation.

Prototyping itself is the key activity of product development in the design process (Chua *et al.*, 2010, p. 5; Ulrich and Eppinger, 2016, pp. 296–299). Researchers like (Hartmann, 2009, p. 6) and (Berglund and Leifer, 2013, 2, 5, 12) recognized the supportive role of prototyping in the development of products the **cognitive benefits** of prototyping reasoning, for instance that “*the construction of concrete artifacts – prototyping - can be an important cognitive strategy to successfully reason about a design problem and its solution space*”. (Houde and Hill, 1997, p. 379) argue that, with a clear purpose for each prototype in the design process, designers can make better decisions about the kinds of prototypes to build. (Kayser, 2017, p. 12)

Both “agile” and “innovation**”** are based on the **act of learning** and on adopting the current approach of implementation. New ideas are worked out first to open the solution space. The concept of “agile” is a **thought-provoking** approach using iterative techniques for ad hoc ideation teams to become better during development. The emphasis is on “solving the problem” by getting continuous customer and quality feedback rather than “following the plan” (Douglass, 2016a, p. 44). Prototyping activities facilitate a common understanding in the development team and allows an intensive cooperation with internal and / or external partners (Gürtler and Lindemann, 2016, p. 491). Agile methods rely on an **evidence-based approach** rather than a theory (plan)-based approach. Fast prototyping and simple orientation tests help to gain insight early and often. Results are not predictable in detail, but a responsible team agrees on common evaluation criteria for each shortly clocked work package.

The biggest obstacle for applying agile methods to systems engineering is that the outcome of software engineering is **implementation** but the outcome of systems engineering is a **system** (Douglass, 2016a, p. 44). In engineering design, there are three aspects for system evaluation: design concepts (Lim *et al.*, 2008), prototypes (Yang, 2005; Neeley *et al.*, 2014), and final products (Boothroyd, 1994). (Menold *et al.*, 2016, p. 87) defines **three perspectives** of a successful product to be verified: minimum desirable, feasible, and viable product. **Startups** only have access to limited resources, and therefore, have a short and less cost-intensive, but assumption-based development process. Startups launch products successfully and more quickly by adopting a combination of business-hypothesis-driven experimentation, iterative product releases, and validated learning (Ries, 2011, p. 20).

“Agile” verifies the work products as they are being created, providing immediate feedback as to correctness of the work product, and on how well the engineering goals are achieved (Douglass, 2016a, p. 42). For innovation, the outcome of a project in terms of innovativeness is dependent on the **customer**. The first **prototype** serves as a basis to be improved. The customer acts as a reviewer to check whether the hypotheses are false or correct. Early prototyping and ongoing requirement reviews are an implicit risk management or rather risk insurance. Thus, agile approaches perform **quality assurance** activities throughout product development and **optimize defect avoidance** rather than defect identification (Douglass, 2016a, p. 42).

3. State of the Art and Research

This chapter outlines the state of the art and research, relevant for the objectives of this work. First, aspects of innovation management are elaborated. Different innovation types and strategies to increase flexibility and speed in innovation processes are examined. Second, agile basics in software development and project management are exemplified for physical products. Third, systems architecting and the effect of digitization for mechatronic systems is outlined. Changeable architectures and correlating development strategies are introduced to deal with uncertainty in the context of mechatronic systems.

3.1 Key Aspects in Innovation Management

Innovation is a precondition for the success of companies in today's markets and involves a complex interplay of various influencing factors. Different innovation types and strategies result in different innovation capabilities. Innovation management balances chaos and structure for successful innovation projects. In innovation research, innovation process models transform towards highly interconnected innovation ecosystems that boost the innovation capability of their community. Flexibility and speed within the innovation process is gaining in importance, as different speeds of innovation bring up new challenges for the lifecycle of a product. For startups, prototyping is central evaluating early versions of a product and to being responsive and adaptive to change.

3.1.1 Innovation Types and Strategies

There are numerous definitions for the term "innovation", all of which contain the element of ”novelty” (Dzedek, 2009, p. 9; Trott, 2010, p. 20). Inventions become innovations when successfully introduced to a new market by developing a product or service iteratively (Wentz, 2008, p. 12). (Szinovatz and Müller, 2014, p. 95; Ehrlenspiel and Meerkamm, 2013, p. 371) formulate the concept of innovation as follows:

$$Innovation = Problem + Idea + Implementation + Market\ Penetration \qquad (3.1)$$

An innovation is the implementation of an idea that solves a customer problem and has managed to penetrate the market. One can distinguish the scope, the subject, the degree of novelty, as well as the relationship to user needs, technologies and the market impact (see Figure 3-1).

The **scope of innovation** is differentiated according to product, process, business model and organizational innovation (Dzedek, 2009, p. 6; Gürtler and Lindemann, 2016, p. 483). Product innovations refer to new or improved material and immaterial (e.g., services) products (Dzedek, 2009, p. 6; Trott, 2010, p. 16). Process innovations are new or improved production processes and include changes in the equipment and technology used in manufacturing (Dzedek, 2009, p. 6). They have the goal of optimizing factors such as costs, time, security and quality in the company (Trott, 2010, p. 20). Business model innovations are structural innovations. These are improved organizational forms and structures (Dzedek, 2009, p. 6). They combine the product portfolio with customer interfaces and the company's infrastructure

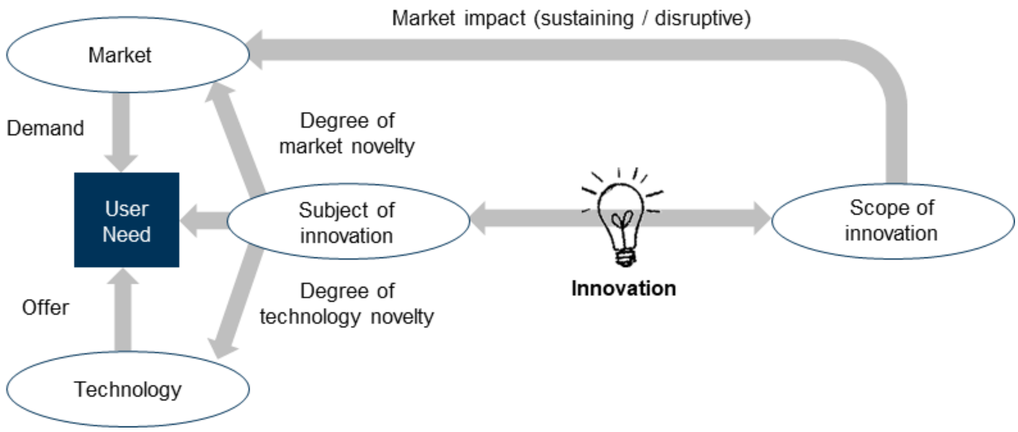

Figure 3-1: Innovation and strategic classification (Kosiol, 2016, p. 14; Gausemeier and Plass, 2014, p. 172).

(Wentz, 2008, p. 16). Organizational innovations or social innovations represent new or changed social relationships within the company (Dzedek, 2009, p. 6).

The **subject of an innovation** differentiates the degree of novelty of an innovation (Stadler, 2016, p. 19 ff.). "New to the world" innovations are those which have never been known before. "New to the industry" innovations are already common in other areas, but newly introduced into a specific industry. "New to the company" innovation is already known in their own industry, but new to the company itself. The relationship between market, technology and novelty of innovation defines certain types of innovation. A **market innovation** describes the development of a new market (Gausemeier and Plass, 2014, p. 172). These "niche innovations" are usually made possible by small technological improvements (Schneider, 2012, p. 30). **Technological innovation** is also referred to as **revolutionary innovations** and relates to the change of an existing market by a new or improved technology (Schneider, 2012, p. 29; Trott, 2010, p. 22). **Incremental innovations** describe small, **evolutionary** changes to existing products, systems or business models and lead to small, continuous improvements (Trott, 2010, p. 7). They only change existing markets by the development of new product generations, for example (Schneider, 2012, p. 29; Gürtler and Lindemann, 2016, p. 484; Gorbea Díaz, 2011, p. 23). **Radical innovations** are major advances and result in significant, complex changes in a company (Gürtler and Lindemann, 2016, p. 484). They include the creation of new markets as well as major leaps in technology development, creating products or processes that have not existed before (Schneider, 2012, p. 30; Gorbea Díaz, 2011, p. 23).

All innovations are based on **user needs**, which are addressed by an innovation. A distinction can be made between the occasion for the emergence of innovation and its trigger. Need-induced innovations arise in response to external events. They are also referred to as "pull" innovations because they are caused by the demand of the customers (Dzedek, 2009, p. 6). Supply-led innovations are usually based on new technologies. They are referred to as "push" innovations because the company "pushes" them onto the market (Dzedek, 2009, p. 6).

The **market impact** of an innovation distinguishes between sustaining and disruptive innovations. **Sustaining innovations** defend the market position and are supposed to maintain the competitiveness of an already existing offering (Schneider, 2012, p. 32). **Disruptive innovations** are often enabled by new technologies and mostly assigned to startups

(Christensen, 1997, p. 4). Established markets are disrupted by more affordable, simpler, smaller or more comfortable solutions (Schneider, 2012, p. 32).

(Qumer and Henderson-Sellers, 2008) describe an innovation framework that considers the product as a **system of components**. The product knowledge is represented by the design core concepts and structure of components linked together that achieve the core concepts (Gorbea Díaz, 2011, pp. 23–24). Figure 3-2 illustrates the innovation typology of (Henderson and Clark, 1990) for a total vehicle architecture broken down into sub-systems and then further into parts. Architectural innovation affects the overall **systems architecture** and requires a re-linking of functions, components and their configuration (Gorbea Díaz, 2011, p. 24). Incremental innovations address **sub-systems** that increase product performance through the incorporation of new technologies. Modular and radical innovation relates to the **sub-component level** and technological innovations, where the linkages between core concepts and components remain unchanged.

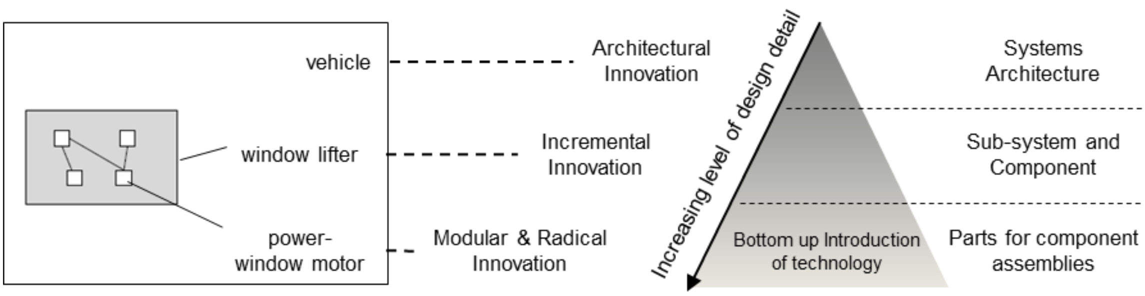

Figure 3-2: Innovation typology framework on systems level, adapted from (Gorbea Díaz, 2011, p. 24).

3.1.2 Innovation Capabilities and Startup Cooperations

Successful innovations are the result of a complex interplay of various influencing factors of the company and the employees involved. An individual’s performance is related to the ability in terms of motivation, knowledge and resource. (Cooper, 2011, p. 6) explains the **success factors of innovations** with an innovation diamond (see Figure 3-3). Three characteristics foster a successful innovation process. First, many innovations fail because the customer needs are not adequately considered (**market input**). A successful innovation process is recursive and is characterized by numerous fractures (Trott, 2010, 20, 35; Wentz, 2008, p. 105). Second, decisions about which projects to continue ("go"), which to "kill" and which to suspend ("shelve") must be made at the right time (**clear decision-making)**. Resources are allocated dynamically on the most promising projects (Wentz, 2008, p. 105). Third, established companies face a cultural conflict between routine and innovation. (Wentz, 2008, p. 195) emphasizes the importance of a balance between chaos and structure for successful innovation management (**innovative culture**). (Gürtler and Lindemann, 2016, p. 486) describe the skills and the willingness of employees as the main factors for successful innovation projects.

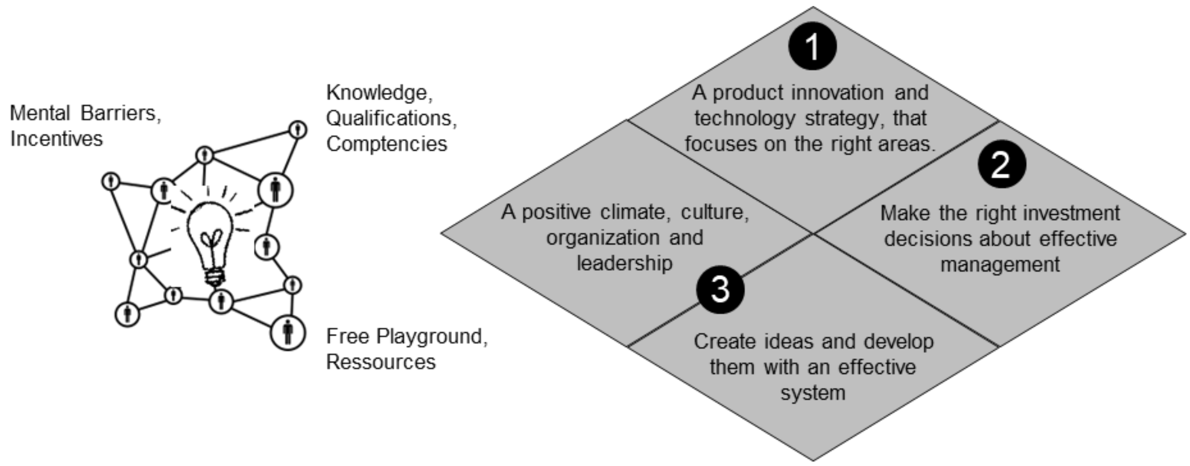

Figure 3-3: Four innovation vectors for successful innovations (based on (Gürtler and Lindemann, 2016, p. 486; Cooper, 2011, p. 6)).

Innovation potential is the assessment of the projected success of an innovation activity. **Innovative ability** describes to what extent a company is capable of developing innovative products and processes and how it adapts to the dynamic conditions (Lindemann and Baumberger, 2004; Link, 2014, p. 69). Figure 3-4 illustrates an innovation dynamics portfolio for an innovation object (e.g. car). The **degree of innovation** refers to the novelty of an innovation in a spectrum from continuous to discontinuous or from evolutionary to revolutionary (Ramsauer, 1997, p. 66). (Wentz, 2008, p. 17) emphasizes that the market's view is crucial for the assessment of the degree of innovation. If something is merely new to the company the innovation causes corporate dynamics but does not address specific user needs.

Innovation opportunities vary in the extent to which they support the strategic orientation of a company. (Terwiesch and Ulrich, 2009) categorizes the various types of innovation into two dimensions of uncertainty (see Figure 3-4, right). **Technological uncertainty** describes the ability to execute with technology that which is available in or outside the company or that which must be discovered. **Market uncertainty** describes the ability to understand and address the needs of the users. For opportunities addressing the current customer base, the market

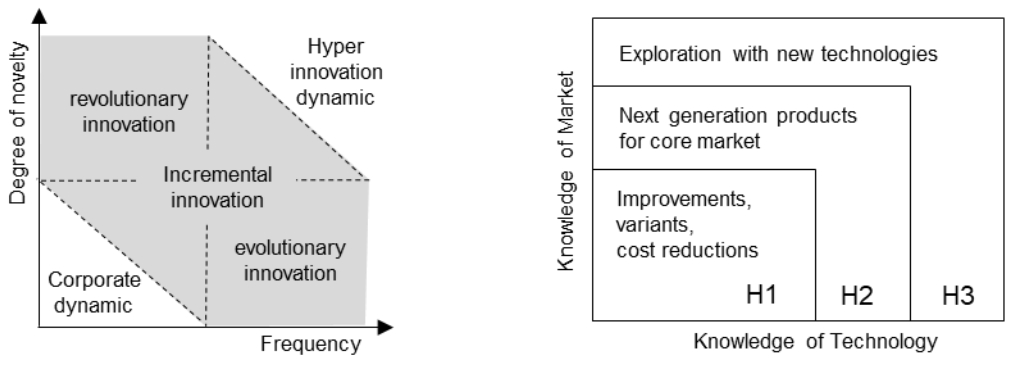

Figure 3-4: lnnovation dynamic portfolio according to (Ramsauer, 1997, p. 66); Horizon analogy according to (Terwiesch and Ulrich, 2009).

uncertainty is low. Market segments beyond the current business model that are either served by competitors or unexploited are of high uncertainty. The terms “Horizon 1”, “Horizon 2”, and “Horizon 3” characterize the increasing risk that a company faces in pursuing the innovation opportunity. (Terwiesch and Ulrich, 2009)

Successful innovation strategy aims for both **exploitation** of existing markets and the **exploration** of new capabilities or technologies. A distinction is made between structural and contextual ambidexterity (Engelen *et al.*, 2015, pp. 131–132). For **structural ambidexterity** exploitation and exploration activities are performed in separate departments or teams. Decisions on division between alignment and adjustment are made top down. **Contextual ambidexterity** promotes bottom-up initiatives, as individual employees arrange their time between exploitation and exploration.

Disruptive innovations of **new competitors** are increasing and changing the industry's competitive landscape (Poguntke, 2014, p. 6 ff.). **Digitization** and the “Internet of Things” provide a variety of **information** that must be systematically analyzed and evaluated. Innovation shifts from product- to service-oriented, and involves new business models that make use of the corporates’ unique strengths (Ang, 2012). (Wentz, 2008, p. 6 ff.) points out that the **pressure to accelerate** will increase in the future, due to greater **transparency** of innovations due to globalization. The accelerated technical progress and the associated, faster dissemination and imitation of innovations result in changing user behavior. Customers are constantly offered new products, also leading to higher expectations. With decreasing cost of innovation and lower barriers to enter, large companies face an increasing short-term pressure for innovation. Large corporates are taking a page from **agile startup strategy** and are embracing less hierarchical management structures. Intrapreneurship programs, like Daimler “Lab1886”, Bosch “grow” or BMW “Innovationswerk Accelerator” attract internal talents and grant access to a worldwide innovation network. Employees learn about entrepreneurial behaviors and how to combine them with existing capabilities.

Internal startups or incubators are both bottom-up or top-down initiatives. **Secret projects** represent bottom-up development projects that are carried out without the knowledge of corporate. As with startups, most of these projects fail, but the few that succeed have a great innovation potential (e.g. BMW 3 Series Touring) (Gürtler and Lindemann, 2016, p. 499). The top-down development of the BMW i3 started independently from the core business. The geographic and organizational independency was an essential success factor for development. With increasing product maturity, the independent working team becomes involved with the core business, thereby benefiting from the influence of top managers. (Gürtler and Lindemann, 2016, p. 499)

(Baltes and Selig, 2017, p. 81 ff.) distinguish three approaches that increase **innovation capability** and corporate agility: Intrapreneurship, Corporate Entrepreneurship and Open Innovation. Intrapreneurship programs address individuals and small teams, whereas Corporate Entrepreneurship is characterized by organized units acting independently from core business (e.g. BMW i Venture) and that can involve external partners in a joint venture (e.g. Drive Now). Open Innovation aim for cooperation with startups and are influenced by Makerspaces, as well as external Incubators (e.g. Telekom hub:raum) and Accelerators (e.g. Global Merck Accelerator). For further information, see (Baltes and Freyth, 2017).

Successful commercialization of an innovation requires **complementary assets**, such as manufacturing or distribution. (Teece *et al.*, 1997) distinguish three complementary assets, depending on the innovation they enable: Generic, Specialized, Cospecialized. A breakthrough insight of this model, supported by empiric evidence in different industries, is that an innovator may not always be in position to capture the profit from the invention (Urquidi Guerrero, 2016, p. 30). (Anthony, 2012) argues that established businesses have some competitive advantages over startups in terms of **entrepreneurial activities**. Large corporates already have a global infrastructure, a brand-image and efficient processes that ensure high quality. Corporates have all necessary complementary assets in-house and benefit from increasing the return of existing knowledge / asset (production efficiency, standardization, routinization and systematic cost reduction) (Engelen *et al.*, 2015, pp. 15–16). A startup usually has less capital, fewer experts, less brand presence, and incomplete business processes (Freeman and Engel, 2007, p. 94). They often lack the time and/or capital to build up the necessary complementary assets. For a brief overview of dis/advantages from startups and corporates, see Appendix A2.

Established companies that have been on the market for many years, have developed organizational structures around a successful business model (Schoss, 2013, p. 59). "*These large dinosaurs are decoupled from the customers, often only deal with themselves and feel little changeability*" (Grichnik and Gassmann, 2013, XI). (Schoss, 2013, p. 55) summarizes a “standard” being a success factor for established companies as follows:

- Management focus on the improvement of the existing
- Own a clear vision of future developments
- Accurate planning
- Managers must implement with great efficiency
- Employees must comply with all rules and perform their duties in the day-to-day business
- Potential losses: customers, reputation, profit, total value
- Aim of the leadership: Preserving company strengths and defending market position
- Standardization of processes
- Optimization of details
- Systematization of competitive advantages

These standards are basic prerequisites to achieve long-term success. The company's goal is to **preserve the strengths** of the company and to defend its position in the market (Schoss, 2013, p. 55). **Corporate culture** develops over the years and leaves little room for traceability (Molina, 2015, p. 229). To achieve the above standards, managers pursue a strategy and try to control the risks (Voigt *et al.*, 2005, pp. 16–17). Managers of large companies plan and control the business processes resource-based. The **short-term** and **medium-term** personal success is not necessarily aligned to the company success, as the career path most often has highest priority (Voigt *et al.*, 2005, p. 17; Schoss, 2013, p. 59).

Cooperation’s between startups and large companies are classified with different approaches, perspectives and intentions. (Scherer, 2015, p. 17 ff.) outlines different **cooperation models**, ranging from learning or license agreements, market transaction to various forms of ventures (e.g. joint venture, venture capital or corporate venture capital). The classification differs when changing the perspective of large companies to the perspective of startups. (Owens and Fernandez, 2014, p. 28) outlines three major forms of startup cooperation: Invest, Acquire, Incubate. (Callaway and Hamilton, 2006) classification refers to the pursuit of **disruptive innovation**. The approach of (Pisano and Verganti, 2008) is far more detailed. It refers to the pursuit of **innovation in general** where the entity of the cooperation partner is not limited to startups alone. The classification of (Weiblen and Chesbrough, 2015) refers to the **collaboration** of corporations and startups **exclusively**. The reasons for the company to engage with startups are to gain speed, promote general innovativeness, seek growth potential, enlargement of the company's network, increase gathering of information and receive tangible benefits. (Ferrary, 2003) classification involves a clear **disruptive innovation** strategy. It deepens the connection between the corporation and the startup, and is limited to the cooperation type of "Corporate Venture Capital". (Bruse, 2016)

The primary question for corporations is the goal to achieve with an engagement. Table 3-1 illustrates four main categories in terms of **equity involvement** (vertical) and direction of **innovation flow** (horizontal). Outside-in innovation is fostering entrepreneurial creativity. Inside-out innovation utilize the startup agility to push a company`s own innovations onto the market. Both strategies try to transform the clash of cultures into a **blend of cultures**. (Szopinska, 2015, p. 90 ff.)

Table 3-1: Typology of corporate engagement models with startups, adapted from (Weiblen and Chesbrough, 2015, p. 81).

	Outside-In	**Inside-Out**
Equity Involvement	**Corporate Venturing** Participation in external innovations Strategic insight into new business areas	**Corporate Incubation** "New" topics Startup environment Independent path to market „Basic-rule“ company
No Equity Involvement	**Startup Program** Insourcing of external innovations Stimulate and generate innovation	**Startup Program (Platform)** Driving external innovations Push existing corporate innovation (= platform)

If a (competence destroying) innovation needs **specialized complementary assets**, incumbents are better positioned (Urquidi Guerrero, 2016, p. 23). New entrants might have a game-changing technology, but they might not have the necessary complementary assets for its commercialization. Collaboration between new entrant and incumbent in the presented setting is profitable for both parties: New entrants can bring their invention to market and established firms can enter the new field (Mitchell, 1989, p. 208 ff.). Concluding, performance of the industry for incumbents gets better if the needed assets are specialized.

Individual firms can differ substantially in terms of their **specific capabilities**. (Rothaermel and Hill, 2005) identified the financial capabilities of a firm together with its R&D strength to be the most important factors in the event of a technological discontinuity. According to (Teece *et al.*, 1997), financial and R&D strength belong to **dynamic capabilities**. These are company abilities to "*integrate, build, and reconfigure internal and external competences to address rapidly changing environments*" (Teece *et al.*, 1997, p. 516). A new entrant possessing a technology that threatens incumbents in the form of a technological discontinuity, the financial strength of the incumbent plays a decisive role. Strong R&D capabilities are more valuable if a new technology needs from specialized assets for its commercialization (Urquidi Guerrero, 2016, pp. 22–23).

3.1.3 From Innovation Process to Open Innovation Ecosystem

Innovation is a dynamic process and there are many factors influencing the development, such as market and environmental changes, technological changes and changing customer requirements (Dzedek, 2009, p. 63; Eller, 2016, p. 8). Innovation processes standardize development activities depending on the intention of the practitioner or researcher (Verworn and Herstatt, 2000, p. 1). The literature classifies innovation process models into three groups: linear models, iterative models, and process models for radical innovations (Lehnhardt, 2015, p. 14). **Linear models** describe the innovation process as a sequential flow of development activities, with either more or less overlap up to parallelization (Bertram, 2011, p. 32). In recent years, it has been shown that a certain degree of flexibility in the processes is of great benefit (Verworn and Herstatt, 2000, p. 11). Strictly sequential processes often imply feedback loops between the ideal-type-separated phases (Gleich *et al.*, 2016, p. 352). New **iterative models** with softer overlapping phase transitions are designed, so that are more flexible and “agile” (Verworn and Herstatt, 2000, p. 11; Link, 2014, p. 71). These models promote feedback loops and repetitive process steps. The adaptation to changing knowledge is fostered, but limited to the predefined process steps (Bertram, 2011, p. 38). **Radical innovation** models are characterized by great uncertainty and have a strong focus on customer integration (Szinovatz and Müller, 2014, p. 93). The early phases of the innovation process facilitate user tests to react to customer feedback rapidly. The late phases often make use of traditional approaches to develop products efficiently and in a controlled manner to create a marketable product (Koen *et al.*, 2016, p. 46 ff.). The most important innovation process models classified into linear, iterative and “radical models” are outlined in Appendix A3.

A major challenge for companies is the complex implementation of **innovations** that are characterized by high **uncertainties** (Gleich *et al.*, 2016, p. 349). (Gleich *et al.*, 2016, p. 349 ff.) distinguishes market, technology, resource and organizational uncertainties. These uncertainties require sufficient **flexibility** in innovation projects and limit planning possibilities (Gürtler and Lindemann, 2016, p. 483). (Lorenz, 2008, p. 38) points out that “Stage-Gate” models support incremental development projects and radical innovations need more flexible approaches. Early products are introduced to pilot markets and modified according to the insights gained. **Iterative experimenting loops** are repeated until the **necessary information** about market and technology is acquired.

New generation of “idea-to-market” processes are designed to overcome some of the deficiencies of the traditional gating model (Cooper, 2015, p. 20). The next-generation Stage-Gate model by (Cooper, 2015) is adaptive and flexible, agile and accelerated. Projects are characterized by frequent experiments, with the evolving product continuously exposed to the user. **Customer integration** has numerous competitive advantages (Trott, 2010, p. 172 ff.):

- **Cost-to-market**: lower actual development costs, as fully attributing to the product
- **Fit-to-market**: Creation of positive market acceptance and greater willingness to pay
- **Time-to-market**: faster market introduction through shorter development times

- **New-to-market**: creating a high degree of innovation perceived by customer

Product specification evolves as customers confirm the product's value proposition through "pretotypes", rapid prototypes, and early beta versions. (Cooper, 2015, p. 28)

Agile models have gained in popularity since 2008, claiming to be more flexible and faster (Komus, 2014). But, even highly iterative models are still limited by "innovation bureaucracy" of too many or inadequate gates (Cross, 2012, p. 79). The early phase of the innovation processes is "blocked" by too many innovation projects that compete for limited resources. The late stages of the innovation process are "empty" due to too strict criteria. Hardly any idea moves to the next level and despite high costs, there are less marketable products in the end (see Figure 3-5). Such **phase-oriented models** are based on the assumption of repeatability, and forecasting. However, it is rarely the case that someone can estimate the potential of an idea. For the "Survival-of-the-Fittest" model by (Szinovatz and Müller, 2014), innovation projects compete for limited resources, and only the most promising survive. There is no "go" or "no-go" criterion for the next stage, but managers invest in projects or adapt project teams to increase the innovation potential. Innovation results add value for the customer, and risk is reduced to an adequate level. The solution space is explored iteratively, and new insights or changes are incorporated by adaption the project. (Szinovatz and Müller, 2014, p. 98)

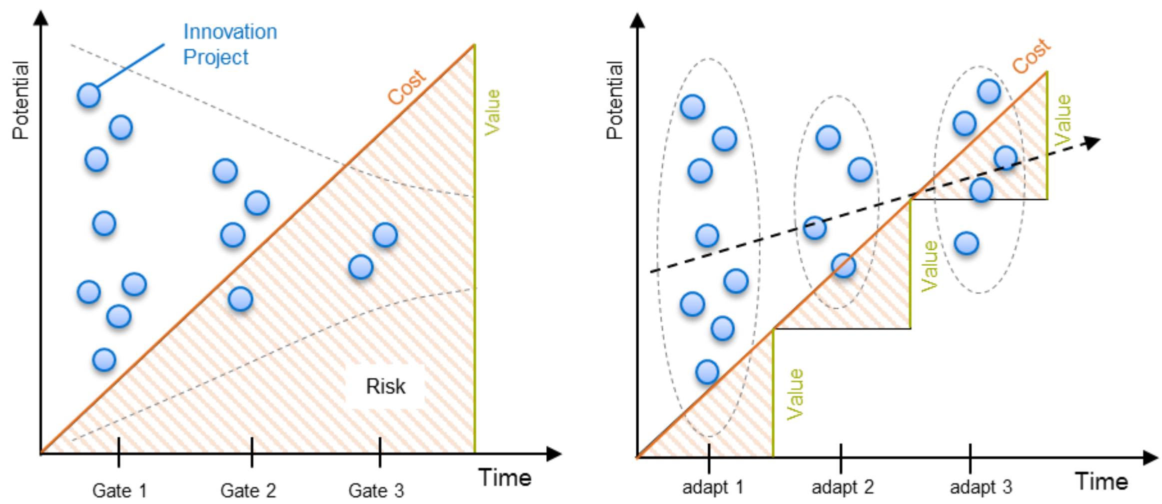

Figure 3-5: Reduction of risk and increase in value for traditional Stage-Gate (left) and Survival-of-the-Fittest (right), adapted from (Szinovatz and Müller, 2014, p. 111).

Open Innovation Paradigm

Taking external factors involving innovation processes into account, networks of different stakeholders are developed. The interaction between the participants in networks - including the consumers - opens new sources of knowledge about needs and solutions and increases the innovative capacity of a company (Gürtler and Lindemann, 2016, p. 486). (Chesbrough and Bogers, 2014, p. 3 ff.) define "Open Innovation" in terms of knowledge transfer through a firm's boundary. (Enkel and Dürmüller, 2013) explore the three modes of Open Innovation in detail: outside-in, inside-out and coupled (see Figure 3-6). The **outside-in** process is the integration of external knowledge into the company (e.g. collaboration with suppliers). Characteristic of companies that use this model is also the modular nature of their products. Using the outside-in approach, companies integrate an individual external module into the product, without making major adjustments to the overall architecture. The **inside-out** process is opposite to the outside-in: companies purposely manage knowledge outflows. Proprietary knowledge can leave the companies boundaries as Intellectual Property license, patents, or commercialization of an invention on a different industry (cross-industry commercialization). The inside-out process is used by companies with large R&D spending that generate spill-overs. These spill-overs are exploited via the inside-out process partly to cover the R&D spending. The **coupled process** is characterized by longer relationships between the collaborating entities, and a deeper transfer of knowledge. It takes the form of collaboration between companies, universities, and research institutes. Joint ventures are often the chosen way of formalizing the collaboration. (Urquidi Guerrero, 2016, p. 25 ff.; Enkel and Dürmüller, 2013; Chesbrough, 2003)

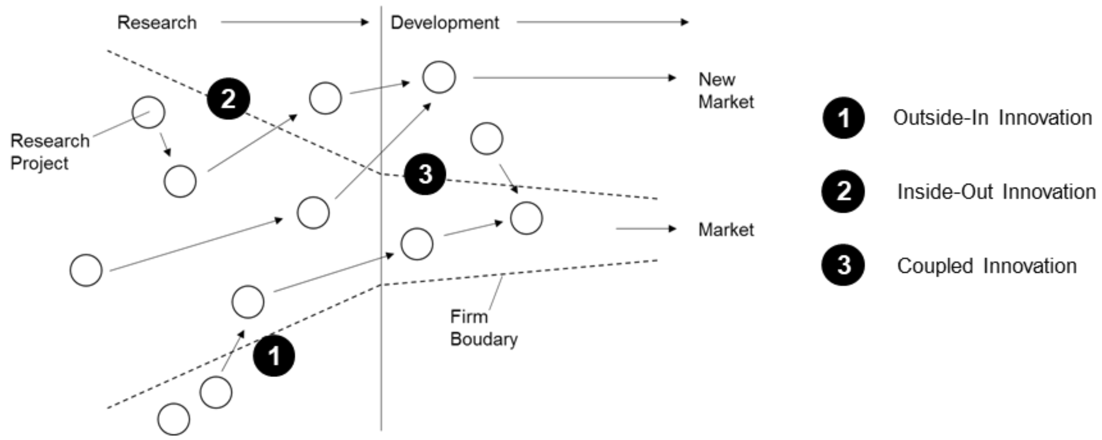

Figure 3-6: The Open Innovation paradigm according to (Chesbrough, 2003, xxv).

According to (Curley and Salmelin, 2017), "Innovation Ecosystems" are part of the so-called Open Innovation 2.0, a new paradigm based on the principles of integrated collaboration / collaboration, co-created value, exponential technologies and exceptionally fast acceptance. A comprehensive literature study on the origin and several definitions of (open) innovation ecosystems is performed by (Kayser, 2015), in order to derive a definition in engineering:

An "Open Innovation Ecosystem" (OIE) is an association of independent stakeholders sharing the same goal, with both stakeholders and individuals networked in a collaborative manner and interacting in either an academic or business environment. The stakeholders and individuals of an OIE aim to actively exchange resources, competencies and skills in close and dynamic collaboration, to complement one another and to satisfy client needs holistically. Stakeholders of an OIE open their innovation processes to achieve complementarity assets. The goal of an

OIE is to address new markets in a very short time, to create added value through innovations. (Kayser, 2015, p. 23)

The best-known example is the **Silicon Valley Ecosystem**, which has pioneered technology and innovation. Silicon Valley has a variety of business organizations and institutions that create a business environment that enables successful creation of startups and disruptive business models (Piscione, 2013). The OIE is characterized by an entrepreneurial, innovative and cooperative culture, innovative large companies and startups, global top-level human resources, business infrastructure, access to risk capital, world-class universities and research facilities (including Xerox Parc) (Gobble, 2014).

The two founders of **Singularity University** (SU), Peter Diamandis and Ray Kurzweil, bring together top thinkers from different disciplines to predict, analyze and create the sciences and technologies of the future (Singularity, 2014). The non-profit educational institution in the heart of Silicon Valley, can build its own innovation ecosystem in an academic environment (see Figure 3-7). The open innovation campus brings together large companies and startups to create new sustainable business solutions[10]. SU has three main approaches for shaping the future: startup programs (or accelerator programs), sharing of business innovation and sufficient funding. SU offers a "TechShop" for rapid prototyping, as a high-tech workshop (or Makerspace) and other high-tech resources (including NASA) (Böhmer and Lindemann, 2015; Singularity, 2014).

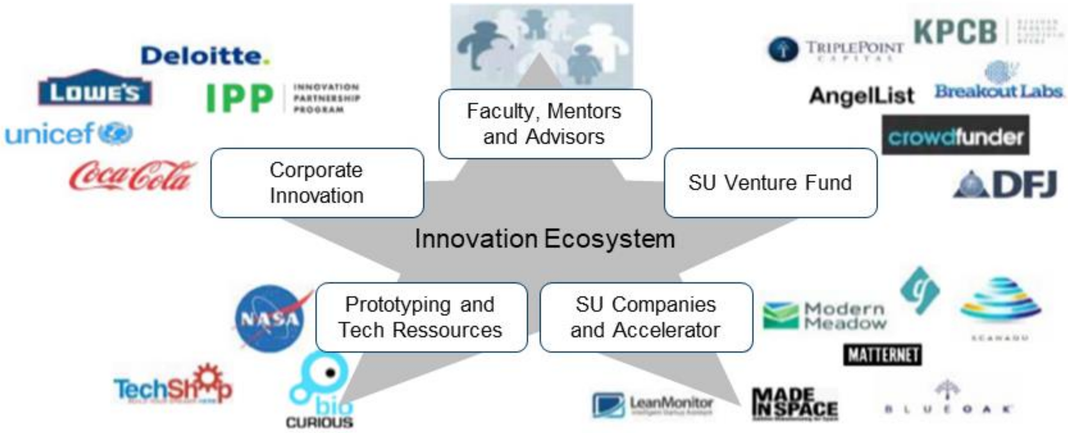

Figure 3-7: Innovation Ecosystem according to Singularity University Labs (Singularity, 2014, p. 59)

3.1.4 Flexibility and Speed within the Design Process

Innovation process models are superficial and do not permit concrete activities (Drescher *et al.*, 2014, p. 1593). (Schömann, 2012, p. 82). The degree of abstraction is often high to cover a broad spectrum, and the focus is on consistent sequences of phases (Klein, 2016, p. 50;

[10] http://singularityu.org/

Graupner, 2010, p. 67). Highly sequential approaches lead to a separation of the customer and the developer. According to (Opelt, 2014, p. 13), the reason for a development ("why") is a crucial piece of information to elaborate innovative solutions. Traditional innovation models are heavy, bureaucratic, slow, and inflexible and do not provide continuous feedback from customers (Link, 2014, p. 76). To develop **innovative products**, knowledge about the product specification must be gathered during the development to adapt the product continuously Although some models claim to serve all disciplines (such as the "V-model"), they offer insufficient support for **interdisciplinary teamwork** and for mechatronic development processes (Diehl, 2008, p. 47 ff.; Hellenbrand, 2013, p. 1).

Digitization promotes a product service system that offers miles per hour, for example. This new scope of a system has inevitably made changes to design criteria, maintenance and a modernization strategy. Different speeds of innovation create new challenges during the development and the lifecycle of a product. On the **product site**, modularization strategies and variant management are approaches to meet new and future requirements. Other approach aims for later retrofit solutions to enhance product performance. The use of predefined interfaces needs additional space or a larger-scale energy supply. Later adaptations of a product have to be carefully assessed to limit the upfront costs to potential future benefits (Schrieverhoff, 2015).

On the **process side**, it is necessary to react to important changes in the sense of "agile" behavior. Over the years, different strategies, characterized by **rapid and early prototyping** have evolved (Gürtler and Lindemann, 2016, p. 491). They base on an act of learning ("Design Thinking"), the avoidance of non-value-added activities ("Lean Development"), the use of different cooperation opportunities ("Open Innovation") and short time periods of working ("Scrum") (Plattner *et al.*, 2015; Moll, 2016; Weiblen and Chesbrough, 2015; Schwaber, 2004). Lean works best in high volume, low variety and predictable environments (e.g. efficiency, cost). Agility is needed in less predictable environments where the demand for variety is high (e.g. responsiveness).

The Design process

The design process is characterized by its iterative nature, including feedback loops, and allows improvements in the design on the basis of a preceding outcome (Dieter and Schmidt, 2013, p. 13; Roozenburg and Eekels, 1995, p. 109). According to (Dieter and Schmidt, 2013, p. 6), "*there is no single universally acclaimed sequence of steps that leads to a workable design*". Designing itself is a special form of problem-solving (Roozenburg and Eekels, 1995, p. 84). (Eggert, 2005, 2, 5) emphasizes that decision-making processes and activities are core to designing, and hence, solving engineering design problems. Engineering design problems are usually ill-structured, ill-defined and open-ended, and have to be set and solved by designers (Eggert, 2005, p. 6).

(Roozenburg and Eekels, 1995, p. 109) argue that a phase model of the design process does not show the problem-solving process, by which solutions for the design problem are generated and refined. Solutions are generated, tested and evaluated in all phases of the design process, where appropriate, by means of working models or prototypes (Roozenburg and Eekels, 1995, p. 109). The problem-solving process can be used at any point in the design process, whether at the conceptual design phase or the design of a component (configuration design) (Roozenburg and Eekels, 1995, p. 83; Dieter and Schmidt, 2013, p. 10).

(Degroot, 1969) was one of the first researchers to introduce a cycle which characterizes the activities of problem-solving. The cycle starts with the observation of the situation in which one acts. Having learned from earlier cycles, a problem solver considers suppositions about actions that might solve the problem as well as expectations about effects of these actions in the problem situation. The problem solver tests the expected effects by comparing them with the desired effect (is the effect good or bad?), and then evaluates the result of his/her thought processes by asking the questions: 'what have I learned?' and 'how can I utilize the experiences gained (in the next cycle)?' (Roozenburg and Eekels, 1995, p. 84 ff.) referring to (Degroot, 1969). (Kayser, 2017, p. 10)

Figure 3-8 shows the thinking (or rather problem-solving) process relevant to this work according to (Dieter and Schmidt, 2013, p. 10) and (Roozenburg and Eekels, 1995, pp. 89, 109). The thinking process can be applied in each phase of the design process and consists of the following six steps: problem definition, gathering information, generation of design concepts, testing and evaluation, decision-making and communication of results. To date, several design methods are being created in engineering design. However, this research work gives priority to systematic learning and a physically oriented design method, according to (Rodenacker, 1966, p. 263 ff.).

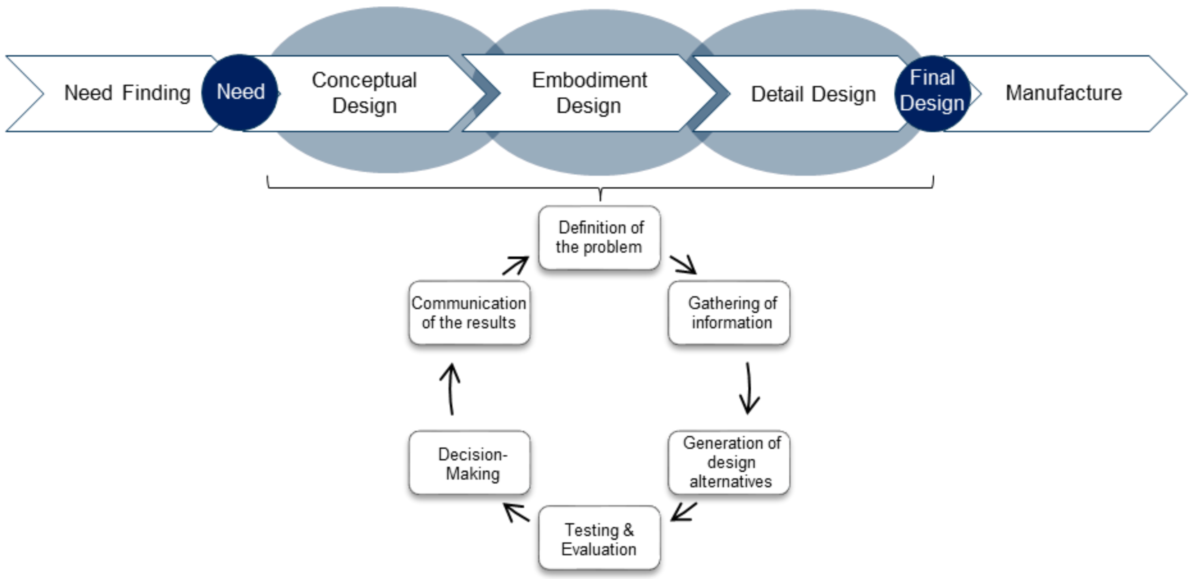

Figure 3-8: Generic (problem-solving) design process model, referring to (Dieter and Schmidt, 2013, p. 10; Roozenburg and Eekels, 1995, pp. 89, 109) following (Kayser, 2017, p. 12).

Makeathon and Makerspaces

(Raatikainen *et al.*, 2013, p. 790) define a "Hackathon" as follows: "*A Hackathon is an event where people in small groups participate in intense prototyping activity for a limited amount* *of time".* (Komssi *et al.*, 2015) note that there is no general definition and that the event usually is held by companies or in cooperation with companies. The term is composed of the words “hack” and “marathon” where people innovate and develop prototypes for only one or a few days (Briscoe and Mulligan, 2014, p. 2). The term "make-a-thon" was used for the first time in 2012 by the design and innovation consultancy IDEO[11] to differentiate it from the concept of the Hackathon. Differences exist in the participants and the products to be developed. While Hackathons are mainly digital software developers and designers, a make-a-thon brings together people from a variety of disciplines, including product designers and architects (Zhang, 2012). In general, the results indicate that such intense events are a promising new approach in engineering, where speed of development is becoming essential. (Beckmann, 2015, p. 39)

The following values and principles are derived from the literature referring to Hackathons or rather Makeathons (Briscoe and Mulligan, 2014, p. 10; Komssi *et al.*, 2015; Raatikainen *et al.*, 2013, 797, 799):

- Create cross-functional and multidisciplinary teams
- Motivated participants and appropriate ideas are required
- Do not deal with everyday tasks during a Hackathon
- Do not organize Hackathons too often, so that they do not become routine
- The events are result-oriented
- Learning and trying new things are important elements
- Failures are valuable
- Have fun

By working with new people and working with new technologies during a Hack-/Makeathon, participants adapt competences and experience a sense of achievement (Komssi *et al.*, 2015). Central aspect of Hackathons and Makeathons are **prototypes** that have only a few functions but are sufficient to prove the concept and value of development.

Makerspaces are (open) high-tech workshops for innovative people, new ideas and do-it-yourself projects (Böhmer *et al.*, 2015). Open innovation, knowledge sharing and peer-to-peer learning in the Makerspace are at the heart of the “Maker ideology” (Böhmer and Lindemann, 2015). According to (Wilczynski, 2015), Makerspaces offer community-oriented spaces or workshops where people come together to collaborate on projects, network, learn from each other, and above all, knowledge and resources. Makerspaces facilitate access to tools and machines such as 3D printers, CNC milling machines, laser cutters, sewing machines, for example, needed for early prototyping activities (Draxler, 2015, p. 25 ff.). The “Maker Community” is an inspiring network of creatives, hobbyists from various disciplines (e.g. mechanical engineers, designers, artists, craftsmen, educators, etc.) setting up an interdisciplinary knowledge pool (Wilczynski, 2015; Ramsauer and Friessnig, 2016, p. 50 ff.).

Makerspaces can be described by different properties or categories (Manas Pont, 2015, p. 42 ff.). They are operated in different environments, e.g. university institutions (academia) or in industry (business). All Makerspaces are accessible to the public but run an organization which

[11] IDEO is a global design company (https://www.ideo.com).

is either "profit-oriented" or "non-profit". Table 3-2 gives an overview of seven exemplary Makerspaces, assigned to the mentioned categories. "MakerSpace" at the Technical University of Munich is a unique open workshop concept in Europe. The high-tech workshop is open both to the students and the general public, and gives startups, engineers, architects, designers and Makers access to machines, tools and software to build prototypes and work in a creative community of "Makers". "TechShop 2.0, LLC" (former TechShop) opened in 2006 in Menlo Park, California, and is an open access high-tech workshop. There are currently eight company-owned locations in the US, with two more in the pipeline[12]. TechShop @ Arizona State University (ASU) is the only example of a TechShop that is not only commercially operated (non-profit) but has also been integrated into an academic environment since 2014. "Fab Lab" is the abbreviation for "fabrication laboratory" and is the result of the MIT Center for Bits and Atoms, which focuses on laboratory research on private manufacturing technologies. Fab Labs aim for democratization of production, by allowing anyone who wants to make something to become a member for a small contribution. (Fastermann, 2014; Kayser, 2015, p. 31)

Table 3-2: Classification of seven exemplary Makerspaces (Forest et al., 2016; Kayser, 2015).

Makerspace / **Characteristic**		MakerSpace @TUM	TechShop[13]	Fab Lab	The Invention Studio @GeorgiaTech	PRL @Stanford	Skylab @DTU	Hobby Shop @MIT
Environment		academic	-	academic	academic	academic	academic	academic
		business	business	business	business	-	business	-
Organization		for-profit	for-profit	-	-	-	-	-
		non-profit	-	non-profit	non-profit	non-profit	non-profit	non-profit

"Invention Studio19" at Georgia Tech, is a good example for how a Makerspace can be successfully implemented within larger communities. The Maker Community is organized by students and undergraduates who build prototypes in the course of a class and for personal projects (Forest *et al.*, 2016). "Product Realization Lab" (PRL) at Stanford University is a Makerspace that is integrated into the university and its curriculum of engineering and design students who use it in their project-based classes. Students learn how to manufacture and design physical prototypes hands-on and how to use different machines and tools (Forest *et al.*, 2016). "Skylab at Denmark Technical University" (DTU) is a special environment for student innovation and entrepreneurship to create a vibrant, experimental space where creativity and entrepreneurial spirit flow[14], enhancing cooperation between students, the business world and other external partners. "Hobby Shop" at MIT focuses on personal projects and hobbies. It fosters the spirit of "learning by doing" by providing tools, training, and assistance to all MIT students, faculty, staff, and alumni interested in turning their ideas into reality[15].

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[12] http://www.techshop.ws/

[13] excluding TechShop @ASU

[14] http://www.skylab.dtu.dk/

[15] https://studentlife.mit.edu/hobbyshop

Makerspaces are community-focused high-tech workshops that promote innovative people and encourage them to meet, socialize, collaborate, and work on new ideas or do-it-yourself projects (Böhmer and Lindemann, 2015, p. 917). The "Maker Movement" is also known as the silent new industrial revolution since the adult playground boosts the innovation capability of its community (Anderson, 2012).

3.1.5 The role of Prototyping

Innovation management is characterized by a strong phase and context orientation. However, the construct of the prototype gains in importance (Vetter, 2011, p. 35). Agile prototyping combines the product and process view to an object-oriented approach to foster an elaborated problem-solution fit (Smith, 2007, xii; Zink *et al.*, 2017, p. 89). Innovation processes are characterized by high uncertainty about the problem and the solution space in the early stages (Link and Lewirck, 2014, p. 5). The creation of prototypes facilitate to validate ideas and to better understand the problem (Link, 2014, p. 65). In physical product development, the potential applications of prototypes are increasingly improving. The costs and time intensity are decreasing due to developments in rapid prototyping (e.g. 3D printing) and the rise of Makerspaces (Smith, 2007, p. 95). Digital technologies also allow the creation of **virtual prototypes,** decreasing one-off expenditure (Vetter, 2011). Physical prototyping plays an important role in the engineers' **creativity**, but it is important to guide developers as to when and for what **purpose prototypes** are to be created (Viswanathan *et al.*, 2016, p. 176). Jang also shows that more successful teams create prototypes earlier and more often throughout the entire process (Elverum and Welo, 2015).

A **prototype** is an early version of a product, designed for a specific test purpose (e.g. communication, integration or demonstration) (Walker *et al.*, 2016, p. 661). Prototypes represent at least one **aspect of the product** to be developed for learning purposes (Ulrich and Eppinger, 2012, p. 289). Prototypes comprise only individual functions or modules of the final product (Woche Buccini, 2018, p. 10). A prototype is not necessarily complex or technically advanced, but allows exploration of an idea in as simple and efficient a way as possible (Lim *et al.*, 2008, p. 4). Prototypes are divided into the three perspectives of the solution space. These are **desirability** (customer perspective), **feasibility** (technical perspective) and **viability** (business perspective) (Menold *et al.*, 2016). Desirability describes the attractiveness of the product for customers and the probability of a purchase, feasibility includes the technical feasibility, and viability the adjustment to time and budget constraints (Menold *et al.*, 2016, p. 75).

Prototyping is a central element of diverse design (project) courses, as researchers emphasizes its cognitive benefits. (Lim *et al.*, 2008) describes a **prototype** by means of "manifestation dimensions" (material, degree of detail and range considered) and "filtering dimensions" (implementation of certain aspects of the final product). The prototyping takes place in the phases of execution and control. Prototypes are not only used to validate ideas (Link, 2014, p. 80), but also to convey ideas, create user interaction and investigate different design concepts. Both low and high fidelity prototypes are used (Menold *et al.*, 2016, p. 70). According to Vetter, the prototypes are "animated" and "played", thus triggering and promoting the interaction and interaction mechanisms between the internal and external persons involved in the company (Vetter, 2011, p. 54).

(Ulrich and Eppinger, 2016, p. 291) **define a prototype** as "*an approximation of the product along one or more aspects of interest*". (Chua *et al.*, 2010, p. 2) describes a prototype as follows: "*an approximation of a product (or system) or its components in some form for definite purpose in its implementation*". These definitions include prototypes ranging from simple concept sketches to mathematical models or simulations to fully functional pre-production versions of the product or even exact replication of the product (Chua *et al.*, 2010, p. 2; Ulrich and Eppinger, 2016, p. 291).

(Chua *et al.*, 2010, p. 2 ff.) provides the following **classification of prototypes** along the aspects of implementation, approximation and form (see Figure 3-9). The aspect of **implementation** considers the range of prototyping from the entire system to only subsystems of the product. The complete prototype is usually implemented full-scale and fully functional. Subassembly or components of the end product are prototypes to investigate special issues (Chua *et al.*, 2010, p. 2 ff.). (Ulrich and Eppinger, 2016, p. 293) classify the degree to which a prototype is comprehensive as opposed to focused. Comprehensive prototypes are a full-scale and fully operational representation of the product (Ulrich and Eppinger, 2016, p. 293). The **degree of approximation** covers the range of foam models to exact full-scale replications of the product (e.g., pre-production prototypes or alpha prototypes). Rough prototypes are used to study general aspects (e.g. form and dimensions) at an early stage. Exact prototypes address manufacturing issues, which is especially important at the end of the product development (Chua *et al.*, 2010, p. 3). **Form aspects** range from virtual prototypes to physical prototypes (tangible manifestations of the product) to test and experiment. (Ulrich and Eppinger, 2016, pp. 293, 296) introduces the degree to which a prototype is physical as opposed to analytical. Virtual or analytical prototypes are nontangible representations of the product (e.g. mathematical models), or computer simulations. Physical prototypes are mock-ups that look and feel much like the real product but are not functional (Chua *et al.*, 2010, p. 3), or proof-of-concept prototypes used to quickly test an idea (Ulrich and Eppinger, 2016, p. 293). (Kayser, 2017, p. 13 ff.)

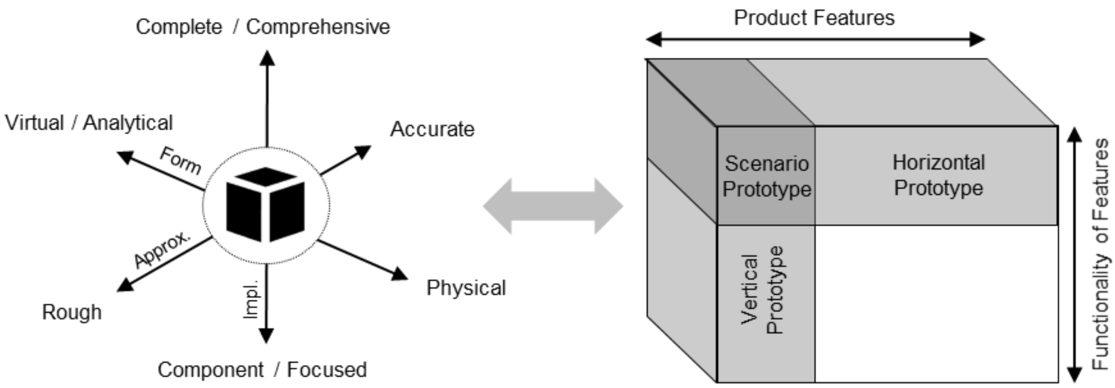

Figure 3-9: Dimension of prototypes according to (Chua et al., 2010, p. 3; Ulrich and Eppinger, 2016, p. 296; Jakob Nielsen, 1990).

(Jakob Nielsen, 1990) described three different types of prototype alongside a scale of features of services and functionality of features (see Figure 3-9, right). **Horizontal** prototypes are prototypes with shallow functionality but a wide range of features. As many functions, as possible are implemented in the prototype, but only to the extent that they can be demonstrated (Elverum and Welo, 2015, p. 73). Various solution alternatives for a problem can be developed to explore the solution space. In the next step, the best design can then be selected (Zink *et al.*, 2017, p. 80). For **vertical prototypes**, a few selected functions are implemented, so that they correspond to the final version (Elverum and Welo, 2015, p. 73). Vertical prototypes are used to assess the technical feasibility of a function or module resulting from horizontal prototyping (Mackay and Beaudouin-Lafon, 2012, p. 126 ff.). They are of narrow features but deep in functionality and focus on implementing a small set of features. **Scenario prototypes** overlapped the two with only parts of features and functionality (Lande and Leifer, 2009, p. 508) according to (Jakob Nielsen, 1990).

Focusing on the purpose of the prototype

Short product lifecycles with frequent product innovations lead to a great importance for models and prototypes (Geuer, 1996, p. 7). Many studies have shown that 80% of **product costs** are already fixed during the first phase of the product development phase (Ehrlenspiel and Meerkamm, 2013). Changes late in the development process or even after the start of production can only be implemented considering the high cost of change. “Rapid Prototyping” facilitates early review of product properties, and thus, planning reliability to determine the cost curve (see Figure 3-10). In product development, physical models reflect the aspects and the shape of the product. (Geuer, 1996, p. 12 ff.)

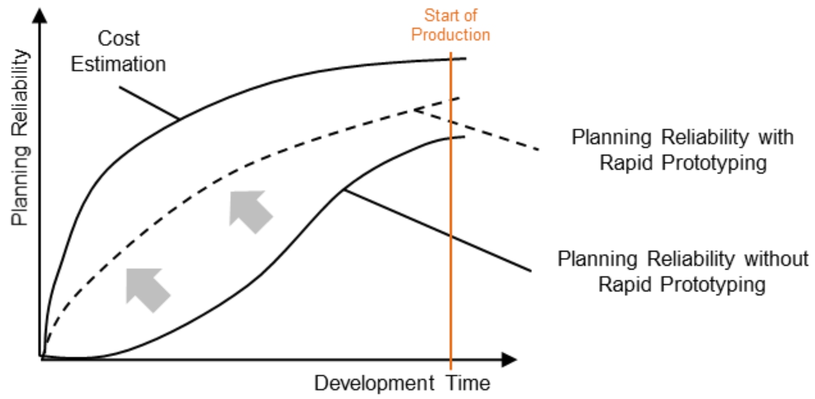

Figure 3-10:Impact of prototypes in terms of planning reliability and cost of change (Geuer, 1996, p. 12).

In the theoretical discourse of prototyping, two main complementary forms of prototypes are differentiated across disciplines: the design prototype and the technological (Ängeslevä *et al.*, 2016, p. 203). The faster physical models are available during the product development phase, the sooner planning reliability is increased. Depending on the properties of the product to be tested, suitable methods for creating a prototype must be selected. Table 3-3 lists different types of prototypes used in in product development that will be explained as follows. (Moeller, 2014) differentiates four prototyping categories within product development: concept models, geometrical prototypes, functional prototypes and technical prototypes.

(Houde and Hill, 1997) introduced a model representing a three-dimensional space which corresponds to important aspects of the design, namely: **role**, **look and feel**, and **implementation**. (Houde and Hill, 1997) identified four types of prototypes, which mainly differ in their purpose: role prototypes, look and feel prototypes, implementation prototypes, and integration prototypes. **Role prototypes** describe the functionality that a user might benefit from, with little attention to how the artifact would look and feel, or how it could be manufactured (Houde and Hill, 1997, pp. 3, 6). **Integration prototypes** occupy the middle of the model. (Kayser, 2017, p. 16)

Table 3-3: Different types of prototypes (Moeller, 2014; Houde and Hill, 1997; Ängeslevä et al., 2016, p. 203)

Type	**Characteristics**
Design Prototype	– Concept model for checking aesthetic and ergonomic features
Geometric Prototype	– Dimensionally accurate model for first attempts at assembly and use and to specify requirements
Functional Prototype	– Prototype that already has crucial functional properties of a later mass-produced component
Technical Prototype	– With the final product largely identical experimental model
Role prototypes	– investigate questions about the function in a user's life – no focus on implementation issues
Look and feel prototypes	– explore and demonstrate options for the concrete experience – concrete sensory experience of using an artifact
Implementation prototypes	– investigate technical questions – requires a working system to be built
Integration prototypes	– balances “role”, “look and feel”, and “implementation” – accurately simulate the final artifact

(Elverum and Welo, 2015, p. 82) introduces "directional prototyping" to test and evaluate new designs and to identify the best options for use. "Incremental prototyping" contributes to a further understanding and optimization of the chosen alternative. The prototype is validated, but no fundamental changes are to be made to the solution. (Brix and Jakobsen, 2015) differentiates “Pretotypes” and “Prototypes”. “Pretotyping” is an approach to develop and evaluate innovation before investing a lot of time and effort. The focus is on user interaction and interest. Some authors classify prototypes according to their **purpose** (see Table 3-4).

Hallgrimsson (2012), classifies the following prototypes according to purposes: exploration, communication, usability and technical verification (Hallgrimsson, 2012). The prototyping canvas of (Rhinow *et al.*, 2013, p. 2) makes product development more efficient. The canvas describes the following five **reasons for** the creation of prototypes in the design thinking process: Xplain as is, Xternalize, Xperience, Xplain to be, and Xploit (Rhinow *et al.*, 2013, p. 10 ff.). (Ängeslevä *et al.*, 2016, p. 203) identified the following main **functional areas** of prototypes: idea generation, user integration, validation and communication. In these categories, one can identify numerous **individual functions** that are comprehensively outlined in the chapter entitled “Perspectives on Future Prototyping—Results from an Expert Discussion” in this volume and in the conference paper bearing the title of “A transdisciplinary perspective on prototyping” (Exner *et al.*, 2015). (Gengnagel *et al.*, 2016, p. 203). (Geuer, 1996,

p. 13 ff.) differentiates four prototypes in terms of a specific purpose: Design, Communication, Functional, and Manufacturing. (Gengnagel *et al.*, 2016, p. 18) summarizes that the manifestation of design ideas has several dimensions and is categorized into functions of prototyping: design and development, external communication, integration of the user, internal communication, and testing and validation.

Table 3-4: Different purposes of prototypes (Hallgrimsson, 2012; Geuer, 1996, p. 13; Gengnagel et al., 2016, p. 18; Rhinow et al., 2013, p. 10 ff.)

Purpose	**Characteristics**
Exploration	– exploration of form, function, material, technology – simple materials (e.g. cardboard) – contribute to the learning effect of the development team
Usability	– check the interaction with the product interfaces – gathering of ergonomic and cognitive requirements – essential for a user-centered development
Communication	– share information, ideas and concepts – get common understanding (inside company), support sales (outside company) – communication of problems and evaluation of design – low feasibility, typically not fully operational
Technical Verification	– test of technical properties (e.g. assembly of products) – typically, virtual prototypes (e.g. CAD)
Functional	– check to what extent the functional requirements are fulfilled – properties of the later production materials – evidence about the product performance
Design	– physical representation – Optical properties (e.g. proportion, size)
Manufacturing	– reference models in the manufacturing process – “Cubing models”

3.2 Agile Basics in Product Development

Electronics and software represent an ever-increasing part of the final product (Eigner, 2014, p. 15). Traditional mechanical engineering, electrical/electronic and software methods cannot just be coordinated, and hence common interdisciplinary design approaches are proposed. Technical change allows to constantly create new products, but also reduces the lifecycle of products as they become technically obsolete (Stark, 2016, p. 71). Smartphone manufacturers, for example, renew their products every year with the latest technology to outdo competition. To deal with changes and uncertainty during the development, agile process models have gained in importance. Hardware-related agility has not yet been studied extensively. However, there are familiar process models, such as Design Thinking (Gurusamy K. *et al.*, 2016, p. 37).

3.2.1 Characteristics of Agile Product Development

The term “agility” is mostly used in the context of software development and describes the “ability to move quickly and easily” (Beckmann, 2015, p. 20 ff.). There is no such thing as being “100 percent agile” because “being agile” always means improving (Ekas and Will, 2014, p. 4). In 2001, the “Manifesto for Agile Software Development” is elaborated by seventeen representatives of different agile approaches (Beck *et al.*, 2001). In **product development**, there are different definitions for the term “agility”. At the system level, agility is understood as the property of a **system** that can be **changed quickly** (Haberfellner and Weck, 2005, p. 1450). (Komus, 2014, p. 6) emphasizes the iterative character and defines the highest possible **feedback rate** as an indicator of agility. (Ekas and Will, 2014, p. 1) promotes **learning effects** and continuous improvement based on the reflection of the prototyping results. (Baron and Hüttermann, 2010, p. 6 ff.) understand agility as a particular way of **thinking and attitude** to work, which fosters close collaboration within the team. (Wiendahl *et al.*, 2014, p. 140 ff.) relate agility to the entire company and describe such companies as agile, which proactively break into new markets. It describes the **responsiveness** of a **company** to stay competitive on the marketplace (Yusuf *et al.*, 1999, p. 39). (Augustine, 2005, p. 2) understands agility as the ability to deliver products with added **user value**. (Highsmith, 2010) characterizes agility as the ability to balance stability and flexibility. Flexibility is the property of a system that can be easily modified. Agility is the combination of system flexibility and a **rapid response**. (Kosiol, 2016; Beckmann, 2015; Meinzinger, 2017)

(Kettunen and Laanti, 2008) differentiates business agility, organizational agility, employee agility, agile information technology, production agility, agile supply chain, and agile software development (Kettunen and Laanti, 2008, p. 193). Zhang describes agility in value chain, product development, production and logistics (Sharifi and Zhang, 1999). (Förster and Wendler, 2012; Hermann and Korn, 2016; Dingsøyr *et al.*, 2012) summarize further definitions or rather conceptual structure underlying agile scholarship. To conclude, there is no single definition of “agility”. Based on a comprehensive analysis of several definitions from various fields of research (see Appendix A4), the following definition is derived for this study:

“*Agility is the capability to react, and adopt to expected and unexpected changes within a dynamic environment constantly and quickly; and to use those changes (if possible) as an advantage*” (Böhmer *et al.*, 2015, p. 4).

(Douglass, 2016a, p. 42) states that agile methods are **adaptive** and **responsive** to changing situations and guide development teams in terms of **product quality** and **engineering efficiency**. The continuous integration and testing are seen as “hygienic” development activities in order to avoid mistakes in the first place. Agile methods facilitate early feedback with the intention of evaluating the product often and early (Douglass, 2016a, p. 43). Agile movement is characterized by central values and principles that are summarized in the following list, according to (Ekas and Will, 2014, p. 42 ff.; Klein, 2016, p. 56 ff.; Boehm and Turner, 2006, p. 17; Link, 2014, p. 74):

- **Flexibility and transparency**: Process and product are characterized by an efficient, lean character that focus on customer's values.
- **Focus on people**: Processes are aligned with the individuals involved and their abilities. Developers work autonomously in close collaboration and independent of strict rules.
- **Involvement of the customer**: The customer is regularly involved in evaluating the project outcome or rather the development progress. The project is (re)planned based on feedback.
- **Considering changes**: Changing requirements are a chance for flexibility, as they are implemented in a more market-oriented way. Changes to requirements are proactive.

- **Iterative and emergent development**: Recurring activities characterize the process. Tasks are organized into manageable packages, and gradually processed.
- **Incremental delivery**: System is structured into subsystems that provide added value to the customer. The development team determines the order of requirements to be implemented and the level of implementation required.
- **Emergent design**: Learning and process improvement is explicitly wanted throughout project. Unsuccessful solutions contribute to learning effects for the team (“fail forward”).

Traditional software development comprises various job types (e.g. architect, UI designer, etc.), whereas agile models define a development team as a cross-functional team that is responsible for the complete development (e.g. designing, building, and testing). Thus, agile product development implies a **decentralized type of decision-making**. In engineering design, decision-making is challenging due to diverse development roles (e.g. mechanical engineer, software developer, etc.) and the uncertain and abstract nature of product development. The “Design Process Paradox” as described by (Ullman, 2010) presents the limited knowledge and insufficient information available early on in a project (see Figure 3-11). With increasing knowledge about the design problem, the potential to influence the design is decreased significantly. Engineers deal with such a paradoxical situation by creating early prototypes to gain maximum insights with minimum effort. (Punkka, 2012, p. 3) outlines how costly mistakes at the end of a project can be avoided by increasing **up-front prototyping**. Early prototyping is a cost-effective and implicit risk insurance that increases product quality (Douglass, 2016a, p. 42).

In software development, early prototyping is more effective than specification-driven development and requires substantially **less effort** and documentation (Punkka, 2012, p. 3). For the development of physical systems, the prototyping effort can be adjusted by using different types of prototypes (Ulrich and Eppinger, 2016, p. 291 ff.). However, final product specification will not be substituted completely, as hardware sets tight requirements for software (Ullman,

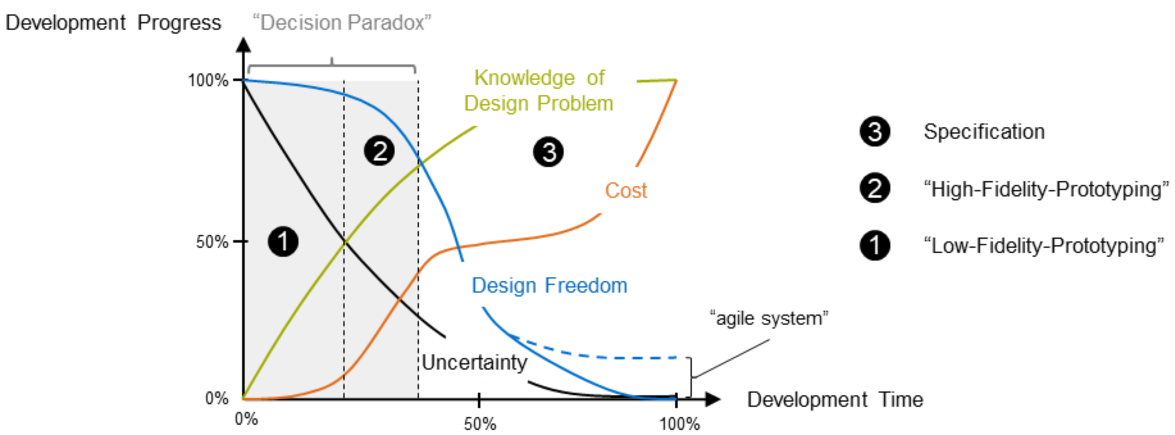

Figure 3-11: Characteristics of agile development of physical products (Smith, 2007, p. 36; Boehm et al., 1984, p. 293; Ullman, 2010, p. 13; Probst et al., 2012, p. 258; Haberfellner and Weck, 2005, p. 1449).

2010, p. 92). Figure 3-11 illustrates the characteristics of agile product development with regard to knowledge increase, uncertainty reduction, cost during development, and design freedom. The design space is explored with simple prototypes (“Low-Fidelity-Prototypes”), knowledge is gained and the uncertainty about which requirements and technology to be used is likewise reduced (Smith, 2007, p. 89). More mature, but cost-intensive prototypes (“High-Fidelity-Prototypes”) facilitate the product specification while maintaining the design freedom (Boehm *et al.*, 1984, p. 291 ff.). The last phase of the development is characterized by detailed product specification, intense documentation and increasing cost caused for late changes (Smith, 2007, p. 36). The design freedom is kept open only for subsystems to address potential changes throughout the lifecycle of the product (“agile systems”) (Haberfellner and Weck, 2005, p. 1449).

The idea of early working prototypes is highly developed in software development. Due to the popularity of “Scrum”, the term “Product Increment” is widely used. A Product Increment is a “finished” (sub-) system functionality with a usable function that could potentially be shipped to the customer with less effort (Maximini, 2013, p. 177; Klein, 2016, p. 86). (Balzert, 2009, p. 443) characterizes a product increment as part of a product model. The Product Increment available to customers is characterized as a set of external deliverables. Internal deliverables are relevant for the project progress of the developing team. In the context of product development, deliverables are a subset of **artifacts**. In the Unified Modeling Language (UML), an artifact is defined as an element that arises during a development process, deployment, or application of a software system. Artifacts are a piece of physical information that is distinguished in material (e.g. source code) or immaterial (e.g. methods) (Fay *et al.*, 2009, p. 81; Rumpe, 2012, p. 12). (Brökel, 2016, p. 21) describes an artifact as an object in which knowledge is stored as information. Even a table is considered an artifact, as reverse engineering creates information, for example. (Gülke, 2014, p. 49) describes the term “artifact” as a virtual or physical business object that can be created, edited, or eliminated in processes. (Klein, 2016, p. 37) limits the understanding of an artifact to a document-like component of a process with regard to the product to be built.

Artifacts are divided into three categories (Liskin, 2015): container, individual element or solution element. **Containers** are generic documents that aggregate the entire project knowledge (e.g. Requirements List). They provide a good overview of the development **situation** and are, therefore, of great importance for the project’s success. Artifacts are constantly updated during the development and are either domain-specific or generic (Liskin, 2015, p. 136). **Individual elements** are either user-oriented (e.g. Use Case) or technical artifacts (e.g. Functional Model). **Solution elements** are either concrete (e.g. GUI Mockup) or abstract artifacts (e.g. Spreadsheet) (Liskin, 2015, p. 137). (Méndez Fernández *et al.*, 2012) classify artifacts by means of different strategies in the implementation with regard to requirement engineering. Three different directions of impact are determined, into which the resulting artifacts are divided. It is a matter of different types of orientation:

- **solution orientation**: focus on the customer
- **functional orientation**: focus on applications and interfaces
- **problem-orientation**: focus on business and economic needs (Méndez Fernández *et al.*, 2012, p. 162 ff.). (Meinzinger, 2017, p. 50)

To conclude, “agile” is a **pragmatic approach** based on a few rules and project roles. Planning upfront is substituted by the creation of a plan only detailed to the **actual degree of information**. This **dynamic planning** refines rough initial plans as more and better information becomes available (Douglass, 2016a, p. 45). By prioritizing and successively implementing requirements, it is ensured that the functionalities with the **greatest user** benefit are realized first (Gürtler and Lindemann, 2016, p. 491). Knowledge silos, caused by barriers over time, project or hierarchy are overcome, and information (to the required extent) is constantly available to the development team (see Figure 3-12).

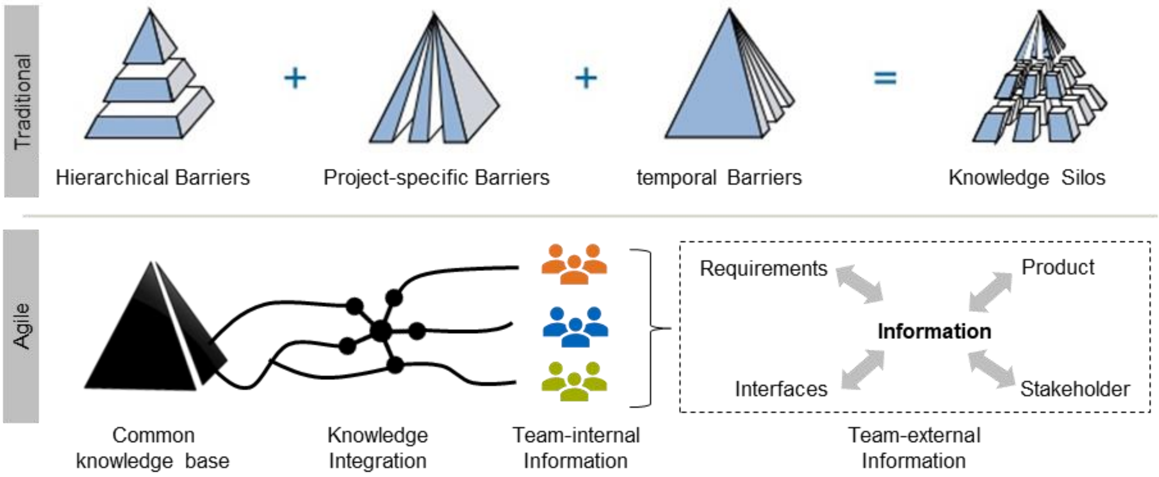

Figure 3-12: Knowledge silos as a result of organizational structure and knowledge network as a result of agile teams according to (Probst et al., 2012, p. 258; Bertsche and Bullinger, 2007, p. 37).

3.2.2 Handling Uncertainty in Agile Projects

Trend research provides several methods and tools (e.g. scenario technique) to forecast future developments (Gausemeier and Plass, 2014, p. 96). Individual influencing factors allow several projections of the future. Such scenarios help to overcome the limits of close-minded thinking and to find new approaches for successful business and product strategies (Gausemeier and Plass, 2014, p. 85). The strategy of agile projects consists of a future draft in the sense of an entrepreneurial vision and a description of the way to realize the future draft. The project path will be incrementally verified by the outcome as being created (Douglass, 2016a). Figure 3-13 illustrates the agile project model by (Oestereich *et al.*, 2014) that is initially characterized by high uncertainty. For each iteration, the development team has a certain scope for decision-making. The scope of the initially planned solution changes during the project as the development team gathers knowledge about the product to be build (Link, 2014, p. 79). The solution space is increasingly defined in detail, and the uncertainty decreases through the learning effect of the product in the team. At the end of the development, the product can differ significantly from the ideas at the beginning of the project. It is important that the developers accept "*that the clarity about the product to be produced does not suddenly arise, but comes* *gradually, and that the goal is not a constant size, but can change over time*" (Oestereich *et al.*, 2014, p. 3). Agile projects focus on fast iterations and continuous adaption of the product to customer needs in order to reduce risks and to bring valuable products to market rapidly.

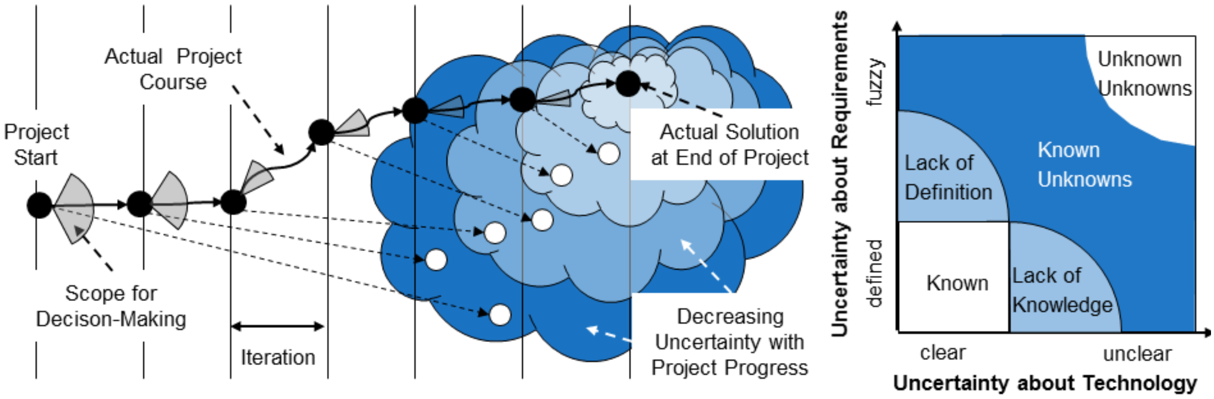

Figure 3-13: Agile project with correlated Stacey Matrix, adapted from (Oestereich et al., 2014; Goll and Hommel, 2015; McManus and Hastings, 2005).

Uncertainty is categorized into lack of knowledge, lack of definition, known unknowns and unknown unknowns (McManus, H. and Hastings, D., 2005). According to Goll and Hommel, the four forms of indeterminacy are represented in the "Stacy Matrix" referring to the complexity of a project. For agile product development, the matrix is referred to uncertainty of a project (Goll and Hommel, 2015, p. 4) (see Figure 3-13). For clear requirements and technology, the development is predictable ("Known") and traditional process models are recommended. **Lack of definition and knowledge** characterize a project that is predictable but is not transparent by everyone. There are uncertainties regarding the requirements and technologies. Development projects have recognizable patterns, but only in retrospective. Both the requirements for the system and the implementation technology are unclear ("Known Unknowns"). For unclear technology and fuzzy requirements, the development is unpredictable, and therefore, not plannable ("Unknown Unknowns"). Based on the adapted Stacy Matrix, action patterns can be derived from the "Cynefin model" developed by (Snowden, 2000). "*The Cynefin model provides an explanation for what happens when the wrong way of working is applied to a problem*" (Goll and Hommel, 2015, p. 8). The categories "known", as well as "lack of definition" and "lack of knowledge" are mastered with plan-driven methods. The field of "known unknowns" and "unknown unknowns" are assigned to agile methods. According to Goll and Hommel, an empirical development process (e.g. PDCA) is ideal for projects where initially the requirements and the technology are unknown (Goll and Hommel, 2015, p. 5).

Uncertainty is commonly referred to as the possibility of deviating from an expected situation (Haberfellner *et al.*, 2015, p. 116). Deviation is defined as opportunity in a positive sense, and as risk, from a negative point of view. (Müller, 1993, p. 3813) differentiates **decision-making** depending on whether the probabilities of occurrence for the environmental conditions are

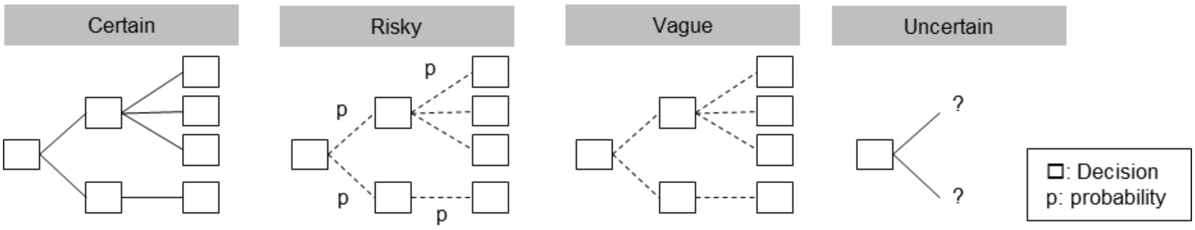

Figure 3-14: Decision-making depending on the available information (Gerling, 2016, p. 21).

known (see Figure 3-14). For risky decisions, the decision maker is aware of the occurrence probabilities "p" of the environmental conditions, being dependent on his decision. For vague decisions, the decision-maker cannot make any statement about the probabilities with which environmental conditions will occur. (Knight, 2014) distinguishes another level of uncertainty, where the decision maker is not aware of the probabilities of occurrence of the environmental conditions.

Agile has a lot in common with "project-based learning" that requires the acquisition of new knowledge. In project-based learning, the central focus of the assignment is the final product, in contrast to "problem-based learning" where the solution process is more important than the end-product (Prince and Felder, 2006, p. 135). **Project-based learning** incorporate basic design activities, such as "*important design activities, such as gathering and evaluating information, framing problems, generating and testing solutions, making and communicating decisions, and iterating*" (Atman *et al.*, 2015, p. 212). Project-based learning is about the application and integration of previously acquired **knowledge**. The method demands developers to formulate or rather design solution strategies and to constantly re-evaluate their approach in answer to any outcomes of their efforts (Prince and Felder, 2006, p. 135).

Agile methods empower co-located teams of less than 10 people and emphasize collaborative practices (Highsmith, 2010; Conforto *et al.*, 2014a). They address the challenge of the increasing rate of change complexity in products by focusing on results (Punkka, 2012, p. 7). Developing small, focused, experiments on partial solutions makes it possible to start learning early, and efficiently. (Thomke and Fujimoto, 2000, p. 132 ff.) outline the prototyping strategy "Front-Loading Problem-Solving" with the intention of increasing development performance. **Up-front prototyping** aims for validated learning through experiments, to learn effectively by trial and error, for example (Punkka, 2012, p. 4 ff.). For agile projects, solutions may be less important than the knowledge gained. Technology allows a new way of thinking, as it gets more flexible and costs less. Many different prototypes tackle uncertainties, and iterative (re)planning enables the team to focus on the most important issues. (Punkka, 2012)

Agile development means that under the given resource and time budgets the product requirements are realized in the best possible way (and not the reverse – namely, the given product requirements at the lowest possible time and under resource budgets). In order to reward **change**, **adaptation**, and **flexibility** of agile projects a new way of measuring project performance is needed. Figure 3-15 shows the transition from "Iron Triangle" to "Agile Triangle" of project management. The measures for agile projects are value (to the customer), quality (required to deliver continuous value to the customer), and constraints (scope, schedule,

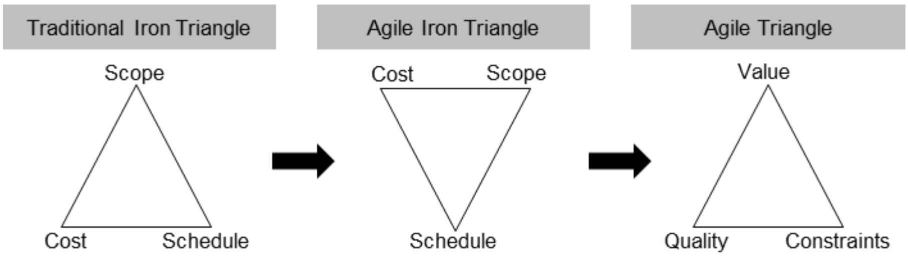

Figure 3-15: Evolution of Agile Triangle in Project Management (Highsmith, 2010, p. 58).

and cost) (Highsmith, 2010, p. 32). Schedule might still be a fixed constraint, but then scope could be adjusted to deliver the highest value within the schedule constraint. (Conforto *et al.*, 2014a) emphasizes that agility is more of a team competency, and that there are critical factors for achieving agility in projects. These critical success factors must be met to prepare for and respond to changing conditions. (Boehm and Turner, 2006, p. 26) outline five critical factors for creating the right balance of agility and stability: team size, project criticality, company culture, number of employees and project dynamism.

3.2.3 From Linear, Iterative to Agile Process Models

Process models divide the innovation and product development process into individual, predictable phases (Lindemann, 2009). Each process model has three main steps: Clarification of goal and problem, Generation of alternative solutions, Decision-making and evaluation (Lindemann, 2009). Depending on the situation, different models are recommended. Agile process models based on the “trial-and-error” approach is perfect to develop working prototypes quickly with limited resources and experience. In the case of larger development projects, systematic and more elaborate process models are valuable. (Gürtler and Lindemann, 2016, p. 488 ff.)

Agile and traditional procedures are applied successfully in software and hardware projects (Komus, 2014). The benefits depend on the different home-grounds, where rather agile or traditional procedures are best used (Boehm and Turner, 2006, p. 51). An agile process model is opposed to sequential, iterative and incremental procedures, using the classification by (Gnatz, 2005, p. 19 ff.). “Agile” combines both iterative and incremental aspects which are mainly used in projects with high uncertainty (Hostettler *et al.*, 2017, p. 790). Starting with an initial vision of the product, customer needs are gathered and taken in to account. After the specification of initial requirements, a period of sketching, designing and prototyping follows. Prototypes are reviewed by the team or customer and serve as a starting point for the next iteration (see Figure 3-16).

Traditional procedures often focus on predefined Stage-Gates and phases as well as a complete requirement specification (Hammers, 2012). Agile procedures follow a mind-set that embraces change and uncertainty throughout the whole process (Beck, 1999). Time-consuming software engineering processes are opposed to result-oriented development approaches (Beck *et al.*,

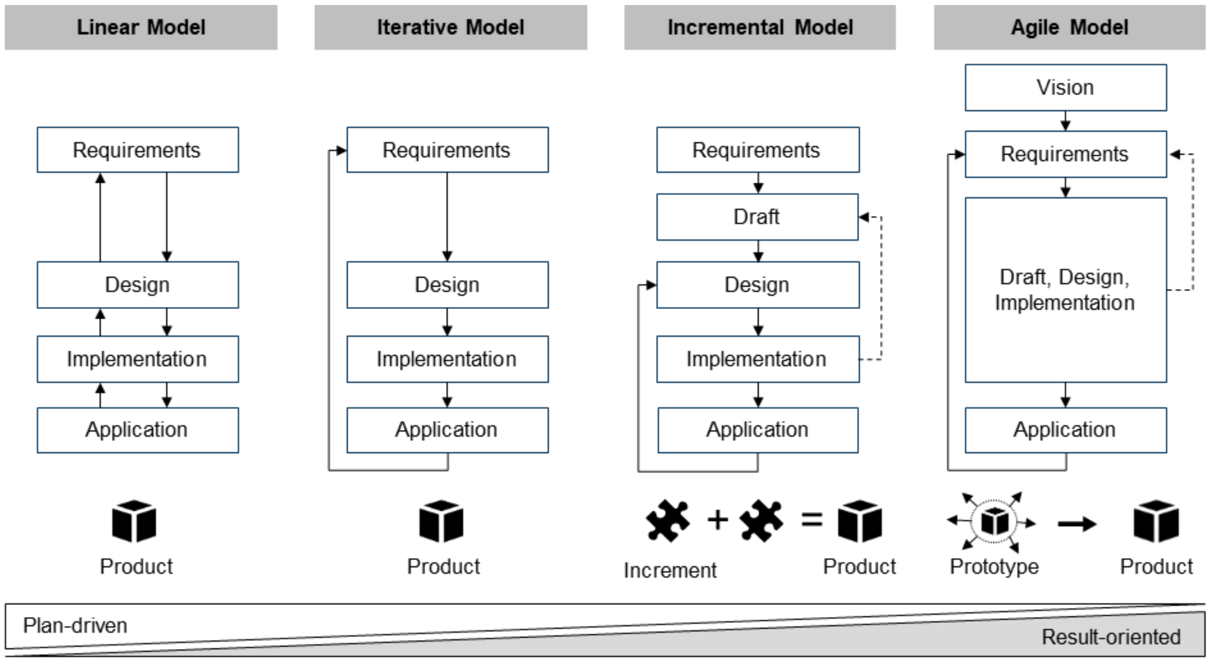

Figure 3-16: Differentiation of process models according to (Gnatz, 2005, p. 19 ff.; Hass, 2008, p. 3).

2001). Requirements are specified, features are realized and evaluated incrementally iteratively throughout the complete development (Schwaber, 2004). (Hostettler *et al.*, 2017, p. 789)

System architecture uses development models to enable system development and management. These models can be categorized into **linear** models, **phased** models with (incremental) iterations and **agile** models (Gorbea Díaz, 2011, p. 87). The following classification focuses on physical systems. However, a clear distinction between incremental-iterative and agile models is not possible (see Figure 3-17).

Linear process models are often described as sequential, classic or traditional and are often referred to as being synonymous to the waterfall model (Hoffmann, 2008, p. 5; Klein and Reinhart, 2016, p. 70). These process models are characterized by extensive and complete planning at the beginning of the project (Hoffmann, 2008, p. 5; Thomke and Fujimoto, 2000). The "Waterfall" model and the "Stage-Gate" model by (Cooper, 1983) are most popular in industry. Gates are decision points in which the results of the previous stage are evaluated. "Go" decisions allow one to move to the next stage, "kill" decisions stop the project, "hold" delays the stage, and "recycle" prolongs the stage until desirable conditions are met for the next phase. (Gorbea Díaz, 2011, p. 87)

Iterative models are more flexible and discover product design with iterative feedback loops. The **entire system** is developed from a general specification in several iterations into detailed design, however not released until all planned iterations are completed (Hass, 2008, p. 14). Common iterative models are the "V-Model" (VDI 2206) (VDI-Richtlinie, 2004), and the "Spiral" model (Boehm, 1988, p. 63). Requirements are formalized and broken down into sub-systems. Components are designed in detail and highly iteratively integrated and tested from

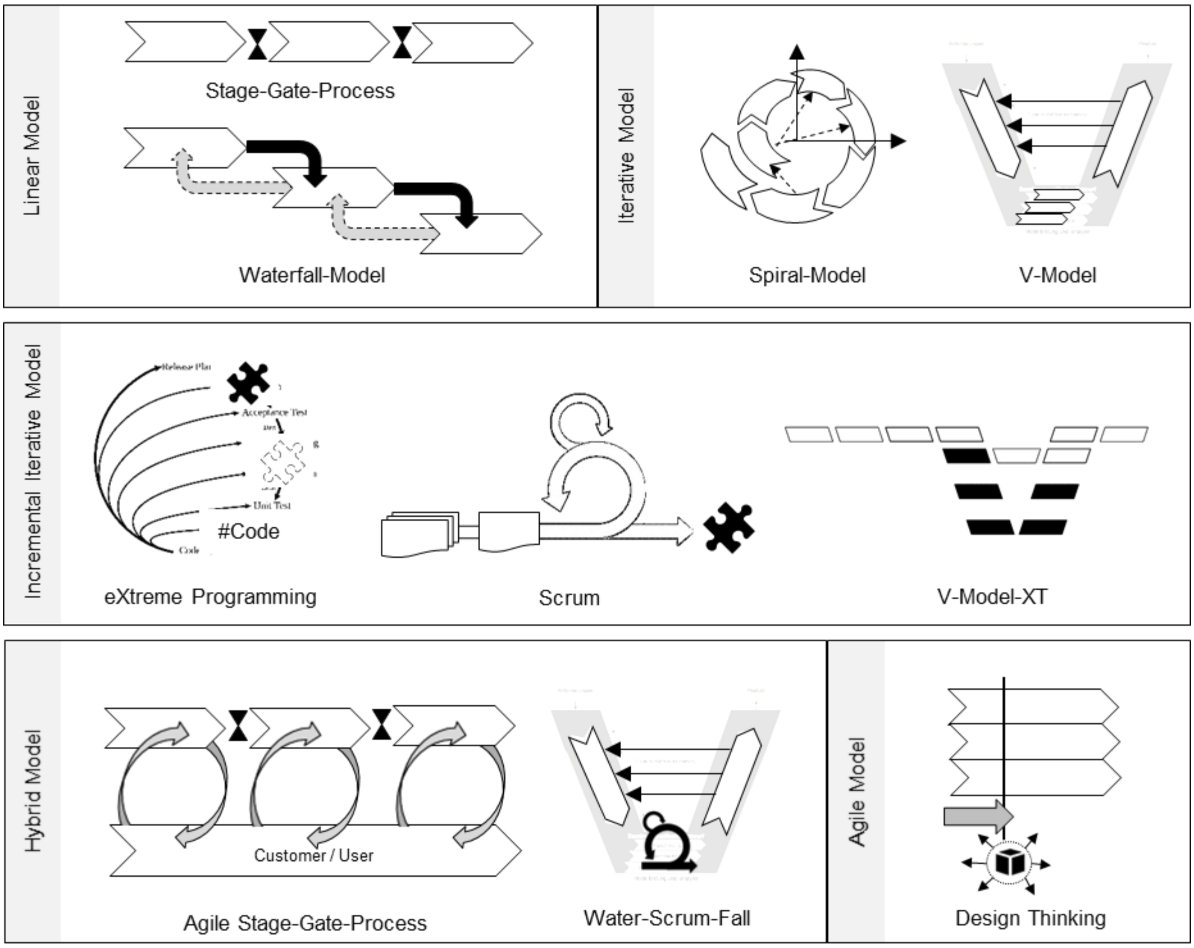

Figure 3-17: Examples for the Evolution of Innovation Processes: from the linear to the agile model, adapted from (Verworn and Herstatt, 2000; Eigner, 2014).

component to system level (Gnatz, 2005, p. 21). Planning steps are less important, and the results achieved in each iteration gain in importance. (Böhmer *et al.*, 2017b, p. 3)

Incremental iterative models build on linear and iterative models, providing a flexible adaption of the design phases to the current situation. Common examples are the "V-Model-XT", "eXtreme Programming" (XP) (Beck, 2000) or "Scrum" (Schwaber, 1997). The models address vague and changing requirements, and testing is incorporated in every iteration ("mini V-models") (Hass, 2008, p. 13). The V-Model XT is a system of "building blocks" that allows an application-specific tailoring for the project context (Höhn *et al.*, 2008). XP is based on the Spiral Model, where a software increment is tested by the user with each iteration. The micro-logic of Scrum is a continuous process that transfers a first draft to a "Minimum Viable Product" (MVP), while iterating with respect to the PDCA-Cycle of Deming (Hostettler *et al.*, 2017, p. 790; Deming, 1986; McKenna, 2016, p. 20; Goll and Hommel, 2015, p. 82).

Hybrid Models describe the mixture of traditional and incremental-iterative models with the aim of unifying the advantages of both approaches. The combination of these models is possible on the macro and micro-level. Typically, plan-driven concepts are used as an overall development framework (macro logic) and supplemented by Scrum or XP at micro level. As a result, constructs such as “Agile-Stage-Gate” or “Water-Scrum-Fall” are created (Theocharis *et al.*, 2015). The evidence in the literature regarding the suitability and performance of “Agile–Stage-Gate” hybrid models for manufacturing firms is very limited (Cooper and Sommer, 2016, p. 517).

Agile Models build on linear and incremental-iterative models and provide a flexible adaption of the design to the current situation. Based on high uncertainty, the product evolves over time by the creation of prototypes and the insights gained (Goll and Hommel, 2015, p. 3 ff.; Rodenacker and Schäfer, 1978, p. 670). These lightweight process models are a collection of best practices that are highly dependent on the use case (Klein, 2016, p. 58). For hardware related products, Design Thinking (Meinel *et al.*, 2011) and the Munich Procedural Model (MPM) (Lindemann, 2009) are worth a mention. Design Thinking supports the early phase of the design process by intensive prototyping and the validation of ideas. The network structure of MPM offers flexibility in levels of detail and implementation by a collection of methods that support the developer’s situation. The MPM is attributable to hands-on experiments (German: “*Handversuche*”) described by (Rodenacker and Schäfer, 1978) aiming to evaluate ideas early in the design process.

3.2.4 Agility in the Context of Hardware

For physical systems, the history of “agile” approaches goes back to 1943, where Lockheed’s chief engineer relayed on handpicked employees to form the “Skunk Works ®” division to build America’s first jet fighter[16]. The engineers, who had 150 days to build the first prototype, created the P-80 Shooting Star in only 143 days. The term, “Skunk Works” describes a highly skilled team within an organization given a high degree of autonomy to work on critical or secret projects (works outside the company rules and regulations). The team, designed to accelerate the development of innovative products or services, typically works under time pressure (Brown, 2004, p. 133).

Agile approaches are considered for software and hardware development projects (Highsmith, 2002; Smith, 2007; Cooper and Sommer, 2016; Thomke and Reinertsen, 1998). An important part of using agile methods is the early creation of prototypes. At the beginning, very simple, fast-to-build models are sufficient, which then become more complex during development (Smith, 2007, p. 101). (Camburn *et al.*, 2014) confirm that successful teams test more than two concepts through prototypes at the beginning of the development. However, physical product development differs from software development (Cooper, 2015; Camburn *et al.*, 2014, p. 2). Iterative prototyping for physical systems involves increased resource cost and needs expensive equipment and prototyping space (Briscoe and Mulligan, 2014, p. 3). (Sommer *et al.*, 2009) found that for projects with low uncertainty traditional planning is the most efficient approach, and that the iterative trial-and-error approach is best for systems with low complexity.

(Jang and Schunn, 2012) found that design teams who created physical models **outperform** their peers with respect to meeting client requirements and technical functionality. (Yang, 2005) observed that early prototypes that are simplified to test only the core function, exceed more

[16] https://www.lockheedmartin.com/us/100years/stories/skunk-works.html

complex prototypes. Prototypes serve as a **learning opportunity** for developers designing the core critical functions (Menold *et al.*, 2016). Research shows that the development of more prototypes often leads to quickly identified challenges (Menold *et al.*, 2016, p. 74).

(Schmidt *et al.*, 2017) outline "constraints of physicality" that lead to the fact that agile practices are rarely used in the development of physical products (Link, 2014). The constraints arise from difficulties in separating and estimating tasks, defining viable product increments, and responding to changes rapidly (Ovesen, 2012). One prominent example of "agile" being used for physical systems, is "Wikispeed ®", a car developed for the X-Prize competition within three months, using Scrum[17]. However, there is no methodical approach for agile physical product development, supporting the higher number and variety of different disciplines (Gregory *et al.*, 2015). First approaches follow the transition of these methods to the development of physical products (Cooper and Sommer, 2016).

The term "Design Thinking" means "inventive thinking" in a transcendental sense (Plattner *et al.*, 2015, p. 59). The Design Thinking framework is composed of loosely networked process steps, from understanding, observing, ideating, prototyping to testing (Plattner *et al.*, 2016). Several methods support each design step (e.g. "Storytelling"). Further aspects, such as the "lead user" theory of (Hippel, 1986) or the theory of "T-shaped" people by (Leonard, 1998, p. 75) are used in Design Thinking as well (Uebernickel *et al.*, 2015, 57, 132; Meinel *et al.*, 2011, p. 13). The central aspect of Design Thinking is the **rapid and iterative** development of **prototypes** that are useful in interdisciplinary teams (Lande and Leifer, 2009). Simple types of prototypes are used to make the idea "visible and communicable" as early as possible to strengthen or weaken an idea thanks to early feedback (Plattner *et al.*, 2015).

At Stanford University, the course "Design Innovation" (ME310) is well-known for the use of Design Thinking to develop innovative (physical) products. A **holistic framework** for structuring ME310 is illustrated in Figure 3-18. At the macro level, the ME310 is characterized by overall milestones that are characterized by prototype stages (e.g. Darkhorse Prototype)

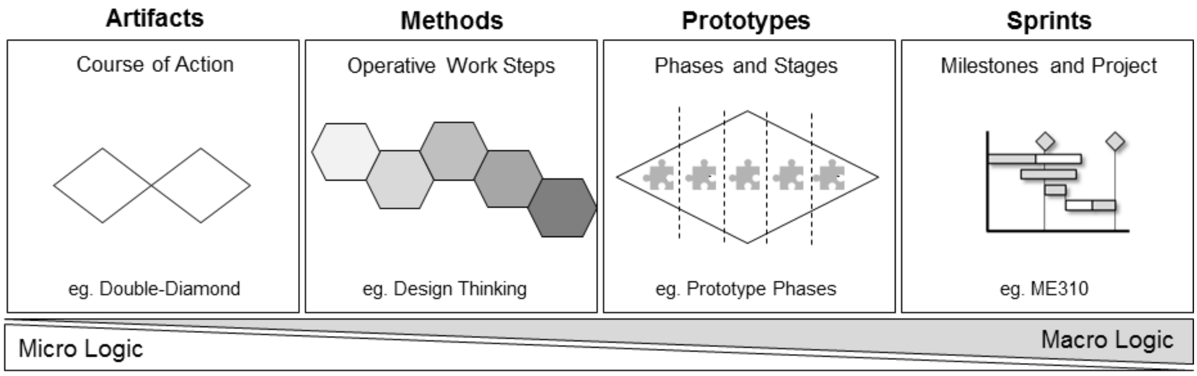

Figure 3-18: Micro and Macro Logic of ME 310 at Stanford University, referring to (Grauvogl, 2018, p. 35; Lindemann, 2009, p. 38).

[17] http://wikispeed.org/car/

(Schindlholzer *et al.*, 2011, p. 32; Ge and Maisch, 2016, p. 174). (Ulrich and Eppinger, 2016, p. 298) introduced the idea of milestone prototypes designed to provide tangible goals, to demonstrate progress and to enforce the schedule. The course of action is supported by Design Thinking methods. On the operative level, the university course follows the “diverge-converge” thinking, illustrated as “Double-Diamond”, to be continuously open to developing a range of potential solutions and delivering prototypes that address a user needs (“Problem-Solution-Fit”) (Grauvogl, 2018, p. 36).

Ries (2011) described “Lean Startup” as a novel way of looking at the development of innovative new products that emphasize fast iterations, customer understanding, a great vision and great goals at the same time (Ries, 2011, p. 30). The idea behind Lean Startup is based on Lean Manufacturing, Design Thinking, Customer Development and Agile Development (Ries, 2011, p. 4). The core of Lean Startup is the feedback loop “Build, Measure, Learn”, where a learning objective based on a critical assumption is specified first, then the effect of the prototype is measured and evaluated (Ries, 2011, p. 78). Innovation accounting is carried out by data collection using a “Minimum Viable Product” (MVP). A MVP is created as quickly as possible with as little effort as possible and has only the features needed to check the hypothesis (Ries 2011, p.110). For the creation of the MVPs, various types of iterative prototyping can be applied. The goal is to minimize the whole time throughout the cycle (Ries 2011, p.76)

Makeathons are classified as an agile framework because, like the other frameworks, they also have the goal of building a prototype over a short period of time in order to quickly determine whether the idea is a success or failure (Raatikainen *et al.*, 2013, p. 790).

3.3 Mechatronic Systems Architecting

Agile methods do not provide guidance to engineering on how to define architecture for incremental development (to encapsulate functionalities in modules). In order to define a suitable architecture for a complex physical product, companies should, therefore, look to the systems engineering community for answers. System architecting plays a central role in the design of complex systems. Complex system architectures combine multiple sub-systems. The system properties are characterized by **structure** and **behavior** of elements within a **complex system** (Gorbea Díaz, 2011, p. 83).

3.3.1 Systems Complexity

The essential principle of systemic thinking is to illustrate systems and complex interrelationships (Haberfellner *et al.*, 2002, p. 10). A system represents products (hardware and software), processes, people, organizations or institutions (Haberfellner *et al.*, 2015, p. 32).

In mechanical engineering, **complexity** refers to a network of elements of a technical system. Depending on which goal is pursued or which methodology is used, the definition for “complexity” differs (Schoeneberg, 2014, p. 14). According to (Ulrich and Probst, 1991, p. 58), a complicated system becomes complex, when the system is constantly changing its state. With increasing innovation dynamics, characterizing the time dependency of a system state, stable systems become complex systems (Lindemann, 2009, p. 10; Baltes and Selig, 2017, p. 87). The

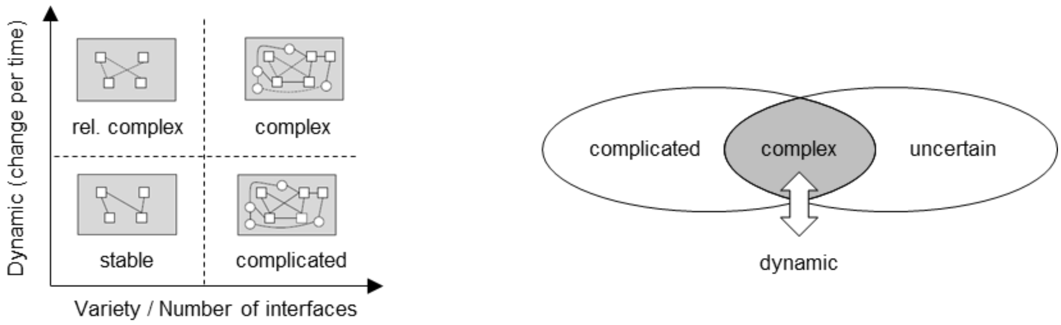

Figure 3-19: Characteristics of complex systems (Ulrich and Probst, 1991, p. 57; Haberfellner et al., 2015, p. 38).

relationship between complicatedness and complexity is illustrated in Figure 3-19 and characterized as follows (Ulrich and Probst, 1991, p. 61). Complicatedness depends on the type of composition and is a function of number and variety of elements, and variety of relationship between elements. Complexity is defined as variability over time, characterized by the variety of element-behavior, and the variability of course of action between elements. Lindemann describes the complexity of a system with regard to number and variety of elements and their relationships, the state of the system, and the (self-) dynamics of the system (Lindemann, 2009, p. 10). In innovation management, the term “complexity” is characterized by great variability, connectivity and dynamics (Schoeneberg, 2014, p. 3, p. 14).

According to (Hellenbrand, 2013, p. 23), there are two main approaches to deal with complexity for the development of mechatronic products: master complex products, and dealing with complex processes. Matrix and graph-based models are used for both approaches. The analysis of existing structures increases cross-disciplinary collaboration and provides a better understanding of the systems and change dependencies (Hellenbrand, 2013, 25, 88; Lindemann, 2009, 37, 39, 42). The strategy of **Systems Engineering** is to cope with complexity, using a problem-solving process subject to system design specifications and project management (see (Eigner, 2014; Haberfellner *et al.*, 2015)).

Structural complexity management is based on three strategies: identify and evaluate, avoid and reduce as well as master and control complexity (Lindemann, 2009, p. 31 ff.). (Maurer, 2007) describes the procedure of structural complexity management as follows. First, the system is defined to define the objective of the analysis. A meta-model is created involving different domains and types of relationships. Domains represent a specific view of a complex system and describe a specific system unit. They include units of the same type, can be decomposed into subdomains, and recombined with other domains through different types of relationships to different system views. Relations exist between the elements of a domain ("intra-domain"), and between the elements of different domains ("inter-domain"). Relevant input data required for creating the model are identified, and the elements and relations of the domains are specified. The result is a model that structurally maps the available information. The actual analysis of the model derives complex relationships based on a matrix representation. Calculations (e.g. matrix multiplications) reveal indirect connections between system elements that are not obvious. For more details, see (Maurer, 2007, p. 71 ff.).

Mechatronic systems have evolved from discrete electrical and mechanical parts to integrated electronic–mechanical systems driven by sophisticated software (Isermann, 2008, p. 14). The increasing electrical, electronic and software percentage is a crucial **complexity driver** for mechatronic systems (Hehenberger and Bradley, 2016, p. 21). Traditional approaches are based on the assumption that the information required for the development is already available in advance (Luckel *et al.*, 2000). The increasing complexity of technical products leads to the **integration** of **different disciplines** into product development. However, the variety of the requirements to be taken into consideration, becomes more complex due to technical differences (Lindemann *et al.*, 2003, p. 102 ff.).

Competence management of different functions and disciplines is a key issue for mechatronics engineering (Adamsson, 2005, 14, 31). Cross-functional engineering teams comprise an adequate integration of software and electronics engineering with mechanical integration. In order to design innovative **mechatronic products** a high level of collaboration is required to include different disciplines in a common development approach (Hellenbrand, 2013, p. 13). The term **collaboration** refers to close teamwork, where mechatronics is a separate discipline apart from pure mechanical engineering, for example. The level of collaboration is differentiated according to trans-, multi- and interdisciplinarity (Hellenbrand, 2013, p. 13). For **multidisciplinary** teams, experts from various disciplines only deal with one aspect of the project (Gengnagel *et al.*, 2016, p. 218). **Interdisciplinarity** is a discipline-specific execution of sub-aspects with a common view of goals and results (Hellenbrand, 2013, p. 13). **Transdisciplinary** refers to interdisciplinarity, however the degree of knowledge integration requires not only aspects for interpersonal integration, but also “individual multi-field competency” (Ropohl, 2010, p. 5).

3.3.2 System Architecting Principles

Mechatronic system design consists of a set of parameters and a set of logical and quantitative relationships between system models (Hehenberger and Bradley, 2016). While the conceptual design evolves to a detailed design, the granularity of models becomes finer and clearer, leading to a hierarchy of models (Gausemeier *et al.*, 2001, p. 888 ff.). The extensive functionality and complex structure of mechatronic systems leads to a multi-objective approach (Eigner, 2014). Single optimizations within each domain will not result in the optimum system design. All domains are treated concurrently, at least at the beginning of the design process. This approach facilitates finding a promising concept for the entire subsystem and not only for a specific domain within the sub-system.

The knowledge of the entire system does not equal the sum of knowledge from the corresponding domains. The domain knowledge must, therefore, be generalized or rather abstracted and integrated. The phenomenon described by (Ehrlenspiel and Meerkamm, 2013) as "wall-thinking" in mechatronics can be resolved by an abstract interdisciplinary approach (see Figure 3-20). The development team builds various prototypes in order to learn, communicate, integrate or demonstrate the system model (also described as a “designer’s multi-dimensional expression”). Agile prototypes are not only functionally reduced experimental models of later product series but deliver feedback that is incorporated into the next iteration. According to (Gorbea Díaz, 2011, p. 85 ff.), several key principles and methodologies to system

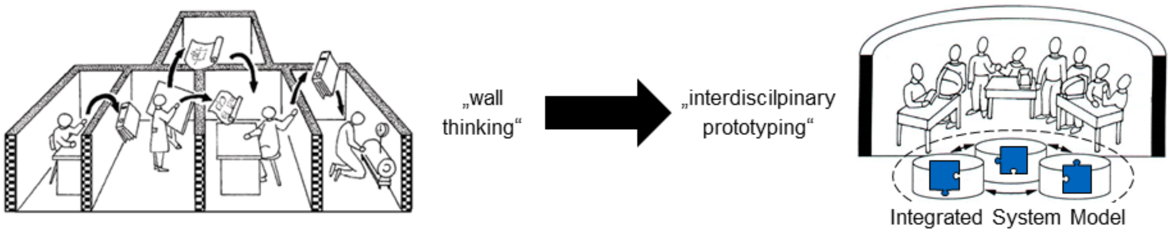

Figure 3-20: From "wall-thinking" to prototype-focused integrated system model (Böhmer et al., 2017a, p. 4; Ehrlenspiel and Meerkamm, 2013, p. 192, p.229).

architecture analysis and handling have been extracted from the fields of system engineering and product development.

Systems Thinking in developing product architecture allows developers to understand the overall systems rather than considering only specific aspects or elements within the systems (Haberfellner *et al.*, 2002; Ehrlenspiel and Meerkamm, 2013; Ulrich and Probst, 1991). **System Partitioning** facilitates the understanding of a system by analyzing the interfaces and a sub-system's reintegration. Product development typically follows the principle of "abstract to concrete" (Pahl *et al.*, 2007). Product planning and development is abstracted to reduce complexity, while developing a detailed product concept (Gausemeier and Plass, 2014, p. 27 ff.). The idea of "Form follows Function" (associated with industrial design) is that the shape of a system is primarily based on its intended function. Product architecture ranges from integral to modular, depending on the functional behavior of the product.

Focusing resources on the "Early Development Phases" fosters detailed product planning and concept development. This "front loading" approach is used in concurrent engineering allowing shorter development cycles, reduced risk and greater flexibility in meeting market demands. (Thomke and Fujimoto, 2000, p. 132 ff.) applies the "Front-Loading Problem-Solving" strategy in the early phases by means of prototyping practices to increase development performance. Cross-functional design efforts consider **lifecycle** parameters such as changing customer requirements or serviceability, for instance. **Thinking in alternatives** is important when dealing with uncertainty stemming from market or technology and increases the chance for a design innovation (Haberfellner *et al.*, 2002). **User-orientation** facilitates the development of products that address a basic user need. Product architectures that fail to meet consumer requirements lack market potential and are not cost-effective due to their lack of utility. Interdisciplinary cooperation in the context of Systems Engineering (Walden *et al.*, 2015) or Set-Based Design (Singer *et al.*, 2009) allows for efficient development projects through the early involvement of all relevant departments. (Gürtler and Lindemann, 2016, p. 484)

3.3.3 Strategies in Product Development

Product development models have emerged from mechanical engineering to initiate the design of multidisciplinary mechatronic system (Ullman, 2010; Pahl *et al.*, 2007; Bricogne *et al.*, 2016, p. 78). Common approaches for the development of mechatronic products are described in the "Mechatronic Systems Development Methodology" (VDI-Richtlinie, 2004), "Methodology for

Developing and Constructing Technical Systems and Products" (VDI-Richtlinie, 1993), as well as "Development Methods for Microelectronic Devices" (VDI-Richtlinie, 1994).

The “V Model”, and the “Spiral Model” of the development of mechatronic products are well-established procedures (Klein, 2016, p. 26; Luckel *et al.*, 2000, p. 25). However, they do not support the collaboration between different disciplines, in particular, the multidisciplinary integration of hardware and software is not supported (Bricogne *et al.*, 2016, p. 78). The design process of the mechatronic system requires a **multidisciplinary** and **holistic development process**.

Product development - when targeting radical innovations – is cross-functional and involves several hierarchical and functional units. The need for a **close collaboration**, especially in the early phase of developments, is undisputed in academia and in practice (Lorenz, 2008, 11, 14). Product development strategies include “Systems Engineering”, "Integrated Product Development", "Model-Based Systems Engineering", “Set-Based Concurrent Engineering / Lean Development" (Lindemann, 2009, p. 14; Diehl, 2008, p. 48 ff.).

Systems Engineering is as an interdisciplinary approach that deals with multidisciplinary design issues, but is limited to gather requirements, establish a functional structure and to propose a preliminary product architecture (Bricogne *et al.*, 2016, p. 78). The theory separates the process of life-cycle-oriented development into manageable parts (Hellenbrand, 2013, p. 57). Product modules are tested at the component level, but the integration with other component sub-assemblies takes place in a bottom-up approach. “Bottom-Up Integration” processes provide feedback to the “Top-Down Development” in terms of design iterations until the required product quality is achieved. **System modeling** is an iterative process of experimental learning, whereby each model serves a clear intent and represents simplified aspects of a complex product. **Documentation** helps in the optimization of the development process. **System architects** learn from failures and save time in future design iterations. Product development is most successful when all stakeholders (e.g. engineers, finance, marketing) are actively involved in the design process. The early **incorporation of interdisciplinary** stakeholders in the design process is a central aspect in integrated product development (Ehrlenspiel and Meerkamm, 2013). (Haberfellner *et al.*, 2002)

Integrated Product Development (IPD) is a goal-oriented combination of organizational, methodical and technical measures / tools that are used by holistic thinking developers (Ehrlenspiel and Meerkamm, 2013, p. 194). The product to be developed is generally understood to be a technical system in the sense of system technology (Ropohl, 2010). **Systems thinking** is based on system engineering, which essentially describes the same basic principle as integrated product development (Chucholowski, 2017, p. 18). IPD primarily focuses on the development of a technical system, while the Systems Engineering deals with any type of system. From a System Engineering point of view, the IPD can be understood as a "bottom-up" approach, starting from the design theory with the **product in the center** (Hellenbrand, 2013, p. 57).

For **Model-based Systems Engineering** (MBSE), system models are used as the central medium for controlling the SE process over all phases. The system is usually modeled using UML (Unified Modeling Language) or SysML. A relevant application of MBSE is to coordinate and synchronize discipline-specific development processes in the phase of domain-specific design (Hellenbrand, 2013, p. 57). An integrated system model provides information about the current state of development for all disciplines. In case of changes, the effects on other subsystems are determinable, which results in an increased transparency and understanding of the system. (Hellenbrand, 2013, p. 57)

Toyota and other carmakers use the agile development process **Set-Based Concurrent Engineering**. This process model fosters the creation of many prototypes during the entire development process. A solution space of design sets is subsequently narrowed down until an optimal solution is found. The methodology supports the elimination of inappropriate solutions and hinders late revisions. This type of development process has made Toyota the fastest and most efficient automaker and is referred to as “Lean Development” or “Lean Innovation”. The Lean principles embrace focus on customer value orientation, continuous improvement, high quality, waste reduction and high integration in a lean value chain. (Link, 2014, p. 66; Lorenz, 2008, p. 45)

3.3.4 Agile Systems Engineering

Agile methods are mainly driven by continuous delivery, while focusing on small iterations. Extensive planning is the basis for traditional approaches such as the V-Model and the lifecycle model. They base on Stage-Gate with strict processes and heavy documentation. Agile approaches are test-driven by nature and assume that a system cannot be specified in advance. Agile principles base on self-organization, customer collaboration and working prototypes. (Stelzmann, 2012) discussed the topic of agile system engineering or agile methods in mechatronics systems, however, only a few examples exist (Böhmer *et al.*, 2017a, p. 2). Large-scale systems, safety and distributed environments challenge the application of pure agile methods. (Böhmer *et al.*, 2017a)

(Klein and Reinhart, 2014, p. 4) differentiates between vertical and horizontal agility approaches. The **vertical agility** approach focuses on the combination of conventional and agile procedures in the intercommunication of disciplines. The horizontal agility approach focuses on the high specialization of disciplines and promotes agile methods for software. According to (Douglass, 2016a), applying the agile Manifesto to Systems Engineering results in incremental working, dynamic planning, active reduction of project risks, constant verification, and continuous integration. (Gloger, 2016, p. 10) states that the strategy of “Agile Engineering” does not focus on the modular product itself and how it is designed, but on its ability to “run”. Agile Engineering focuses on specific work packages and operational steps required for efficient planning and implementation (Klein, 2016, p. 93). (Douglass, 2016a) mentioned that verifiable models are required for agile systems engineering, to allow continuous verification of engineering data. The key benefits of agile methods in systems engineering are as follows (Douglass, 2016a, p. 42).

According to (Douglass, 2016a), early verification improves **quality** of innovation data and product specifications, since the creation of prototypes demonstrates “true” progress. Continuous verification results in less rework (“waste”), and thus in an improved innovation **efficiency**. The progress of agile projects is **tracked** against objectives, giving earlier indications of a project risk or the likelihood of project success. (Haberfellner and Weck, 2005) differentiated between two strategies within agile systems engineering. Agile Systems (Engineering) focuses on the system and its flexible design that can be changed rapidly. Agile systems are highly modular and imply high investment into interfaces and necessary capacity for upgrading a system over its life-time (“Plug`n`Play”). Agile (Systems) Engineering focuses on the development of complex products. Development is characterized by late decision-making, transparent documentation, and an available common knowledge base.

“Design Space Exploration” (DSE) refers to a mathematical development and evaluation of design alternatives during system development (Kang E., Jackson E., Schulte W., 2011, p. 33). A series of prototypes is created to understand the impact of design decisions, while incorporating the dynamics of complex systems (“Rapid Prototyping”). DSE facilitates finding promising assemblies and configurations that meet all requirements (“System Integration”). Design Space is the total number of possible system variants from which the System Designer explores the best possible combination. An effective design space exploration framework should include the following components (Kang E., Jackson E., Schulte W., 2011, p. 34). An appropriate representation of the Design Space (“Appearance”), incorporation of methods to evaluate potential solutions (“Analysis”), creating alternatives until a promising solution is found (“Exploration”).

Changeable Architectures

Changeability of products over product lifecycle gains in importance for products with a lifecycle of more than 10 years, as user requirements change significantly (Gorbea Díaz, 2011, p. 95). The need for changeable architectures result from three key factors (Gorbea Díaz, 2011, p. 95): **Technological change** in mechatronic products, volatile and dynamic markets, and environmental changes. The **development cycles** of mechatronic technologies are significantly shorter than that of the overall system architecture. Staying ahead of the competition includes reducing the gap between design freeze and system delivery. Self-optimizing systems react autonomously and flexibly to changing environments (Gausemeier *et al.*, 2006, p. 62 ff.). The adaptability to a **changing environment** involves incorporation of external product features such as the connection to Smartphone Apps. Such systems will learn and optimize their performance during their product lifecycle.

There are three aspects of changeable systems: **Agile products** are characterized by the ability to be adapted quickly to changing requirements over their life-time (Haberfellner and Weck, 2005, p. 1449). The product takes on new functionality through common interfaces or integrability. **Flexibility** is embedded by adding or modifying individual modules, without causing great change costs or increased complexity (Fricke and Schulz, 2005, p. 343; Haberfellner and Weck, 2005, p. 1450). **Adaptable products** adapt themselves to environmental changes without external actuation. They are characterized by significant initial investment costs (Haberfellner and Weck, 2005, p. 1462).

(Kosiol, 2016, p. 48) outlines five key approaches that are useful to increase the flexibility in product structure: modularization, structuring principles for agile systems, Rapp's product structure management, upgraded product design, and “Open Architecture Products”. The individual strategies do not compete but complement each other and partially overlap. The most important **modular product** architecture strategies are the following: Decoupled Subsystems, Standardized Interfaces, Robustness to Changes (see (Gebhardt, 2012, p. 123; Kosiol, 2016, p. 48; Koppenhagen, 2014, p. 123; Blees *et al.*, 2011, pp. 2, 13, 16)). Dove (1995, quoted in Rapp 2010, p. 70) has defined ten design principles to assist in the development of **agile systems**. The principles are also partially applicable to product structuring. Principles based on the principle of reusability, the principle of reconfigurability, and the principle of scalability (Rapp, 2010, p. 70 ff.).

Product structure types represent **product structures** that are particularly well suited for specific applications (Rapp, 2010, p. 48). The most common product structure types are (Lindemann, 2009, p. 8): modules, building blocks, model series and packages. Platforms are increasingly being used in combination with product structure types. **Upgradeable product design**, design for upgradeability or lifetime flexibilization enables the retrofit of products. It is based on modularization and aims to adapt a product to specific conditions by replacing modules or to extend the functionality and performance of the product over its life-time (Blees *et al.*, 2011, p. 97).

(Koren *et al.*, 2013) defines "Open Architecture Products" that are designed in such a way, so that components or entire modules can be added to the original structure or replaced. The aim is to adapt the functionality to specific customer needs by developing new product functions within innovative modules that can be subsequently integrated into the main product.

4. Need for Agility within Product Development

Based on the current state in research and practice the need for agility within product development is discussed. Missing strategies to integrate the concept of "agile" in the context of mechatronic systems are outlined. As a result, requirements for an agile development of physical products are derived. For evaluation purposes, requirements for an agile innovation strategy are gathered to increase the innovation capability in large corporations.

4.1 Conclusions on the Research Area

"*Organizations […] are constrained to produce designs which are copies of the communication structures of these organizations*." – Melvin E. Conway

Traditionally development processes are based on theoretical "front-loading" and the assumption that a product can be specified upfront. Products usually have more features but no greater usability. This "over specification" is widespread for new products and caused by rigid development processes that attempt to **forecast** all possible features that users might need, or competitors might offer. Traditional process models also do not support an adequate mechatronic product development (Hellenbrand, 2013, p. 1). Mechatronic design processes are sequential and discipline specific and base on organizational models, business standards or IT solutions (Bricogne *et al.*, 2016, p. 76 ff.).

Digitization leads to dynamic systems that are affected by different development and technology cycles, but also by **new business** markets. **Innovation** is driven by the **short life cycle** of some technologies, and companies face constantly **changing** customer **needs**. The speed of development has become a decisive competitive factor, and the high innovation and technology dynamic leads to **uncertainty** in the planning and specification of future products. In this context, traditional (product-) developments methods have a **limited effectiveness**, wherefore the incorporation of new ones is required (Gürtler and Lindemann, 2016, p. 484). To design innovative mechatronic systems an **intensive collaboration** between engineers from **different domains** is required (Lefèvre *et al.*, 2014, p. 130). Electronics and software represent an increasing part of the final product, and common **interdisciplinary design approaches** must be proposed. To avoid unnecessary long innovation processes, current development processes need to become leaner, agile, and more fast-paced (Thomke and Reinertsen, 1998, p. 11).

"Agile" is a **lightweight** methodology with only a few rules and practices that assumes that the success of products depends on placing a working product in the users' hands (Smith, 2007, p. 36). **Rapid feedback** allows a team to develop the most **valuable features** and to incorporate product changes early in the development process. **Fast-paced markets** are mastered by iterative and rapid design of products with the latest features customers desire and expect (Ro and Fixson, 2008, p. 218). According to (Haberfellner and Weck, 2005, p. 1450), agile systems engineering follows the idea that agility (in the sense of flexibility, adaptability, etc.) is based on both, the **course of action** (= development process), as well as on the **result** (= realized system).

The term “agility” describes a team`s competency or rather a company's **ability** to remain nimble, changing and updating operations as innovations become available. The notion of **adapting** is central to understanding why agile approaches are so effective for **product innovations**. Agile teams rely on continuous (re)planning and product adaptation based on feedback and past iterations to minimize the risk of a “wrong” product being launched too late. According to (Yusuf *et al.*, 1999), change is the main driver for agility in product development. (Mollbach and Bergstein, 2014, p. 8) state the following four central drivers are primary causes for the need for a company to develop and realize the ability of being “agile”:

1. Increased **competition intensity** in the industry and market of the company.
2. Many and rapid **technological changes** in the industry and the company`s market.
3. Frequent and abrupt changes in **customer needs** and behavior in the company's market.
4. Continuous and rapid change of **environment** and general conditions (e.g. fast and unpredictable changes in legislation, have a great impact on the corporate development).

Agile processes accommodate changes by welcoming new or changing requirements for each iteration. Traditional **front-loading** is reduced to a minimum, and continuous user feedback gains in importance. Iterative prototyping is an important success factor in the early phases of product innovation. The need for large projects is minimized in order to lower the risk of projects. Critical hypothesizes are tested, and new insights are incorporated into the ongoing development process. A feature that seemed important at the beginning of the project might be bumped repeatedly and never make it into the final product.

For established companies, “agile” has a lot in common with **startup practices**. Companies experiment with “Scrum”, “Lean Startup” and “Design Thinking” to shift from “Stage-Gate” to iterative and agile process models. Agile development requires organizational and cultural aspects, such as commitment and excitement to form a dedicated cross-functional team. (Conforto *et al.*, 2014b) outline **internal capabilities** that favor the proper use of the management practices critical for agility (see Appendix A5). **Agile teams** are fully allocated, face end-to-end responsibility and have a certain scope for decision-making. Such high-performance teams benefit from “T-shaped” persons, who have a deep knowledge and strong **skill-set** in one area but are able to **collaborate** beyond their area of expertise in other disciplines.

“Agile” is most effective and easiest to implement, when the solution is initially unknown, the work can be modularized, and a close collaboration with users is feasible to acquire rapid feedback. Both, innovation projects and agile projects are an **act of learning** that adapt the current approach of implementation. They build on cumulative **knowledge** throughout the project phases, reducing **uncertainty** along the way. Development projects start with a **vision** that is achieved in several iterations for which product properties are evaluated early. Prototypes represent the progress towards the product vision that is driven by continuous feedback loops. The product evolves from abstract to concrete while implementing and testing only relevant aspects of the whole system.

Digital products create a unique interaction between user and product allowing immediate testing of ideas. The **assumption-based** product development is shortened, and product properties are evaluated with the user quickly. However, agile development of **physical**

systems has to date been explored and only a few examples on industrial applications exist in literature (Bricogne *et al.*, 2016, p. 81).

The aim of this research is to understand the **agile development** of mechatronic systems. To this end, a reference model has been developed and tested in close collaboration with the interdisciplinary consortium involved in the lab. course "Think.Make.Start.[18]" (TMS). Based on the findings, strategies are derived to integrate and evaluate the concept of "Agile Product Development" in a complex mechatronic development environment (see Figure 4-1). Based on identified internal barriers and associated enablers an "Agile Innovation Strategy" is derived to increase the **innovation capabilities** of the OEM. Concrete actions that support the implementation of agile projects within the traditional development process are outlined. The concept is derived from the fields of innovation management, systems architecting, and organizational aspects.

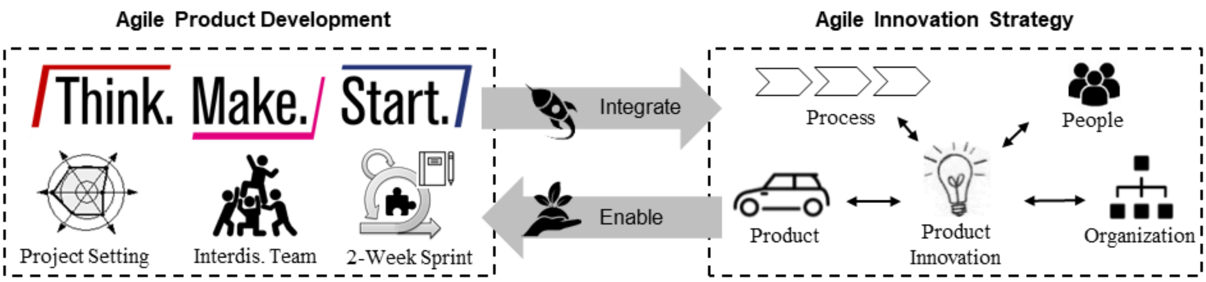

Figure 4-1: Overview of the two main objectives of the research approach.

First, the necessary elements of agile development of physical systems are to be examined. In accordance with (Conforto *et al.*, 2014b), TMS represents an agile project setting that benefits no development task, but uncertainty about the product to be build. According to the understanding of "agile" being more of a team competency, the focus is on interdisciplinary teams that comprise a skill-set that matches the product to be build. During the 2-week development sprint, the students are taught both, traditional and agile methods to elaborate a hybrid mixture as suggested by (Blöchl, 2013, p. 81). The students are encouraged to create many prototypes and perform early user tests to derive a result-driven development approach for mechatronic systems.

Second, the concept of agile development of physical products is evaluated in the innovation context of an OEM. "Agile" works best for innovation projects, as they are typically uncertain or complex. To understand the complex context of the OEM, the innovation capability and several innovation projects are analyzed. Based on the identified potentials and challenges, a strategy is derived to enable agile innovation projects. The strategy addresses all relevant levels of the corporate (e.g. product, process, people, and organization). The previously defined agile elements are integrated into the context of the OEM to remove internal barriers. An adapted version of TMS is evaluated with employees from different divisions to increase the innovation capability.

[18] Think.Make.Start. is an interdisciplinary lab course at Technical University of Munich

4.2 Requirements for Agile Product Development

"*If I'd asked my customers what they wanted, they'd have said 'a faster horse'.*" – Henry Ford (according to (Brown and Kātz, 2009, p. 39))

Based on the state of the art and research, an **agile process model** unifies the product and process view of a product. An **innovation object** shall support the shift from a planned phase view of the processes to an object specific perspective. By the creation of different **prototypes** and a creative atmosphere the process shall evolve over time. To overcome the limitations of low fidelity prototypes, a high-tech workshop (e.g. Makerspace) shall be integrated to exhaust the possibilities of rapid prototyping practices. The creation of prototypes should not be limited by a discipline but address a **mechatronic system**.

Agile development is assumed to be **limited in time**, and therefore, only focuses on relevant aspects of the product to be developed. For each development sprint, the approach must facilitate an interdisciplinary team formation that is aligned with the necessary **skill-set** for the product to be build. The approach shall promote dedicated teams to explore the design space and allow iterative (re)planning and adjusting of the project (e.g. reviews with relevant stakeholders). A **project setting** is to be defined that favors the proper use of agile methods and resource-efficient prototyping practices. The approach should be flexible in project duration and frequency to foster not only creative concepts, but also **feasible or marketable products**.

The focus is on **product innovation** and the early phase of the innovation process. The user is central for the evaluation of product properties but enhanced by technical aspects and market viability. To allow a **system** to evolve over time, necessary team roles are to be found (e.g. systems architect). The implementation of subsystems should be based on the level of uncertainty and focus value-adding features. To develop complex products, the approach should balance the use of agile and systematic methods. Such a **hybrid model** comprises control and planning mechanisms, necessary for the development of physical systems. Thus, agile frameworks (e.g. Scrum), are to be enriched by traditional development methods (e.g. VDI 2221).

4.3 Requirements for Agile Innovation Strategy

"*If the rate of change outside exceeds the rate of change on the inside, the end is in sight*" – Jack Welch (CEO, General Electric)

A large company is not a big startup; the essential feature of **startups** is the uncertain environment and the inherent processes (Kühnapfel, 2015, p. 3). Startups often use innovations to exploit unique opportunities in **market niches** (Brinkmann, 2009, p. 24). Startup practices are characterized by limited availability of financial and human resources (Freiling and Kollmann, 2015, p. 7). The Agile Innovation Strategy takes inspiration from startup strategies to manage the **fuzzy-front** end of product innovation. The aim is to overcome internal barriers (e.g. legacy corporate structures, politics, and culture) for a limited time frame to increase the innovation capability of the corporate. The idea is to create a **startup-like atmosphere** to incentivize entrepreneurial employees, and to implement "Venture Capital-like" decision criteria. Non-incremental innovation is promoted, and the isolation of the innovation team should be dependent on degree of innovation as well as project maturity.

Innovation is a joint product of several people and departments with different expertise, background and experience. The innovation strategy shall mobilize the whole group and foster close collaboration across silos. The power is given to small teams to promote flexible communication paths and low bureaucratic efforts. Therefore, strategies must consider **dynamic resource allocation** (e.g. more spontaneous project staffing). Strategies are to be found to form self-managed, user-focused and interdisciplinary teams. Such teams must be limited in time and comprise both, technical and entrepreneurial know-how. Top management needs to be involved to in triggering new behaviors and establishing a “fail-friendly” environment to cultivate a learning culture and to encourage continuous improvement (vs. authority-driven decision-making).

The innovation strategy shall enrich the current strategic foresight with an entrepreneurial shortsight to explore new opportunities, while meanwhile exploit the current business. It should be built upon existing strategies (e.g. Skunk works ®) and make use of the **company strengths** (e.g. knowledge and resources) to compete with agile startups, when leaving the established path. Dedicated innovation teams shall churn out innovations faster and accelerate profitable growth. The cost-intensive and **assumption-based** product development should be shortened by the creation of **early prototypes**. Based on direct user feedback, agile teams shall develop the product "desired" to speedily capitalize on the technology advancement. The compatibility with plan-driven Stage-Gate-models must be ensured, while shifting the focus onto **value-driven activities** for agile teams. Innovation teams shall be independent but aligned with the overall innovation management.

5. Agile Product Development

This chapter summarizes the findings of seven Makeathons at the Technical University of Munich (TUM). The applied 10-day development sprint unites experts from various disciplines and allows studying product development in an agile project setting. It provides a free playground and freedom of choice of inputs about business and engineering methods as well as prototyping practices. The understanding of agile engineering is elaborated and deepened by the exploration of the design space. Based on the idea of "agile" being more of a "team's competence", an agile project is characterized to explain the agile process view. A human-centered, prototyping framework is derived from 75 mechatronic products that balances agility with stability. It leverages systems design and is based on many prototypes, thereby allowing continuous adaption to the current situation. The main findings are summarized in two enablers for agile development of mechatronic systems.

5.1 Definition of Agile Engineering

Agile Engineering starts with a problem/idea and an initial **product vision** (see Figure 5-1). The vision describes the desired result and determines the direction of the project. It is important that all persons involved in the project acknowledge the vision and orient themselves towards it (Goll and Hommel, 2015, p. 100). The vision serves as a superordinate goal, and hypotheses are derived from it. This "validated learning" is characterized by **user-centered design** and **visual thinking**. Prototypes allow direct user interaction and triggers thought processes (Grots and Pratschke, 2009, p. 22). A physical manifestation enables efficient communication between interdisciplinary developers (Haberfellner *et al.*, 2015, p. 96). The process of validated learning is supported by **self-organization** that should be managed moderately. It is as an adaptive process that should be guided systematically to not end up in "agile chaos". For self-organized teams, the resources are provided by the project-carrying organization but managed independently.

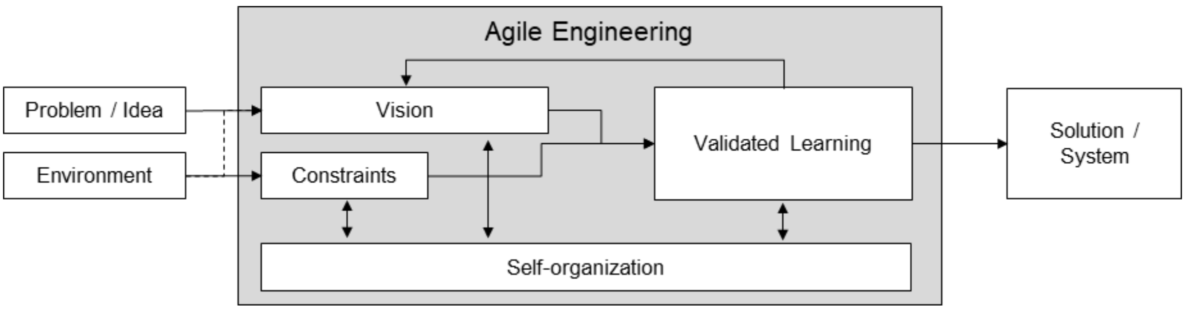

Figure 5-1: Relationship within Agile Engineering (Gerling, 2016, p. 59)

The minimum system plays a central role, representing the simplest form of the product idea, based on the **information available**. The aim is to reduce uncertainty with minimum time and effort by testing the hypothesis to learning from the feedback. The increase in knowledge is to be maximized for each iteration. The learning process can include system functions, customer requirements, pricing and distribution channels (Ries, 2011, p. 46). A simple system with minimum functionality adds new functions step by step and is evaluated with relevant stakeholders. Each iteration generates knowledge that is incorporated into the next iteration (Ries, 2011, p. 69).

In the following account, the concept of Agile Engineering is opposed to several frameworks, relevant for this thesis. The evaluation is bases on the following criteria, derived from the previously outlined characteristics (see (Gerling, 2016, p. 59 ff.)). A **vision** is supported if a **rough objective** is formulated at the beginning of the project. The elementary design is called when the **smallest possible unit** is started. **Learning by iteration** refers to the regular planning of goals or learning contents to be achieved in a certain period and the results of which are fed into the next iteration. A **human-centered design** is followed when the development steps are reflected with the user. **Design thinking** is when the development process is supported by **visual or haptic elements**. **Self-organization** is supported if there are guidelines showing the team how it can organize itself.

The characteristics of the considered frameworks, in terms of the defined criteria, are shown in Table 5-1. Negative or obstructive influences is indicated by "-", indifferent characteristics are identified by "o". Strong influences are expressed by "++" and less strong by "+".

Table 5-1 Correlation of agile approaches to Agile Engineering, adapted from (Gerling, 2016, p. 62).

	DT	LS	Scrum	MPM	Makeathon	XP	VDI 2221
Vision	o	+	++	+	+	o	o
Creation of elementary	++	++	+	+	++	++	o
Learning by iteration	+	++	++	+	+	+	+
Human-centered Design	++	+	+	o	o	o	o
Visual Thinking	++	o	+	+	+	o	o
Self-organization	o	o	++	+	+	+	o
DT: Design Thinking, LS: Lean Startup, MPM: Munich Procedural Model, XP: eXtreme Programming							

Vision: In Design Thinking the vision is a “problem-solution-fit” that is created by emphasizing people to derive their user needs. Lean Startup aims for a Minimum Viable Product that is adapted during the development and facilitates maximum learning. Scrum explicitly describes a “Product Vision” that serves as a common goal for the project team and represents the desired result of a product. The MPM comprises methods to create a product vision. The goal of a Makeathon is to implement the product vision within the limited time frame. XP and VDI 2221 do not mention a product vision.

Creation of elementary: In Design Thinking, extensive paper prototyping and quick visualization foster the construction of elementary. Lean Startup comprises the idea of an elementary structure in the definition of a MVP. Scrum develops “Product Increments” for each iteration. Tracing the MPM back to (Rodenacker and Schäfer, 1978), prototypes are created early in the development (German: “*Handversuche*”). Makeathons are all about prototyping, just as eXtreme Programming. VDI 2221 focuses on high fidelity prototypes, late in the development.

Learning by iteration: The Design Thinking process is iterative and flexible. The “Build Measure Learn” cycle at Lean Startup implies iterative (re)planning. Scrum bases on iterative “Sprint Planning” for each iteration. The network structure of the MPM allows a flexible adaption of the process associated with new insights gained. For Makeathons iterative “Trial-and-error” approaches are necessary to deal with limited resources. XP and VDI are based on iterations, however, these iterations describe the development per se and do not focus on learning aspects.

Human-centered design: Design Thinking incorporates aspects of empathic-design and explicitly focuses on the user. Lean Startup and Scrum indirectly focus on the user. However, the user is accustomed to evaluating product properties (“Build-Measure-Learn”) or is represented by a “Product Owner” that prioritizes user-relevant features. The MPM, Makeathon, XP and VDI 2221 do not provide information about user-centricity.

Visual thinking: Design Thinking fosters visual thinking to trigger thought processes in the development team. At Lean Startup there is no indication for visual thinking. Scrum visualizes the project status at the “Scrum Board” to actively involve all team members. The MPM comprises visual methods (e.g. 6-3-5-Method). Makeathons are typically characterized by sketches and simple prototypes as the focus is on implementation and not on documentation. Neither XP nor VDI 2221 mentions visual tools during the development.

Self-organization: Design Thinking and Lean Startup do not mention self-organization of the team. Scrum supports the self-organization by team autonomy and specific project roles. MPM facilitates self-organization using development methods that guide a team through the project. Makeathon and XP require self-organized teams but promote this status only by an autonomous project setting.

In conclusion, none of the approaches fully supports the characteristics of the Agile Engineering, but only partial aspects thereof. However, problem- and person-dependent **agile elements** can be chosen from the various approaches.

5.2 Exploration of the Design Space

Systems Engineering deals intensively with requirements to identify the context and performance variables. Once identified, these are assumed to be **static**. The design space is concretized from the outside ("from rough to detail") and the concept is detailed (Haberfellner *et al.*, 2015, p. 59). This approach becomes challenging when the context and performance variables change during development. The design space cannot be changed easily, due to a comprehensive definition of the overall concept.

For **Agile Engineering**, the context and performance variables are initially not further specified and thus kept **abstract**. Context and performance variables are similar to the constraints and requirements described in the Systems Engineering. However, the term “variable” expresses here that they can change during development. The aim of the context and performance variables is to limit the actual design space. They describe the "what" as well as its limitations.

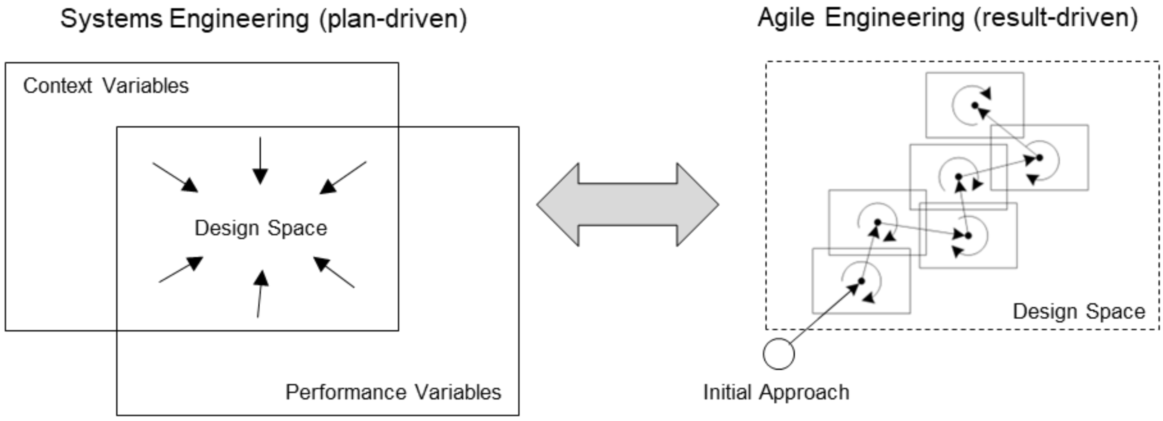

Figure 5-2: Exploration of the Design Spaces for Systems Engineering and Agile Engineering.

Agile Engineering is an **iterative** form that is determined by means of variation and selection measures (Szinovatz and Müller, 2014, p. 111). Starting from an initial approach (e.g. idea, hypothesis), the **design space** is explored from the inside to the outside (see Figure 5-2). Context and performance variables are flexibly adapted to the situation. The information gained from an iteration determines the search direction or the space for the next iteration (Haberfellner *et al.*, 2015, p. 58).

The main difference is the problem-related and solution-related **assessment of information**. In Systems Engineering, the information acquisition in the initial phase (problem identification and requirements specification) is mainly problem-oriented. For the subsequent solution development, the information acquisition is primarily solution-oriented (Haberfellner *et al.*, 2015, p. 79). The information acquisition for Agile Engineering is characterized by a constant **interplay** between **problems** and **solutions**. This iterative approach is ideal for **novel projects** that comprise high uncertainty about the problem and solution space (Haberfellner *et al.*, 2015, p. 214). Essential is the change from convergent and divergent or problem-oriented and solution-oriented thinking (Link, 2014, p. 81) for learning iteratively (see Figure 5-3).

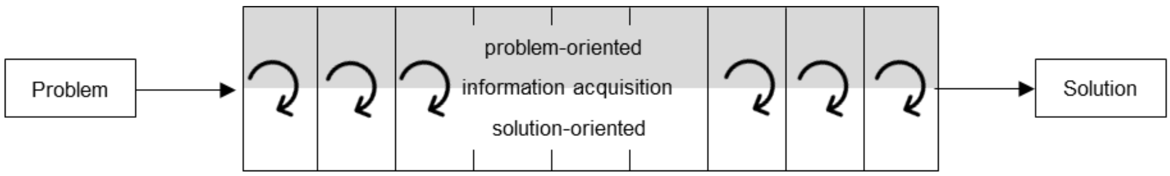

Figure 5-3: Information acquisition in Agile Engineering (following (Haberfellner et al., 2015, p. 72)

Rarely teams find better solutions or new products through familiar routines, which is why a variety of methods and heuristics exist to explore the solution space (Haberfellner *et al.*, 2015, p. 242). Agile Engineering is characterized by a limited solution space, a starting point for the exploration, strategies to find the solutions as well as creativity (Haberfellner *et al.*, 2015, p. 242 ff.). Search strategies are distinguished into systematic, heuristic and mathematic approaches (Haberfellner *et al.*, 2015, p. 245 ff.).

Systematic search strategies are used to scan the solution space while focusing on the most promising ideas (Rittel, 1992, p. 78). According to (Haberfellner *et al.*, 2015, p. 245 ff.), search strategies are categorized into linear procedures, non-optimizing strategies, single-stage optimization and multi-stage optimization. **Cyclic search strategy**, as illustrated in Figure 5-4, tries to solve a problem with an initial solution. If the current approach does not give any indication of a desired result or hinders the solution of other problems, one returns to the starting point. With the knowledge gained, the search for possible solutions restarts, which ultimately results in a gradual scanning of the solution space (Rittel, 1992, p. 78). The concept of **constant adaptation** and responsiveness to empirical findings and the re-adapting of the strategy ultimately make agile approaches successful (Goll and Hommel, 2015, p. 10).

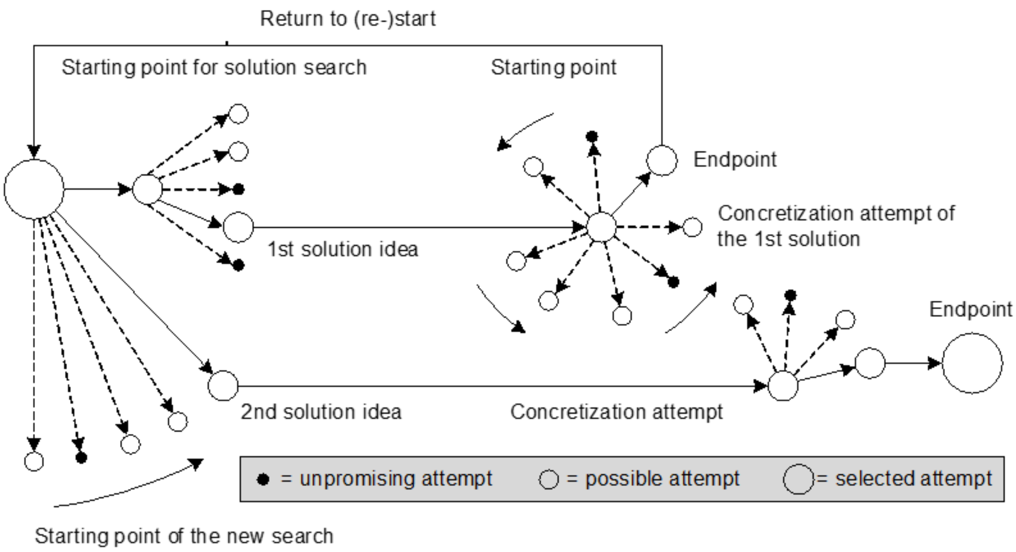

Figure 5-4: Cyclic search strategy following (Haberfellner et al., 2015, p. 248), referring to (Rittel, 1992).

Systems and Agile Engineering require creativity to generate solution variants, which are supported by the use of methods. These **methods** range from non-systematic (“trial-and-error”) to systematic strategies (Haberfellner *et al.*, 2015, p. 245). Variant formation is promoted by a morphological box, whereas agile methods have a stronger focus on visual or haptic interaction through prototyping to stimulate creative processes. System Engineering characteristics are compared to Agile Engineering in Table 5-2.

Table 5-2 Design space exploration of system and agile engineering (Gerling, 2016, p. 73).

Characteristics	**Systems Engineering**	**Agile Engineering**
Limitation of the solution space	requirements and boundary conditions	initially kept open
Start for search of solutions	from the outside to the inside	from the inside to the outside
Search strategy	single-stage optimization	cyclic ("scanning process")
Creativity	supported by methods	

Prototypes take on new roles in agile product development, which go beyond the validation of functionalities. Teams are more successful when prototyping **earlier and more often** (Jang and

Schunn, 2012). Prototypes are used to **communicate ideas**, generate user feedback, explore further designs, and help with **decision-making** (Menold *et al.*, 2016, p. 73). **Physical prototypes** have a greater potential for exploring the solution space than virtual ones (Elverum and Welo, 2015)

5.3 Prototyping for Systems Development

In **engineering**, prototyping is part of **system development** and prevents engineers from moving too quickly to a high-resolution, "pixel perfect" design (Haberfellner *et al.*, 2015, p. 73). Prototyping efforts help to keep the solution space open to react to changing requirements or boundary conditions. The **optimal level of fidelity** is the **minimum amount of fidelity** needed for project progress. In this context, the term "Pretotype" occurs, being a preliminary stage to the prototype. The **Pretotyping Manifesto** by (Savoia, 2009), is to evaluate ideas with minimal effort and in direct interaction with the user. It triggers the tipping point, when the effort of prototyping becomes greater than the learning. The pretotyping values are as follows:

- Innovators beat ideas
- Pretotypes beat prototype
- Doing beats talking
- Simplicity beats complexity (number of features)
- Now beats later
- Commitment beats committees
- Data beats opinions

A common misunderstanding of these values is that pretotyping is dine in absence of a specific goal or plan. However, these values represent the **mind-set** necessary **to prototype** and **learn** efficiently and effectively. In agreement with the "Flexibility Index" of (Smith, 2007, p. 197), learning is an quotation of the time needed for evaluation and the necessary development time:

$$Learning = Evaluation\ Time\ /\ Development\ Time \quad (5.1)$$

This metric is useful for **design sprint evaluation** but does not work for highly iterative cycles (Smith, 2007, p. 197). Prototypes are used to gather relevant information and to manage the **level of detail** needed. Prototyping efforts without learning are a waste in effort, which is why different **types of prototypes** are used for the achievement of different objectives. The "Wizard of Oz", for example, fakes product features to gather user feedback cheaply and early. Before investing a huge amount of time and resources, such a prototype tests the desirability of a feature first. A high degree of modularization facilitates **changing or adding features** (Böhmer *et al.*, 2016). There are several companies providing open-source electronic **prototyping platforms** enabling users to create interactive electronic objects (e.g. Arduino®).

In design theory, the **embodiment process** is to make needed information available. (Ullman, 2010), for example, states that the **proof of feasibility** for a new product is often exclusively based on the design engineer's knowledge. According to (Bernard, 1999, p. 56), components which "carry" the property to be evaluated must be brought quickly to a **provisional embodiment** degree which enables a decent **early evaluation**. Embodiment prototypes express

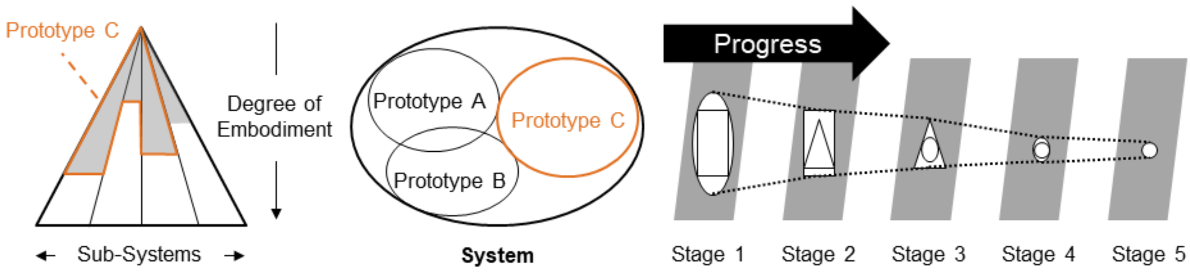

Figure 5-5: Prototypes represent a degree of embodiment of several subsystems, to increase design freedom during development progress, according to (Andreasen and Hein, 1987; Bernard, 1999; Haberfellner et al., 2015).

a design concept in sufficient detail to test the idea in hardware. According to (Andreasen and Hein, 1987), the **embodiment degree** of different **sub-systems** can be inhomogeneous (see Figure 5-5). This **inhomogeneity** is related to software or hardware components of a system, for example. For complex products, this systems architecting is inevitable in order to evaluate the complete product in an efficient manner.

5.4 Human-centered Design

Everyone has their own perspective of the world – their own version of reality, which one accepts as truth. Biases define the (limited) perspective of a designer and the **understanding** of the user. Engineers typically have an **over-engineering** perspective, narrowing their view angle based on technology and corporate requirements. Especially experienced employees tend to become “naysayers” due to their knowledge about why changes are not possible or hard to implement. By consciously looking at background characteristics of users, the designer’s view angle is broadened. **Empathy** as perspective taking ability is necessary to understand a foreign culture, and their implications, for example. This advanced understanding of the user’s world can lead to important insights, which are relevant for the solution space, and eventually, for the final solution. (vonUnold, 2017, p. 66)

The **Human-centered design** approach is a problem-solving process that starts with people and their problems and results in solutions that address their needs. It is rooted in an iterative and creative process and emphasizes the use of prototypes for inspiration and user feedback. As shown in Figure 5-6, **innovative solutions** are desirable, feasible, and viable. Human-centered design starts with the users’ needs to detect what is most desirable. Subsequent, the technological feasibility and financial viability is tested and achieved iteratively. Eventually, all the three aspects must be considered, as successful and sustainable solutions are achieved in the **sweet spot** of desirability, viability and feasibility. (Kelley and Kelley, 2013, p. 19)

The term “user-centered design” is often used instead of human-centered design (Cockton *et al.*, 2016; Humayoun *et al.*, 2011). Since humans do not only include user, but also other stakeholders, user-centered design is considered as a subset of human-centered design that positions the end user of a solution at the center of the design (Humayoun *et al.*, 2011, p. 55). For this work, design thinking, empathic design, participatory design, inclusive design and

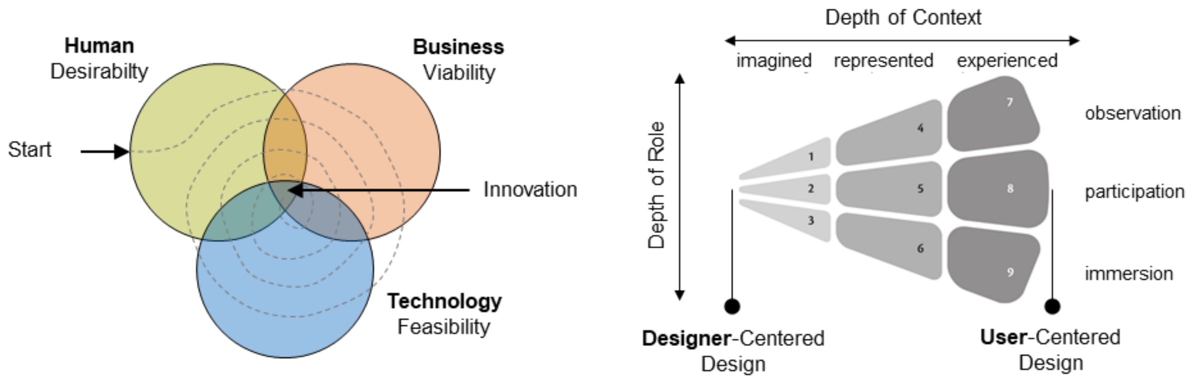

Figure 5-6: Project path of human-centered design (left) and design radar of design research methods (right) (vonUnold, 2017, 10, 24).

universal design are defined as subsets or variations of human-centered design (vonUnold, 2017, p. 12).

According to the work of (vonUnold, 2017), design research methods are segmented with the **design radar** (see Figure 5-6). The abscissa represents the depth of context. On the left are methods like brainstorming, which are based on the imagination of the designer (cells 1-3). Methods that rely on secondary data are in the represented section of the radar (cells 4-6). Here, documents and statistics are used. User research that enables a direct contact with users is located on the right of the design radar (cells 7-9). In the ordinate, the depth of the role of the designer is expressed. As opposed to participatory methods, observational methods are the ones, where designers observe the users as a bystander and do not participate in the life of the user. In the immersion-fields, the designer enters the world of the users to see it from the user's perspective. (vonUnold, 2017, p. 24)

5.5 Linking Theory and Research Practice

Think.Make.Start. (TMS) is a product development seminar in the form of a **Makeathon** at Technical University of Munich in partnership with UnternehmerTUM GmbH[19]. TMS was introduced in 2015 and has been held twice a year since then. Every semester, the course brings together ~50 master students from TUM. Team size is limited to five students and comprises at least three representatives of the **four core departments** (Mechanical Engineering, Electrical and Information Technology, Informatics and the School of Management). Students work on their own product ideas for **two weeks**, daily, in interdisciplinary teams. The teams develop a **functional prototype** that addresses a specific **user need** and comprises a **feasible business model**. All participating teams benefit of a prototyping budget of 400 EUR and have free access to the MakerSpace at the TUM campus. The 1,500-square meter high-tech workshop provides a variety of rapid prototyping and manufacturing tools.

[19] UnternehmerTUM - Center for Innovation and Business Creation at TUM

TMS represents an agile project setting that is based on the central values and principles presented in Chapter 3.2. The aim is to identify **agile elements** that are relevant for an interdisciplinary team aiming to develop mechatronic products collaboratively. The outcome of each TMS batch is a collection of **agile project paths** that give information about the (agile) methods used and the artifacts generated. Therefore, the documentation of each TMS-team is analyzed, and the results are confirmed by interviews and observations. For each team, the prototyping roadmap is elaborated in order to understand the agile development characteristics in the mechatronic context.

Table 5-3 gives an overview of the seven TMS-Makeathons that took place between 2015 and 2018. An overview of the **75 mechatronic products** that have been created during the seven generations of Think.Make.Start., is outlined in Appendix A6. The success of the course is underlined by ~10 startups having been created after TMS (e.g. Hawa Dawa[20], ParkHere[21], Kewazo[22], or Solos[23]).

Table 5-3: Overview of the TMS batches with correlated number of students and projects.

Time Frame	Batch Number	Number of Applications	Number of Students	Number of Projects
18.03. - 31.03.2015	TMS #1	51	43	9
29.09. - 12.10.2015	TMS #2	63	45	10
30.03. - 12.04.2016	TMS #3	126	53	10
05.10. - 18.10.2016	TMS #4	140	50	10
29.03. - 11.04.2017	TMS #5	182	68	12
04.10. - 17.10.2017	TMS #6	150	50	10
14.03.- 27.03.2018	TMS #7	248	80	14

5.5.1 Characterization of an Agile Project

For the introduction of a pure **agile process model**, known control and planning mechanisms might become redundant. Such uncontrolled activities can end up in an "agile chaos", which is why agile models are mostly used in practice as a hybrid or selective (Komus, 2014, p. 84). A flexible and mixed use of agile and traditional frameworks and their methods is important for agile product development for **interdisciplinary projects** (Boehm *et al.*, 2010, p. 187). (Meinzinger, 2017, p. 28)

The objective of an **agile project** is the exploration of the design space. The problem-solving approach is guided by methods, which are derived from frameworks. These frameworks comprise several process steps with regard to the overall product development process (see Figure 5-7). Different values and principles correlate to the different frameworks. Design

[20] Air quality monitoring system, see https://www.hawadawa.com/

[21] Self-powered parking sensor, see http://park-here.eu/

[22] Intelligent robotic construction system, see https://www.kewazo.com/

[23] Instant visual feedback training system, see http://solosmirrors.com/

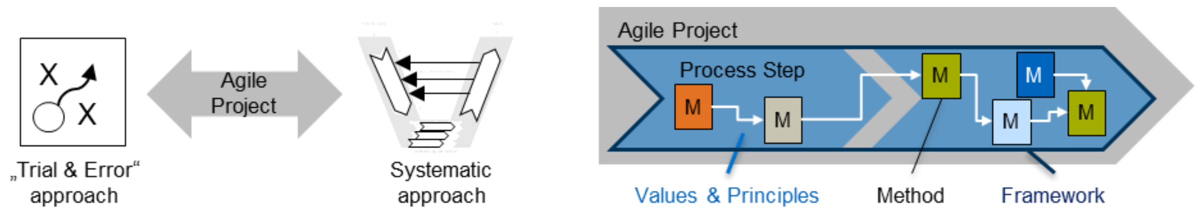

Figure 5-7: Characteristics of an agile Project, adapted from (Böhmer et al., 2016, p. 921).

Thinking, for example, focuses prototyping as a thinking tool, whereas the V-Model fosters systematic thinking. According to the literature, the terms are defined for this work as follows:

- **Framework**: It provides the scope within which a project team can move freely (Brandes *et al.*, 2014, p. 77). A framework contains values, principles and methods, which are usually linked to each other or are modularly connected to one another. Each framework combines a set of elements that support the problem solution and can be supplemented or modified in an undogmatic way (Haberfellner *et al.*, 2002, XXIII). The term "framework" expresses the **comprehensive character**.
- **Values and Principles**: Each framework includes certain values and principles. Principles are more concrete than the values and thus bridge the gap between the agile values and the methods. Principles contain the logical structure on which the problem solution is oriented (guidelines).
- **Method**: According to (Lindemann, 2009), the term "method" describes a rule-based and planned procedure, according to which activities are carried out to achieve a certain goal. In contrast to the values and principles, methods and methodologies are concrete procedures, which can be applied using clear instructions and the right tools. Often, they represent a formalism that determines how steps are to be carried out and / or how work results to be documented (Lindemann, 2009, p. 57).

For agile product development, the use of **methods** facilitates the creation of the “right” **artifacts** and supports the “right” **prototyping** activities. As with prototypes the use of method

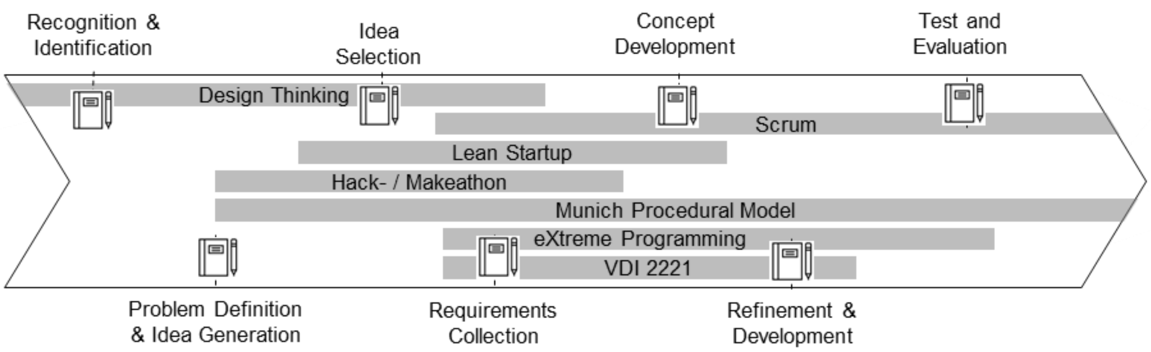

Figure 5-8: Derivation of methods from different frameworks covering a generic innovation process, adapted from (Beckmann, 2015, p. 5; Meinzinger, 2017, p. 29).

refers to a designer specific situation. To find a **happy medium** between trial-and-error and systematic approaches, methods are derived from more agile frameworks (e.g. Design Thinking) and more systematic frameworks (e.g. VDI 2221). The methods are assigned to the respective process phase that reflects a typical development situations (see Figure 5-8) (Lindemann, 2009, p. 36 ff.). This allows a reconfiguration with regard to the agile process model, discussed in Chapter 3.2. The methods catalog guides the teams to manage the experimental approach without getting lost in "agile chaos" (Nagl, 2016, p. 43).

5.5.2 Agile Process Model for Physical Systems

Agile development projects are characterized by many artifacts being created. **Artifacts** contain all the information that is required for product development. These information carriers are either physical / tangible or virtual / immaterial. **Methods** and accompanied tools and skills support the development or modification of artifacts. Figure 5-9 illustrates an agile procedural model that bases on the creation of artifacts. According to (Hammers, 2012), the procedure model defines "who" is responsible for the creation of artifacts (product model) at "which time" artifacts are to be created (process model). Likewise, it specifies different **roles** that are required to perform certain activities. For the development of mechatronic systems, the sum of artifacts is gathered in a **prototype** that brings together domain-specific **knowledge** in a system.

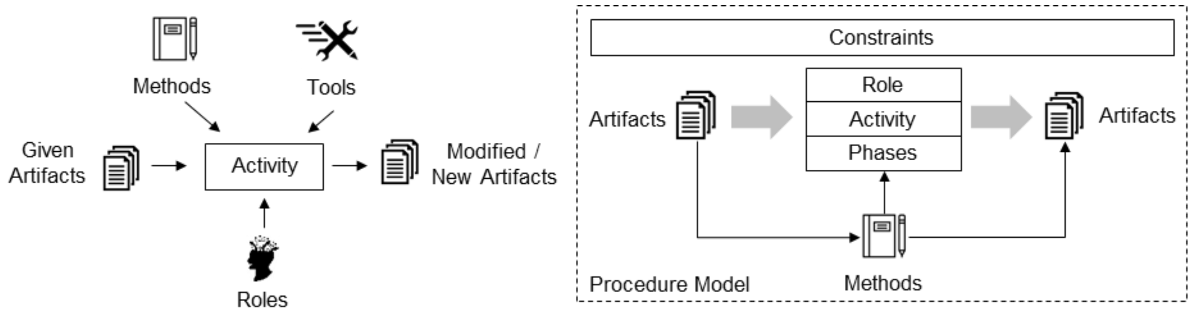

Figure 5-9: Elements of an agile procedure model following (Fischer et al., 1998, p. 17; Hammers, 2012; Balzert, 2009, p. 443; Meinzinger, 2017, p. 14).

Agile process models do not focus on long-term planning, but the user and the interim results have the highest priority (Goll and Hommel, 2015, p. 55). Requirements are initially roughly defined and detailed with the project`s progress (Gnatz, 2005, p. 23). Agile approaches focus on adaptability and flexibility, which is why unpredictable events are consciously accepted (Link, 2014, p. 74). The entire development is divided into sections within the individual development phases in the absence of a fixed sequence (Oestereich, 2008, p. 19). Agile projects are strongly characterized by the **implicit knowledge** and **skills** of the team (Cockburn, 2002, p. 7).

For physical systems, the creation of prototypes are an important factor (Gurusamy K. *et al.*, 2016, p. 36). Prototypes are the bridge between iterative-incremental and agile process models, presented in Chapter 3.2.3. For complex physical systems, **systems architecture** and the **changeability** of a system is crucial for successful implementation. Agile process models for physical systems can only be realized by virtualization (e.g. “Digital Twin”), a high degree of modularization or by a prototypical representation. The system is detailed from a rough vision, and requirements are specified with each prototype implementation (Goll and Hommel, 2015, p. 55).

Figure 5-10 illustrates the frequency of artifacts and prototypes created for the example of the fifth batch of TMS (TMS #5). The projects are standardized to eight iterations to allow a comparison across all teams. An iteration ends, whenever the objective of the prototyping activities shifts. The graph shows that within one iteration, several stages of the generic innovation process are passed. The number of **artifacts** is divided into **three larger blocks** (indicated by different colors). The first block refers to the steps involved in the first three phases of the generic innovation process and extends to iteration 4. The second block starts in iteration 4 and covers the last three phases from “Concept Development” to “Test and Evaluation”. The third block is assigned to the process phase “Requirement Collection”, and artifacts are created from the first iteration until the end of the project. These artifacts are a connection or **transmission element** between the product idea and the detailed product itself. These artifacts are categorized as **containers** as they support the team with consolidation of information and give an overview of the development for each iteration. They facilitate cost-efficient and hypothesis-based efforts for the project. Making and using prototypes as **experimental objects** is constant over all iterations. For further details on methods used and artifacts created, see (Meinzinger, 2017; Kamprath, 2017).

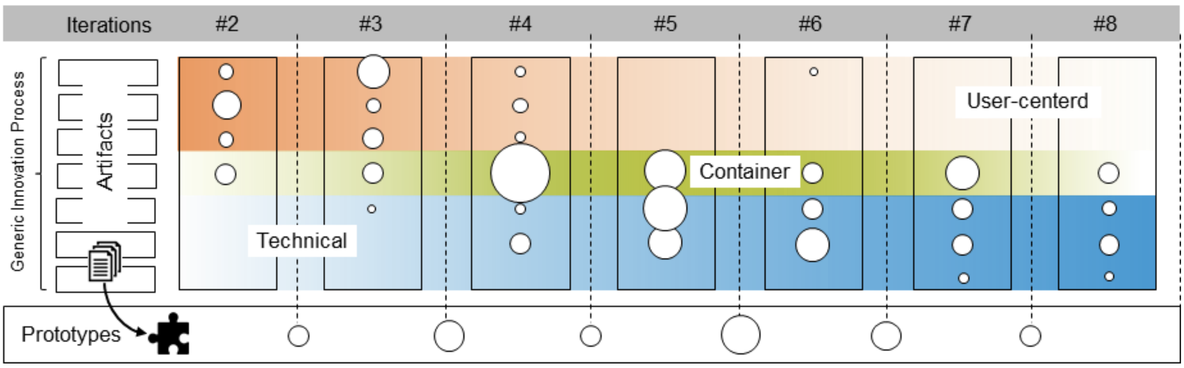

Figure 5-10: Number of artifacts created during TMS #5 in an agile process model (Böhmer et al., 2017b, p. 3).

5.5.3 Prototyping as a Thinking Tool in Design

Results from seven iterations of Think.Make.Start. revealed that three factors influence the **prototyping results**: prototyping experience and knowledge, community input or support, and building the right prototype for where or what the project is (see Figure 5-11). Usually, one

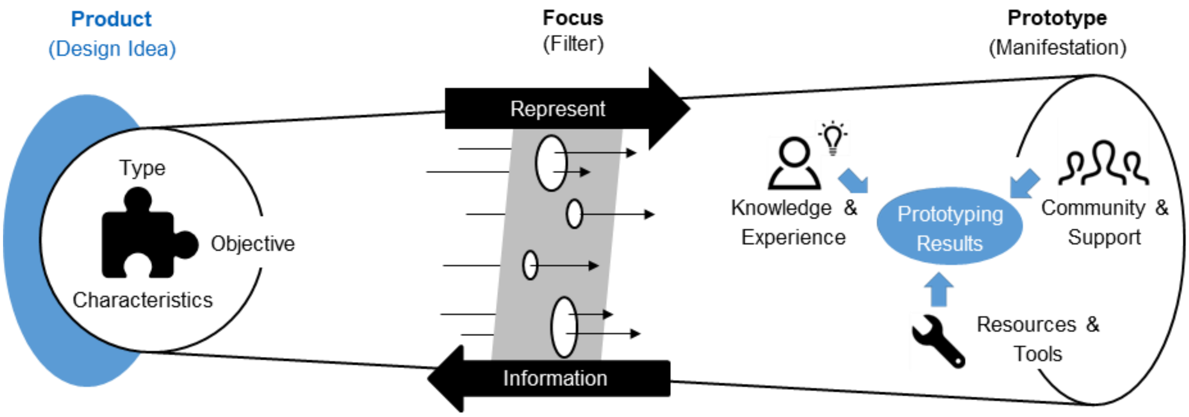

Figure 5-11: Factors affecting prototyping results, adapted from (Kayser, 2015, p. 71).

prototype is not enough, but more prototypes are necessary to discover the complete solution space from **several perspectives**. It is not possible to assign a specific prototype to only one discipline. However, interrelations between the **different types of prototyping** are found within the involved disciplines. Referring to (Exner *et al.*, 2015), a multiple dimension of the prototyping strategies is investigated with regard to **specific perspectives**:

- Objectives (e.g. explorative)
- Characteristics (e.g. material)
- Type (e.g. Real-Scale Prototype)

In the early phase of the innovation process, prototypes visualize ideas or create a basis for a common understanding. At later stages, prototypes support the understanding of product complexity and aspects to be explored. The implementation characteristics of the prototypes depend on the hypothesis to be tested and are assigned to a certain type of prototype. Paper Prototypes are used at the beginning of the development process to answer basic questions. These low-fidelity prototypes are characterized by simple materials. For more sophisticated hypotheses, more complex (high-fidelity) prototypes are created (e.g. CAD model). The overall goal of the prototyping approach is to test hypotheses in a **resource-efficient** manner.

It has also been shown that the use of prototypes varies from team to team, depending on what is important for the development of the product. Each prototyping activity fulfills an important purpose in the **learning process** of the development team. Prototypes are an important tool to obtain information, make decisions and to plan the next step in the design process. Prototypes are used to involve user or other relevant stakeholders and to manifest the status quo (e.g. knowledge, understanding, expertise, point of view, …) (Zink, 2017, p. 16). This strategy allows one to keep track of a complex project across-domains.

The analysis of the product development projects at Think.Make.Start. found five different reasons to prototype that are in accordance with (Chua *et al.*, 2010, p. 5) and (Ulrich and Eppinger, 2016, p. 296–299). Prototypes are used as follows:

- **Support** the thinking, planning, experimenting and learning process of a team.

- **Testing** and providing ideas for the development with the aim of checking if it works as expected.
- **Facilitate** and support the communication of information, team internally (e.g. interdisciplinary collaboration) and team externally (e.g. user feedback).
- **Synthesize** the product concept by integrating the various components and subassemblies.
- **Demonstrate** that the product has achieved a desired level of functionality.

The data allow the conclusion that a prototype is specifically created to obtain concrete knowledge. In total, there are only **five knowledge combinations** that are related to: desirability, desirability and feasibility, feasibility, feasibility and viability, and none (Zink, 2017, p. 40). The teams created prototypes which have suitable proportions and dimensions for the available analysis environment (small space, reduced loads, changed climate). The prototypes are simplified in detail, to **maximize learning**, while **minimizing** necessary **time and effort**. Only those features of a product which are essential to the study are modelled. At one point the prototype is made to the original size, to avoid size-scale effects. Prototype characteristics are within the limited resources (material, budget, time, personnel, knowledge and equipment). Available **skills** are the key factor for prototyping practices as team have no time for an in-depth research or very sophisticated designs. An across-team knowledge exchange and a "best practice" discussion support the team individual performance.

5.5.4 Result-Driven Development

Agile product development is characterized by specifying results and measurable objectives the development team wants to achieve. Prototypes show the progress towards a vision that is driven by the results. To examine the prototype alignment during an iteration, the model of horizontal and vertical prototyping is used, referring to (Mackay and Beaudouin-Lafon, 2012; Elverum and Welo, 2015). **Horizontal prototypes** are all those that are used for testing and exploring a design. It is intended to compare different designs and thus to gather information for selecting the best option. **Vertical prototypes** are used to further develop, detail and optimize the selected design in technical aspects. They focus on the "best" implementation of a design variant. It is also possible that a prototype has effects on both levels; it moves, so to speak, diagonally.

For the example of TMS batch 5, the prototypes assigned to a specific iteration are separated according to their horizontal and vertical focus (see Figure 5-12). A shift from horizontal to vertical was detected over the development process. Prototypes, built in the first two iterations, all had a horizontal component. Afterwards, the share decreased within every iteration. In iteration 7 and 8, 20% of the prototypes showed a horizontal focus. The reverse was the case for the vertical prototypes. While in iteration 2, only 4% of the prototypes were vertical, in iteration 7 and 8, every prototype had a vertical focus. The prototyping roadmap from horizontal to vertical is similar for all seven TMS-Makeathons, only the shift from horizontal to vertical varies between iterations 4 and 6 (see (Woche Buccini, 2018; Kamprath, 2017; Bachmeier, 2016)).

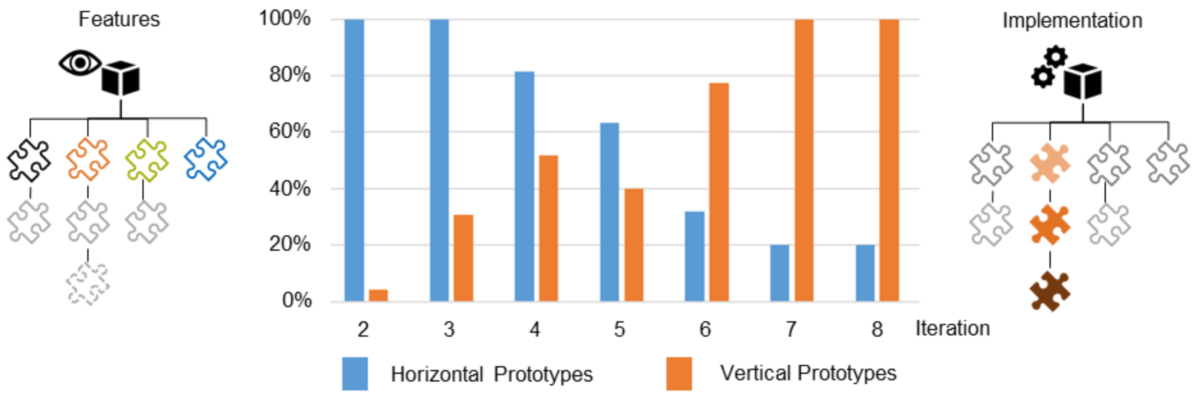

Figure 5-12: Horizontal and vertical prototypes during TMS #5 (Zink et al., 2017), following (Mackay and Beaudouin-Lafon, 2012; Elverum and Welo, 2015).

The shift from a horizontal to a vertical is also aligned with the product architecture that is initially **highly modular** and becomes more integrated at the end of the Makeathon. With development progress, design exploration becomes less important, and the focus shifts towards a detailed implementation of the design. The data illustrates the importance of horizontal prototyping even in later stages to **adapt** the product concept because of new findings. Horizontal prototypes facilitate diverging the problem-solution space, whereas vertical prototype promote diverging. (Zink, 2017, p. 40)

A link between exploratory prototyping, the horizontal alignment and the simplified material of the prototypes was found. Teams used **exploratory prototypes** to a large extent to explore the solution space, especially at the beginning of the development. The teams created many **simple** prototypes during these phases and focused on a **fast** and **cost-effective** implementation. The frequent use of simple prototypes for **testing** and researching **design variants** is evidence of the use of prototypes in the **learning process**. As the development progresses, the prototyping purpose is related to the **vertical** alignment, and the focus is now on **validating** and **optimizing** a selected design. Teams also intuitively combined **multiple objectives** for a prototype. Only the combination of exploratory and technical objectives was never used simultaneously in any prototype. This again underlines a clear transition phase from exploration to specification in agile product development.

At the systems level, the product- and process-specific view merge and the system evolves iteratively. Product properties and the necessary process steps are identified within the course of the development. Horizontal prototypes are used to identify critical functionalities for the main feature set of the complete system. These agile subsystems usually are not domain-specific but unite all domains (e.g. software, electric and electronics, and mechanical engineering). The specification and arrangement of these subsystems are done by vertical prototypes. The “balanced approach” of horizontal, modular systems design and vertical, integration is identified as powerful in order to gain knowledge about unknown or risky properties. The decomposition of the product with respect to the early evaluation of its critical subsystems, is relevant where the subsystem…

- properties are highly relevant to the user

- is usually developed with a high degree of process integration
- is heavily integrated into the overall system
- is part of a very complex overall system (Bernard, 1999, p. 42).

The evaluation of interdisciplinary subsystems is facilitated by the creation of prototypes. However, domain-specific evaluation is facilitated by the creation of artifacts. Development methods support the creation of the "right" artifacts and structure the evaluation of more advanced prototypes.

5.5.5 Agile Toolbox – Balancing Creativity and Discipline

Design teams face three types of problems when including prototyping practices in design. Teams are not **aware** of the user background, for example, because they do not think about it. When they are aware of it, some teams have problems in **understanding** the user and the correlating of the user situation. Some teams fail to **integrate** the insights gained into the product, being biased by individual skills and competencies. Integration of methods and prototyping practices requires both, awareness and understanding. The awareness lays the foundation, and the integration eventually ensures that prototyping aspects are considered in the product (Ehrlenspiel, 2003, p. 27).

Based on the seven iterations of TMS, an "Agile Toolbox" is derived that comprises development methods, prototyping strategies, and mind-set cards (see Figure 5-13). In total, 231 methods, 90 prototyping strategies and 37 mind-set cards are found that reflect the applied methods or strategies in the projects and correlate with the final product. A detailed list of development methods, prototyping strategies, and mind-set cards is listed in Appendix A7.

The development methods are assigned to the **process** of the innovation project, whereas the prototyping strategies are assigned to the **product** and the mind-set cards to the **people**. The use of methods allows a situational adaption of the development activities and facilitates to broaden the teams` points of view. In alignment with the findings of (vonUnold, 2017), prototyping strategies are assigned to the category of discovery, enlightenment, and integration, to support the exploration of the problem-solution space (see Figure 5-13). Prototyping for discovery helps teams consciously to think about the user background and to reduce biases in terms of bias awareness, for example. Prototyping for enlightenment support the understanding

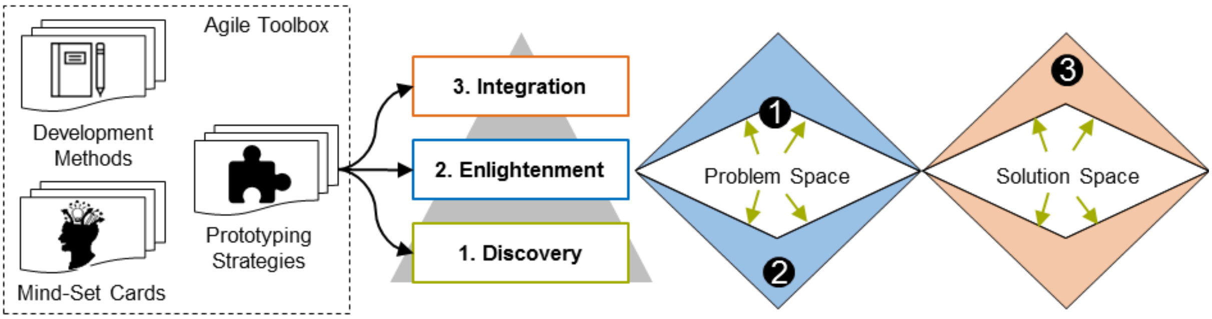

Figure 5-13: Agile Toolbox to explore the problem and solution space, adapted from (vonUnold, 2017, p. 75).

of the user or the requirements of a system. Prototyping for integration facilitate the translation of user insights into technical specifications and product features (vonUnold, 2017, p. 74 ff.). The identified mind-set cards help to internalize the values and principles of a startup or agile project (e.g. “to build to test not to last”) as discussed in Chapter 5.1.

5.6 Agile Development of Mechatronic Systems

Many innovation **projects fail** due to uncertainties in the development process (Gaubinger *et al.*, 2015). Late clarification of technical feasibility, for example, of a new product being implemented at reasonable cost is a common reason for failure in late stages. To deal with increasing **uncertainty** early in the process, agile projects address new user needs and incorporate **new technologies** continuously (Link, 2014). Companies experiment with agile frameworks, however face the challenge of limited effectiveness of such approaches within given (organizational) structures (Hostettler *et al.*, 2017, p. 788). A **holistic framework** is needed to structure an agile process model into individual design sprints.

5.6.1 Makeathon – In 10 Days from Idea to Prototype

Think.Make.Start. represents the process from idea to prototype within 10 days in form of a Makeathon. Key characteristics of the Makeathon include **time pressure**, early user tests, and team competition in an open but collaborative work environment. The TMS-Makeathon focuses on project-based learning, while empowering the team and values execution over planning. A prototype represents partial aspects of the product to be built. Prototypes are a process until the product stabilizes, and the team is certain that the minimum set of implemented features satisfy a particular need / solve a problem. The participants build and test various prototypes in an intense and creative atmosphere. The aim is to focus on the most relevant questions to capture the essence of the product vision.

The TMS-projects are a **co-evolution** of technology, product and business models to ensure all relevant aspects of a successful innovation. To achieve this, the prototyping approach is inspired by the Design Thinking process by “d.school” (Stanford University) and the Munich Procedure Model by (Lindemann, 2009) at TUM. The project setting follows principles of Scrum by (Gloger, 2016), and business aspects are incorporated by Lean Startup by (Ries, 2011). The students are taught both, traditional and agile methods. The agile mind-set is transferred through **hands-on** learning and rapid prototyping strategies. The intense 10-day setting of Think.Make.Start. requires an intense **collaboration** of the students from different disciplines. The course starts every morning with a daily input session about relevant product development aspects. The input sessions comprise a selection of methods that are in alignment with the three dimensions of a successful innovation: Desirability (e.g. User Stories), Feasibility (e.g. morphological box), Viability (e.g. Lean Canvas). During the day, the teams **work independently**, and the coaches inspire and challenge the teams with regard to project execution. The coaches represent the four core departments and accelerate the learning process of the teams.

Each day concludes with daily progress presentation where each team discusses the challenges they are facing, how they overcame past challenges and what is planned for the next day. The latest prototyping activities and **lessons learned** are presented in the plenum, providing the teams an opportunity to gather feedback on their approach. This transparent project situation also helps to set the context for the coming day's work and allows for individual feedback from coaches on the team's specific situation. This feedback also leads to new ideas, helps to get different perspectives on the product and triggers an open knowledge exchange across teams. (Woche Buccini, 2018, p. 22)

The agenda of TMS comprises four phases that are not assigned to concrete development steps but guide the teams holistically (see Figure 5-14). Prior to the Makeathon, a "PreEvent" takes place, where all participants meet each other, while identifying problems worth solving. The PreEvent takes place in a specific environment to experience the user in a real-life setting. The aim of the PreEvent is to identify an initial "Problem – Solution – Fit". A fit is achieved, when (a) the team has identified at least 12 users stating they must have a solution for the problem the team is trying to solve, (b) another 12 users stating that the initial solution is a "must have" and (c) at least 5 early adopters are willing to pay for 1 feature of the solution. The PreEvent initiates the interdisciplinary team formation with **complementary skills** to achieve the product vision. The time until the start of TMS is declared as the research phase to verify the identified needs and to get an overall picture of the topic area.

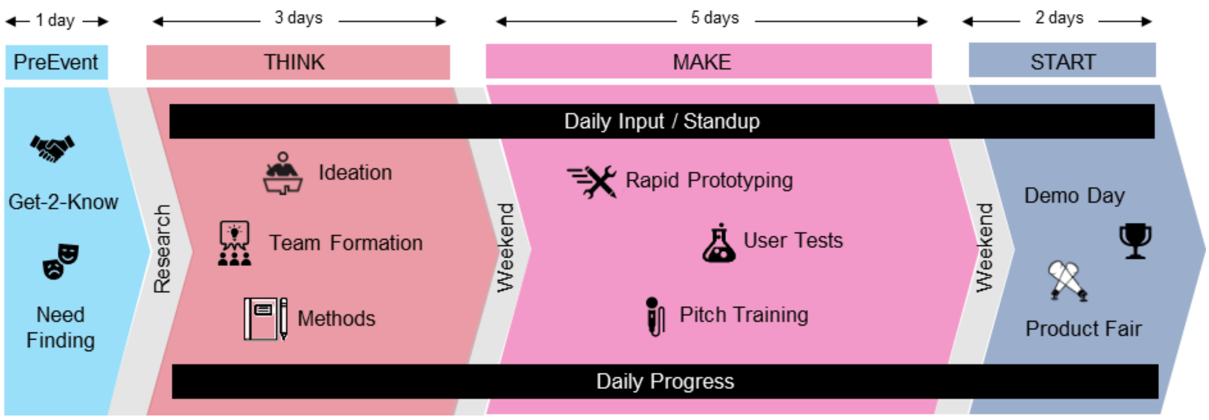

Figure 5-14: Think.Make.Start. course schedule at Technical University of Munich.

The **"Think" period** serves as a reference point for the next days and guide the students through the overall TMS approach. The phase starts with an ideation session that builds on the insights of the PreEvent and promotes an "Idea – Team – Fit". The ideation and team formation are a fluent process that is inspired by Design Thinking methods (e.g. User Journey) and creativity methods (e.g. 6-3-5 method). Each team receives an introduction into agile approaches (e.g. Product Increment), identifies critical hypothesis to be tested and learns how to undertake user tests. The teams plan and assign their daily task using the "TMS Project Board" (see Appendix A8). The project board helps the team to visualize their progress and lessons learned so as not to not get lost in "agile chaos". At the end of the phase, the participants learn basic development methods (e.g. functional modeling) and get an introduction into best prototyping practices.

The **“Make” period** is the central element of TMS and fosters three goals: 1) early development of working soft-/hardware, 2) iterative prototyping and user tests and 3) flexible reaction on (user) feedback. The MakerSpace facilitates rapid prototyping and a “Hardware Library”, comprising standard technologies (e.g. Arduino ®), allows a quick creation of prototypes. The prototyping budget is free to be used for the project specific hardware. The input sessions focus on business aspects (e.g. ballpark costs) and startup aspects (e.g. Landing Page). Students have a team individual pitch training and define their “Problem – Solution – Fit” more precisely.

The **“Start” period** initializes the grand finale of TMS, the public “Demo Day”, where the teams present their final and working product ideas to up to ~300 visitors. For this event, the teams are forced to bring the design and testing together in one working prototype. There are three awards that represent the “best” idea (“Think” award), the most sophisticated implementation (“Make” award) and the most promising team (“Start” award). Startups, industry representatives, investors, and members from academia are invited to serve as a jury for the “Think” awards. Based on the teams’ overall progress, final prototype and pitch performance, the remaining two teams are awarded. The **winner ceremony** rewards the teams for their non-stop effort and triggers networking.

5.6.2 Framework for Agile Development of Mechatronic Systems

Agile Engineering bases on **experimental learning** and converts information into design knowledge. Active experimentalists test their beliefs through external activities and then use reflection to examine and manipulate gathered information within the team (Berglund and Leifer, 2013, p. 6). Prototyping frameworks proposed by (Christie *et al.*, 2012) or (Camburn *et al.*, 2014) define prototyping strategies as a “set of decisions” related to **business and engineering actions**. (Menold *et al.*, 2016) incorporate **user-centered design practices** in a prototyping framework. However, existing prototyping frameworks do not focus on the whole product related to its feasibility, desirability, and viability. Factors such as user perceived value, manufacturability, and market entry are to be considered in order to **decrease uncertainty**.

Based on an intense literature review and the iterative learning process through the 75 development projects of the TMS-Makeathons, the agile prototyping framework, “TAF”, has been derived (see Appendix A9). The essence of TAF is to optimize the learning iterations for individual projects. Based on the findings in Chapter 5.5., a Product Increment is represented by different prototypes that combine the created artifacts of several process phases. The micro and macro logic of TAF are illustrated in Figure 5-15. The agile framework structures prototyping activities and the creation of artifacts using development methods during each design sprint. The sum of artifacts results in a prototype that represents certain aspects of the product to be build. On operative level, the framework follows the PDCA cycle by (Deming, 1986). On the project level, TAF refers to design sprints, which allows an easy incorporation into existing linear models, since it is applicable to different development phases.

TAF starts with a product vision and the main goal is to **reduce uncertainty** on relevant aspects of the product with limited time and resources. The aim is to identify the main feature set that makes the product most desirable and to solve only the critical (most uncertain) functionality that is required to implement the product idea. After successful evaluation of the individual

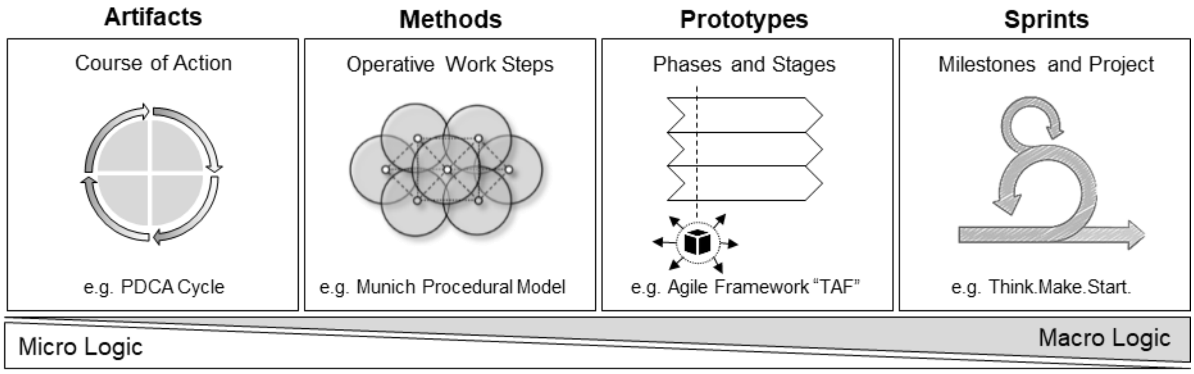

Figure 5-15: Micro and macro logic of the agile framework "TAF", following (Lindemann, 2009, p. 38; Braun, 2005, p. 29; Gnatz, 2005, p. 22).

functionalities, the product is to be integrated in an appealing design. The approach maintains flexibility in design through prototyping, which allows one to adapt the system and to react to changing conditions. Thus, the framework features **four core elements** that are structured by a PDCA-cycle (see Figure 5-16). The underlying **mind-set** of TAF focuses on continuous improvement to increase the product quality. With each iteration (PDCA-Cycle), an embodiment stage is achieved that specifies the product but maintains the solution space as much as possible. The creation of artifacts is facilitated by the use of methods and results in prototypes that bundle domain-specific knowledge.

TAF helps project teams to manage the experimental approach of agile projects within a limited time frame. The starting point for TAF is a "Problem – Solution – Fit" that addresses relevant user needs and comprises specific hypothesis to be tested (see Figure 5-17). In alignment with the aspects of a successful innovation, TAF comprises three PDCA cycles by (Deming, 1986). Referring to human-centered design, TAF starts with a desirability cycle that is followed by the feasibility cycle and concludes with a viability cycle. The feasibility cycle depends on at least one desirability cycle to derive relevant functional requirements. The viability cycle depends on a completed feasibility cycle to estimate market relevant costs (e.g. manufacturing cost)

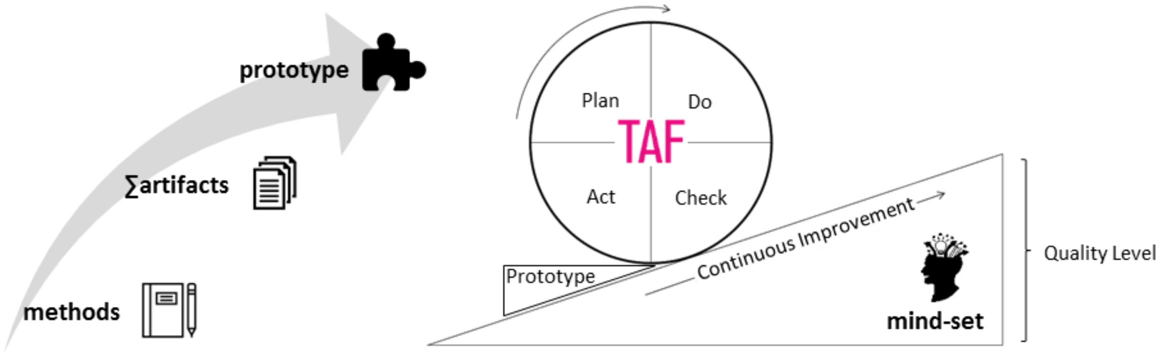

Figure 5-16: Core elements of agile prototyping framework (TAF), adapted from (Deming, 1986).

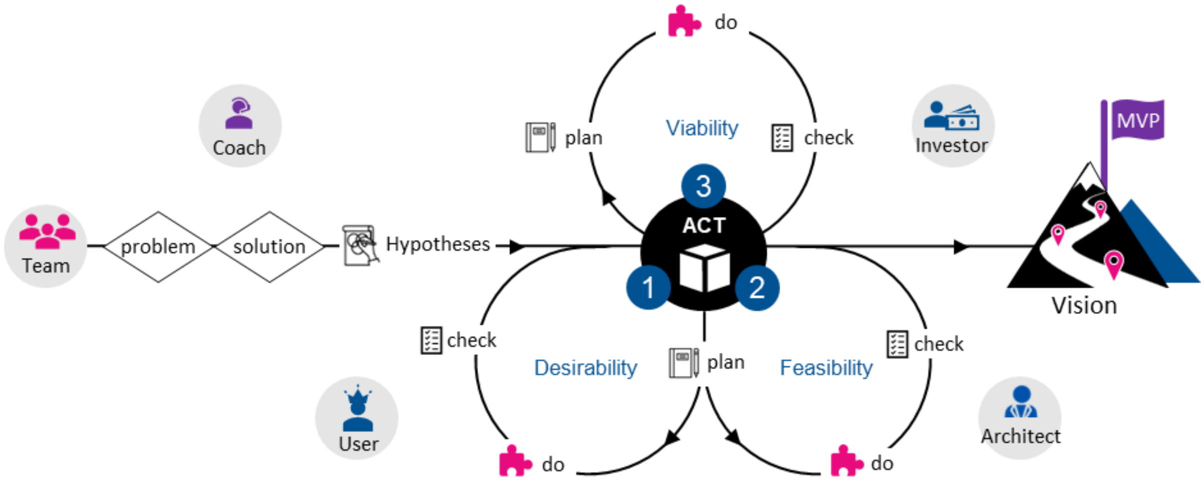

Figure 5-17: Agile prototyping framework "TAF"; approach and roles.

(Hostettler *et al.*, 2017, p. 792). Each cycle creates or modifies existing artifacts and fosters the creation of prototypes, representing the joint knowledge of the interdisciplinary team.

For the two-week sprint at TMS, every team documents their development approach using Google Drive folders that are aligned with the three PDCA cycles. For each iteration, the team documents the methods they used (Plan), their prototyping activities (Do), the evaluation of the hypothesis to be tested (Check), and the lessons learned, or decisions made (Act). The aim of the **desirability cycle** is to create prototypes that explore the design space with regard to added user value of a product. The **main feature set** is to be identified by the creation of simple prototypes (e.g. paper prototypes). Desirability prototypes focus on user interaction and are typical **low fidelity** prototypes. Feasibility prototypes help to understand the overall systems, its components and key sub-systems, relevant for the main feature set. Based on previously gathered user insights, the required **critical functionality** is derived and is most uncertain when implementing the overall product (feasibility cycle). The criticality depends on both, the team competency and technological possibilities. Basic assumptions of the business environment are validated in the **viability cycle**. Viability prototypes test the fit of a product into time and budget constraints, for example. The "act" phase is the central **integration point** of gathered information and facilitates **decentralized decision-making**. For interdisciplinary teams, the "act" phase shapes the overall systems architecture and merges highly modular products into an attractive (integral) design, for example. The remaining uncertainty, being a function of the product vision, achieved results and tested hypotheses, is to be evaluated for the next iterations, and necessary **resources are allocated**, accordingly. The creation of prototypes as the team moves through the cycles is critical and requires continual revisits to product specifications when going through creative and technical phases.

Prototypes play an elementary role in agile development and are used in any form and at every stage of the innovation process. They serve primarily as an experiment to obtain important information and conclusions. Even in the early phase of idea generation, a simple cardboard model can be made, which is then passed on to potential customers for feedback. The focus is on developing a product that **delivers value** to the customer (Brown and Kātz, 2009, p. 20).

Inexperienced teams create many prototypes that are not fit for the purpose they are intended to serve. The selection of the procedure is mostly intuitive and arbitrary. The development of “false” prototypes causes a great loss of time, as they comprise a high degree of detail or trigger misleading feedback (Rhinow *et al.*, 2013, p. 6; Christie *et al.*, 2012, p. 2). For TAF the **product** to be developed is considered as **holistically** taking into account the user, the business and the technical perspective throughout all process phases (Spreiter, 2017, p. 121). While building and testing different product models, the team learns about the user and continually adjusts the product to be developed. The result then provides a product that solves a user need and is successful on the market. (Woche Buccini, 2018, p. 13)

5.6.3 Exemplary Project Description

The developed framework is outlined for the exemplary TMS-project: “SOLOS”. The purpose of this description is to demonstrate the Makeathon format, the developed agile framework, as well as the outcome of the project results. The iterative development is not time-dependent or component-dependent but related to the purpose of the prototype. An iteration ends whenever the objective that is being tracked changes. The interdisciplinary team met at the 4th batch of Think.Make.Start. (TMS #4) and identified the following **user needs** at the PreEvent. It is challenging to teach children how to brush their teeth properly, and adults are stressed out to browse “how to`s” on the mobile phone, for example. The initial **solution idea** was to develop a „Smart Mirror” that features interactive tutorials to teach a person, “how to tie a tie” or explain to children “how to brush their teeth properly”, for instance. Based on personal preferences, the mirror displays news, calendaring or weather information. The **team** consists of three computer science students, an electrical engineer and a business administrator. The **vision** of SOLOS was to develop an interactive and customizable Smart Mirror for daily use cases at home. While achieving a “Problem-Solution-Fit”, the team learned about other relevant use cases for gyms and Kindergartens. The corresponding **hypotheses** to be tested with prototypes were as follows:

1. People would like animated tutorials (e.g. tie one`s tie)
2. People would like a Smart Mirror in a Kindergarten
3. People would like a Smart Mirror at a gym
4. People need customized interactive mirrors (e.g. news banner)

Figure 5-18 illustrates the prototyping approach of team Solos, aligned with the overall focus of the three development loops of TAF. When entering the **desirability loop**, the team prepared semi structured interviews (“Plan”) at Kindergartens, consumer electronics stores, shopping centers, child care centers and fitness studios. In parallel, they did a market and competitor analysis of similar solutions (e.g. Magic Mirror). They identified the following features: news, calendar, alarm clock, face recognition, virtual dressing in shops, and health predictions.

The team made their idea come alive (“Do”) with a **paper prototype**, made of card board, an aluminum foil, pictures and some post-its. The prototype features represent exemplary use cases to test the corresponding hypothesis (e.g. play tutorial “how to …”). The team conducted 12 interviews with parents, kindergarteners and child care nurses. Moreover, the team interviewed 21 persons at several fitness studios. The prototypes were presented to 18 (tech-affine) persons at customer electronic stores to receive generic feedback on hypotheses 1 and 4.

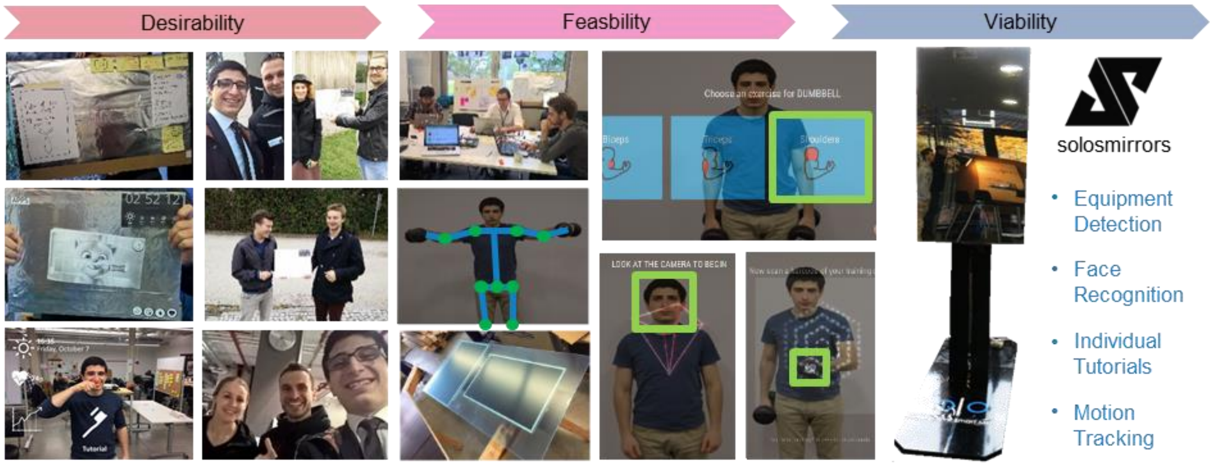

Figure 5-18: Extract of the prototyping approach of team "SOLOS" at TMS #4.

The feedback on the desirability prototypes ("Check") was very positive; hypotheses 1 and 4 were partly confirmed, hypothesis 2 declined and hypothesis 3 confirmed. The team **learned** that 8 out of 12 parents would like animated tutorials. However, no one wanted the children to be exposed to more digital offerings. The team got 90% positive feedback from gym users, trainers and gym managers on their idea of a Smart Mirror at the gym. Including the remaining interview results, the team concluded that there is a clear need for customized interactive mirrors, and these would be nice to have at gyms.

For the next steps ("Act"), the team gave up on highly individual customer preferences and decided to focus on promising use cases of Smart Mirrors at the fitness studios. During the questioning, the team captured several requirements of an intelligent mirror at a gym (e.g. fitness tracker). The team refined their problem-solution-fit towards an **interactive Smart Mirror in fitness studios**. The team captured the following insights into a Lean Canvas: At the gym, support and assistance is an important part of training, however, the availability of trainers is often limited and expensive. A Smart Mirror could do a real-time analysis of workout postures, provide instant feedback, track individual user progress and adapt to the current user habits when exercising.

Entering the **feasibility loop**, user stories were framed to translate the user needs into product specifications ("Plan"). The team started research on gym tutorials, a competitor analysis and explored technical aspects (e.g. object and face recognition) to implement the most promising features. The research findings were gathered in a requirements list. The team identified a competitor that implemented a touchscreen in the equipment and another direct competitor that used a 3D camera system that determines body orientation. To check the hypothesis about fitness studio specific product features, semi-structured interviews were prepared.

The first (functional) prototype ("Do") featured face recognition to identify a user and sport equipment via a QR-Code. The second (geometric) prototype was made of Plexiglas with two monitors being installed in the back. The size of the prototype was in alignment with upper body movements and comprised a pulse-sensor, speakers, and a microphone. A Kinect[24] ® was integrated to measure health condition and sense motions. To conclude, the prototype could recognize customers' faces, sport equipment, customers' movements, show specific tutorial videos and measure the angles of the persons` movements.

The team conducted 32 qualitative interviews with the functional prototype in different fitness studios ("Check"). The feedback was very positive, and the team agreed on a Smart Mirror for gyms that guides, measures and tracks users' training progress. Based on the good feedback on the proof-of-concept, the team started to explore viability aspects ("Act"). The competitor analysis revealed that Smart Mirror must be less than 5.000 EUR to outdo competition and be attractive for fitness studios. The unique selling proposition (USP) of SOLOS is to track the users` fitness profile via a Smart Mirror and offer individual work-out tutorials.

When entering the **viability loop**, the team captured market-relevant information about their product using the Lean Canvas ("Plan"). They estimated ball park cost with respect to a revised feasibility prototype. The team set up a Landing Page with a first Mockup to demonstrate the Smart Mirror features and to acquire pilot users. They finalized their logo and started the market research to identify sales channels. The team prepared a Pitch Deck outlining their product features: equipment detection, face recognition, individual tutorials, real-time motion and training progress tracking. They estimated a market size of 9.5 million members in Germany with 4.8 billion EUR revenue from the fitness industry in Germany.

The next steps, after TMS involved a pilot study with a revised proof-of-concept prototype ("Do & Check"). Following this, the team planned to proceed with a high-fidelity viable prototype, comprising marketable technologies ("Viability loop"). Thus, the team started the communication of SOLOS and applied for the ISPO Brandnew[25], a launch pad for startups in international Sports Business. Only three months after TMS #4, team SOLOS won the ISPO brand new award 2017 (Thieringer, 2017).

"(...) Think.Make.Start was definitely one of the greatest experiences for all of us. It is unbelievable what we have achieved in two weeks. It seems like we have been working on the project for a couple of months. We met awesome people and have many new friends now. Currently we continue to work on our idea and we all believe in it. Thank you for everything Think.Make.Start." – Team Solos, 17.10.2016

5.7 Conclusion on Agile Product Development

Think.Make.Start. empowers motivated persons to just get started in interdisciplinary teams, while collaborating on a common vision. Highly skilled talents experience the feeling of "nothing is impossible" while prototyping at the Makerspace facility. Teams compete with other teams, but also help each other to "survive" the intense format. Participants understand how other disciplines think, work and develop skills required to work in an interdisciplinary

[24] Kinect is a line of motion sensing input device that was produced by Microsoft for Xbox.

[25] https://www.ispo.com/

team (“t-shaped”). Some of the positive “side-effects” of the intense TMS course are some remarkable teams, and moreover, arising Startups: Hawa Dawa, Solos and Kewazo.

TMS fosters experimental learning based on individual prototyping efforts encouraged by the latest results of (Menold *et al.*, 2016). The prototyping stages are not defined by a predetermined order, but by aspects of a successful product innovation. Results of former development activities cannot often be foreseen and planned in detail. To co-ordinate the evaluation activities, the teams set up a “frame” in order to evaluate the critical properties and to incorporate analysis activities (Bernard, 1999, p. 56). Agile projects require highly skilled and interdisciplinary teams, to be able to react and adapt rapidly with limited time and resources. This work has given rise to five major improvements:

- An understanding of “agile” in the context of **physical product development**.
- A new understanding, which treats the product, the process and the team, as **one single system** to be developed.
- A **shortened and flexible development process**, which also provides greater transparency to the activities.
- A **closer collaboration**, which creates greater unity amongst and within the teams.
- A **user integration** and other relevant stakeholders (non-technical disciplines).

Figure 5-19 illustrates the two core elements that are necessary for agile development of mechatronic systems. The study supports the assumption that there is not "one" approach in agile product development. It is much more likely to be unique to each product, which is also one of the strengths of the “agile concept”, as it allows for flexible reactions to changes. The data show that a certain plannability is possible. However, agility is most-effective, where uncertainty is high (Smith, 2007, p. 7). Thus, the research results are split into a **project setting** that provides the necessary preconditions to “be agile” (Makeathon: “Think.Make.Start.”) and a **project-based learning** approach that supports the exploration of the design space in the early phase of product development (“TAF”).

The aim of agile product development is to reduce **uncertainty** within minimum time and with minimum effort. A project room fosters co-location and face-to-face interaction which in turn promotes high performing teams to work collaboratively in a flexible environment. Prototyping

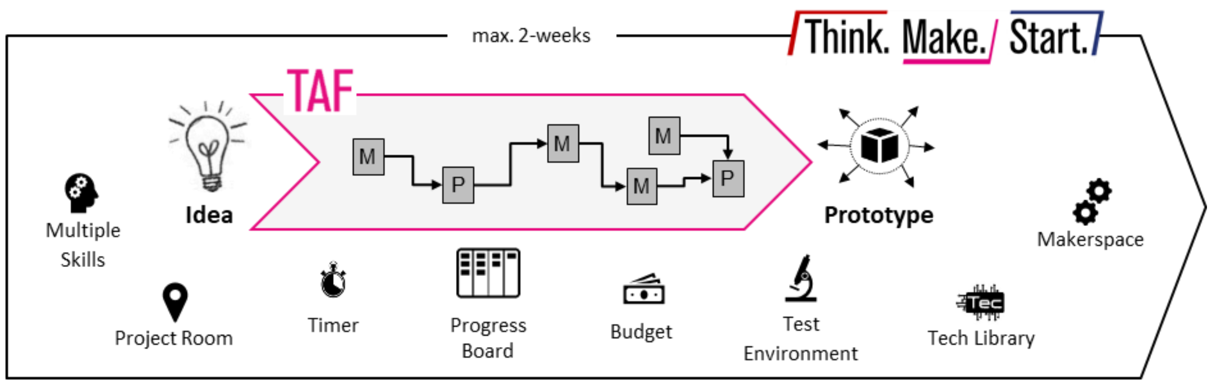

Figure 5-19: Two core elements for agile development of mechatronic systems.

activities are enhanced by an available budget, basic technologies and access to a Makerspace. The "Maker Community" is an inspiring network of "creatives" and experts from various disciplines. The result is an interdisciplinary knowledge pool that supports the rapid execution of design tasks. The three core elements of TMS are as follows. 1) Autonomy 2) Empowerment 3) Competition and Collaboration. Participants develop their products self-initiated and in self-organized interdisciplinary teams (1). Besides the high-tech workshop and a technology library, coaches advise the teams with expertise or entrepreneurial actions (2). The iterative prototyping approach is fostered by daily progress presentations and the final demo day (3).

Prototypes manifest the knowledge of highly skilled and interdisciplinary teams concerning the problem and solution space. **Systems architecture** evolves iteratively with projects progress, and prototyping facilitates the quick evaluation of product properties in a real-life (test) environment. Prototypes serve as a basis for **decision-making** related to business and engineering actions that incorporate user-centered design practices. The team`s individual development path is guided by appropriate (agile) development methods, adopted, for the specific project situation. Prototyping strategies and mind-set cards facilitate the exploration of the design space and help the teams to optimize their learning for each iteration. The phase-orientation shifts towards the innovation object itself to gradually reach the product vision. The resulting prototyping roadmap shows the progress towards the vision that is driven by the results. The scope of decision-making decreases throughout the developmental work. The early phase is characterized by exploration and the later phase by systematic product specification.

It is to find out whether agile development of physical systems also works in a more **complex context**, such as the **automotive industry**. Innovations are developed independently, but at some point, must be integrated into an overall traditional ("Waterfall") process model. Thus, agile development of complex systems shifts from an **active** to a **passive approach** (see Figure 5-20). The overall systems architecture is developed in the traditional process but comprises "agile subsystems" that are heavily affected by innovation dynamics. These subsystems represent the **changeability of a system** on systems ("upgrade") or domain level ("update"). Long-term architecture planning is enriched by **short-term execution**. According to (Bertsche and Bullinger, 2007, p. 35), this can only be handled by optimizing team-internal **knowledge** and **collaboration** strategies, which is examined using the example of an OEM. The aim is to understand the innovation potential of "agile" in the context of complex mechatronic systems.

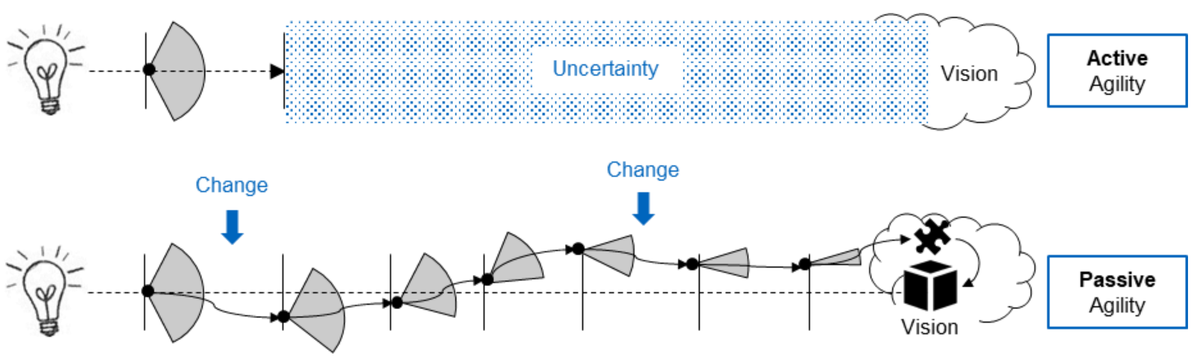

Figure 5-20: Active and passive agile development projects.

6. Digital Transformation of the Automotive Industry

The digital revolution has transformed the traditional mechanical automotive industry into a computerized electromechanical industry. Agile drivers, such as shorter technology cycles result in new customer expectations and are central drivers for changing customer behavior. To increase the digital product performance and the usability thereof, agile subsystems of a vehicle are being defined. The innovation capability of a large OEM is analyzed to derive potentials and challenges for the implementation of agile principles (rapid prototyping, failing, learning, and adapting). Three agile projects are exemplified to provide an insight into internal barriers.

6.1 Agile Driver in the Automotive Context

"The automobile will change more in the next decade than in the last fifty years" (Fröhlich, 2015) – Klaus Fröhlich, Member of the Board of Management BMW AG.

OEMs are not only challenged by continuously increasing regulatory requirements but also new competitors and new customer behavior (Wagner *et al.*, 2015, p. 3). Personal automobiles dominated the market for decades, but now people are buying fewer cars and some are skipping the expense all together. **Shared mobility** has become a billion-dollar industry, driven by aggressive companies like Uber or Lyft. **Self-driving** cars are looming on the horizon as traditional carmakers and tech companies rush to be the first on the road. German OEMs are operating within this fiercely competitive landscape.

The paradigm change in mobility and new **digital offerings** could make previous lucrative business models (e.g. navigation system) redundant. The customer preferences shift towards new digital expectations such as mobility services and fully connected vehicles (Wagner *et al.*, 2015, p. 7). (Ueding, 2014, p. 70) argues that premium manufacturers often rely on their brand and focus less on the customer value. The change in **mobility behavior** is potentially weakening the power of the brand image. It makes overestimation of current business models projected into the future more substantial. Globalization leads to **new competitors** and the premium market is gaining more inflows from the over-crowded low-end market (Gorbea Díaz, 2011, 57f).

Long-term sustainable financial success is achieved with a complete and consistent range of models, clearly differentiated by functionality, for instance, size or performance (Weber, 2009, p. 23). To meet the individual customer requirements, OEMs have greatly diversified their offerings and created a considerable **variety of models and variants** (Bratzel, 2014, p. 95). The **increased complexity** has led to a prolongation of the entire product development process, which is now in direct contradiction to the **fast-paced markets**. Product complexity is characterized by more than 3.000 suppliers, about 10.000 parts per vehicle and a high-volume production rate of up to 2.000 cars per day. The management of this complexity is described as a decisive distinguishing capability of OEMs (Schömann, 2012, 117ff).

Shorter **technology cycles** lead to new customer expectations and result in an increasing innovation dynamics (Baltes and Selig, 2017, p. 87). For digital innovations, **the time to market** plays a crucial role (Wedeniwski, 2015, p. 275). Companies must **react quickly** in uncertain environments to new user needs or technology available and integrate those into the **ongoing** development. However, large companies often lack the adaptation and implementation speed necessary to cope with fast and iterative cycles of **digital technology**. Revenues are moved from the time of sale to the product life-cycle (former after sales market) and high customer involvement gains in importance. OEMs do not just manufacture a car, but provide digital services, such as automated maintenance or location-based information over the product life-cycle. The already complex design process becomes even more complex and OEMs must cope with dynamic environments through the development.

The Effect of Digitization

"I like [that] they made changes while keeping the classic style. They have done a good job." – OEM Customer, 2016, USA

The increased competition leads to increased price pressure as the quality requirements on product characteristics and technologies increase. Automobile manufacturers face the challenge of managing their current business as efficiently as possible, but developing new products to ensure long-term success at the same time (Dzedek, 2009, p. 1). The trend of decreasing **auto-affinity** is shown in developed industrialized countries such as Germany, especially in the age group between 18 and 25 years (Bratzel, 2014, p. 95; Kortus-Schultes *et al.*, 2014, p. 118). (Spath and Dangelmaier, 2016, p. 5) see this trend not only among the younger generation. They speak in general terms of a **paradigm shift**, in which the **availability of mobility** will in the future be given a higher priority than ownership of one's vehicle of its own. This also means that immaterial benefits such as the statutory symbol of a brand are losing their value (Bratzel, 2014, p. 105). Reasons for this trend are especially to be found in **urban areas** with regard to traffic jams and limited parking spaces, which greatly reduce the attractiveness of the car (Bratzel, 2014, 102ff).

The **speed of development** has become the key competitive factor, and new competitors are already forcing large automobile groups to become more "agile" (Gorbea Díaz, 2011, p. 35; Cooper, 2011, p. 35). (Fricke and Schulz, 2005, p. 343) emphasize the importance of shortening the period between design freeze and delivery to deal with the changing market and rapid technology change. Iterative development cycles allow one to handle current customer requirements with **more certainty**, but this trend is also increasing **product complexity** (Wildemann, 2014, p. 9).

(Kortus-Schultes *et al.*, 2014, p. 130) consider it imperative for OEMs to keep their offers attractive and dynamic in the future and to adapt to the **short innovation cycles** of the **information technology** and **consumer electronics** industry. The combination of electrical, electronic and software components in mechatronics is accompanied by advantages such as extended functional scope, but has become a crucial complexity driver (Hellenbrand, 2013, p. 193). Over the last decades, cars have become **complex systems** of electrical and electronic systems and are currently opposed to agile software development (Weber, 2009, p. 53). The development cycles of the different disciplines differ greatly, which results in a clash of cultures between the "*old economy*" and the "*new economy*". Agile software development is confronted by slow, bureaucratic and strictly regimented vehicle development. Automotive manufacturers must constantly rethink, reduce and master the complexity of their products and processes, to prevent **longer innovation cycles**, resulting in serious **competitive disadvantages**.

Many authors state that **technological trends** are the **central driver** for changing customer requirements and the main potential for disruptive innovation (Eller, 2016, p. 12; Koren *et al.*, 2013, p. 728; Ebel and Hofer, 2014, p. 547). (Gorbea Díaz, 2011, p. 77) compares the dynamics of the spread of **new technologies** in the market with a so-called "*snowball system*". After sufficient customers have taken on a new market standard, the sales figures are increasing exponentially. Figure 6-1 shows the spread of a technological advancement and the associated replacement of an older technology, using the example of music entertainment systems in the vehicle. The lines represent different car models that are sold with a cassette deck, CD player or Bluetooth / USB as a percentage of the total number of cars sold. The advent of compact disc technology has led to the **continuous repression** of the cassette technology, until it was finally completely withdrawn from the program in 2004. Since 2007, the Bluetooth or USB technology has been used to reproduce music in the vehicle.

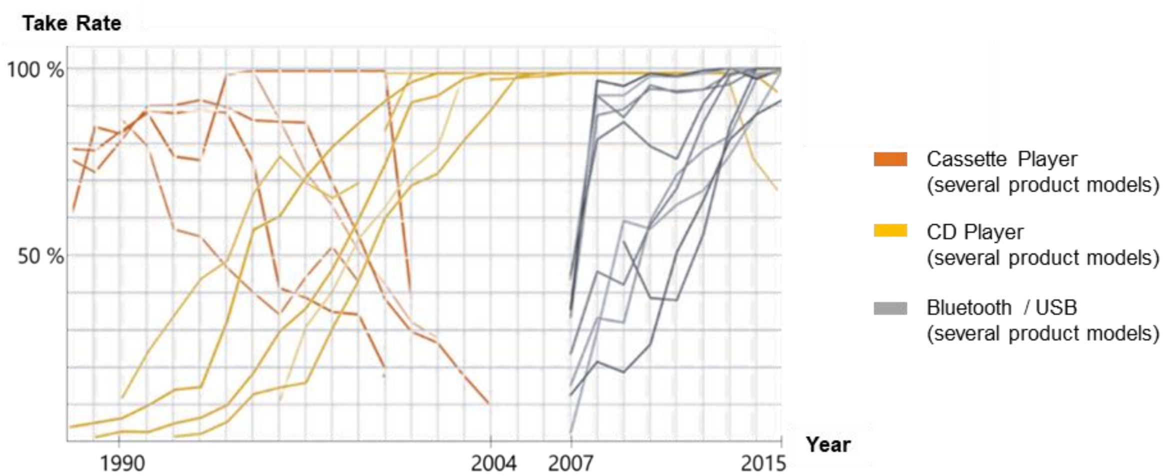

Figure 6-1: Impact of technology innovations on music player systems for vehicles, based on (Jansen, 2018).

Recent research on **hidden needs** identified that customers are often limited in their ability to express specific product requirements (Poguntke, 2014, p. 54; Eller, 2016). Especially radical innovations have a higher acceptance rate, when experienced at a prototype stage. **Autonomous driving**, for example, is a much-discussed topic, where users can discuss pros and cons theoretically, or explore the innovation and experience it in a real life setting to form an opinion (e.g. Google Car). As with agile development, early **user feedback** promotes the adaption of the product. Figure 6-2 shows the existing potential of customer needs that are not explicitly articulated. The needs of customer groups that have not yet been served offer **great market potential** (Wildemann, 2014, p. 48). Studies showed that between 34% and up to 90% of newly released **products fail** because of **unmet user needs**, but even for successful products, still half

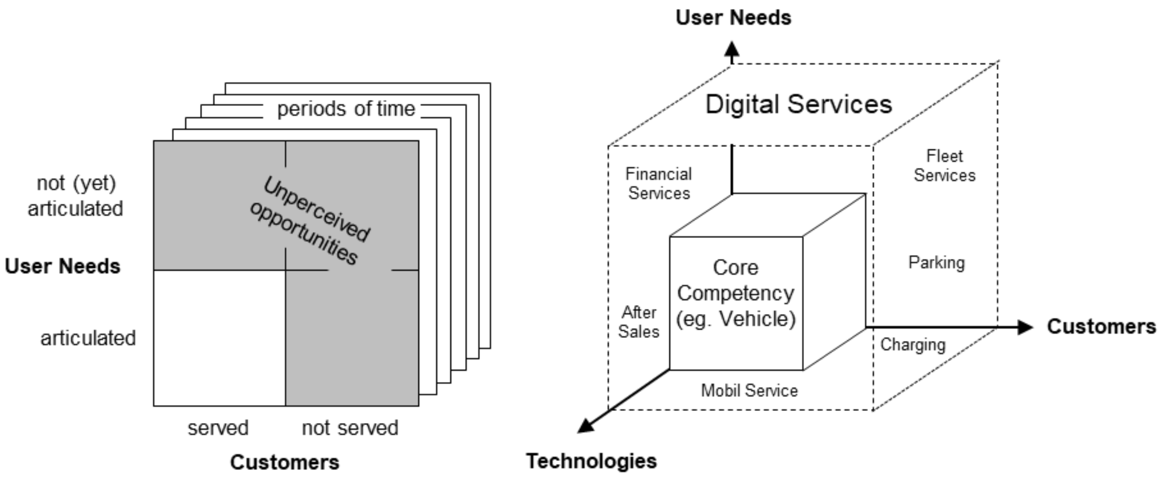

Figure 6-2: Innovation potential of holistic customer orientation in a three-axis model, referring to (Wentz, 2008, p. 59; Wildemann, 2014, p. 48; Gausemeier and Plass, 2014, p. 11).

of all product **features** are **not used** or appear not to offer any added value for the users (Moll, 2016, p. 583; Ehrlenspiel and Meerkamm, 2013, p. 23; Ekas and Will, 2014, p. 30).

For the **digital era**, it is not sufficient to adapt products based on market studies. Customer wishes must be anticipated in the **long term**, as technological progress leads to **new customer requirements**. The challenge is to prevent a product to be already outdated when entering the market, but **meeting the pulse of the times** (Gassmann and Sutter, 2013, p. 113). (Wentz, 2008) presents the three-axis model that is used to the dimensions the innovation is addressing (see Figure 6-2, right). The company's current **core competencies** are the basis. For each dimension, an analysis is made of how an innovation idea can help to **attract new customers** and **satisfy new user needs** and establish which **new technologies** are involved (Wentz, 2008, p. 59). (Gausemeier *et al.*, 2015, p. 26 ff.) emphasize an efficient forecasting in order to draw the necessary conclusions for the development of business, product and technology strategies.

Incremental innovations leading to considerable price reductions are also highly promising for corporations (Wentz, 2008, p. 20). The relevance of more **radical innovations** arises from new digital competitors. Apple and Google are just two examples of automotive industry-independent technology firms that have been involved in the business in the field of autonomous driving (Viereckl *et al.*, 2015, p. 4). Thus, an agile organization must be prepared for changes when new technologies emerge, business models change, or business processes have to satisfy new performance profiles (Gausemeier and Plass, 2014, p. 391).

Impact of Innovations on the Vehicle Architecture

The **vehicle architecture** describes the physical and functional structure of the entire vehicle. It combines the required vehicle functionality with the corresponding modules and components (= product architecture). It is not limited to a specific vehicle, but used for vehicle series (Wedeniwski, 2015, p. 38). The automotive industry is strongly characterized by **platform strategies** that include economies of scale and potential loss of brand differentiation. The product architecture lifecycle is decoupled from the product life cycles. This enables communal

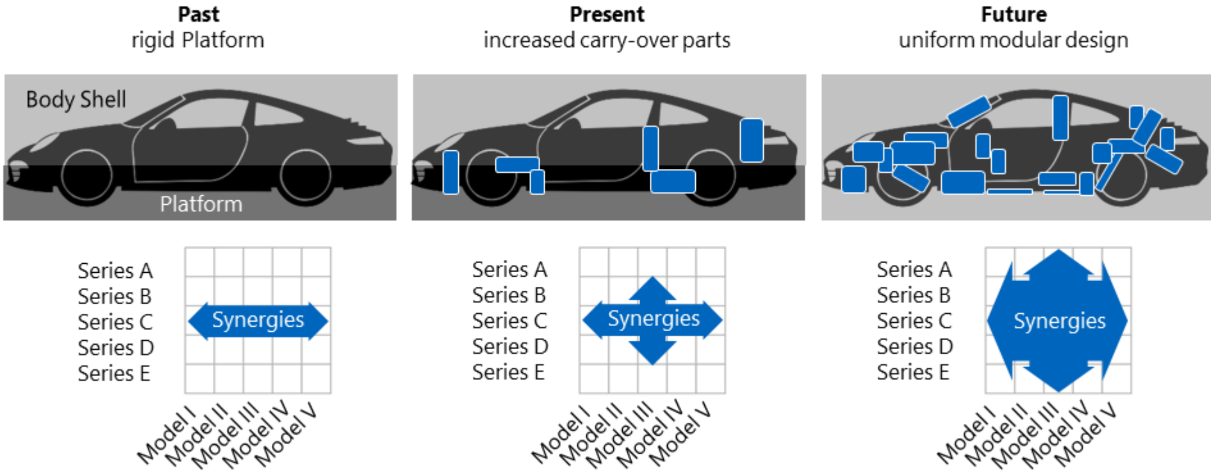

Figure 6-3: Synergy effects of rigid platforms with increased use of carry-over parts by a consistent modularization (following (Gutzmer and P., 1998).

use of carry-over parts for several product life cycles. **Scalable modular design** expands the concept of communality by considering similarities between product families. The use of the modules and the resulting synergy effects in module development are key advantages of the module strategy (see Figure 6-3). This leads to drastically reduced **time-to-market** and continuous **cost reduction**. A flexible and modular product architecture creates **communalities** across product families and ensures the **ability to innovate**, and clearly defined **interfaces** allow an **easy reusability** (Gutzmer and P., 1998). However, modular vehicles require **long-term** module **planning** which is why ~50 % of the vehicle architecture is already predefined from the start of the development. Early product specifications and long development cycles are opposed to the fast-paced nature of markets and technologies. The impact of continuous technology change increases the need for product **adaptability**, and results in a **limited effectiveness** of long-term module definitions (Rapp, 2010, p. 14).

With the rapid increase of electronic functions over the last decades, OEMs introduced **systems engineering** as a sustainable approach to developing reliable “Electric and Electronic” (E/E) architectures. An E/E system is composed of several **artifacts** (e.g. electronic control units (ECUs)) and interconnects different **domains** (e.g. infotainment and connectivity (I&C)) (see Figure 6-4). The E/E system is developed **independently** across products and specifies common requirements of various components. The requirements describe “what” the E/E

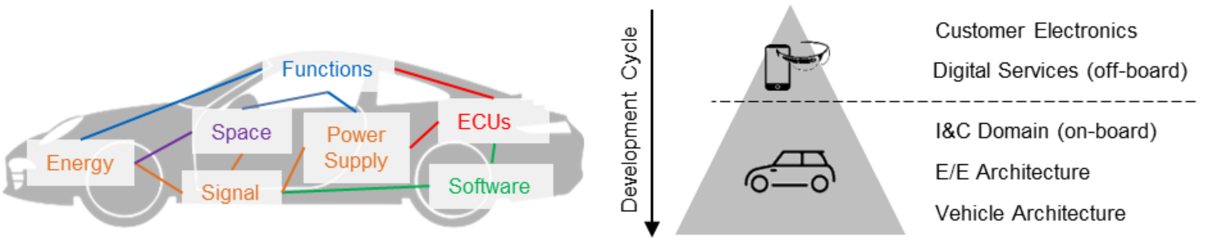

Figure 6-4: Complexity of E/E Architecture and related system levels of a vehicle for the integration of innovation.

system should do, and the system architecture describes "how" the system should do it. The creation of the system architecture is a core competency of an automotive OEM as the single components are usually developed and manufactured by suppliers (Weber, 2009, p. 59).

The impact of **technological change** on the vehicle architecture is dependent on the **system level**, into which the technology is integrated. Technological change at the component level has a strong effect on the subsystem level, but a small impact on the overall system (Gorbea Díaz, 2011, p. 31). **Digital innovations** are distinguished between domain-specific innovations or architecture-relevant innovation. Architecture-relevant innovations (e.g. Head-up Display) are either highly interconnected with several domains or include new ECUs. Domain-specific innovation (e.g. Car Dashboard) only makes use of relevant information and signals from the available sensors, ECUs, and BUS systems to implement a new functionality.

With the rise of **digital services**, traditional development of **E/E architecture is limited**. Traditional approaches are characterized by heavy front-loading of requirement specifications and several testing loops. Agile developed systems are designed for continuous updates to improve the performance of the overall system. **Digital systems architecture** must be designed **flexibly** and enable **easy adaptation** to changes (Gorbea Díaz, 2011, p. 36). Companies such as Apple, Facebook and Google are lauded as "new economy" heroes. Their digital development is characterized by iterations and updates to **improve** the functionality and to allow **customization** with regard to user specific habits throughout the product`s lifecycle.

6.2 Identification of Agile Subsystems

"No place to put my phone (...) I need to see my phone while driving."- OEM Customer, 2016, USA

Digitization brings new technologies across industries and is dramatically changing future customer expectations. The focus shifts from single product features to overall **digital product performance** and the usability thereof. To envision a user-centered reorientation of the vehicle design, **agile subsystems**, highly affected by innovation dynamics are identified. To succeed in the future, these subsystems need to be developed in a highly iterative and agile manner to react quickly to changes in the market and in technology. In the following study, a methodology by (Kosiol, 2016) is outlined for identification of such components, highly affected by innovation dynamics. The model brings the influencing factors into relation with affected product components. Based on this, the influencing strength for each individual component is evaluated. The developed model is applied to the interior of an existing vehicle.

6.2.1 Systems Boundary

Flexibility allows one to make changes relatively late in the development process (low cost of change). Using this capability to full advantage is difficult. It involves **identifying areas** where **change is most likely** and collecting information related to the change in advance. Figure 6-5 shows the study results of customers of an OEM over last 12 years that raised objections in the first months after purchasing a new car. It is noticeable that in 2004 about the same number of complaints regarding the exterior were registered as for the **interior**. In 2016, only 2 % of

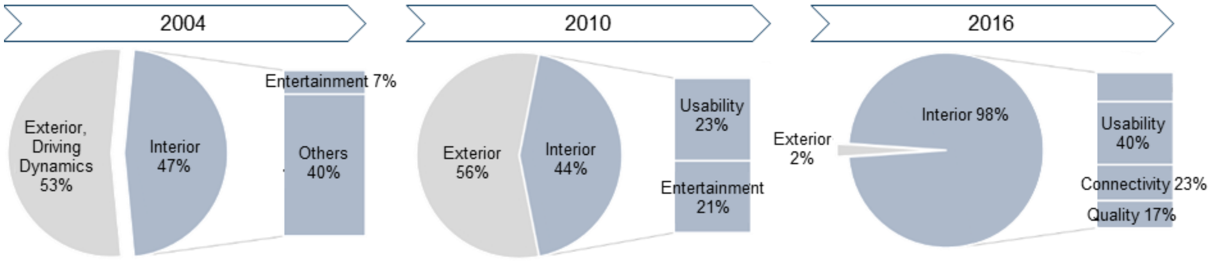

Figure 6-5: Registered complaints from customers of an OEM between 2004 and 2016 (Kosiol, 2016, p. 89).

complaints concern the exterior. It becomes obvious that the customer is increasingly complaining about the interior, and topics like **connectivity features** and the **entertainment system**. The infotainment system is, like no other, affected by rapid technological change. In telecommunications, the standards are changing **faster than the development** of the vehicle with its high integration requirements (Wedeniwski, 2015, p. 45). Thus, outdated systems are launched, which are not compatible with the technological standards outside the automobile sector (e.g. smartphones).

Due to the relevance of the **interior** for the customer and regarding technology progress, the following system boundaries have been defined: The analysis takes all components of the vehicle interior into account that the customer can **see** and is **directly in contact with**. The goal of this study is not to redefine the whole systems architecture but to raise the user-value thanks to increased adaptability of agile subsystems. An existing car model is chosen for the identification of these subsystems. This agrees with the assumption that "agile" is only necessary for certain subsystems of the product highly affected by innovation dynamics. Variants and special equipment are not included in the analysis. The methodology developed in the work of (Kosiol, 2016) is to identify innovative areas based on the approach of structural complexity management by (Maurer, 2007) as presented in Chapter 3.3.

6.2.2 Methodology for Identification of Agile Subsystems

Innovative areas are those that are strongly influenced by innovation dynamics. To define the meta-model, the domains and relations must first be determined. The agile drivers analyzed in Chapter 6.1 provide the following domains: Technology Trends (T), Customer Wishes (W) and Innovation Ideas (I). The domain Components (C) is required to connect to the existing product. The defined domain order is determined by the degree of concretization of the drivers (see Figure 6-6): Technology trends concretize themselves in customer wishes, which in turn, can be expressed in concrete innovation ideas. These innovative ideas are ultimately directly related to the components needed to realize them.

The structure of the model is based on the Multiple-Domain-Matrix (MDM) illustrated in Figure 6-6. It shows the relationships between the domains and is the basis for the subsequent analysis and optimization. To identify innovative areas on the component level, it is only relevant whether there is a link between the elements of two domains. All Domain-Mapping-Matrices (DMMs) below the main diagonal are obtained by transposing the corresponding

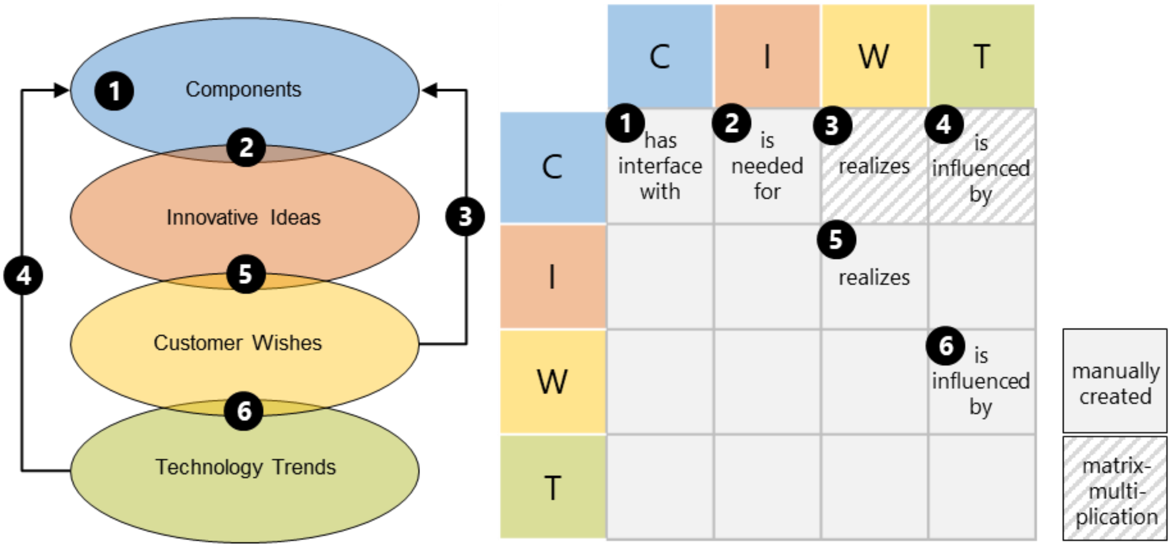

Figure 6-6: Meta-model for the identification of innovative areas (Böhmer et al., 2017a, p. 8).

DMM above the main diagonal. On the main diagonal, the dependencies between the elements of the respective domains are represented in the form of Design-Structure-Matrix (DSMs).

The following fields of the MDM are relevant for this analysis: The $DSM_{C\text{-}C}$ (①) contains the geometric dependencies between the components considered as relations and thus represents the building structure in the form of a product DSM. The $DMM_{C\text{-}I}$ (②) shows which components are directly affected by a considered innovation idea or are required to implement the innovation ideas. The $DMM_{I\text{-}W}$ (⑤) describes the purpose of the respective innovation ideas by linking the customer wishes with an innovation idea addressed by the implementation of the innovation idea. The $DMM_{W\text{-}T}$ (⑥) shows the connection between further technological developments and the resulting customer requirements. The $DMM_{C\text{-}W}$ (③) results from matrix multiplications and is needed to classify the influence of customer requirements on individual components. The same applies to the influence of technology grades in the $DMM_{C\text{-}T}$ (④). In addition, the $DMM_{I\text{-}T}$ could also be calculated. However, since the identification of components is in the foreground, this matrix is not relevant.

After the domains have been filled with elements and relations by means of the acquired information, the next step is the identification of not directly apparent connections. To identify innovative areas, a reference to the components of the system is established. There is no direct link between customer wishes and technology trends with a specific component. The implicit existing relationships between the domains of technology and customer requirements is established. Customer's wishes have an influence on a specific component, which is addressed by an innovation idea, which in turn, has a relation to a component. The same is true of the connection between components and new technologies. By using a matrix-based model, the indirect relationships are calculated using the following matrix multiplications:

$$③: DMM_{C-W} = DMM_{C-I} \; x \; DMM_{I-W} \qquad (6.1)$$

$$④: DMM_{C-T} = DMM_{C-I} \; x \; DMM_{I-W} \; x \; DMM_{W-T} \qquad (6.2)$$

Thus, the model provides a complete overview of the relationship between agile drivers and the components of the product under consideration.

The structural analysis focuses on the investigation of the different domains on components domain. The matrices DMM_{C-I}, DMM_{C-W} and DMM_{C-T} show which components are influenced by which innovation ideas, customer wishes and technology trends. Each element of these matrices represents the number of links that a component (“line index”) has with a corresponding technology, customer wish or innovation (“column index”).

The elements of the matrix DMM_{C-I} only contain either a “1” (link) or a “0” (no link). DMM_{C-W} and DMM_{C-T} also contain numbers greater than “1”, for example, if a component is linked to a customer wish via different innovative ideas (see Figure 6-7). For a component, the same customer wish is fulfilled by two different innovative ideas. In the matrix multiplication (Equation 6.1), all possible paths are considered between component and customer wish. The same applies to the matrix multiplication for the derivation of the relationships between components and technology (Equation 6.2). It is possible that several customer whishes are influenced by the same technology. In this case, all three paths from the component are considered.

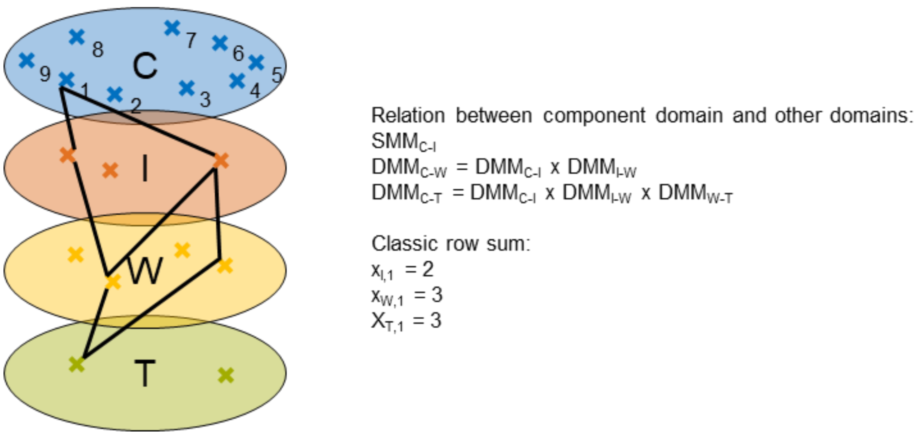

Figure 6-7: Indirect dependencies between components and customer requirements, or between components and technology (Kosiol, 2016, p. 77).

The row sums of each matrix correspond to the number of direct and indirect links between a component and all the innovation ideas (lines of matrix DMM_{C-I}), all customer whishes (lines of matrix DMM_{C-W}) and all technology lines (lines of matrix DMM_{C-T}). For all N components, these row sums are represented by the variables $x_{(D, n)}$, where D ∈ {I, C, T} and n ∈ {1, N}. The more relations between a component and an innovation idea, the more the component is subject to innovation dynamics. The same applies to the interactions with customer whishes or technology trends. For each component n, $x_{(I, n)}$, $x_{(C, n)}$, and $x_{(T, n)}$ describe the number of links to elements of the corresponding domains.

The influence on the components by means of innovative ideas, customer wishes, and technology trends is considered equally for each component. Therefore, the line sums of the various DMMs are simply added. The number of items per domain depends on the information available. Their absolute number has no meaning, but rather a higher relative strength of the dependency compared to other components. To allow an element of a smaller domain to be as much involved in the estimation as an element of a large domain, a “Fischer-Z-Transformation” is performed. This common statistical method is used for comparing randomly distributed random variables. The different number of domain elements is compensated, and the significance of the value is increased. First, the difference between the number of relations of each component and the average number of relations of a component is formed in the corresponding DMM. This difference is then divided by the standard deviation with respect to the DMM under consideration (Equation 6.3). This means that the average value of the new values is “0” and the standard deviation is “1”.

$$Z_{D,n} = \frac{x_{D,n} - \overline{x_D}}{\sqrt{\sigma_D^2}} \tag{6.3}$$

With D∈ {I, K, T}, ($\overline{x_D}$): mean value of the domain D and σ_D^2: variance of the domain D.

The standard deviation is generally calculated

$$\sigma = \sqrt{\frac{\sum(x_{D,n} - \overline{x_I})^2}{N}} \tag{6.4}$$

With N: total number of components, n∈ {1, N} and D∈ {I, W, T}

The result $Z_{(D, n)}$ indicates how many standard deviations σ_D the output value $x_{(D, n)}$ is removed from the mean value (x_D).

To allow a direct comparability of the components regarding their innovation potential, a value $E_{(C, n)}$ is determined for each component which combines the influencing of all three domains. For this purpose, the arithmetic average of the standardized values is formed by the following calculation rule:

$$E_{C,n} = \frac{1}{3}\left(Z_{I,n} + Z_{C,n} + Z_{T,n}\right) \quad \begin{cases} = 0, & influenced\ on\ average \\ < 0, & influenced\ below\ average \\ > 0, & influenced\ above\ average \end{cases} \tag{6.5}$$

Accordingly, a component is strongly influenced on the average when $E_{(C, n)} = 0$. $E_{(C, n)} > 0$ stands for an above-average influence on the corresponding component and $E_{(C, n)} < 0$ corresponds to an under-average strong influence (Böhmer *et al.*, 2017a, p. 8).

After the calculation (Equation 6.5) has been done for each component, a ranking is obtained for the analyzed components, which estimates the influence by innovation dynamics. In addition, the results of the software-based modeling are assigned to each component for further analysis.

6.2.3 Vehicle Architecture fit for the Future

Relevant information in terms of technology trends, customer wishes, innovative ideas and the product structure are gathered (for details, see (Kosiol, 2016, p. 90 ff.)), the calculation of the influence value $E_{C,n}$ of the innovation dynamics on a particular component is obtained. The value is determined using the equations (6.3) to (6.5). The results in the form of the explicit values as well as a ranking of the components are listed in (Kosiol, 2016, A6). The order of priority represents the **priority of the components** with regard to increased **reactivity** and **adaptability**.

Figure 6-8 shows the categorization of the components divided into three groups (A, B, and C) with decreasing importance. All components with $E_{(B, n)} \leq 0$ have a below-average innovation potential, and are, thus, classified as “C components”. These components are not or only slightly affected by technology and innovation dynamics, and can, therefore, be traditionally developed. The “C components” account for 68% of the total components considered. The “B components” account for 28% percent and are subject to an above-average influence by innovation dynamics ($0 < E_{(B, n)} < 1$). The remaining 4% of the components with $E_{(B, n)} > 1$, are on average more than a standard deviation above the strongly influenced components (“A components”).

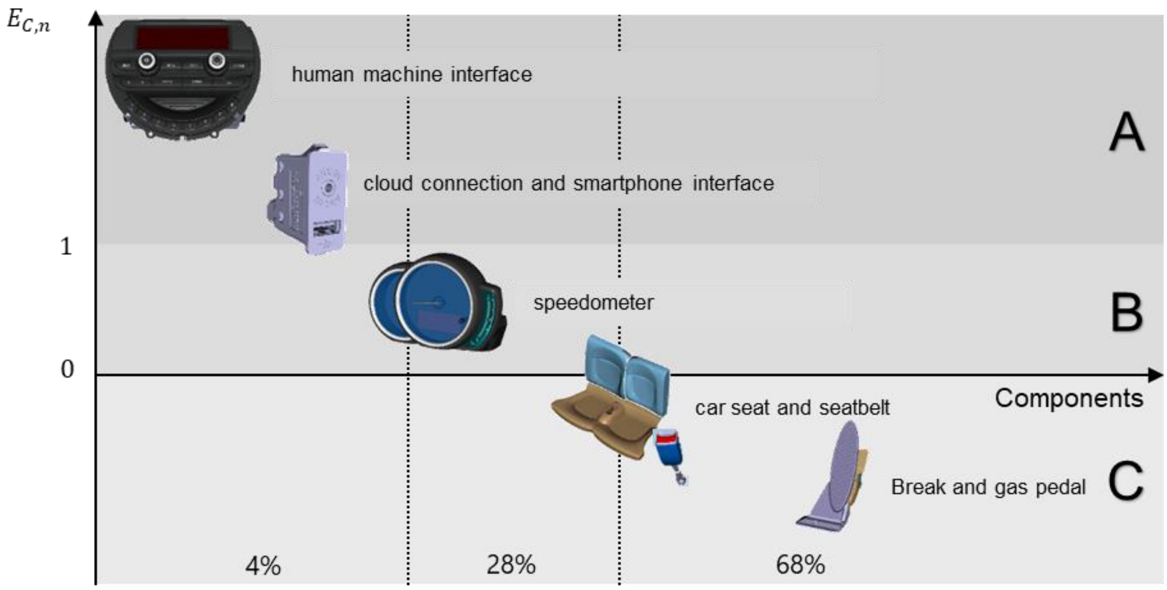

Figure 6-8: Innovation dynamic of interior components categorized to group A, B or C (not true to scale), adapted from (Kosiol, 2016, p. 105).

Components that are assigned to category “A” are software, radio, internet connection, smartphone interface, navigation system, sound system, cloud connection and the glove compartment. For two-thirds of all innovation ideas, a corresponding software is required. The radio component represents the human machine interface of the entertainment system. Internet and cloud connections are equally relevant for numerous innovative ideas such as customer wishes. A smartphone interface in combination with the internet connection makes a vehicle-based navigation system superfluous. However, the availability of a navigation system will stay indispensable in the future. Cloud connection and internet connection are required for a variety of activities, while driving. The glove compartment represents historically used space that has been assigned to many innovative ideas, pointing out alternative space utilization. (Kosiol, 2016, p. 105)

The analysis shows that the relevance of software, entertainment system and smartphone connectivity are particularly affected by innovation dynamics. The key technologies related to innovations in the vehicle are **big data**, **ubiquitous computing** and **connectivity**. To handle these "innovative areas" the company must define agile subsystems and corresponding agile teams. (Böhmer *et al.*, 2017a, p. 10)

(Koren *et al.*, 2013, p. 723) outlines a visionary example of the **car interior** that could be individualized by Open Architecture strategy (compare Chapter 5.5.5). (Koren *et al.*, 2013) states that an **Open Architecture Interior** for third parties could potentially become a new, successful business model for OEMs. Upcoming changes that occur during the product lifecycle are addressed by adding, removing or modifying modules. However, there are still many open questions, regarding the design process, production, and assembly. However, the viability of the vision is demonstrated by the **motorhome sector**, where the individual interior design has already been successfully achieved (Koren *et al.*, 2013, p. 725).

6.3 Innovation Capabilities

"*The arrogance of success is to think that what you did yesterday will be sufficient for tomorrow.*" – William Pollard, (1828-1893), referring to (Cooper, 2011, p. 120)

A clear, comprehensive picture of the corporate culture is the prerequisite for the development of a promising corporate strategy. A strategy can only be implemented if it is in harmony with the self-image, the thinking and the collaboration practices of the employees in the company (Gausemeier and Plass, 2014, p. 149). New product innovations and projects usually fail due to **rigid structures** of the company that suppress creativity and innovation. Corporate structures evolve over time to master complexity and define standardized processes for efficiency. However, the competition is no longer the other enterprise, but startups that are geared for **rapid execution** (Owens and Fernandez, 2014). Highly volatile market environments call for adaptive companies that react quickly to shifting markets and rapid technological change. To bring new products and services to market, creative teams must be able to act flexibly and autonomously.

6.3.1 Innovation Management at an OEM

Innovation opportunities vary to the extent in which they support the corporate strategy (Terwiesch and Ulrich, 2009, p. 4–14). In the past German OEMs consistently focused not only on the exploitation of existing markets or technology opportunities, but also on the exploration of new ones. The "Project i" of BMW Group or the car sharing solution "Car 2 Go" of Daimler are well-known examples. **Digital transformation** increases the pulse to what extent such discontinuous innovations must happen. Future trends within the automotive industry changing the whole industry arise from the following four areas: Shared Mobility, Electromobility, Connectivity, and Autonomous Driving (see Figure 6-9). To broaden the leadership within these fields, OEMs need to focus on an intelligent connection of these four trends. From a strategic long-term view, this already started with e.g. the acquisition of the open map platform "HERE" by a consortium of German car makers. Such cooperation allows the companies to leverage each other's individual strengths, capabilities and resources.

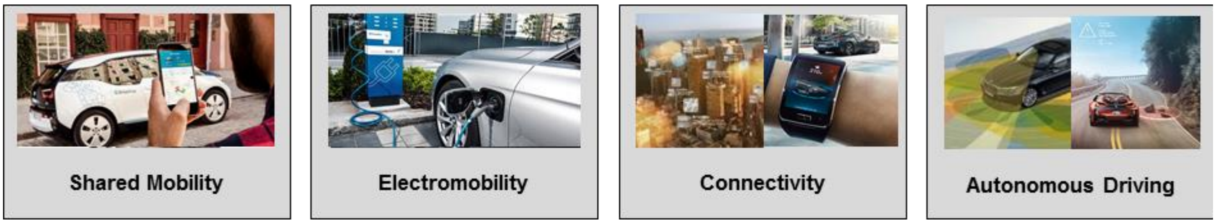

Figure 6-9: Strategic focus topics for the digital era of German OEMs.

Innovation management balances identified customer requirements and the corporate strategy. Future technologies and market trends are explored as wells as upcoming regulations, new competitors, and customer needs. The different stages of an innovation project are usually managed by using a Stage-Gate process model (see Figure 6-10). Departments are given the opportunity to apply for funding to implement their project ideas. The proposals are evaluated by department managers with regard to project doubling, available resources, and feasibility. For each innovation project, the development budget, in terms of internal or external services as well as prototyping issues, are estimated. Based on this information, the innovation managers assess and prioritize the ideas.

Figure 6-10: Innovation project Stage-Gate-process, adapted from (Ertl, 2007, p. 66; vonBary, 2016, p. 47 ff.).

The traditional innovation management focus is on (sustaining) **vehicle innovations** and / or enablers, and therefore, on **long-term projects**. Budget allocation differs in point of time, decision-maker and type of project. Some OEMs have additional **innovation funds** that allow adaptability to changing markets. Independent innovation funds facilitate projects across innovation fields and allow them to react to "Top-Down" projects during the year. Most importantly, innovation funds enable short-dated funding of small innovation projects. **Highly innovative** and **risky projects** are initially explored with relatively low budgets. Most OEMs host **innovation fairs** that brings together different departments and allow a glimpse of the potential future for top managers and the members of the board.

From efficient Innovation Processes to an Open Innovation Ecosystem

To stay competitive in the future, traditional innovation processes transform towards an "Open Innovation Ecosystem" (OIE). An OIE fosters transformational growth by incorporating

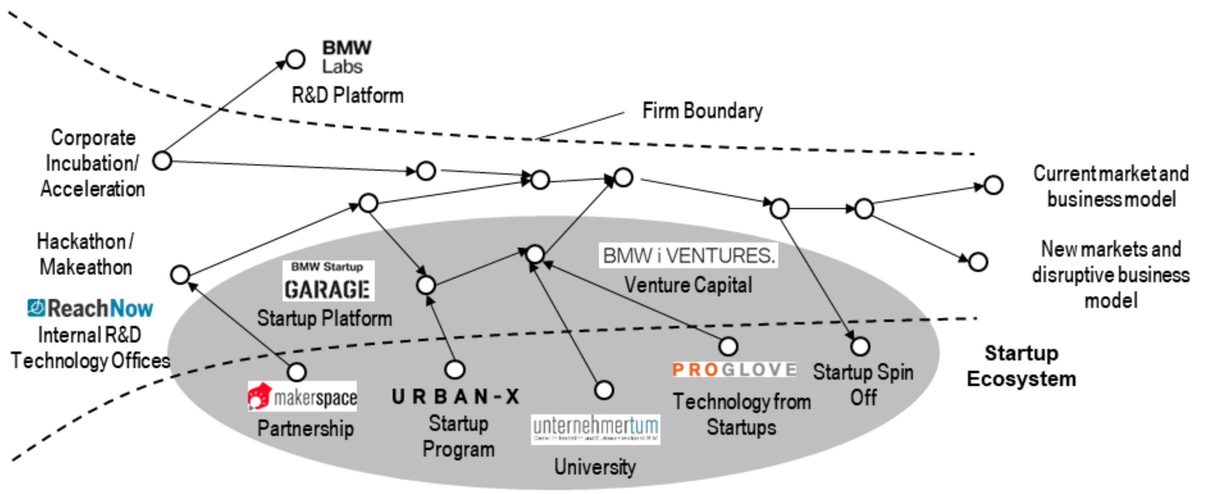

Figure 6-11: Exemplary Open Innovation Ecosystem of BMW Group.

external partners. In the following example the exemplary innovation ecosystem of BMW Group is presented (see Figure 6-11).

Collaboration is a vital part of running a business and to unlock new opportunities to create more value. The global car corporation BMW Group has an **investment** arm, "BMW iVentures[26]", representing one of the ways it works with startups. BMW iVentures' collaboration with the Israeli startup Moovit is one of its big success stories and shows how investment can lead to product partnerships (BMW Group, 2015). "BMW Startup Garage[27]" is looking for **startups** that have cutting edge solutions for any division: automotive, mobility services, manufacturing, IT, sales & marketing and HR. Startups can validate their solution and benefit from BMW`s global supplier network (Szopinska, 2015, p. 75). The Digital Product School is a three-month full-time training program of UnternehmerTUM GmbH that enables ambitious talents, students, graduates and employees to solve real-world problems around mobility and transportation.[28]

The **startup accelerator** program "URBAN-X[29]" is built by MINI and Urban Us. Together they invested in many of the leading startups working on city solutions. In 2014, BMW Group and UnternehmerTUM launched the "TechFounders[30]" accelerator program (BMW Group, 2014). One successful Munich-based startup to mention is the wearable "ProGlove[31]" by "Workaround GmbH" that tested its smart glove in Munich and Dingolfing to optimize this for industrial use, while working together with the BMW Group (BMW Group, 2016a).

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[26] http://bmwiventures.com/

[27] https://www.bmwstartupgarage.com/

[28] https://www.digitalproductschool.io/index

[29] https://www.urban-x.com/

[30] https://www.techfounders.com/

[31] http://www.proglove.de/

Internal R&D initiatives foster the core strength of the company and push the boundaries from the inside. "ReachNow" and "DriveNow" are carsharing services operated by the BMW Group offering a modern mobility concept that combines highest quality with simple, flexible usage (BMW Group, 2018). BMW Car IT GmbH, founded in 2001, is a software company working on both research and development topics, as well as software components in final production[32]. Local think tanks that reflect the spirit of technological innovation (so called "Technology Offices") represent the internationally established research and development network of BMW Group in the USA, China, and Japan, for instance[33]. In 2015, the first open workshop concept in Europe ("MakerSpace[34]") was realized in cooperation with the BMW Group and UnternehmerTUM at the Entrepreneurship Center of TUM (TUM, 2015). The workshop is accessible to all BMW employees as an innovation incubator, enabling them to respond to new ideas and test them directly in an accelerated process, without lengthy processes and procedures[35].

Fostering entrepreneurial thinking and breaking silos, accelerator or incubator programs have been started (e.g. "Innovationswerk Accelerator") (Pelzl, 2016, p. 1). Hackathon[36] and Makeathon are a valuable tool to focus on internal or external talent for the creation of new ideas (P&G, 2017, p. 3). The platform "BMW labs[37]" allows R&D departments direct access to customers. New BMW Connected Drive customer functions are offered to an interested, self-supporting customer community in order to get early feedback (BMW Group, 2016b). Since Designworks, taken over by the BMW Group in 1995, is a consultancy that focuses on mobility, product and digital life design as well as strategic design consulting[38].

6.3.2 Potentials and Limitations

Innovation Horizons are a useful way of encouraging forward-thinking outside the box. It is an important framework for thinking about transformative innovation and to link the present with the future. The three horizons help to understand the relationship between the present and the future and support participants to work with uncertain futures (Sharpe *et al.*, 2016, p. 1). Horizon 1 (H1) is where most of the immediate revenue making activities are. Horizon 2 (H2) is associated with extending existing business to new areas of revenue-driving activities (e.g. launching new product lines). Unproven and potentially unprofitable ideas are assigned to Horizon 3 (H3). This encompasses research projects, pilot studies or new revenue lines that require great upfront investment. To master the transition from "business as usual" (H1) to a

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[32] http://www.bmw-carit.de

[33] https://www.bmwgroup.jobs/us/en/location/location-silicon-valley.html#location=US/SiliconValley

[34] https://www.maker-space.de

[35] https://www.maker-space.de/faqs.html

[36] www.hackthedrive.com

[37] https://labs.bmw.com/

[38] http://www.bmwgroupdesignworks.com

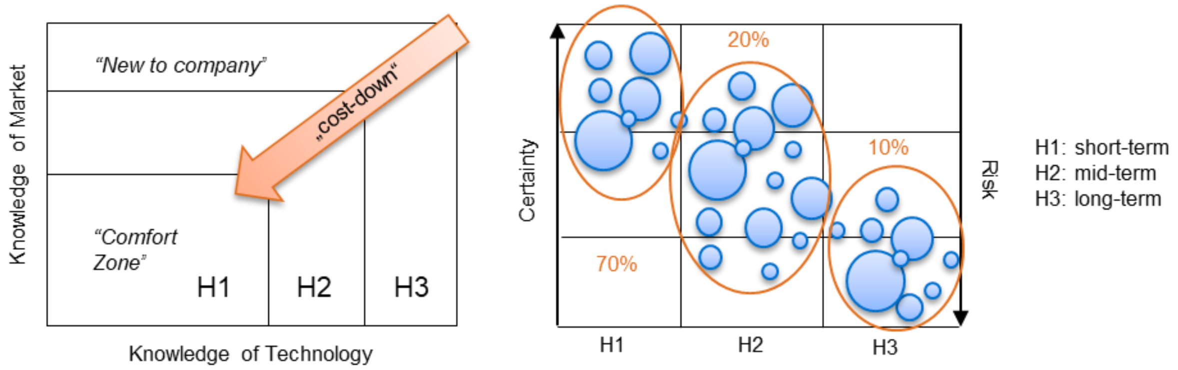

Figure 6-12: Three-Innovation Horizon, adapted from (Sharpe et al., 2016).

"viable future" (H3), companies develop new businesses and master the "world of transition" (H2) (Sharpe *et al.*, 2016, p. 4). After putting this theory into practice and developing a strategic plan, companies can apply the 70/20/10 rule. Roughly 70% of the innovation activity is invested in H1, around 20% is allocated for H2 and the remaining 10% is put into H3 efforts (research and experimentation with light product launches).

Figure 6-12 illustrates the ideal assignment of innovation projects to the three-innovation horizons. The focus of innovation management is derived from the overall company strategy and aims for strategic **long-term** success (H3 innovation projects). With increasing cost-down pressure and the omni-present risk-averse culture, most large companies shift from H2 and H3 activities to maintain and defend core business (H1). Activities that create new business (H3) are reduced, so that innovation management deals with conflicting goals of both short-term and long-term success.

Figure 6-13 illustrates the effect of strategic foresight of innovation management for an OEM. Most innovation projects are assigned to future car models, but in the near-term, there are only a few mature innovations. Innovation projects of 2014 are categorized according to (Cooper, 2011). As stated in Chapter 3.1, most innovation projects are incremental improvements of existing (e.g. LED light) or addition to existing (e.g. seat heating). In the automotive industry, innovations are mostly related to a car model. With the rise of **digital innovations**, the focus

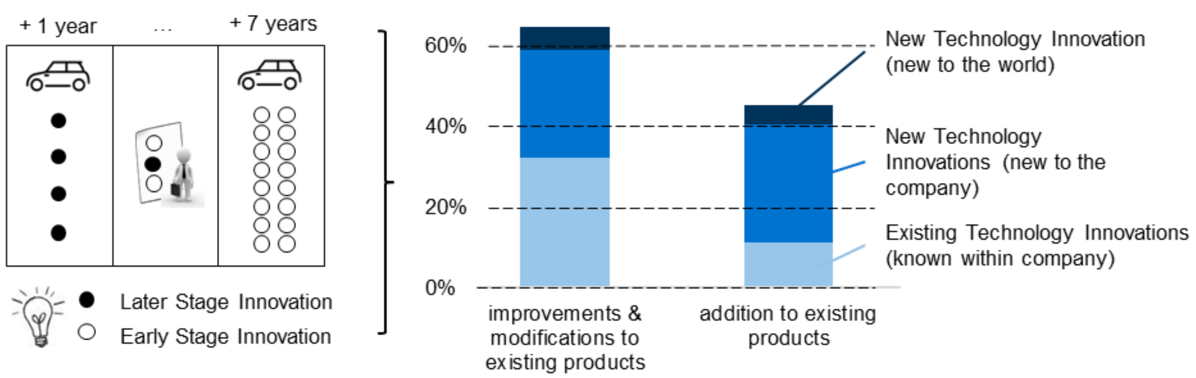

Figure 6-13: Analysis of innovation projects of an OEM in 2014, referring to (Cooper, 2011).

on the vehicle becomes both crucial and obsolete. The long development cycles of a car results in innovations being outdated once hitting the market. At the same time, the car becomes a crucial enabler for digital innovations entering the market. In the past, the vehicle architecture limited the innovation potential. For the future, the dependency of innovation and vehicle is inverted; so that digital innovations are setting the pace, and in turn, limit the vehicle requirements.

An **interview study** in the context of innovation management and innovation transfer for an OEM unveiled several limitations. The interview was conducted with several stakeholders from development, sales, purchasing, innovation management, and vehicle project leader. Seven main areas of improvement have been identified:

1. **Innovation front-end**: Innovation scouting is very abstract, and the innovation speed is slow due to annual budget planning.
2. **Innovation fair**: Innovation events foster management-orientation that is contradicting with user-centricity and does not promote knowledge exchange or learning from mistakes.
3. **Resource allocation:** Funding of project ideas during the year requires high effort and innovation funds get disrupted by re-priorization or cost-down practices.
4. **Predevelopment**: Project goals are missed due to poor preparation of relevant vehicle data, resulting in an insufficient maturity of the innovation. Projects across-departments often end in “agile chaos”, as there is no standard process to be followed.
5. **Innovation transfer:** The incorporation of innovations in later stages is limited by traditional development processes. System requirements are either unclear or fixed.
6. **Market-ready product:** Innovation must pay off in terms of vehicle sales. High one-off expenditures assumed take-rates hinder potentially value-adding features.
7. **Decision-Making**: The aim of vehicle projects is to minimize risk, which is why decisions are made with care and often in a defensive manner. Figure 6-14 illustrates two effects that lengthen cross-functional innovation projects. Decisions are made in several department-related committees, wherein the hierarchy is highly structured.

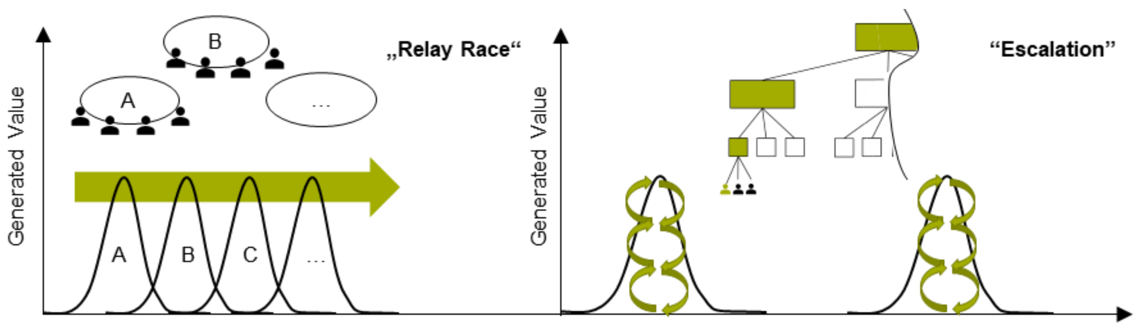

Figure 6-14: Two ways of decision-making at large corporates with hierarchical structure.

6.4 Towards Agile Projects within a Corporate

"*There are few things that we are certain about in product development, except one fact – your numbers are always wrong*." – Robert G. Cooper, Creator of Stage-Gate-Model (cited according to (Cooper, 2011, p. 227)

For traditional projects, a plan is elaborated up-front, and stakeholders take over tasks within their area of responsibility, and the process is optimized with regard to efficiency. When it comes to uncertainty, the existing processes and structures cannot be followed. To explore the necessary steps and synchronize the requirements of different departments, agile methodologies facilitate to master the unknown project path. An iterative search strategy is recommended to figure out the project path together with the relevant stakeholders (see also (Gerling, 2016, p. 21, p. 69).

Six **innovation projects** of an OEM are analyzed to identify the top potentials and challenges that limit non-incremental innovation projects within a large corporate (see Figure 6-15). The projects represent company-wide innovations that are new to the company, imply a digital business model, or are disruptive to the organizational structures. Three representative cases are outlined in the following. The insights show that dedicated **innovation teams** drive an **innovative culture** internally and stimulate the influx of external innovation. However, innovation teams struggle to achieve their objective, and much of their time and effort is spent **gaining legitimacy** and power within their own organization. Teams often lack the right connections to bring the solutions to the core business. They must overcome organizational barriers (e.g. process, timeline, meetings) and find a critical path through the organization to bring their idea to market.

Figure 6-15: Constantly overcoming internal barriers calls for creativity.

Project 1: New Technology for a New Business Model

The mission of the first project was to offer the customers 3D-printed upgrade products, with the design of their making. The 3D printing procedure allows the production of large numbers of individual products. Customized part designs are digitally transferred to production facilities and can be integrated by the customer into the product. The aim of the project was to provide a new customer experience, to industrialize a new technology and establish a new path to market.

The team was characterized by strong **cooperation** and the complex project did not follow a standardized process. While gathering all relevant requirements, most of the time was spend in discussions and knowledge exchange. Quickly, the team lost focus and it became more complicated to get relevant stakeholders involved and updated. Traditional project management tools (e.g. “To-Do-List”) did not provide the necessary level of **transparency** for the complexity of the project.

Key stakeholders, responsible for the liability of new components, were **skeptical** (“Naysayer”), which limited the innovation potential from the beginning. Team performance was limited by **changing team members**. Unclear **project roles** and responsibilities also resulted in misleading project outcomes or rather misleading **knowledge gaps**. A high level of labor division results in a **decentralized responsibility** within the team. The number of correlated stakeholders brought up various aspects of the correlated departments. **Internal coordination** took about 90% of the project time and caused project delays. Figure 6-16 illustrates the results of multiple domain matrix (MDM) of the first project. The analysis shows that the project was **highly interconnected** in the organizational structure.

The teams faced conflicting **business models** of direct sales ex-factory and the after sales market. The business model of the innovation was negatively impacted by a high **one-off expenditure** and the qualification of a new distribution channel. Potential supplier offers were extraorbitanty high, because of strict requirement standards for a relatively new technology. Costs are reduced by 50% through **in-house manufacturing** by the OEM itself, and budget was saved by not investing into supplier development. The initial market feedback was acquired by an early **pilot** study in cooperation with a startup.

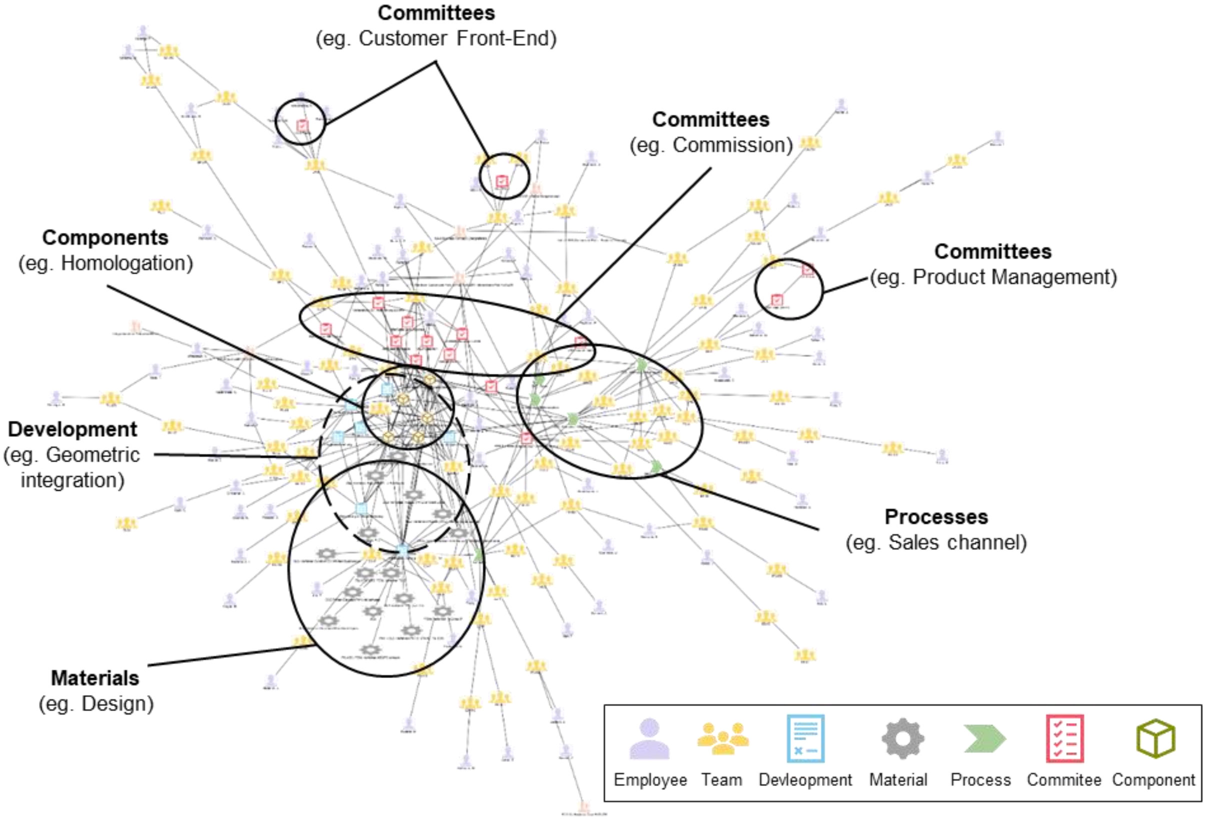

Figure 6-16: Exemplary visualization of MDM of a cross-functional project to show internal complexity.

The overall **Waterfall development** of a car limited the solution space, as the product is not designed for adaptability. The robust product architecture is characterized by great amounts of carry-over parts and modules across-architectures. With development, progress changes become very cost-intensive or even impossible. The product complexity of a car is handled by involving several hundred **suppliers**, which is why a relatively small change of a car component might affect the placing of several orders.

The automotive industry like hardly any other industry is affected by **legal regulations** in terms of safety features, fuel-economy and other expenses. Across models, the **cost of flexibility** is only invested in vehicles, where the technology or business case is most promising. However, the full potential of the innovation is than limited to the number of vehicles on the market. Finally, the requirement specifications of the 3D-printed component were taken from the previous component that has been manufactured by injection moulding. The missing adaption of the technical requirement specifications led to over-priced offers by suppliers as they allow for project risks due to a new technology but extensive requirements.

Key Learnings: Highly inter-divisional Project

Companies face the conflict of existing products, innovations that are immediately scaled to mass production and changing customer needs. Employees often walk right into the trap of focusing too early on product-related solutions, disregarding the user and his needs. User-centered design is also limited by a high level of specialization. Employees rarely interact with the product and relevant product specifications are dependent on a single person. The high **expertise** of employees often results in the "over-engineering" of products.

Prototyping allows a team to spend minutes finding an amazing idea, instead of hours discussing pros and cons of theoretical solutions. **Car sharing** platforms are promising for testing new product features early with the user. The feedback allows one to improve product specifications, without the risk of "big-bang" innovation announcements. An **innovation object** (e.g. vehicle) serves as a **learning platform** to test new ideas and explore opportunities. Prototypes are directly implemented on the car-platform and used for communication issues across silos. Small **market pilots** help one to focus on most relevant key features ("must haves") for product success and provide early insights into **customer-acceptance**. After successful validation, an agile team can make use of the corporates` unfair advantages (e.g. large-scale product variety and market channels) to **scale** the product **immediately** ("start small and scale fast*")*. The pilot project defines "best practices" which are implemented from headquarters to the overall markets.

Facing **uncertainties**, an agile team is not working within given processes, timeline and structure. It must be given the necessary level of **autarky** to successfully promote their project. The team (re)plans the next step with each iteration based on the information available. A **full team allocation** fosters the formation of an autonomous team with one common vision. In contrast to multi-project management, the committed team feel obliged to the outcome of the project ("end-to-end responsibility"). A **stakeholder analysis** helps the team to focus on most relevant stakeholders with regard to the project goals. It facilitates the definition of team roles and responsibilities for the project.

A common **project vision** keeps the project team on track. Breaking visionary goals ("epics") down to concrete sprint goals facilitates dealing with project **complexity**. By setting priorities and breaking the innovation project into smaller tasks ("sprints"), the work is more manageable and less intimidating. Project **transparency** is enabled by a visible project board. One look at the project board allows every team member to know exactly what the rest of the team is doing. Everyone is aware of his/her role and responsibility in the overall project status.

Close connections to an **interdisciplinary top management** committee facilitates decision-making. **Mentors** can help to overcome resistance and initiate interest for new ideas. They can promote the decision-making process and agreement within the hierarchy for projects not following the standard process.

For a project sprint **no change** of team members is allowed, thereby ensuring availability of employees, and thus, **knowledge acquisition**. The team constellation matches the sprint goals and meets the necessary **skills** and **resources** to implement a prototype ("Manpower feasibility"). Information must be accessible for all team members to allow quick communication and knowledge transfer. Empowerment of the employees prevents exorbitant costs for external services or dependency on any one supplier.

Project 2: Flexible Module for Digital Business Models

As **connectivity** becomes an **integral part** of an automobile's **value chain**, companies from non-automotive industries become key players. OEMs are facing shifts in their sales concept that is getting more complex but not necessarily significantly bigger. There are different implementation variants to offer connectivity services in a vehicle: ex-factory-installed connectivity module, connectivity retro-fit modules, and App based via smartphone sensors. Car manufacturers focus on a set of key "differentiators" to compete successfully (e.g. HMI integration).

The vision of the second project was to compete in the highly dynamic mobility market. Thus, a **flexible module** was designed serving as an **open platform** for third parties (only reading and limited writing) to offer various **digital services** to the end user. The aim of the project was to address the **mismatch** between long development **cycles** of a vehicle and the accelerated development of digital technologies. A **connectivity retrofit solution** was developed to explore the potential of various services for both, future and current vehicles.

In traditional mechanical engineering companies, responsibility is related to physical components. Technical solutions are developed in high **alignment** with the product architecture and **integrated** into the system. Such a **car-dependent** development limits the range of features for products not designed for changeability. To be profitable with digital services, innovations must be **scaled** across car models from local to glocal. For **digital customer**, the brand gains in importance. A traditional car **differentiation** (Mercedes S-Class vs. A-Class) is no more relevant.

The main challenge for digital services is conflicting goals within the corporate. Figure 6-17 illustrates the characteristic "thinking in silos" that often results in the "not invented here" syndrome. Traditional product management focuses on the end-user, who is a car-owner. Car sharing solutions address mobility customers, with different expectations (e.g. availability of

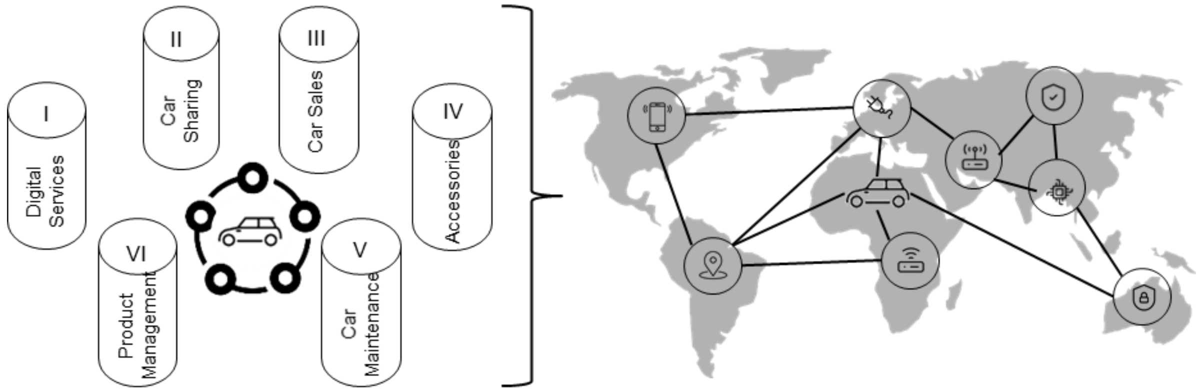

Figure 6-17: From silos to user-centered mobility provider.

vehicle). In the future both worlds will merge, and the company will need to deal with several revenue streams, involving traditional vehicle sales and mobility services. The automotive industry will be a **data-driven industry**, with connected vehicles collecting data about driver behavior, traffic environment, parking lots, etc. The consumer will be in the center of these efforts and benefit from new personal services and a secure system protecting consumer data.

With the rise of digital solutions, two different **mind-sets** or cultures clash within the corporate. The **traditional economy** defining quality in terms of a security by an extensively validated and the closed system assigned to a specific car model. The **new economy** defines quality in terms of added user value and continuous improvement across the entire car fleet. Traditional business models hinder the development of digital solutions, as OEMs face the challenge of comparably small profit margins in contrast to the traditional car sales. The inability of large corporates to quickly adapt to changing environments also results in a separation of the business model into known sales-concept (e.g. sales and after-sales).

Key learnings: Digital Service Project

Digital companies use agile development practices to deliver goods and services to customers more efficiently and with greater reliability. The development takes place across all business units and product groups. Increasing car connectivity requires **silo-independent teams**, flexible enough to implement **faster life cycle updates** and accommodate **new partnerships** with IT players.

The "Innovators dilemma" describes the challenge of established corporates that already have a customer base and a working **business model**. The given structure and processes are well-matched to the product development and existing sales channels. Digital products require direct interaction with the user and an independent entity that **integrates marketing** and **sales insights** regarding new customer demands and trends. Minimum Viable Products (MVPs) are developed for a specific market, and features are adapted with regard to user feedback. After successful evaluation, the MVP is scaled within a car fleet. Car manufacturers are provided with potential for significant additional revenue streams. They can use vehicle data to create fully-integrated digital experiences and profit from service-based revenue.

Scaling of digital innovations instantly requires upfront investment in **product changeability**. Traditional front-loading processes, late implementation strategies and cost-down activities, result in current E/E systems that have almost reached their capacity limit. To address today`s digital niche market, two main strategies, with regard to product-related digital transformation, become apparent: **enable** the entire fleet and **decouple** relevant modules from product lifecycle.

With progress in the electronic industry, **hardware upgrades** can be offered by OEMs ("Digital Facelift"). Such a Digital Facelift allows an OEM to be up-to-date when customer electronics change over the lifecycle of a car. For future mobility, the focus shifts from selling a car to the entire vehicle lifecycle, including updates and upgrades to **keep** the **fleet up-to-date**. The potential for a premium robo fleet was evaluated by (vonPeinen, 2017).

The typical show stoppers for innovations are security issues and **liability** disclaimers. Early **prototypes** help to run pilot tests and ensure initial liability for focus groups or certain markets. However, large corporates often lack **entrepreneurial culture**, but rely on traditional concepts (specification, development, evaluation, and implementation). Top managers need to anticipate an entrepreneurial mindset and invest in people as **corporate culture** mainly influences the innovation potential of a group. Corporates are limited by established strengths and competencies, which is why human resources need to build up an ambivalent organization that attracts both managers and agile talents. A **digital entity** calls for skilled employees, ready to create and implement products.

Project 3: An Agile Team to Master Organizational Challenges

Successful companies often cannot withdraw from the profitable core business to the extent necessary to compete in new markets. Established processes and structures hinder unleashing the full innovation potential and the exploration of new ideas. Management decisions are contrary to disruptive innovations for strategic reasons (risk, low margins, etc.). They invest in further development of existing products with predictable profit expectations. To meet these circumstances, corporations start "Innovation Hubs", Labs and Accelerators to become more innovative. Unfortunately, these entities are unable to sustain high Group expectations. There are two main strategies to establish Innovation Hubs in the current management culture. First, these Hubs are set-up as an organizational unit **without freedom** but being involved in existing decision-making. They often serve as a hygiene factor for internal and external marketing. Second, hubs work self-sufficiently as **far away** as possible, without making use of the unfair advantages a corporate offer (e.g. expertise, experience and network of employees). Rarely one of these two scenarios results in a **lasting transformation** of the existing organization. Organizations close the hubs again or cut their budgets without having taken any further steps.

In contrast to the former constellation (independent Innovation Hub), the hub tries to **spark new ideas** collaboratively with the core development team members.

The overserved team consists of highly skilled people from different backgrounds and from the non-automotive sector (e.g. Airbus, Industrial Design for exclusive furniture). The team members are part of the Innovation Hub, but confronted and dependent from traditional development teams. The agile team itself was autonomous, but in charge of orchestrating department-dependent developers. To foster the maturity of the innovation projects, a **technical committee** was installed.

The **collaboration model** of the team and the related departments are outlined in Figure 6-18. A user-centered **focus area** was defined, with each focus area related to one core development department (colored in blue, orange, and green). Relevant stakeholder from the company were involved in the collaboration (e.g. Design, R&D). The team was given support from **top management**, being responsible for the entire interior department. Innovation projects that did not have a **responsibility** within the given structure of the group where adopted by the agile team. Project budget was mainly allocated to the hub and not to the individual development departments.

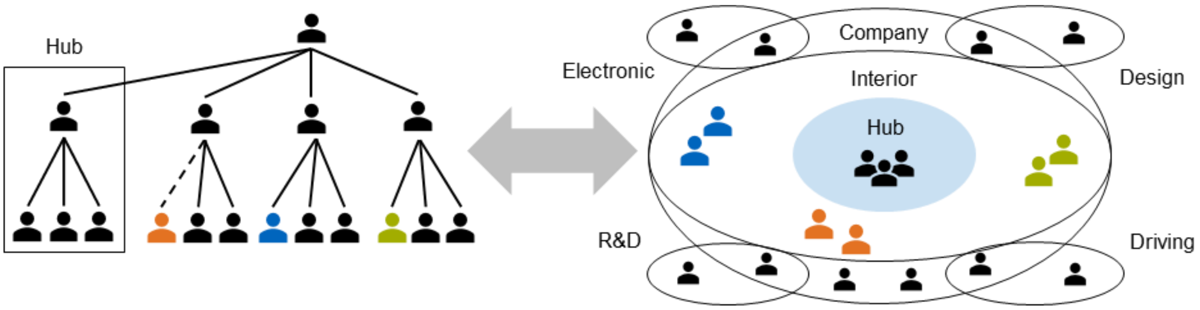

Figure 6-18: Innovation Hub – Team constellation.

Key learnings: Agile Team within large organizations

Successful innovations **across-departments** benefit from the right expertise, experience or network of people related to the idea. However, the organizational structure has great influence on the implementation of innovations. In the early phase, an innovation team must be far away from the corporate to gain the needed freedom to explore new solutions. With progress of the project, the expertise and experience of employees are considered to increase maturity of concept. After successful evaluation, a continuation of the project within the given structure is facilitated by an **adoption** of the most relevant team members. Responsibility is assigned to the department by a new employee. Further interference between agile teams and the waterfall process might be overcome by **process loyalty**.

Traditional process partners stick to their standard processes, and it is difficult to negotiate process adaptations without interfering with process efficiency. For a **lasting transformation**, the innovation entity must be placed in the center of the headquarters to involve and confront employees continuously. **Delaying tactics**, are prevented with skilled people that are capable of creating early prototypes and implementing innovations directly in the car platform. Process partners are convinced by a working prototype that already solves feasibility issues. A rapid pace of implementation and early user feedback helps to reduce various requirements that emerge from risk-averse mind-sets.

Committees are important for **information flow**, but do not guarantee active involvement of needed departments. The **power of prototype** is facilitated by rapid implementation and an innovation object. “Hacking” existing vehicles not only supports feasibility issues, but also makes “code come alive”. Realistic user tests are possible, and internal experts can evaluate the implementation. In contrast to typical innovation fairs, the user and the user journey is in focus. A **cultural shift** may be enhanced by proving process partners the benefits for this rapid execution approach. Decisions are not made at customer level, which is why top management need to be convinced by a working prototype that makes an idea come alive.

An autarkic Innovation Hub is ideal for partners with external partners. Working outside the given processes allows fast decision-making and rapid execution. The physical allocation of a team bundles the relevant knowledge and necessary expertise locally. Besides, team commitment increases and fewer team members are needed for the same task, without level of skills and network being lost in "agile chaos".

6.5 Conclusions on Agile Drivers, Barriers, and Enablers

"*While methodologies, management techniques, and technical approaches are valuable, the most critical success factors are much more likely to be in the realm of people factors.*" — Richard Turner and Barry Boehm

The qualitative content analysis of six innovation projects at an OEM identified drivers, barriers, and enablers to define an agile reference model for the agile development of complex physical systems. Further expert interviews also outside the automotive industry were conducted and evaluated by (Adam, 2017). Companies foster "agility" (= **driver**), increase flexibility in development, reduce time to market, increase the attractiveness for new talents, reduce cost, and establish stable processes for volatile markets (Adam, 2017, p. 45). However, the specific properties of physical systems make adaptations to agile frameworks necessary.

Four fundamental **barriers** for applying the agile process model to the development of physical products are identified: breaking the product into well-defined product increments, getting rapid feedback on design ideas, aligning large scale manufacturing with the idea of a "Minimum Viable Product" and setting up an organizational structure that supports the agile process model (Adam, 2017, p. 48). A set of possible adaptations (= **enablers**) were identified, to overcome these obstacles with respect to the people, product, process, and organization level (see Appendix A10). These adaptations have strong interconnections with each other, which is why a set of adaptations should be chosen, depending on the project circumstances and the identified barriers (see (Adam, 2017, p. 54 ff.)).

Especially for **mechatronic systems**, driving innovation in a corporation can be as exhausting as working in a startup. The main challenges are the highly cooperative work and communication among different disciplines and the simultaneous consideration of interdisciplinary aspects during the design process (Bricogne *et al.*, 2016, p. 80). Agile Methods address these challenges by an improved collaboration. However, large-scale systems, traceability, safety issues and a distributed environment imply to switching to a pure agile process model is (almost) impossible. In agreement with (Conforto *et al.*, 2014a), agility is more to do with a team`s competency. It relies on people's skills, culture, abilities, experiences and diversity, to work in a very dynamic and innovative project environment. The explicitly iterative nature of agile projects allows a team to experiment different solutions early but in a controlled manner.

Innovation projects that are new to the company are very time-consuming, as there is no predefined process to follow. High division of labor results in many repeating discussions with potentially relevant stakeholders. The exchange between silos becomes more important in order to understand trends as a whole. In times of change, **horizontal networks** are important to understand different perspectives, and to promote “trial-and-error” approaches. Vertical networks promote risk-averse leaders who dare to experiment. “Spotify[39] ®”, for example organize their development teams in “Squads” promoting the idea of interdisciplinary and autonomous teams (Gehrckens, 2016, p. 96). The co-location of a team leads to close communication, which results in faster acquisition of knowledge and skills.

Acknowledging the need for **iterations** is accompanied by the realization that requirements and specifications emerge in the ongoing design process. Development teams are comfortable in admitting that some aspects are not known up-front. This makes assumptions explicit and incentivizes the team to test them explicitly. Through the iterative nature failure is explicitly part of the process and loses its stigma, thus lowering the mental barrier for trying new things. This enables more creativity, and therefore, potentially innovative breakthroughs. It also introduces a “bias for action”, preventing the team from conducting lengthy feasibility studies when the same or even more knowledge could be gathered by simple prototypes.

Prototyping is the process of incrementally developing, evaluating, and refining until the final product is created. Prototypes anticipate implementation and validation aspects of the overall development. Prototypes facilitate the implementation of product features in a user-centered way and product maturity can be measured objectively. Relevant interfaces are discussed early with internal and external stakeholders to design product features iteratively. Different solutions can be experimentally tested and discussed with the client. OEMs already create several prototypes for different reasons (e.g. Design), however, they are mainly used for generic (e.g. Design Freeze) and mostly internal evaluation purposes (e.g. Board of Management).

[39] https://www.spotify.com/de/

7. Agile Innovation Strategy

For mechatronic systems, the speed of the different technology cycles is increasing significantly, resulting in proven models not being able to deal with the resulting dynamics. New approaches are required to handle the mismatch between new features arising during a multi-year development time of complex products. Traditional innovation management that relies on long-term corporate strategy, is enriched by an entrepreneurial short-sight to handle the upcoming innovation dynamics.

Based on the outcome of the previous insights gained, an innovation strategy is derived to overcome corporate challenges in the digital age. Entrepreneurial talents and skills are embraced to transform a rigid organization into energetic entities of fresh, marketable products and services. The Agile Innovation Strategy is structured into three parts. First, an integration model is derived iteratively from the identified agile capabilities and associated enablers. Second, a structural delimitation is elaborated to allow innovations by adjusting the level of "project freedom". This systematic agility is characterized by situative frequency of innovation sprints, using the companies' resources to deliver value to the user early and continuously. Third, the Makeathon "Think.Make.Start." is introduced to an OEM to solve internal contradictions by taking inspiration from startup strategies, embracing open innovation, less hierarchical management and the integration of entrepreneurial behaviors.

7.1 Integration Model

The Agile philosophy simply asks you to work collaboratively as much as possible with your teams and client to build products with quality, shipping early and often, while learning and relearning along the way. — Peter Saddington, Organizational Consultant and Agile Coach

Digitization and globalization result in shorter life cycles, faster technological changes, and a higher competitive intensity (Link, 2014, p. 67). New products and technologies need to be launched more rapidly and at shorter intervals, and the variety of products and services offered is increasing. This **external complexity** is intensified by **internal complexity drivers**, such as size of the company, number of organizational units and external partners (e.g. suppliers). The number of employees is a measure of the **inertia** of a company (Wedeniwski, 2015, p. 26). **Agile methods** are an appropriate way to deal with the **increasing complexity** throughout the various phases of the product life cycle. They are a radical alternative to command-and-control-style management and are spreading across a broad range of industries. According to (Nuhn *et al.*, 2016, p. 32), agility affects five different domains:

1. mind-set of employees
2. research and development culture
3. process scenery
4. systems architecture (product changeability)
5. organizational structure

While the first domain relates to **engineers** and managers, the second domain indicates cultural contradictions of agile practices in a traditional company. The most common "mindset problems" are **change affinity**, **authoritarian** leadership behavior and lack of understanding **agile roles**. The third domain analyzes the extent to which existing processes are suitable to support agile practices. The fourth stage addresses **organizational** structure to support **value-adding** activities. The mind-set and the systems architecture result in more hurdles and resistances than the two steps between them. The most challenging organizational units are the following departments: "purchasing", "quality management" and "controlling". To conclude, agile development cannot be considered from only one perspective (see Figure 7-1). (Nuhn *et al.*, 2016, p. 32)

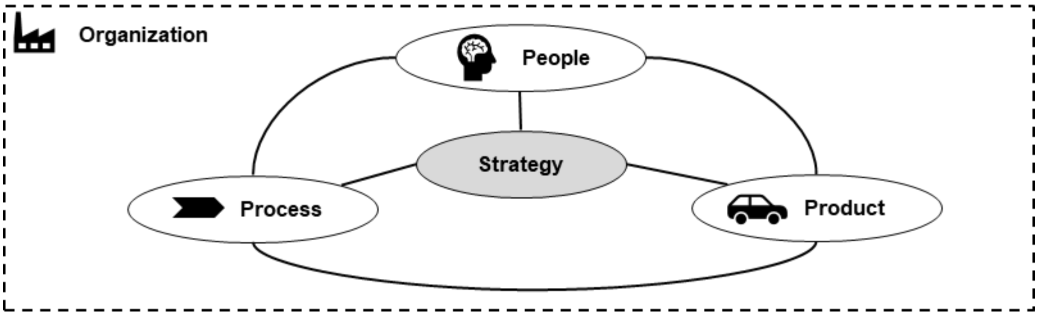

Figure 7-1: Four levels of the integration strategy.

Organization Level

"Conway Law" indicates the clear correlation of the evolved organizational structure and the modularity of the product (MacCormack *et al.*, 2012). It has been shown that innovations that change the product architecture require a change in knowledge architecture and company structure (Henderson and Clark, 1990). Thus, innovation is most challenging, where it is most disruptive to organizational structures. However, such innovations represent a unique combination of company strengths.

Organizational theory differentiates between mechanistic and organic organizational structures (Engelen et al., 2015, p. 106) (see Figure 7-2). **Mechanistic structures** have a high degree of horizontal differentiation and formalism. The decision-making process is centralized, which makes the communication between hierarchical levels long and time consuming. Moreover, the coordination between departments is time consuming, and single employees do not see the overall picture, but narrow areas of responsibility. **Organic structures** create the preconditions for the development of entrepreneurial behavior. They benefit from a low degree of horizontal differentiation and formalism. The decision-making process is highly decentralized, leading to a flexible coordination between autonomous departments or rather teams. Single employees have tasks within small teams and see the progress and work of the whole group. Communication channels between teams and departments are less time consuming.

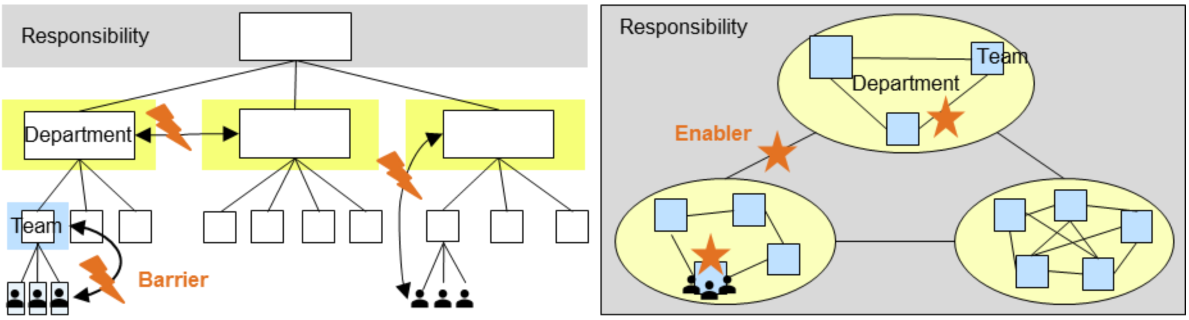

Figure 7-2: Responsibility within an mechanistic (left) and organic (right) organizational structure according to (Engelen et al., 2015, p. 106)

A **close collaboration** within the organizational structure facilitates the use of corporate available infrastructure and resources. (Hannemann, 2011) points out that a size of 80,000 employees worldwide is an advantage as there are competent partners, which can be internally advanced. However, corporates need to change their traditional leadership approaches to make use of these "unfair advantages", when competing with startups.

Among other things, managers are measured with metrics that represent existing, highly standardized processes. The system, however, does not leave much room for **entrepreneurial initiatives**. "Objectives and Key Results" (OKR) are a way to define, communicate and monitor quarterly goals and results in an organization (Niven and Lamonte, 2017, p. 13 ff.). OKRs connect the objectives of the company, team and employee in a hierarchical way to align all employees to a common vision. The **lightweight leadership** process uses shorter goal setting cycles, enabling dynamic planning and faster adaptation to change. OKRs promote transparency, as they are kept public, giving strong benefits for productivity, focus and company culture. **Stretching goals** take team out of their comfort zone and make them reach maximum performance (Niven and Lamonte, 2017, p. 103). Individual goals are decoupled from salary and promotions, so that a team also goes for challenging goals (Niven and Lamonte, 2017, p. 147). Organizational issues become less important, and the team competency gains in importance.

People Level

To deal with the emergent character of agile process models, the mind-set and skill-set of people gain in importance to form optimal teams. A project subject to change is unpredictable, and not applicable to standardized processes. To deal with change effectively, a team must be able to communicate changes quickly and accurately to those who are affected. Established corporates have a huge technology expertise in various departments. However, the intelligent interconnection of these experts is challenging. Effective **communication tools** help to manage change well and let information flow as needed. Agile projects require individuals who feel comfortable in working in a dynamic environment (Smith, 2007, p. 132 ff.). At 3M there is a separate department that assists colleagues to find the right contact person within the group (Engelen *et al.*, 2015, p. 178).

Agile teams benefit of individuals that are highly **committed** to one team with the best of intentions and are allocated **full time** working on one project. The employees are **eager** to solve problems and reflect all the time on “how to improve”. There is a clear **focus** on the **user** to meet possibly changing customer expectations. Team members possess an impressive **skill-set** in one discipline and the ability to collaborate and exchange knowledge with experts in other areas (“T-shaped individuals”). Functional experts are taken out of their silo to form cross-functional teams that represent the necessary expertise to develop a product in a user-centered way (see also Figure 7-3).

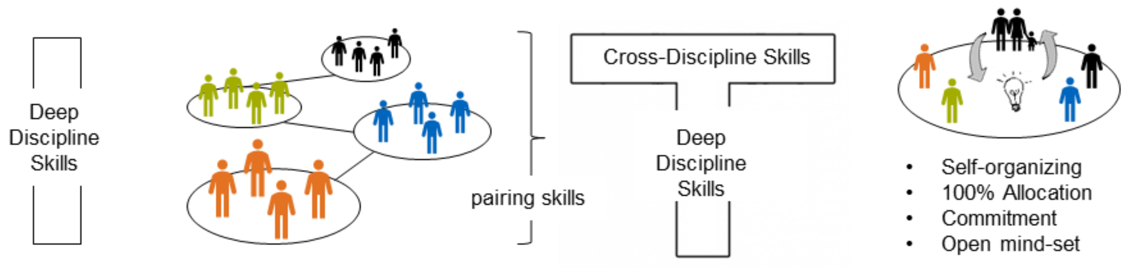

Figure 7-3: From silos, limited communication and multiple hand-overs to cross-functional, highly collaborative result-orientation and frequent user interaction.

Agile teams rely on iterative learning and have a positive **attitude** toward changes. With increasing knowledge, they identify threats and opportunities. They arrange themselves to meet immediate challenges best (“self-organizing”). A **co-location** enhances team performance and communication greatly. Fast decision-making is possible by giving the team **adequate authority** and resources to reach the project goals with minimum time employing the last effort. New behavior by **senior management** and their influence on others play a pivotal role in change. Autonomy of a team requires trust of the higher management in the judgment and wisdom of the team. Executive sponsorship and management commitment protect the team from organizational or individual resistance. The role of a manager shifts towards a **facilitator**, who eliminates impediments for the project’s success. The team members contribute their full talents and capabilities for the successful completion of the project.

Agile teams are most efficient, when dealing with great **uncertainty**, which is commonly found in innovative projects. Figure 7-4 illustrates “Agility Critical Factors”, adapted from (Conforto *et al.*, 2014a, p. 21) that enable project teams to act like a startup, even while being employed at a large corporate. The **level of agility** increases with the number and characteristics of these factors. Experienced teams benefit from previous projects with similar challenges. Fully dedicated teams are staffed with the necessary skill-set to ideate, prototype, and test an idea. Team **size** tends to be small (<12 team members) but needs multiple competencies. A close team proximity favors frequent interactions and face-to-face meetings that improve teamwork experience. An iterative development is limited by the availability of the team members, which is why high performing teams work exclusively on one project (Conforto *et al.*, 2014a, p. 21). A client or market representative needs to be available and committed for active involvement. This allows one to easily check and validate the intermediate results, using an overall innovation object.

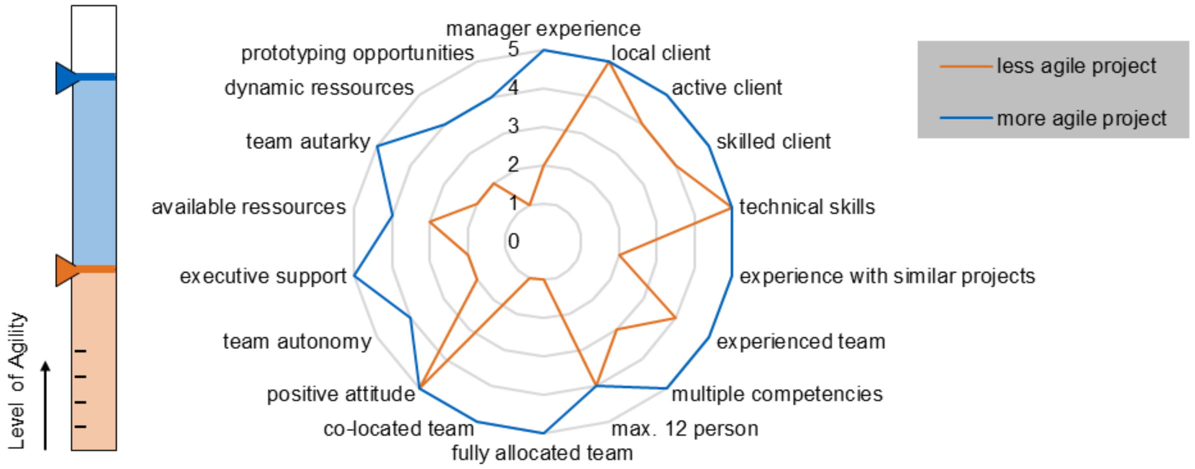

Figure 7-4: Agility Critical Factors for development projects, adapted from (Conforto et al., 2014a, p. 21).

Product level

Agile product development balances both, the user "outside", and the structure “inside” the organization. Management is ultimately responsible for the creation of structure and an orientation towards the customer. Reorientation of employees towards the market and constantly changing conditions allows a common view on the overall product (see Figure 7-5).

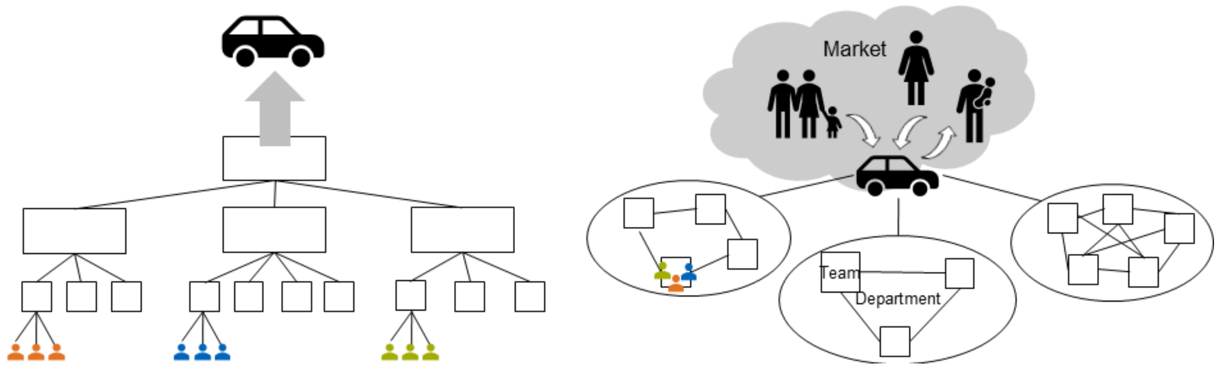

Figure 7-5: Refocused perspective of an organizational structure according to (Gloger and Margetich, 2014, p. 76; Engelen et al., 2015, p. 106).

On the systems level, a “Digital Twin” allows different perspectives on a physical system and a seamless analysis of all stages of the product lifecycle. Data from design, development to production, logistics or final operation are tracked in real time and used for permanent process optimization. A Digital Twin also enables analytics solutions that can predict future events. In this way, they become a key driver for new service concepts (e.g. predictive maintenance). Digital market entry strategies (e.g. updating or upgrading), maintain a certain level of agility just before or even after SOP. Products on the market become fit for the future owing to backwards compatible features.

Complex products, however, involve many stakeholders, which results in an increased communication effort. Thus, the **level of agility** is dependent on the degree of **modularization** and the lifecycle of a product. For complex systems, agile subsystems most relevant for the user value are decoupled from the overall system. Such subsystems are developed iteratively as a black box with standardized interfaces to allow late changes in the overall development process. For this study, ideas, user needs, and technology trends are mapped to single components of the overall system (compare Chapter 6.2), to identify **agile subsystems**.

Figure 7-6 illustrates the hierarchic product structure of a module organization. The product consists of three modules, which comprise a total of nine components. For each component, the intensity of the innovation dynamic is calculated. Components that are strongly influenced by the innovation dynamics ($E_{(C,\ n)} > 0$) are framed in pink. Referring to (Koppenhagen, 2014), these components are grouped together as agile subsystems to increase changeability and responsiveness of the overall system. This restructuring represents a starting point for a digital product architecture that allows **quick and flexible integration** of innovations into the overall product. (Böhmer *et al.*, 2017a, p. 10)

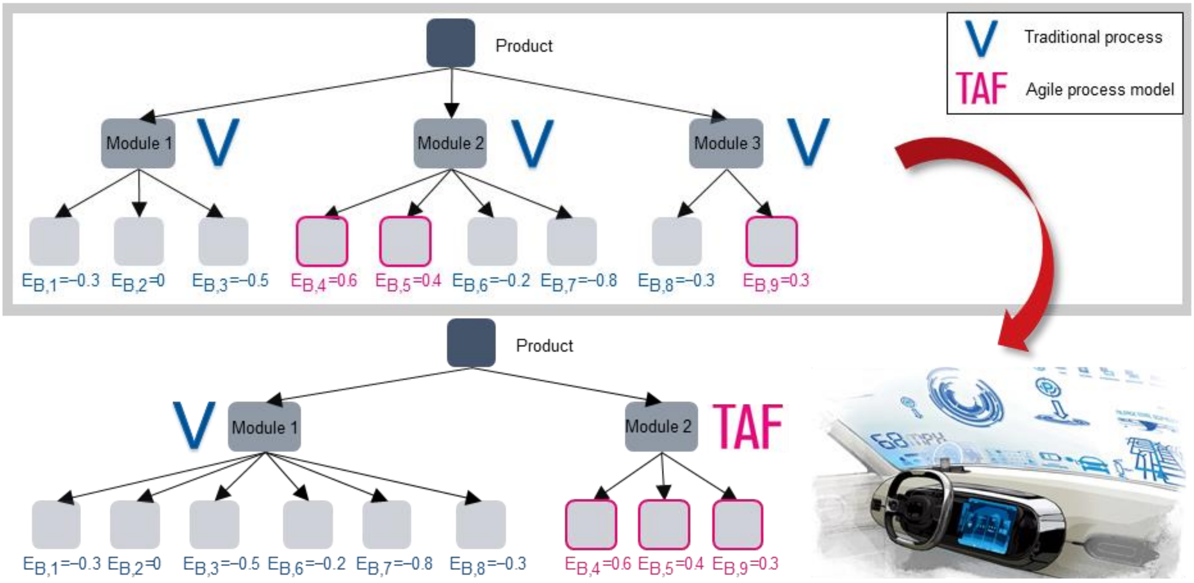

Figure 7-6: Restructuring of the module organization based on the innovation potential to align the subsystems with agile or traditional development processes (Böhmer et al., 2017a, p. 11; Wachenje, 2013).

Agile product development calls for **in-house** manufacturing, where companies build their own products and stop buying from large suppliers (Murman, 2002, p. 119). The full ownership of systems gives freedom to the companies to design solutions as they see fit. It allows value driven development to a broader extent, building what is needed the most and releasing product features immediately when they are ready.

Process level

Focusing on **automotive development**, it has often been criticized that standardized product design processes with their milestones and delivery results do not provide a good basis for agile methods (Ro and Fixson, 2008, p. 218). A high level of **synchronization** in the development of complex systems result in only 50-60 % value adding activities (Klein and Reinhart, 2014, p. 228). **Agile processes models** establish a more flexible and lean process that is characterized by iterative cycles and direct user feedback. Project work is not coordinated by bureaucracy with rules, plans and reports, but by **creating value** to the customer. However, **constraints of physicality** cause difficulties in presenting a prototype early to the customer and in responding to change quickly (Ovesen, 2012, p. 151).

For OEMs, there are several hundreds of people involved for core development and several hundred more suppliers. To handle this complexity, organizations engage in specialization, such as manufacturing, R&D or marketing. For traditional development projects, the user focus gets lost, and discipline specific conflicts occur (see Figure 7-7). Integrated development relies on a strong interplay between divisions and agile development fosters fast **prototyping cycles** (Ulrich and Eppinger, 2012, p. 35). Changes are regarded as necessary and integrated into the development contemporarily (Welge *et al.*, 2012, p. 342). The product is protected from traditional **cost-down** initiatives, as the team can **prove the viability** via pilot studies. Agile projects are measured by the quality required to deliver value to the customer within given constraints (scope, schedule, and cost) (Highsmith, 2010, p. 32).

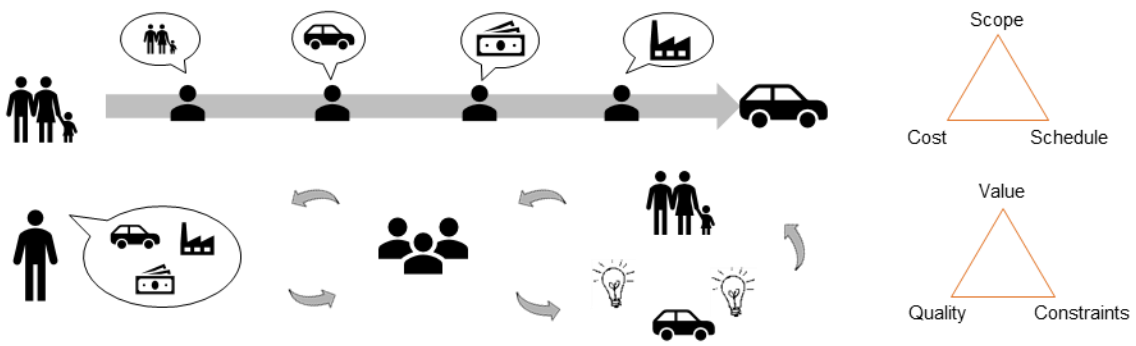

Figure 7-7: Focus on the customer for traditional and agile development process within given project constraints.

The concept of cross-functional integration requires not only a function-specific but also a stage-specific strategy (Song *et al.*, 1998). However, established mechatronic development processes cannot be adapted to “agile” in the short run. It involves **transdisciplinary perspective** and a **high level of integration**. Prototypes represent a specific stage of development, where requirements across disciplines are fulfilled in a multi-competent team (Ängeslevä *et al.*, 2016, p. 206). From the early phase of development, the prototypes increase in fidelity, but also in complexity. A typical prototyping process follows the course of a first embodiment of an idea, to a representative model, functional demonstrator, working prototype, through to a product (Kampker *et al.*, 2016, p. 69).

As mentioned in Chapter 5.6.3, one can distinguish active and passive agility. Autonomous driving, for example, is subject to changes (e.g. law regulations), but the product features are specified by “levels” of autonomy. The development teams know “what” to do, but not “how” to implement it (**passive agility**). Innovations are characterized by high uncertainty about the problem and solution space that must be explored actively. Agile teams perform pilot studies to understand “what” the user needs, while implementing potential solutions (**active agility**). To handle agile development cycles within a multi-gate process, relevant deliverables are defined to align these with the standard process (see Figure 7-8). For physical systems, agile teams develop their ideas to a point where the potential is conceivable and ready to scale. The project is iteratively transferred to core business to switch to traditional efficiency-oriented processes (Lehnhardt, 2015, p. 57).

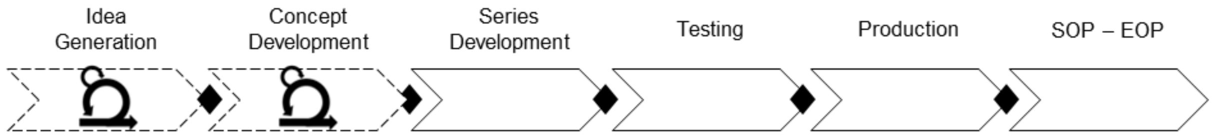

Figure 7-8: Agile development for physical systems at a generic process, adapted from (Lehnhardt, 2015, p. 57).

Potential and Limitations

The following **paradoxes** in implementation approaches are to be considered carefully. **Multi-project management** is a result of the great workload in large companies. For innovation projects, however, this mode of operation is time-consuming and hinders focused implementation. Agile projects require dynamic resource allocation to promote and elaborate an idea. Agile teams allocate resources above average, which is why only a limited number of projects are feasible for a **limited time**.

A **high division of labor** causes many and time-intensive handovers. Agile teams rely on cross-functional teams that overcome the strict work-sharing process, and thus, develop faster. An **innovation object** allows the discovery of the current solution with all the senses, which in turn, ignites the creative spark. With increasing maturity, more but different specialists are set to work on the prototypes, collaboratively.

Car development is **highly cooperative**, but due to high complexity, the responsibility is split into departments with the risk of becoming **silos**. The original common goal is divided up into department-specific conflicting sub goals. Budget, modular systems and geometric space hinder a user-oriented product development. Agile projects run outside the given structure, timeline and responsibilities (see Figure 7-9). Top management act as **promoters** for agile projects, and can be distinguished into specialist promoters, promoters of strength, and promoters of process (Folkerts and Hauschildt, 2001, p. 10; Hüttner and Pullen, 2014, p. 227). Specialists solve product-related, technological problems and recognize opportunities for technological innovation. Promoters of strength are hierarchical persons that provide necessary resources and protect the team from unwanted influence from third parties. Process promoters know the

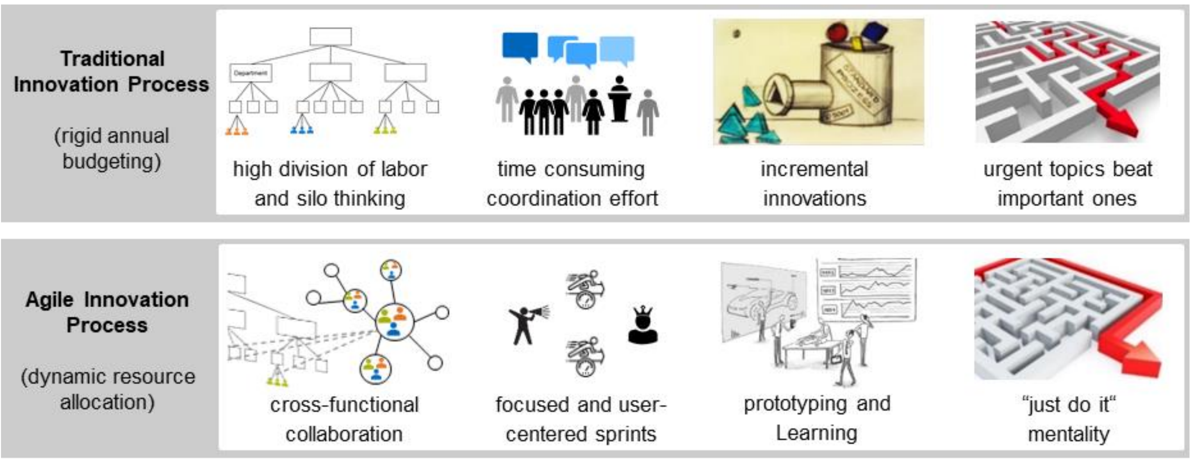

Figure 7-9: From traditional innovation process to time-boxed cross-functional innovation sprints with direct user interaction, adapted from (Böhmer et al., 2017a, p. 12).

organization best, and connect with advocates, powerful stakeholders or experts in the internal network.

Large corporations typically do not attract **entrepreneurial behavior**. Work-live balance is important to most employees as family is of significance to them. Figure 7-10 provides an overview of good management practices in medium-sized and large companies as opposed to startup practices. To embrace "agile", innovation projects need a special environment that is necessary to innovate. Companies launch separate units for startup collaboration that promotes "thinking for yourself" and finds ways to obey rules and hierarchical awareness. Innovation centers are often subject to criticism (being called "tinker labs"), which is why such labs are more successful, when located in the center of core business which lets others experience the setting.

Figure 7-10: Overview of good management practices in medium-sized and large companies, opposed to startup practices, adapted from (Engelen et al., 2015, p. 22).

The **innovator`s dilemma** describes why it is common that market leaders and incumbents fail to seize the next wave of innovation in their respective industries. A corporate already has a business model, and innovation projects must fit the overall strategic orientation. Startups launch products more rapidly by adopting a combination of business-hypothesis-driven experimentation (Ries, 2011, p. 20). A startup develops a viable product and aims for scaling to reduce costs and increase market share. The large corporate deals with scaling effects from the early beginnings of product development. The focus of development shifts from user-centered to **cost-efficient**. Updates during the product lifecycle are limited to storage space, compatibility, and connectivity. In the past, OEM typically bought the smallest possible storage within the scope of economy measures. A chip saving 1 EUR results in a saving of several Mio EUR for the whole car production. In the future, vehicle data will become the new currency of the automotive world (Wedeniwski, 2015, p. 267 ff.).

Agile groups take startups as an example and provide their employees an **opportunity field** to explore new ideas, independent of the current business model (see Figure 7-11). Such a strategy involves three important steps: Unfreezing, Moving, and Refreezing. Hackathons and **Makeathons** empower employees from the whole group, while providing the space and resources necessary to innovate. Latest tech is explored in a creative environment, and users are involved in testing product ideas iteratively. Early working prototypes not only increase team happiness and engagement, but also improve the chance of success for new businesses. The last step is to stabilize the new state to go beyond corporate boundaries.

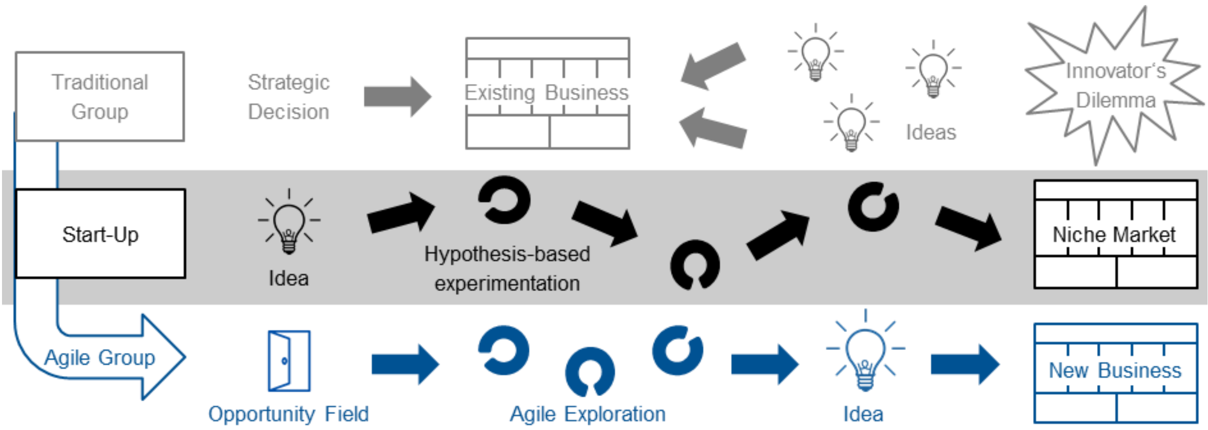

Figure 7-11: Business innovation of startups, traditional and agile groups, adapted from (Böhmer and Lindemann, p. 8).

7.2 Systematic Agility – Transition from Idea to Product

"*Before investing months or years of effort towards building a product, the first step is determining if this product is something worth doing.*" – Ash Maurya, Running Lean

Internal innovation efforts require the same constraints and freedom as innovation projects of startups. The concept of **systematic agility** establishes an entrepreneurial path within the company. It combines the best of both worlds: **startup practices** with **corporate resources** and **scaling expertise**. It brings together **internal** talents with ambitions beyond the current job and **external** talents, who appreciate the strengths of an established company (Owens and Fernandez, 2014, xix). The aim is to provide employees of established companies the **innovative power** that is normally a startup`s capability. **Innovation sprints** are started by the initiative of single employees (Bottom-Up) or are initiated by a call of the top management for strategic relevant topics (Top-Down). New ventures and direct contacts to the startup world open the innovation capability, while providing a systematic path beyond traditional management objectives.

Innovation Sprints – from Idea to Concept

Annual budgeting processes require detailed project plans to allocate all spending for the next year. Capital is provided from a strategic, central function and the budgeting and control systems are designed to minimize resource allocation risks (Albers, 2010, p. 220). With rising innovation dynamic, the number of agile innovation projects is increasing and the need for alternative sources of funding. New approaches implicate a **financial scope** that is known from “secret projects” that are typically run by engineers on the side in their free time. IBM, for example, is practicing so-called "Innovation Jam", where generated ideas are financed by some sort of **internal venturing**. P&G provides its employees free access to a Makerspace and a Customer Innovation Lab, to prototype and test innovative ideas instantly. (Humble *et al.*, 2015, p. 17)

The concept of “systematic agility” is inspired by the “Survival-of-the-Fittest” (SoF) model by (Szinovatz and Müller, 2014, p. 93). Innovation is characterized by a **controlled competition** of ideas and accompanied by limited resources. The light-weight process model bases on a **dynamic resource allocation** that benefit from the skills and talent in its workforce. Managers **invest in dedicated teams** so that thy implement their ideas and close the gap between “over-thinking” and “under-doing”. The ultimate goal of a creative innovation culture is to fail fast, cheap and early. Innovation management coordinates **temporary allocated** innovation teams and promotes high performing teams to drive new innovations. OKRs allow maintaining of a direct connection between actions and results. This dynamic innovation approach comprises the following five steps (see Figure 7-12):

1. **Opportunity Field**: pooling of interdisciplinary employees
2. **Setup Cross-Functional-Team**: provide necessary resources (spare-time, budget, …)
3. **X-Week-Sprint**: predefined period for rapid execution (no interruption by daily business)
4. **Evaluate Outcome**: presentation of prototype, lessons learned and user feedback
5. **Adapt Resources**: adjust team constellation and resources to increase survival rate

For a limited number of participants, an **opportunity field** is provided. Entrepreneurial employees meet virtual (e.g. platform) or physical (e.g. meetup) to discuss ideas. Crowdsourcing platforms are great to reach out widely across the business and to involve many participants. The power of Hackathons or Makeathons is that they focus on talented employees from different backgrounds, working whole-hearted on innovations within a limited time frame. Early prototyping of ideas allows an objectivation of innovation projects. The most promising projects are continued by **cross-functional teams** (CFT) that comprise complementary skill-set and face end-to-end responsibility. The teams are provided the necessary resources to

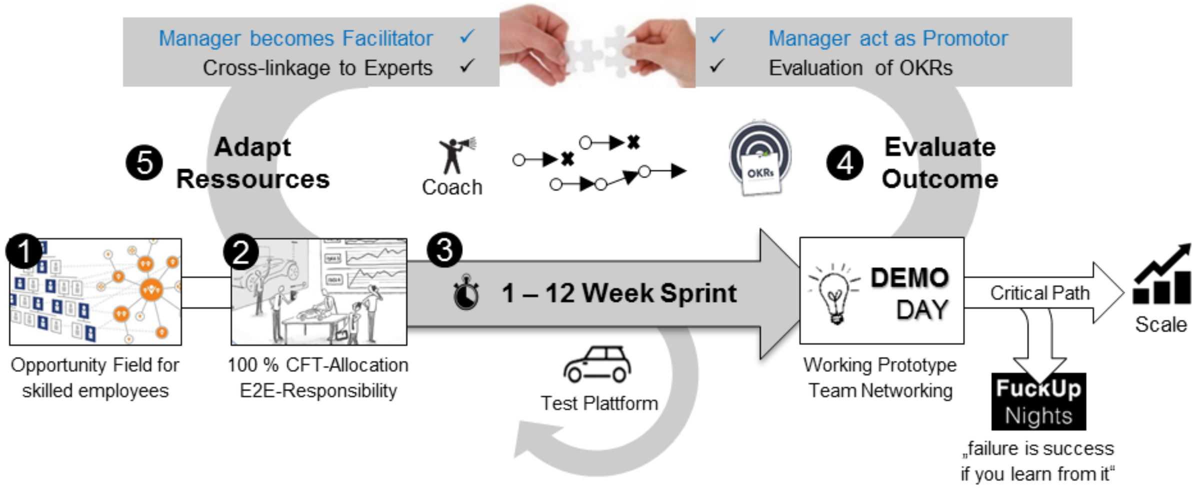

Figure 7-12: Systematic Agility through time-boxed innovation sprints with limited scope.

elaborate their project for at least another week (max. 12 weeks). A high level of collaboration across silos allows to overcome conflicting (department) goals and to focus on value-adding activities. CFTs are ideal for rapid exploration of project ideas that do not fit to the organizational structure or rather responsibilities.

Innovation sprints do not focus on the perfect project plan but on the "right" prototype and the knowledge gained. The power is given to the team, who defines the key results to be achieved in each time frame. During a one-week sprint no changes or day-to-day distractions from the outside of the team is allowed. Dedicated innovation teams will outperform their peers and stay motivated even in the face of failure. An "Agile Coach" supports the team to stick to the intense and disciplined procedure (e.g. daily stand-ups). Innovation teams rely on internal experts but must ensure their availability during a sprint.

The **outcome** of several innovation teams is **evaluated** monthly or quarterly with relevant stakeholders ("Demo Day"). Project progress is not measured in maturity stages, but by tangible prototypes that are evaluated by users or a pilot study. The evaluation is characterized by entrepreneurial thinking and experts or systems architects are consulted. The concept of "Fuckup Nights" is to learn from his mistakes. In keeping up with the motto "failure is success if you learn from it", teams present also unsuccessful projects to share the knowledge gained. To accelerate the progress for promising projects, a "Critical Path" is scheduled. The critical path is a set of project activities and recombines the process model according to the situation-specific and case-specific issue. This short-term method allows rapid execution and integration of latest technology into the product.

Decision-makers are involved to emphasize the relevance within the corporate and to align the teams with relevant strategic decisions. The role of a manager shifts form controller to facilitator who promotes self-organizing teams with his power, expertise, and network. For disruptive projects, a counsellor (e.g. top management) qualifies a team and ensures strategic alignment.

Resources are **adapted** based on regularly reviews of the high-level objectives that are set out across multiple perspectives (e.g. operations) (Humble *et al.*, 2015, p. 17). According to the teams` progress resources comprise additional prototyping budget, an adapted team composition or a strategic realignment. Teams are stopped (no more investment), teamed up (involvement of relevant stakeholders with adjusted funding) or the focus is adjusted for the next sprint (another round of investment).

A **dynamic coordination** of cross-functional, self-organized teams that act outside the given area of responsibility is facilitated by “Objectives and Key Results” (OKRs) (see Figure 7-13). OKRs are shared between the teams and members from different departments. Objectives are only to be achieved by collaboration creation and teams learn from each other and apply the knowledge learned to accelerate the progress. They are an effective tool to develop new innovations and to find opportunities hidden in existing processes. OKRs enable frequent goal setting cycles and takes teams out of the comfort zone. Transparent and clear priorities are set that create a **horizontal alignment** (across business units) in the organization. Teams work in iterations, specifying target objectives for innovation projects and are provided the time and resources to run experiments to meet the target objectives for the next iteration (Humble *et al.*, 2015, p. 17)

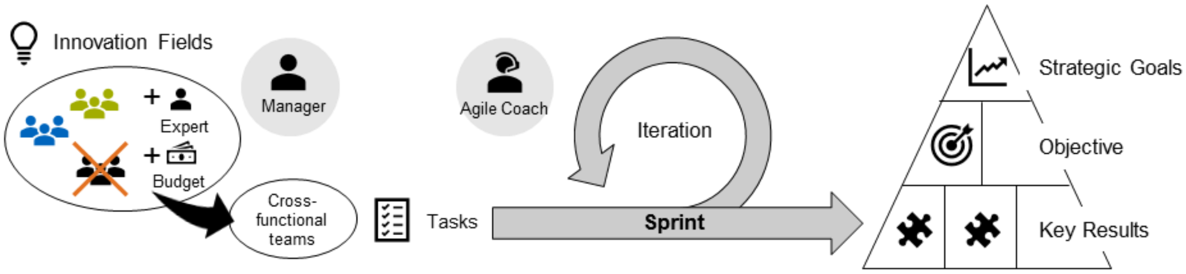

Figure 7-13: Dynamic resource allocation for each innovation sprint to achieve objective key results.

Agile Development – from Concept to Product

The early phase of these projects is characterized by full protection from existing management objectives. Temporary agile teams are dismissed from daily business for a limited time frame to develop their project idea further towards series development. The team is given autonomy to innovate and a tolerance for failures promotes the willingness to change. The predominant values of agile teams are transparency and continuous improvement. The proximity of an innovation team to the core business is dependent on degree of innovativeness and level of maturity. More radical and immature projects are to be protected from corporate structure, whereas more mature projects must be actively involved to make use of company resources.

With project progress, the level for agility is reduced and shifts towards a traditional approach. Experts are brought in as-needed on a temporary basis to help to transfer their scaling expertise to the team. With increasing product specification, the agile teams are dissolved, and functional experts take over (see Figure 7-14). The **ambidextrous transition phase** is facilitated by “information bees” that guide the teams effectively, connect relevant projects and ensure

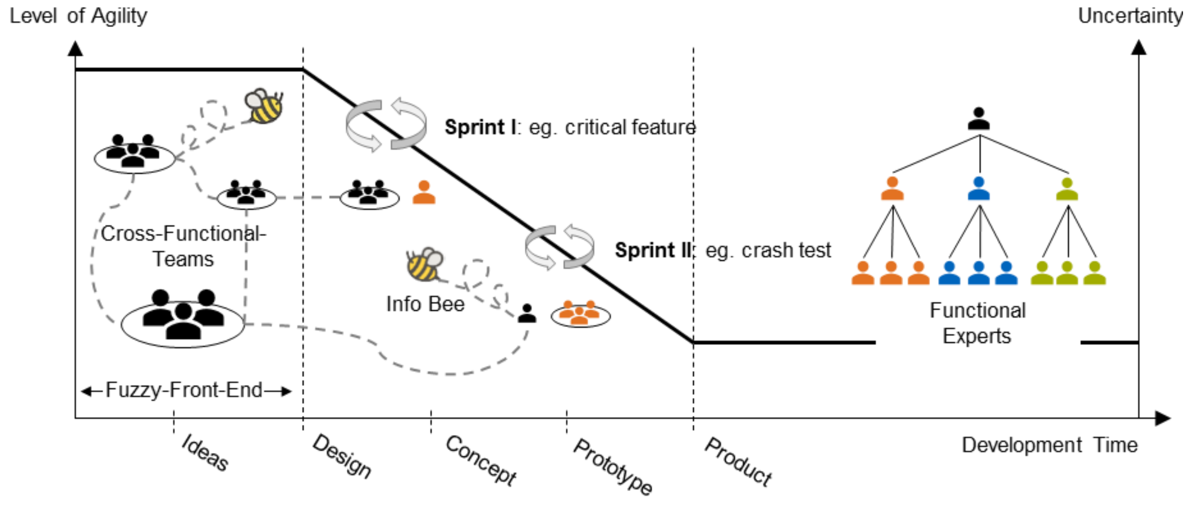

Figure 7-14: Transition phase from "agile to traditional" is supported by information "bees" to support knowledge exchange; with project progress uncertainty decreases and functional experts take over.

knowledge transfer. The transfer from the initial innovation team towards series development is supported by time-boxed development sprints. The functional experts specify deliverables that are to be achieved during a sprint. To hinder a shift towards over-engineering, each sprint comprises prototyping activities. An integration into an existing (car) platform supports communication and hinders NIH-syndrome from naysayers.

The aspect of **systems architecting**, or rather the role "systems architect" is mandatory for hardware related products. Cross-functional innovation teams focus on "build the right product", and form interest groups that are related to development experts to "build it right". Basic team roles (e.g. Design) cooperate on expert level to discuss ideas and exchange project outcomes. The transition phase from concept to product is completed via adoption of one or more team members (see Figure 7-15). For innovations, new to the company, the complete innovation team is adopted to continue with the innovation project. The team benefits from related departments that are relevant for further development but have enough time and resource

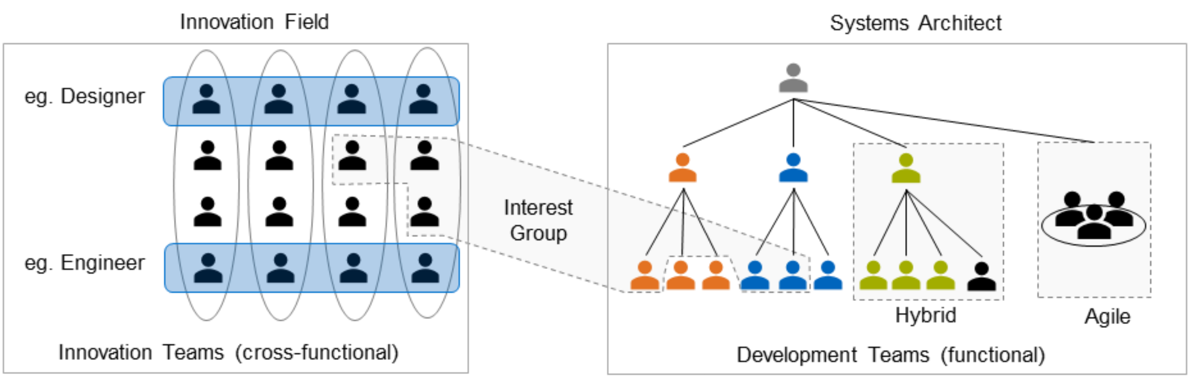

Figure 7-15: Ambidextrous transition phase from innovation team to development team.

to handle complex projects. For innovations, new to the department, one or two team members are adopted to promote the innovation within the responsible development team (= hybrid).

Studies indicate that agile innovation teams can significantly improve **performance** (Kraft, 2012, p. 1). Agile projects benefit from increased motivation, improved communication, collaboration, and greater transparency in terms of resistance and barriers. Progress of innovation projects is facilitated by uncompromising **transparency**. Innovation teams document their project progress so that it is visible to related departments. This allows early involvement of experts and challenges the team to reflect on progress made and next steps to be made. Transparency of project status is an important aspect that allow the ability to respond quickly and flexibly to changing circumstances. It must be ensured that the **communication chain** is limited to two managers to allow iterative development and fast access to decision-making. Iterative development and continuous reviews on the project progress allow smoother effort with less risk over time. Early prototypes ensure feasibility and facilitate user-tests, to reflect on added user-value (see Figure 7-16).

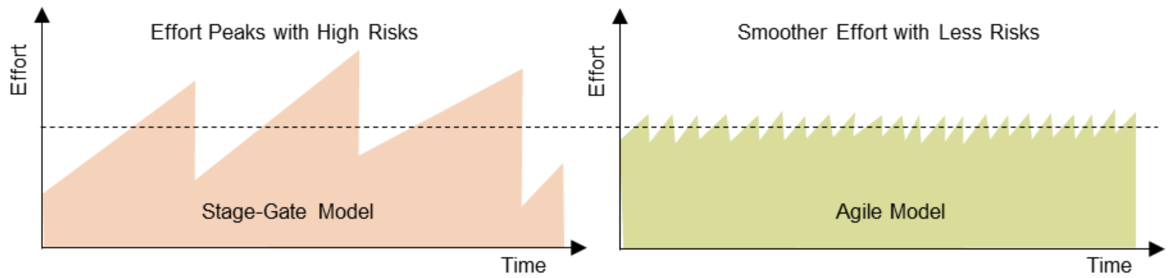

Figure 7-16: From effort peaks to continuous innovations with agile methods.

Some organizations, like Apple, Google and Zara, do things differently. These firms constitute what has been called the “Creative Economy”. They have shifted the goal of the entire organization from maximizing shareholder value to **delighting the customer**. These are organizations in which all the management layers adopt the philosophy of “customer-value first.” Making money becomes the result, not the goal of the organization. For successful execution innovation and development teams are clearly separated. Innovation teams comprise the necessary skills to prototype and learn, independently from the core business. Core business focuses on daily business, series development and increasing regulation issues.

To ensure the integration of the agile project into a traditional project, three aspects must be considered: project management, change management, and quality management (Kraft, 2012, p. 7). The combination of agile and traditional approaches is dependent on the **individual situation**. For OEMs, the main benefit of an agile process model is the increase in process efficiency (through reduction of cycle time and process costs) as well as customer quality (by increasing product maturity and innovation strength). Agile implementation aims for revising the current development process in the direction of a "multi-speed" development and to align the various life and development cycles of individual vehicle components and properties. Short-term method is to reduce cycle times and cycle costs to be consistently aligned with a critical path. The critical path recombines the process model according to the situation-specific and case-specific issue. A “Fastlane” process for new innovations allows rapid execution and integration of latest technology into the product. A technology cycle-oriented development process facilitates to manage the dynamics of the technologies over lifetime. Innovation projects are decoupled but synchronized with related product components. Requirement management is extended from SOP to EOP. Decoupling and virtualization facilitate the time restricted integration and allows flexibilization of the integration process. The product must be enabled for continuous architecture development and improved forward and backward compatibility. The encapsulation of subsystems and systematic definition of interfaces allows continuous delivery with regard to software or hardware.

7.3 Mastering Execution – Agile Innovation at a Corporate

„It’s amazing how fast a prototype can be built when a team is not limited by a given structure, process, or meetings” - Think.Make.Start. Corporate #1

With Think.Make.Start. (TMS), being introduced to a corporate, a format was created to empower employees and give them the freedom needed to innovate. The format bases on the verified assumption that the company has no lack of ideas, but the necessary freedom to focus on the idea implementation. Due to increasing higher vehicle and process complexity, there are limited resources to explore the potential of new ideas effectively. The **early phase** of the innovation process is **blocked** with immature conceptual ideas. Leaving the company with many **raw diamonds** not hitting the market. The format benefits from the partnership of MakerSpace® and the corporate. The high-tech workshop is accessible to all employees as an **innovation incubator**. The Makerspace enables the employees to respond to new ideas and test them directly in an accelerated process, without lengthy processes and procedures. Think.Make.Start. fosters rapid execution, fosters teamwork and promotes collaboration across divisions. Participants gain valuable impulses about agile methods that are necessary to become more like a startup and to do things differently than before.

7.3.1 Nine Generations of Makeathons at an OEM

The overall topic for the TMS-Makeathons are framed by three megatrends in the automotive sector: Digitization, Individualization, and Urbanization. Each Makeathon attracted employees from various departments with different background and expertise. In total ~325 applicants got selected. The application process is not limited to ideas but focuses on the skill-set and experience of the applicants. Ideas may change, but a high-performing team can face any challenge. Nine TMS-Makeathons took place between 2016 and 2018 with employees from every division (see Table 4). Each TMS batch represents a perfect blend of competence variety and people diversity found in the corporate. The skill-set ranged from electric and electronics, to programming, mechanical engineering, or economics, for example. The participation also included international guest, taking innovation on a global scale. The topic of most Makeathons dealt with the product itself, but one Makeathon focused more on the production area.

The aim of Think.Make.Start. in a corporate context is to provide motivated employees an agile project setting (compare Chapter 7.1). Participating teams are given the necessary freedom to pursue their ideas in keeping up with the motto “fail fast, cheap, and early”. The goal of the 5-

day workshop is to have a validated "Problem-Solution-Fit" that is implemented and tested with users. Each Makeathon has a mentor, who acts as internal promoter for the initiative and guarantees the teams executive support. The format fosters horizontal alignment across silos to work together on a common vision with a positive mind-set.

Table 4: Overview of Makeathons participation.

Makeathon	Number of Teams	Period	Number of Participants	Applications	Divisions
TMS #1	~5	December 2016	~25	~50	~4
TMS #2	~10	July 2017	~50	~100	~5
TMS Special #1	~5	August 2017	~25	~50	~3
TMS #3	~10	December 2017	~50	~150	~7
TMS Special #2	~5	February 2018	~25	~50	~3
TMS Special #3	~5	February 2018	~25	~50	~3
TMS #4	~10	July 2018	~50	~200	~7
TMS #5	~10	July 2018	~50	~100	~5
TMS Special #4	~5	August 2018	~25	~50	~3

The teams work in a project room, at the Makerspace, where they have access to an innovation object (e.g. vehicle) to rapidly test their prototypes. TMS features free prototyping budget that facilitates an unbureaucratic purchase of small electronics or materials, without the necessity of an ordering process. The technology library compromises rapid prototyping systems (e.g. Arduino®) to accelerate the first prototyping phases. Experienced "Maker Experts" join the Makeathon to help the innovation teams with best practices and the use of the machines.

The agenda of Think.Make.Start. at a corporate is adapted to a shorter time frame and with focus on project continuation subsequent to the Makeathon itself. A reconciliation with past innovation projects and an expert assessment helps to manage the novelty of the project ideas. For more focused topics, the Makeathon was adapted in terms of participants, and agenda ("TMS Special"). Experienced team member guide unbiased talents and provide valuable suggestions to structure the solution process.

The user is always in focus and prototyping activities help to learn about the problem and to improve the idea and the implementation thereof. Employees develop their concepts iteratively following TAF. Agile coaches support the teams with best practices from previous Makeathons and help the team from a holistic view to focus on the most important task. Early user tests push quality-conscious employees out of their comfort zone while keeping up with the motto "if you are not ashamed of your first prototype, you`ve waited too long". Each team passes the Makeathon with a pitch of the working prototype to top management and a public audience. The continuation of the projects is facilitated by internal incubator or accelerator programs. The award ceremony rewards the teams for their non-stop effort and triggers networking.

7.3.2 Discussion and Implications

Central idea of the Makeathon is the creative space that provides the teams a "free playground" to unleash their innovation potential by making ideas, experience and learnings visible (see Figure 7-17). The Makeathon gives employees the opportunity to unite **existing competences** in-house or to build them on own strength. Having the expertise of the whole company available, allows to come up with an innovative solution that covers several perspectives on product design. Think.Make.Start. seeks for an entrepreneurial short-sight by less bureaucracy, less hierarchical management and integration of entrepreneurial behaviors. Agile working values the fact that rules only arise through the teamwork of the developer group and are thus actually necessary. The Makeathon promotes "do-it-yourself" activities and knowledge transfer across departments by co-location of the teams. Most participants applied for TMS to work hands-on. Two-third joined the Makeathon to turn own ideas into reality and to “escape” the daily business for a while. Two-third wanted to work in interdisciplinary teams. Besides, the participants wanted to get to know the MakerSpace and were curious about agile development.

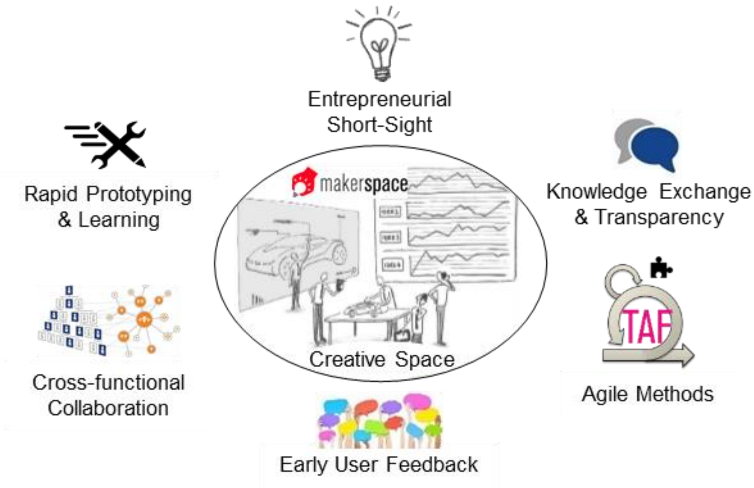

Figure 7-17: Think.Make.Start. characteristics in the context of a corporate.

TMS enables the teams to work on their product vision in absence of traditional decision-making processes or day-to-day distractions. Teams are accompanied by experienced coaches, who help to focus on the most critical or rather important step to do. The format depends on strict time-boxing, as there is no time or resource for non-value adding activities. Rapid prototyping is enabled by access to Makerspace and a small but free to use budget. Prototyping facilitates learning from short trial-and-error cycles and with each prototype, the development process is flexible and accelerated. The team spends limited time on documenting but focuses more on the evolution of the product properties. In contrast to a fixed process sequence, the project is carried out in very close contact with the client/user. The innovation object serves as a fix point and maximizing the employees’ strengths and improves the intercultural performance and behavior. The empowerment of the teams affects all participants and triggers a cultural change from delegation towards DIY. Employees learn to work in a cross-functional team, prototype early and exploit synergies and complementary assets.

Reflection on Approach

The “PreEvent” is a great kick-off and unleashes the creativity of the participants. The day is very intense, but a perfect introduction to the rapid pace of agile product development. For a long-term collaboration, personality tests are a great supplementation to balance the team on a personal level. The time between PreEvent and the Makeathon itself is ideal to catch up with internal experts, and to gather necessary material and resources: “*best preparation is necessary to have success: skilled people*”.

At TMS, participants **experience** agile product development hands-on and get involved in applying the agile mind-set over project time. The creative space gets the employees out of normal, however, the challenge for most teams is to balance wild ideas and realistic implementation. The agile framework “TAF” helps to break predefined plans, as it fosters different perspectives on the product idea. Every project is different, and the cycles are dependent on what needs to be learned. Most of the participants (87,7%) state that early prototyping of ideas with minimum resources and effort is essential for successful innovation.

The Makeathon **qualifies employees** to work independently and to reflect on agile values: commitment, courage, focus, openness and respect. On the downside, the absence of a team member, for example, may cause self-consciousness and frustration. The pace is kept with the daily progress presentation and participants experienced “motivation by loyalty”. After successful completion of TMS, every team gets a T-Shirt, which is perceived as a **symbol of the new and** made the experience more tangible.

The creative atmosphere of Makerspace enriching and facilitates a new mode of operation, far away from day-to-day distraction; “*We have looked outside the box and have been able to network across divisions in the company*”. The intense format fosters **cultural change** and a small group of “naysayers” transforms towards adventurous innovators: “*positive mood of [everybody] involved*”. Participants appreciated the “*opportunity to network*” and the “*support without interference and the [limited number of] rules*”.

Despite the time pressure the teams experienced “*creativity, a great teamwork (...) and a great team feeling on the output”* that has been *“achieved in such a short time*”. Teams enjoyed the energy and professionality “*and the overall passion for the projects*”. Although the teams are competing, they helped each other and compensated missing skills. The innovation object was very valuable as it allows to “*just get started on a real platform*”. Teams stated that they felt like “*working in a startup*” or at least in a “*startup atmosphere*”. User feedback “*in early stages is helpful even if the prototype is not yet as ready as*” the team “*wish it to be*”. A successful collaboration is also about “*finding the right tasks for everyone to get involved*”. The limited time and resources force a team to get “*into a new topic as fast as possible to gain in-depth knowledge to be able to have a prototype within as little time as possible*”.

The interdisciplinary teams learned *“how other people approach such problems”* and that *“most ideas come during prototyping”*. The biggest takeaway from the Makeathon are to “*be unshackled from thought patterns and being able to make one's ideas come true in a physical form in an insane speed*”. The co-location of the team promoted fast decision-making which was very much appreciated by the teams. Participants also stated that they learned to “*be agile”* while experiencing a “*shift in mindset*”. Several employees were amazed by the “w*ork* *progress*” they can achieve, when focusing “*on one thing*” (vs. multi-project management). However, the teams also stated that “*agile mentality is not for everybody*” and implies a huge cultural shift when expanding to the entire group.

Reflection on Outcomes

Makerspaces or innovation labs facilitate project-based learning; however, employees must be provided an initiative to trigger the use thereof. The emerging community is key enabler to integrate prototyping practices and knowledge transfer within and beyond the corporate. The corporate "*(...) is open to new working methods and is ready to change. This is necessary to become faster and more flexible and to make the best possible use of the potential of our employees. In addition, we create and give them scope for their innovative strength.*"

Sustainable transformation is both a “top-down” and “bottom-up” approach. Core element of agile practices is the team that is empowered by TMS, providing a perfect set-up to let employees experience agile product development “hands-on”. After successful participation, the team members either pursue their project or adapt certain practices to their daily job. Each employee getting excited about agile projects, may change the whole organization eventually. TMS is "a*n ingenious way to gain insights into other business areas. This is about designing and producing something together. For me, attending was a very rewarding experience.*"

When comparing the innovation projects at TMS with traditional innovation process, the effort in time and resources is reduced to ~2,22% in time and ~0,8% in budget. As with the statement, “*One thing I learned, innovation does not come from processes*”, the heavy-weight innovation process is reduced to its essential core: “trial and error”. Project ideas are not selected in advance, but teams are given a chance to explore the potential of their idea; in keeping with the motto “*From things may start, to Think.Make.Start.*”. The Makeathon approach seems especially valuable for “*the early phases to solve "insoluble" problems*”.

Each project idea was significantly improved by customer feedback. The teams fully understood the user`s context and how the user is using the prototype. The “error-culture” at TMS also promotes a shift in mind-set. "*(...) We discovered that, thanks to new methodology, it is possible to develop quick solutions. At the same time, failure is allowed, which can be a way to a better solution.*" The outcome of the Makeathons are not necessarily "new" ideas, but an elaborated concept and a working prototype; one participant stated the key take-away as follows: “q*uick decisions and consistent implementation, target-oriented development to the needs of the customer, continuous questioning of requirements and alignment with customer needs, (...) prototypes on a small budget, [and] creativity in general*”. The number of patents related to the Makeathon increased significantly.

Working in a cross-functional team had two main effects. First, the teams worked the same function or sub-function in parallel, rather than in sequence. "*(...) It is very challenging to develop and implement ideas under the very high time pressure, without neglecting creativity. This works only in an interdisciplinary team (...) where you agree on a common [vision] right from the beginning.*". Second, the more heterogeneous the team the better the implementation, as the team has a holistic perspective on the idea. A top manager commented on the entire campaign: "*We must be able to be open again, to admit new methods and to enable structures beyond rigid teams. This finding was confirmed in this project week, because the* *inhomogeneous team composition of planners, business economists, developers and craftsmen has made it possible to develop a concrete solution in just one week.*"

However, only half of the project teams stated that they will continue their project after the Makeathon. This challenge of "how to bring it home" is related to the nature of the cross-functional projects, and limited legitimacy and power within their own organization. Teams stated that "*in addition to an idea and a prototype, the customer wishes, the business case, the startup phase and a good pitch are also essential to continue the project*" and that the "*management must believe in the idea*".

TMS is a great starting point, but not sufficient as a long-lasting innovation cell. Successful continuation of an innovation project is also dependent on the right balance of autonomy and strategic alignment. The difference between autonomy and empowerment is that **autonomy** is self-initiated; freedom to act or function independently while **empowerment** is the granting of political, social or economic power to an individual or group. (Robertson, 2016) introduces the term "Holacracy", a new management system to organize the decision-making processes and thus the hierarchical power within an organization more effectively. The power of decision-making at the top of an organization is transferred to a high decision autonomy for the employee. The promised benefits include a greater involvement and participation of the employees, greater responsiveness to market changes, and greater customer proximity.

Based on the attempts made, by the TMS-teams, and the feedback gathered, the "Corporate Canvas" (CC) is derived to support a successful continuation of the TMS-projects (see Figure 7-18). The Corporate Canvas is a strategic management and lean startup template for

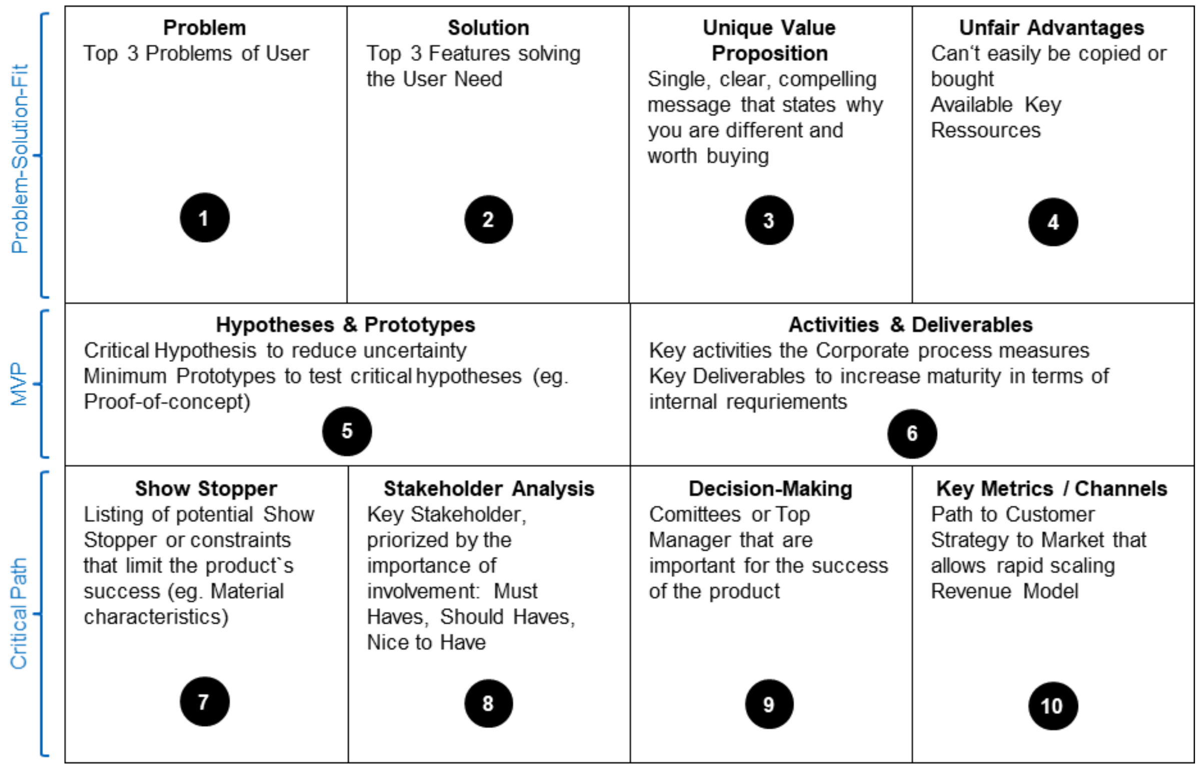

Figure 7-18: Corporate Canvas.

developing new products in a user-centered way, but within the framework of an existing business. It is a visual chart with elements describing a product`s unique value proposition, infrastructure, stakeholders, and decision-making. It assists **intrapreneurial teams** within a corporate to aligning their activities with the core business by illustrating potential trade-offs. Intrapreneurs make use of internal expertise and resources in terms of **unfair advantage** (e.g. key resources) to create a Minimum Viable Product. This new product is created independently from existing processes and decision-making to reduce time-to-market but is designed for **rapid scaling** within the corporate framework.

The template is structured into 10 segments that can be clustered into 3 key areas an intrapreneurial startup must focus on. First, the team identifies a "problem-solution-fit" to offer a unique added value to a user problem (1 – 4). Second, a Minimum Viable Product is built iteratively through prototyping and learning while testing critical hypotheses to reduce uncertainty for this product idea (5). These prototyping activities are aligned with internal activities and necessary deliverables to facilitate early involvement of both valuable stakeholders and resources (5). Third, a **critical path** is identified, by circumventing the internal "Show Stopper", using key stakeholders and by strategically making use of decision-making processes to allow a successful market entry of the developed MVP via gradual rollout or rapid scaling across products.

7.4 From Startup Agility to Corporate Stability

„You have to give ideas the chance to come true" – Thomas Alva Edison

Collaboration with startups combine the best of both worlds. Large corporations have a strategic and global planning strength and successful startups benefit from a culture of permanent innovation, creativity and risk-taking. However, differences in terms of culture, for example, challenge successful cooperation between corporates and startups. The lasting ambidexterity of "Startup Agility" and "Corporate Quality" may be boosted by an "X-Program". Temporary cross-functional teams are protected from existing management objectives, and are given autonomy, incentives, and focus required to innovate. Developing ecosystems inside a

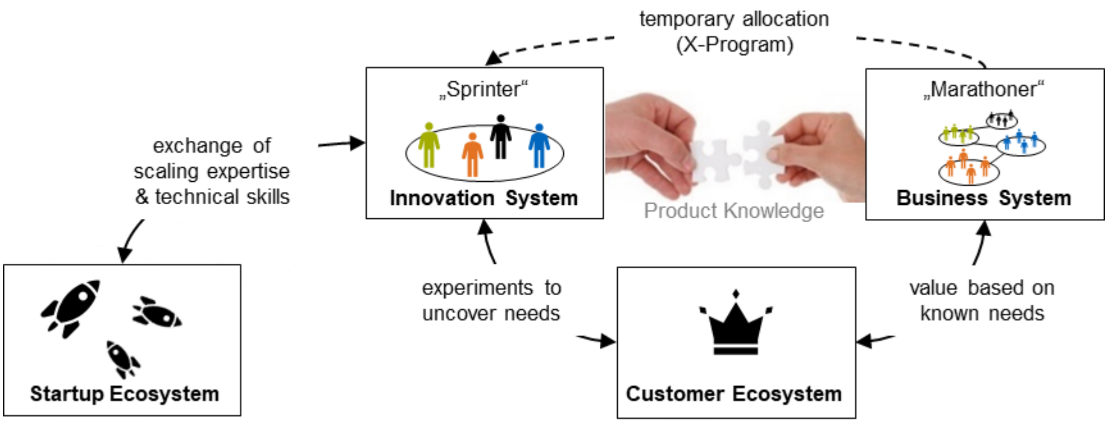

Figure 7-19: Cross-functional Teams as part of an innovations system, enabling innovations new to the company. (Böhmer et al., 2017a, p. 15)

corporate to promote entrepreneurial activity may change organizational behavior from within. Such a program can increase the tolerance to failures, promote the willing to change and may ultimately transform the organization into an agile innovation system (see Figure 7-19). The program must balance entrepreneurial activities with efficient process as outlined in Chapter 7.2., to successfully collaborate with startups while making use of corporate resources.

The digital age requires a model, where innovation is realized quickly by collaborations and efficient infrastructures. The availability and accessibility of information is the key for successful innovation projects. Thus, a "X-Program" is also a lasting conglomerate in form of an innovation hub that supports knowledge management in innovation. Teams comprise both, entrepreneurial thinkers and professional enthusiasts. Highly skilled and committed teams act across all departments, are fully allocated to one project and experience end-2-end responsibility. The teams are independent from the existing structure and processes but have access to the experts from other departments (see Figure 7-20). Main goal of the assigned "X-teams" is to do fast and early pilot studies to acquire relevant information. The teams are provided the necessary resource and freedom to deliver results with limited funds. Partnering with startups extends established infrastructures, with the benefit of faster time-to-market compared to building internally from the ground up. The "X"-branding protects brand or quality standards of series development.

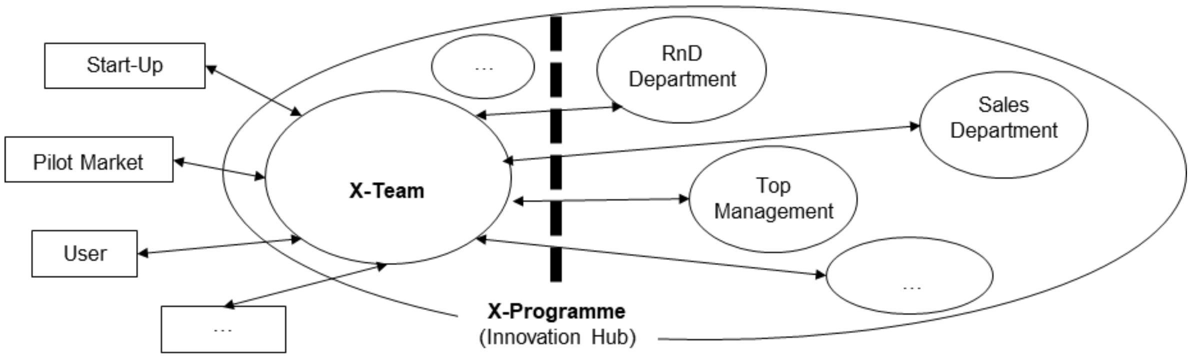

Figure 7-20: The Innovation Hub and its Role in the Organization, adapted from (Leifer et al., 2001, p. 112).

Innovation Hubs are ideal for non-incremental innovations that typically demand more management attention. Highly innovative projects must overcome organizational barriers (e.g. process, timeline, meetings) and find a critical path through the organization to bring their idea to market. Facing the big challenges needs time, skills, and motivation to keep pushing even in the face of failure. To foster change and increase the innovation capability, all X-teams shall be in the center of headquarters. The proximity supports knowledge exchanges as employees are randomly passing by and explore the innovation projects. A permanent exhibition space allows one to continuously gather feedback from experts and users. It also facilitates internal communication and fosters the teams to focus on value-adding activities. The experience of early prototypes helps to involve relevant experts, and theoretical discussions are reduced to a minimum as decisions are made based on the prototype outcome and related user tests.

8. Conclusion and Outlook

This chapter summarizes the research and outlines future research questions of interest. First, the agile development is explored for interdisciplinary teams and mechatronic products. Second, a strategy is derived to integrate agile approaches into the complex context of a corporate aiming to unleash the innovation capability. The research contributed to the current understanding of agile development of physical products, but also resulted in further questions to be answered in future research.

8.1 Conclusions from the Research Work

Digitization enables new business models that emerge at a breathtaking pace and overturn whole industries. Established companies experience volatile markets and must learn to adapt to a fast-changing environment. They face the challenge of balancing the exploitation of their existing business with exploration of new market potentials. Striking this balance is becoming harder due to the high **uncertainty** of various emerging digital technologies and new customer expectations. Fast-paced markets lead to a **shorter horizon of forecasts** and make specifying product requirements upfront less effective. Especially for mechatronics, the speed of the different **technology cycles** is increasing significant, resulting in proven models not being able to deal with the resulting **dynamics**. The challenge of innovation is getting technology to market more quickly to compete with startups that are geared for rapid execution.

New approaches are required to handle the mismatch between new features arising during a several-year development time of complex mechatronic products. To address this, **agile product development** relies on **rapid testing** and early **user feedback**, based on iterative cycles and actual degree of information. The implementation of its principles (rapid prototyping, failing, learning, and adapting), however, is an ordeal within large organizations. Large corporates often lack the required **mind-set** of imperfect prototypes to test and learn ("error culture"), but also the **responsiveness** and **adaptability** for **operative agility**.

The aim of this research was to understand the potential of **agility** within product development of physical products and to evaluate it in a complex **mechatronic** development environment. To assess the current state in research and practice, available literature and data were reviewed. Informal qualitative discussions with customers, employees, management and competitors are conducted. As **hardware-related** agility has not been studied extensively, this research began with an explorative study of seven Makeathons ("Think.Make.Start.") at Technical University of Munich. The applied 5 – 10 days development sprint united experts from various disciplines and allowed them to study the development of mechatronic systems in an agile project setting.

Think.Make.Start. (TMS) fosters **flexible** use of technologies, modified **management** processes (e.g. decision-making), leverages systems design and bases on a **high number of prototypes** (for user testing, increase in knowledge and system integration aspects). The approach ultimately resulted in a **result-driven** development and a continuous adaption of the system to the current situation. Participants learned about prototyping practices, as well as business and engineering methods, but applied them in their project only when needed. In total

75 TMS-projects paths were analyzed, and the findings were summarized in an agile development framework for mechatronic systems (“TAF”). The project setting, and the framework helped development teams to deal with (un)expected changes, and to use those changes as an advantage. The emergent character of the iterative learning approach fostered the reduction of uncertainty with minimum time and effort.

The application and evaluation of the insights gained were elaborated in a **conductive case study** research through interviews, and a hypothesis-based analysis of six innovation projects at a corporate in the automotive sector. In the future, mobility solutions will have shorter life cycles and consumers will be constantly aware of **technological advances**. The increasing **speed of innovation** requires the capability to be adaptive at handling change to continuously generate sustainable competitive advantage. Agile capabilities allow big companies to incorporate new product features **flexibly** and **quickly** into the ongoing multi-year development and to **positively** respond to new user demands. To embrace the strengths of agility within a **large-scale system**, it has been shown that there is not a “one size fits all” solution, but several starting points, such as 100% team allocation.

Systems adaptability and changeability do not necessarily apply to the whole system, but certainly to where speed of innovation exceeds the development time. Enabling an **independent development** of such subsystems affected by innovation dynamics is crucial to apply agility to an **appropriate extent**. The car interior is analyzed from a user-centered perspective, and it is found that changes in software, entertainment systems and smartphone connectivity are particularly important (to the user). Key technologies to drive innovations in the vehicle are big data, ubiquitous computing and connectivity. The results indicate system reorganization towards a **digital systems architecture** that is designed for updates and upgrades. This enables functional improvements and the adaptation to user specific habits over lifecycle of the vehicle.

Established mechatronic development processes cannot be adapted to “agile” in the short run. It involves co-engineering of different disciplines, which requires a **high level of integration**. Based on the identified capabilities and associated enablers an Agile Innovation Strategy is derived iteratively. It combines the advantages of both phase-oriented, multi-gate approaches and result-oriented, agile models, in a systematic and scalable agile process model. **Cross-functional teams** are put together bottom-up or top-down, recurrently in contact with core managers, using the **companies’ resources**, and delivering value to the user early and continuously. Internal contradictions are solved by taking inspiration from **startup strategies**, embracing open innovation, less hierarchical management and integration of **entrepreneurial behaviors**. As a starting point, TMS was implemented and elaborated nine times at a corporate. An entrepreneurial short-sight was established, giving rise to the idea of a Minimum Viable Product. As a result, two products developed during TMS will hit the market one year after.

In conclusion, driving innovation in a corporation can be as exhausting as working in a startup. To overcome the lasting **ambidexterity** of “Startup Agility” and “Corporate Stability” an X-program is described. Temporary cross-functional teams are protected from existing **management objectives**, and are given autonomy, incentives, and the focus required to drive innovation. The program increases the tolerance to failure, promotes the willing to change and may ultimately transform the organization into an **agile innovation system** enabling it to go beyond existing company boundaries.

8.2 Outlook to Future Research

Research has shown that the degree of agility in companies can vary widely. Many companies are still at the beginning of a long transformation process and have just begun to understand what agility means. Further research studies should elaborate the concept of “Agile Leadership” to resolve the tension between the agile mind-set and the management while “aligning” agile teams with corporate goals. As long as there is a top-down “the manager is the boss” mind-set, it will remain challenging to implement agile practices effectively. Continuing friction between different goals limits introducing agile practices at team level. Current efforts to “scale agile” (e.g. SAFe or Less) risk being incomplete and dysfunctional, and counterproductive.

Agile product development is organized around the team and its activities, which makes traditional matrix management difficult. The understanding of team dynamics of agile projects is important, when (re)structuring the organization and developing departmental divisions. Agile transformation describes the process from rigid structures to agile networks. Thus, Human Resources (HR) becomes one of the key player in this transition phase. However, agile projects allocate more resources because developers and users must constantly interact with each other. It is to find out to which extent this resource intense approach is still effective and how the idea of “agile staffing” works in practice. Thus, new HR management concepts are necessary to allow dynamic resource allocation and to adapt teams, if necessary. Also new incentives are to be found to promote employees in the absence of hierarchy.

The research study revealed that current agile practices are limited to pre-development and software development and are rarely applied to collaborative OEM-supplier projects. In the automotive industry, R&D value chains require agile collaboration with suppliers. According to (Scherer, 2017), new sales concepts are to be proposed to allow agile collaboration in the absence of a specified budget or schedule. Further research studies are required to understand how agile management solutions work for a more efficient, demand-driven supply chain.

The key to success in agile projects is to balance flexibility with stability. There is a variety of digital tools to support agile product development projects. Most tools help to track the project and organize the team's progress. However, to date only very little research exists about how to use software products to coordinate autonomous development teams. Virtual design and rapid prototyping are levers for applying “agile” outside the area of software development. The other finding of this research work was that interdisciplinary projects aim for a holistic virtual engineering environment that enables collaboration, and breaking location and domain-specific barriers.

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Zink, L., Böhmer, A.I., Hostettler, R., Lindemann, U. and Knoll, A. (2017), “The use of prototypes within agile product development”, *23th International ICE Conference on Engineering, Technology and Innovation (ICE'17),* Vol. 23, pp. 80–89.

10. List of Abbreviations

ACF	Agility Critical Factors
CFT	Cross Functional Team
DIY	Do it yourself
DSE	Design Space Exploration
DSM	Design Structure Matrix
E/E	Electric and Electronic
E2E	End-2-End (Responsibility)
EOP	End of Production
IPD	Integrated Product Development
MBSE	Model-based Systems Engineering
MDM	Multiple Domain Matrix
MVP	Minimum Viable Product
OEM	Original Equipment Manufacturer
OIE	Open Innovation Ecosystem
OKR	Objective Key Results
R&D	Research and Development
SOF	Survival of the Fittest
SOP	Start of Production
SU	Singularity University
TAF	The Agile Framework
TMS	Think.Make.Start.

11. Appendix

A1 Most relevant Student Theses in the Context of this Work

A2 (Dis)Advantages of Startups and Corporates

A3 Innovation Process Models

A4 Definition of “agility”

A5 Agility Critical Factors

A6 TMS Projects at TUM

A7 Agile Toolbox

A8 Think.Make.Start. Templates

A9 TAF Agile Framework

A10 Agile enabler for physical products

A1 Most relevant Student Theses in the Context of this Work

Table 11-1 represents the most relevant student theses for this research study that were supervised and closely guided by the author, and to some extent became content of this work:

Table 11-1: Overview of most relevant student theses for this work.

Title	Student Name	Year
Konzept für einen individualisierbaren Kaffeevollautomaten	Kosiol, Maike	2014
Aktive Kundenintegration im Entwicklungsprozess am Beispiel des Studentischen Entwicklungsprojektes "FLlink"	Weyerer, Georg	2014
Analysis and Comparison of Representative Locations in the General Makerspace Panorama	Manas Pont, Eduardo	2015
Makerspaces im Innovationsprozess	Beckmann, Andreas	2015
Systematische Moddellierung eines Open Innovation Ecosystem	Kayser, Liza	2015
Analyse der Nutzungsweise des Makerspaces im Innovationsprozess	Draxler, Lisa	2015
Integration von Lean-Startup-Ansätzen in die Produktentwicklung	von Unold, Benedikt	2015
Wie können Großkonzerne durch die Kooperation mit z.B. Startups innovativ bleiben?	Szopinska, Katarzyna	2015
Vereinbarkeit von linearen Prozessmodellen und agilen Frameworks im Innovationsprozess	Lehnhardt, Alexander	2015
Kooperation von Startups und etablierten Unternehmen	Scherer, Andreas	2015
Strategische Bewertung und Priorisierung von Innovationen in großen Unternehmen sowie deren gezielte Umsetzung durch Einbindung eines MakerSpace	von Bary, Nikolaus	2016
Which forms of cooperation with startups are pursued by large companies to enhance their access to disruptive innovation?	Bruse, Florian Andreas	2016
Systematischer Einsatz von Methoden in Hardware-Startups	Nagl, Maximilian	2016
Agile development for Hardware Products - From Idea Generation to Concept Validation	Bender Sao Leao Ferreira, Igor	2016
Methoden des agilen Projektmanagements am Beispiel von Motius GmbH	Devecka, Jakub	2016
A strategic framework for Implementing Open Innovation	Urquidi Guerrero, Josu	2016
Agile Produktentwicklung - Analyse von Prototypen und deren Komplexität	Bachmeier, Julian	2016
Exploration des Design Spaces: Einfluss der Produktkomplexität auf die agile Entwicklung	Gerling, Christoph	2016
Begrenzende Faktoren der Übertragung agiler Methoden auf die physische Produktentwicklung	Hüttel, Joscha	2016
Nutzerzentrierte und agile Methoden im Innovationsprozess: Analyse, Anwendung und Bewertung im Rahmen eines studentischen Konstruktionsprojekts	Künzel, Florian	2016
Einfluss der Innovationsdynamik auf die agile Produktentwicklung	Kosiol Maike	2016
Anwendung von Scrum in der Hardwareentwicklung am Beispiel eines passiven Exoskeletts	Hugger Philip	2017
Erstellen und Anwenden eines agilen Frameworks für Entwicklungsprojekte physischer Produktinnovationen - Analyse des Einflusses von Artefakten und Methoden	Maximilian Meinzinger	2017
Verwendung von Protoypen in der agile Produktentwicklung	Zink, Lucas	2017
Prototyping as a thinking apporach in design	Kayser, Liza	2017
How can the prototyping result be positively influenced by the coaching of methods?	von und zu Auseß, Lisa	2017
Fostering Innovations by Contextual Empatic Design	von Unold, Ben	2017

Potentials and challenges of applying agile methods in the context of systems engineering	Robert Adam	2017
Evaluation des TAF Agile Framework anhand der Entwicklung eines innovativen Wearables für Senioren	Spreiter Lucas	2017
Agile Produktentwicklung unter Zuhilfenahme eines agilen Frameworks - Logische Verknüpfungen zwischen Entwicklungsartefakten und Prototypen	Kamprath, Steve	2017
Anwendung von Scrum in der Konzeptentwicklung einer Evaluationsmetrik für die Absicherung des hochautomatisierten Fahrens aus Kundensicht	Hierlmeier, Tobias	2017
Development of a Robotic Arm and Modular Backbone withina TAF Agile Framework	Oskar, Haller	2017
Roboy - Agil in der Wissenschaft? Agilitätsmessung eines studentischen Entwicklungsprojekts	Christoph, Gerling	2017
Agile Produktentwicklung - Analyse des Prototypings bei einem Makeathon	Daniel, Woche Buccini	2018
Objektzentrierte agile Produktentwicklung - situationsspezifisch erklärt	Constantin Grauvogel	2018

A2 (Dis)Advantages of Startups and Corporates

Table 11-2: (Dis)Advantages of Startups and Corporates (Schoss, 2013, p. 58; Voigt et al., 2005, p. 117).

	Startups	**Corporates**
Advantages	Growth orientation	Competitive advantage
	Small team size	Technological know-how
	Close to the user	Equipment and financial and physical resources
	High flexibility	Experience and its established marketing and sales channels
	High dynamic	External scientific and technological networks
	High innovativeness	Comprehensive range of management skills
	Entrepreneurial spirit	Global infrastructure
	Rapid response	Pronounced brand reputation
	Efficient communication	Established partnerships
	Interactive management style	Scientific knowledge
	Willingness to take risks	Operational excellence
Disadvantages	High Uncertainty	Hierarchical barriers
	Missing routine, standards, and structures	Risk-averse mind-set
	Missing reputation, less legitimacy	Slow innovation processes
	Limited availability of data	Structures and processes
	Limited expert knowledge	
	Limited resources	
	Less capital	
	Less brand presence	
	Fewer strategic alliances	
	Lack of business process	

A3 Innovation Process Models

Table 11-3: Linear innovation process models (Verworn and Herstatt, 2000; Lehnhardt, 2015; Beckmann, 2015)

Linear Models	**Source**	**Description**
Phase-Review by Hughes	Hughes & Chafin, 1996, S.92	Pure engineering methodology; hard go-no-go criteria
Process model by Ulrich und Eppinger	Ulrich et al. (1995), S. 15	
Innovation process: simultaneous activities	Crawford (1994), S. 27	
Value proposition cycle	Hughes et al. (1996), S. 93)	
Innovation process by Witt	Witt (1996), S. 10	
Three-Phases-Model by Thom	Thom, 1992, S. 9	
Stage-Gate-Process by Cooper	(Cooper, 1983, p. 5)	Decision gate after each phase
Stage-Gate-Process by Cooper (Generation 2)	Cooper, 1990, S. 45	
Stage-Gate-Process by Cooper (Generation 3)	Cooper (1996), S. 479	
Process model by Hauschildt	Hauschildt & Salomo, 2007, S. 26-27	
Phase model by Brockhoff	Brockhoff, 1999, S. 36	Explicit presentation of the process stops
Innovation process by Vahs	Vahs et al. (1999), S. 89; Vahs & Brem, 2013, S. 226	Supplement to innovation controlling
Process model by Pleschak & Sabisch	Pleschak & Sabisch, 1996, S. 26	
Innovation process by Herstatt	Herstatt (1999), S. 73; Herstatt et al., 2007, S. 11	Focus on early phases („fuzzy front end“)
Waterfall model by Royce	Royce, 1970, S.330	Adaptation to product life cycles, returns to previous phase possible
Overall process of the work specification	Ebert et al. (1992), S. 148	

Table 11-4: Iterative innovation process models (Verworn and Herstatt, 2000; Lehnhardt, 2015; Beckmann, 2015)

Iterative Models	Source	Characteristics
Model by Ropohl	Ropohl, 1989, S.19	Feedback loops between the stages
Circle model by Roy & Cross	Bertram, 2011, S.40	Influence of ideas on each phase possible
Chain-linked model by Kline & Rosenberg	Kline und Rosenberg, 1986, S. 290	Complex model with a variety of possible routes
V-Model / VDI 2206	(VDI-Richtlinie, 2004)	Focus on early stages of development of mechatronic systems
Innovation cycle by von Au	von Au, 2011, S. 57	Overall routine of innovation, adaptation necessary
Technology innovation process by Fraunhofer IAO	Knospe et al., 2011, S.17	Cyclic arrangement of the last 5 phases
Simultaneous / Concurrent Engineering	Borchert & Hagenhoff, 2003, S. 41	Parallelization of the development phases, many feedback loops, but also time savings
Spiral model by Boehm	referring Boehm, 1988, S.64	Work steps in four cyclic phases for each case
Next-Generation Stage-Gate-Process	(Cooper, 2015, p. 21)	Iteration with customer

Table 11-5: Radical innovation process models (Verworn and Herstatt, 2000; Lehnhardt, 2015; Beckmann, 2015)

Process Models for Radical Innovation	Source	Characteristics
Process model for radical innovation by Veryzer	Veryzer, 1998, S.317	Focus on early stages, early prototyping and customer engagement
Model for radical innovation by Scigliano	Rüggeberg & Burmeister, 2008, S.19	Division into project unspecific and -specific part
5-Phases-Approach for radical innovation by Lichtenthaler	Lichtenthaler et al., 2003, S. 267	Focus on early stages

A4 Definitions of "agility"

Table 11-6: Definitions of the term „agility" (Beckmann, 2015; Meinzinger, 2017).

Definition	Source
„Responding to change (anticipated or unexpected) in proper ways and due time." und „Exploiting changes and taking advantage of them as opportunities."	(Sharifi & Zhang 1999, S.10)
„Agility is the successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) through the integration of reconfigurable resources and best practices in a knowledge-rich environment to provide customer-driven products and services in a fast changing market environment"	(Yusuf et al. 1999, S.37)
„Agility might, therefore, be defined as the ability of an organization to respond rapidly to changes in demand, both in terms of volume and variety."	(Christopher 2000, S.38)
„Agility is the ability to both create and respond to change in order to profit in a turbulent business environment."	(Jim Highsmith 2002, S.17)
„'Agile' refers to maneuverability, the ability to respond to changes in the environment."	(Alistair Cockburn 2002, S.6)
„Agility applies memory and history to adjust to new environments, react and adapt, take advantage of unexpected opportunities, and update the experience base for the future."	(Boehm & Turner 2004)
„Agility is a persistent behaviour or ability of a sensitive entity that exhibits flexibility to accommodate expected or unexpected changes rapidly, follows the shortest time span, uses economical, simple and quality instruments in a dynamic environment and applies updated prior knowledge and experience to learn from the internal and external environment."	(Qumer & Henderson-Sellers 2006, S.505)
Agility is the ability to thrive in a competitive environment of continuous and unanticipated change and to respond quickly to rapidly changing, fragmenting global markets that are served by networked competitors with routine access to a worldwide production system and are driven by demand for high-quality, high-performance, low-cost, customer-configured products and services.	(Goldman *et al.*, 1995)
Agile manufacturing aims to meet the changing market requirements by suitable alliances based on core-competencies, by organizing to manage change and uncertainty, and by leveraging people and information.	(Gunasekaran *et al.*, 2002)
Agility is more formally defined as the ability of an enterprise to operate profitably in a rapidly changing and continuously fragmenting global market environment by producing high-quality, high-performance, customer-configured goods and services.	(Tsourveloudis and Valavanis, 2002)
Agility is a persistent behavior or ability of a sensitive entity that exhibits flexibility to accommodate expected or unexpected changes rapidly, follows the shortest time span, uses economical, simple and quality instruments in a dynamic environment and applies updated prior knowledge and experience to learn from the internal and external environment.	(Qumer and Henderson-Sellers, 2008)
Agile enterprises react quickly and effectively to changing markets, driven by customized products and services.	(Bottani, 2009)
The movement towards a new agility-based paradigm, the term 'agile organisation' has arisen and is increasingly utilised in literature on operations management and business administration to mean a model of flexible organisation, capability of rapidly adapting to changes in the environment and setting a variety of products on the market to satisfy the requirements of increasing demand and well-informed customers.	(Eshlaghy *et al.*, 2010)

Agility is a dynamic organization design capability that can sense the need for change from both internal and external sources, carry out those changes routinely, and sustain above average performance.	(Worley and Lawler, 2010)
Agile enterprises are concerned with change, uncertainty and unpredictability within their business environment and with making an appropriate response.	(Tseng and Lin, 2011)
Goal: To satisfy the customer through early and continuous delivery of software that is of value to the customer.	(Iivari and Iivari, 2011)

A5 Agility Critical Factors

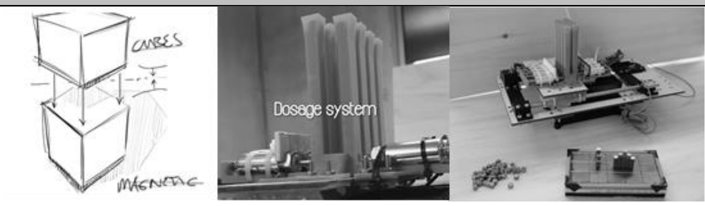
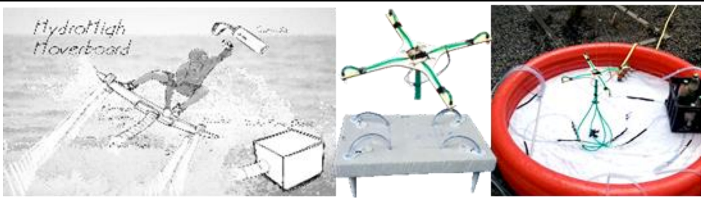
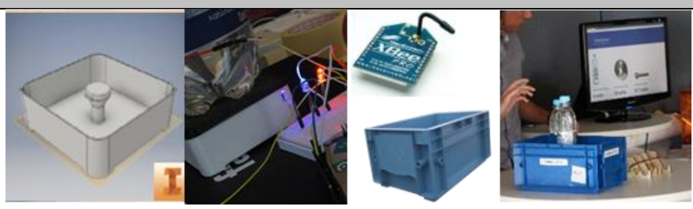
Table 11-7: Overview of Agility Critical Factors, adapted from (Conforto et al., 2014b).

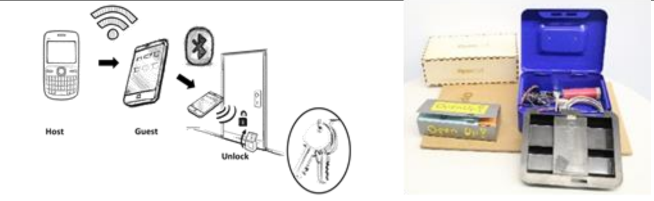
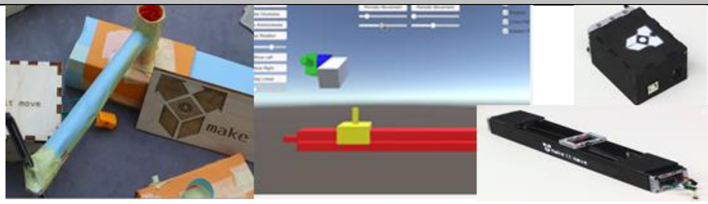
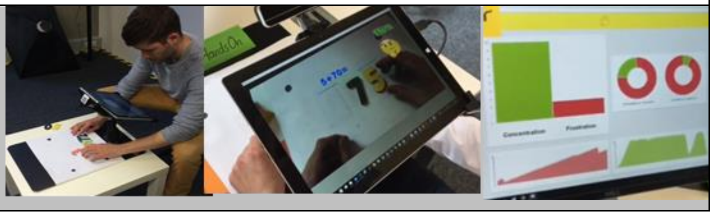
Number	Motivational Quote
AF1	Project manager years of experience in leadership positions
AF2	Client/market representative & project team members working geographically close
AF3	Having client or market representative available and committed to be actively involved in the project development
AF4	Client/market representative possesses required knowledge regarding product's technology to be helpful an easily check & validate partial results
AF5	Team member's greater technology competences
AF6	Project manager being highly experienced working on similar projects
AF7	Team member's experience on working on similar projects, with the same challenges, degree of innovation, complexity, etc.
AF8	Having project teams with multiple competences
AF9	Having small project teams working on the project
AF10	Having full allocated project team members working exclusively dedicates to one project at a time
AF11	All project team members work in the same room (or very close), favoring face-to-face-communication
AF12	Project team's more positive attitude toward dealing with and accepting changes during project lifecycle
AF13	Project team's autonomy to make decisions

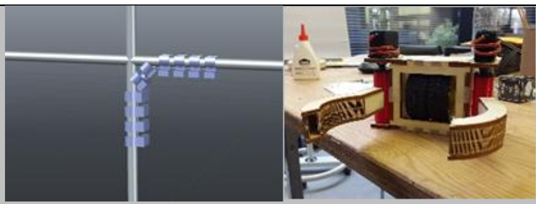
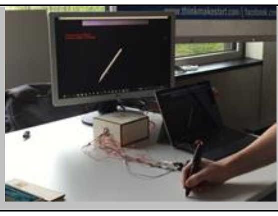
A6 Think.Make.Start. Projects at TUM

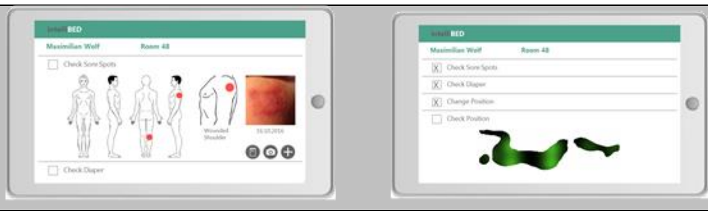
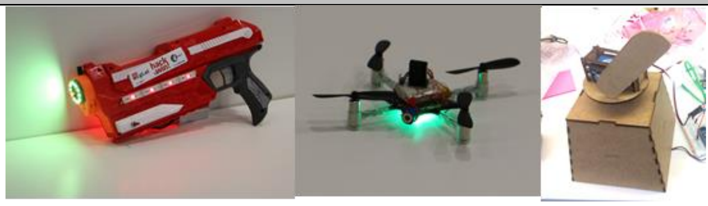
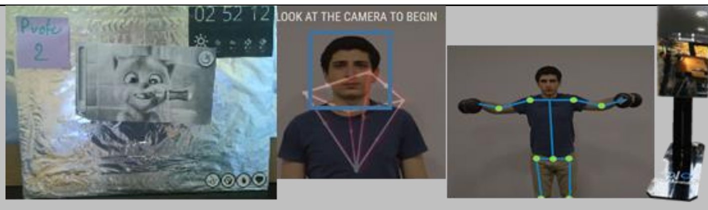
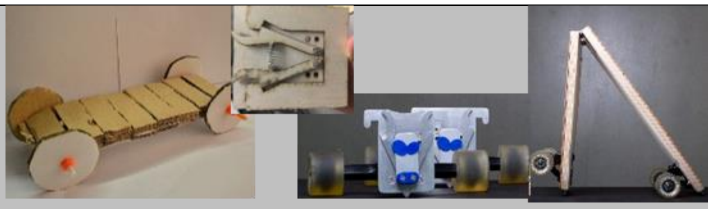
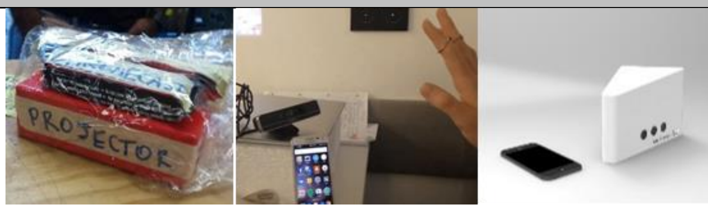
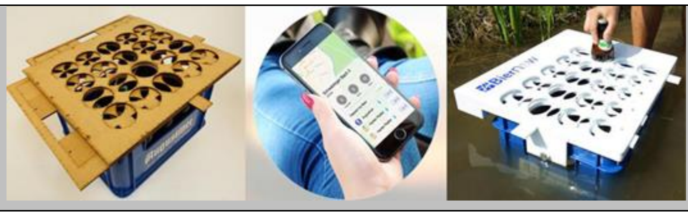
Table 11-8: Overview of the TMS projects at Technical University of Munich (2015 – 2018).

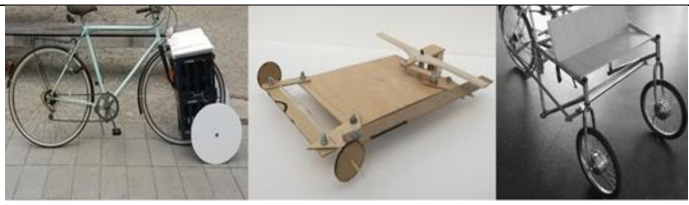
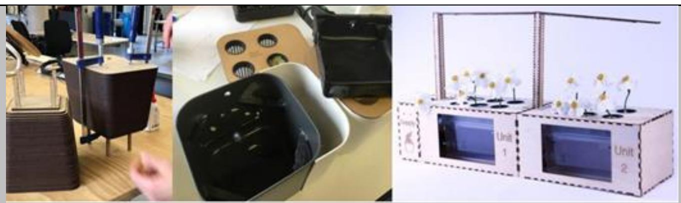
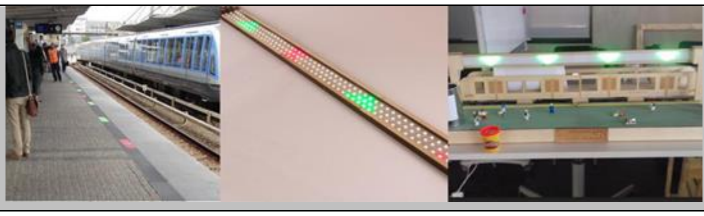
Batch	Team	Prototypes	Description
TMS #1	Awesome Bot		Robotics science experience kit, with mobile robot platform, POV control
TMS #1	Hawa Dawa		Distributed wearable air quality sensor to build air quality map
TMS #1	Airon		Automated ironing cupboard
TMS #1	Gyro		Box to stabilize a bike with flywheels
TMS #1	Smart Weights		Self-tracked dumbbells that count automatically and warn the user when handled wrongly
TMS #1	jMouse		A PCB that makes it easy to connect external periphery to the Jolla phone and use it as the compute node
TMS #1	Visual Caffeine		Build office lamp with sunlight spectrum and add a button that turns light bluish that triggers wakeup reflex

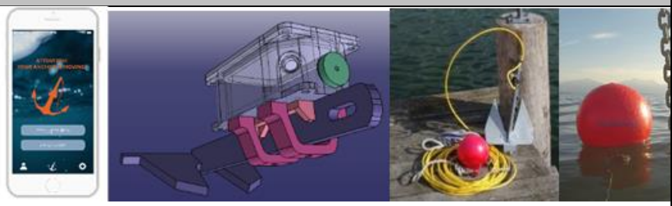
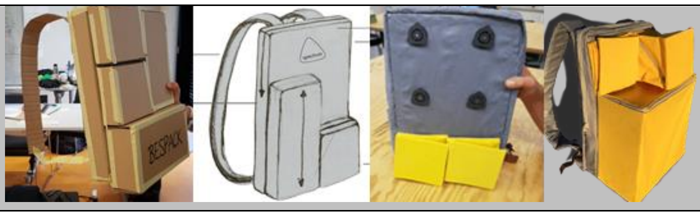
TMS #1	EcoPlug		A kit of tools (water turbine, solar, wind) to make charging possible in the wild
TMS #1	ParkHere		Energy autarkic sensor embedded into parking space
TMS #2	Rise		3D displays based on stacking magnetic cubes
TMS #2	Meelo		Individual food timetable with online grocery ordering
TMS #2	HydroHigh		Waterjet hover board
TMS #2	Sign2Speech		Myo tracker based sign language to speech translator
TMS #2	Smartainers		sensor tag based tracking solution for boxes in intralogistics with embedded scale to estimate box filling
TMS #2	Park Me James		Intelligent parking system that guides a vehicle to a free parking lot

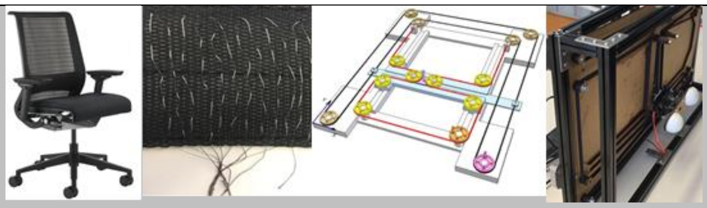
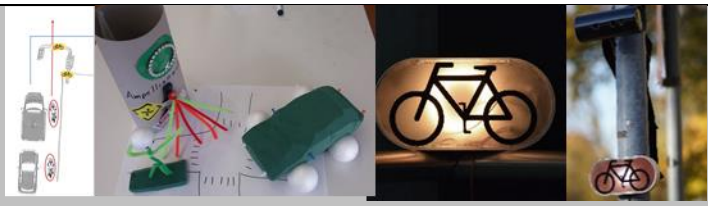
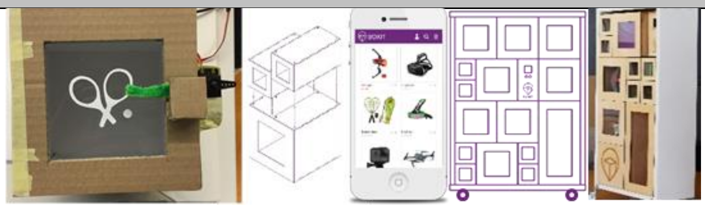
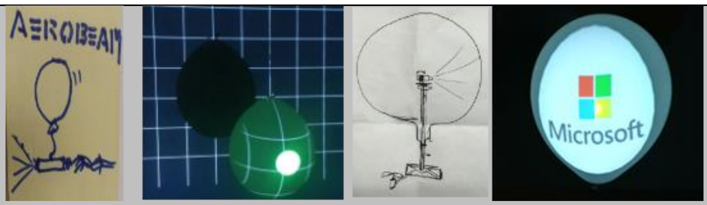
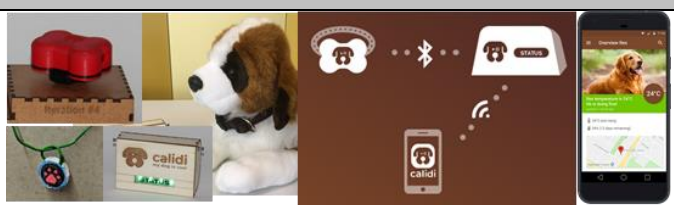
TMS #2	Open Up		Key-box with app unlocking
TMS #2	Solemove		Shoe with integrated fall detection
TMS #2	Make it Move		Modular simple robotics toolkit
TMS #3	EpicBoard		Electric skateboard controlled by leaning
TMS #3	Butt Box		Gamified box to collect cigarette butts
TMS #3	Carisma		Unified in car entertainment and communication system
TMS #3	Clap Flaps		Split-flap display for advertisement
TMS #3	Hands On		Augmented learning system that tracks attention of the student

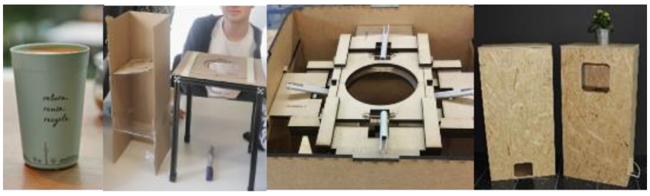
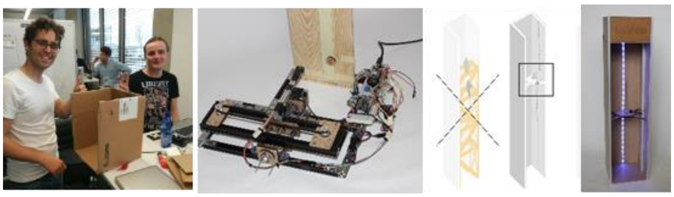
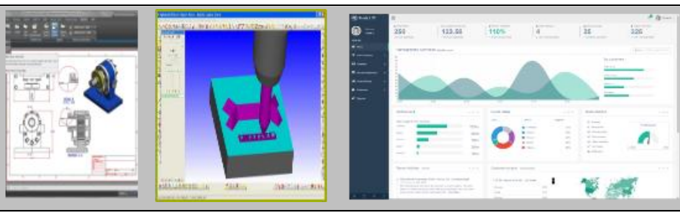
TMS #3	Blue Caterpillar		Automated document scanning & archiving
TMS #3	Kewazo		Scaffolding assembly robot
TMS #3	Lazy Loundry		Laundry folding automaton
TMS #3	Lumi Nav		Bike light with integrated navigation display
TMS #3	Taste My Spätzle		Spätzle vending machine
TMS #4	FurNEWture		Electrically adjustable multifunctional furniture for constraint spaces
TMS #4	FANcam		Ball tracking camera for sports
TMS #4	MiMero		Tracked pen to learn writing

TMS #4	Bikorsa		Stylish bike seat-pocket with integrated backlight
TMS #4	IntelliBed		Decubitus prevention through intelligent mattress with app
TMS #4	Drone Tag		Laser tag with drones and VR remote play
TMS #4	Solos		One-way mirror that displays workout and tracks users' performance
TMS #4	Oasis		Infusion-based healthy sparkling drink machine
TMS #4	LongShoard		Foldable longboard
TMS #4	MyScreen		Mobile screen with gesture control
TMS #5	BierNow		App-based beer storage box in the English Garden

TMS #5	eCarus		Front-mounted bicycle trailer with electric drive
TMS #5	Hallo		Communication bracelet, app-based
TMS #5	Cuberry		"Curiosity Cube", sex toy
TMS #5	BullBindings		Automatically adjusting ski binding
TMS #5	Meetifiy		Automatic protocolling, app-based
TMS #5	StattGarten		Automated irrigation system for plants
TMS #5	Tidy Up		Dish storage system for dishwashers
TMS #5	Crowdless		Optical orientation system on train station for entrance

TMS #5	VertiClean		Window cleaning robot for facades
TMS #5	We R‘ Cars		Remote-controlled vehicles with virtual projections (route, noises, game options, etc.)
TMS #5	PreMain		Predictive maintenance warning system for failures of escalators
TMS #5	ConDR		Autonomous drone for bird defense at e.g. wine-growing area
TMS #6	Anchora		Accurate anchor system; anchor orientation and emergency alert when moving
TMS #6	Traffic Hero		Smart devices that deliver reliable, high quality data about traffic flows.
TMS #6	Brain Guard		EEG measurement of brain activity with fatigue trigger at cap to keep drivers safe
TMS #6	Spectrum		Customizable plug’n’go backpack; with removable straps, hidden safety mechanism

TMS #6	Intonar		High-Tech solution to continue playing an instrument by making it easier and more fun
TMS #6	Painkillers		Office chair module to reduce period pain or lower back pain; discreet heat and massage.
TMS #6	Mein TV		Box with simple TV application for seniors 65+; included speech control
TMS #6	Ampelligence		Intelligent blinking light with horn; biker detection to warn the driver to prevent accidents.
TMS #6	BoxIT		Modular storage system to design the locker system according to individual needs.
TMS #7	AreoBeam		An airborne platform for individual air advertising.
TMS #7	Calidi		Device that rescues dogs from overheating in e.g. vehicles.
TMS #7	EmoConn		Emotional tracking for psychiatric treatment, meditation or movie (content) analysis.

TMS #7	The GreenMachine		A complete - recycling and refund - system for reusable cups.
TMS #7	JamBuddy		Empower jamming for everyone, playing their own tempo based on current skills
TMS #7	LEVARU		Robot system for elevator installation to optimize the adjustment of the guide rails
TMS #7	[ɛːmmaː]		Improvement of presentation skills by finding the right speed and volume for the audience.
TMS #7	Nachbarstrom		AI based Rooftop Software to calculate individual Photovoltaic for sharing local energy in the neighbourhood.
TMS #7	Pickeru		Smartphone-based real-time retrofit shopping system for retail stores
TMS #7	PoolHeroes		Bracelets to monitor constantly children in the pool to prevent them from drowning accidents
TMS #7	Predict.IT		Use of AI to derive features from the initial CAD file

TMS #7	RowSync		Intelligent solution to optimize the synchronization of all rowers in a boat
TMS #7	Stad`X		IoT for interactive games, provide people with a new way to play, act and interact as a team
TMS #7	Ternow / Lovai		Deep learning-based service, offering an encompassing dating experience.

A7 Agile Toolbox

A7.1 List of Development Methods

Table 11-9: Overview of development methods, adapted from (Beckmann, 2015; Nagl, 2016; Meinzinger, 2017).

Process Phase	Framework	Method	Reference
Recognition and Identification	Design Thinking	Definition of the question	(Uebernickel et al., 2015, S. 88)
	Design Thinking	Stretch Goals	(Kerr & Landauer, 2004)
	Design Thinking	Framing und Re-Framing	(Morgan, 2006)
	Design Thinking	Inspiration from the “Future”	(Uebernickel et al., 2015, S. 94)
	Design Thinking	Observation or rather Ethnography	(Laurel, 2003, S. 26f)
	Design Thinking	Shadow Studies (German: "Schattenstudien")	(Laurel, 2003, S. 45)
	Design Thinking	Customer Intercepts	(Ingle, 2013, S. 22)
	Design Thinking	Engagement	(Uebernickel et al., 2015, S. 111)
	Design Thinking	Camera Studies (Spontaneous Cinema)	(Laurel, 2003, S. 118)
	Design Thinking	Analog Empathy	(d.school Stanford, o.J., S. 12)
	Design Thinking	Studies	(Laurel, 2003, S. 45)
	Design Thinking	Expert Interview	(Laurel, 2003, S. 45)
	Design Thinking	Wake-Up Interview	(Laurel, 2003, S. 45)
	Design Thinking	Context Interview	(Laurel, 2003, S. 45)
	Design Thinking	Longitudinal interview (German: "Längsschnitt Interview")	(Laurel, 2003, S. 45)
	Design Thinking	focus groups	(Laurel, 2003, S. 45; Hom, 1998, S. 12)
	Design Thinking	User Journey	(Richter & Flückiger, 2013b, S. 38–47)
	Design Thinking	Lead User Interview	(Herstatt & von Hippel, 1992)
	Design Thinking	Laddering (5-Warum)	(Uebernickel et al., 2015, S. 128f)
	Design Thinking	Field Notes	(Emerson et al., 2011)
	Design Thinking	Frameworks	(Beckman & Barry, 2007, S. 36; Richter & Flückiger, 2013b, S. 38–47)
	Design Thinking	Mood board	(Gray et al., 2010, S. 186)
	Design Thinking	Sensitive diagram	(Gray et al., 2010)
	Design Thinking	Point of View or Do-The-Pig	(Uebernickel et al., 2015, S. 130)
	Design Thinking	Affinity Diagram	(Courage & Baxter, 2005, S. 715)
	Design Thinking	(Service) Blueprints	(Stickdorn & Schneider, 2011, S. 204)
	Design Thinking	Customer Journey Map	(Stickdorn & Schneider, 2011, S. 158)
	Design Thinking	User Profile	(Courage & Baxter, 2005, S. 43)
	Design Thinking	Persona	(Courage & Baxter, 2005, S. 47f; Richter & Flückiger, 2013b, S. 38–47)
	Design Thinking	Scenarios and Use Cases	(Courage & Baxter, 2005, S. 52; Patton et al., 2014, S. 40)
	Design Thinking	Context or Stakeholder Map	(Stickdorn & Schneider, 2011, S. 225)

	Design Thinking	Context Analysis	(Richter & Flückiger, 2013b, S. 38–47)
	Design Thinking	Storyboard	(Stickdorn & Schneider, 2011, S. 186; Richter & Flückiger, 2013b, pp. 38–47)
	Design Thinking	2x2 Matrix	(d.school Stanford, o.J., S. 22)
	Design Thinking	Story Maps	(Patton et al., 2014)
Refinement and Development	MPM	cost-benefit analysis	(Lindemann, 2009, S. 285)
	MPM	sensitivity analysis	(Lindemann, 2009, S. 306)
	VDI 2221	3-criteria evaluation	(VDI-Richtlinie 2221, S. 37)
	VDI 2221	business case	(VDI-Richtlinie 2221, S. 36)
	VDI 2221	capital budgeting	(VDI-Richtlinie 2221, S. 36)
	VDI 2221	dimensioning	(VDI-Richtlinie 2221, S. 36)
Problem Definition and Idea Generation	Design Thinking	Six Thinking Hats	(Bono, 1999)
	Design Thinking	Power of Ten	(d.school Stanford, o.J., S. 21) (Kerr&Landauer,È
	Design Thinking	How might we?	(d.school Stanford, o.J., S. 29)
	Design Thinking	Real Customer Involvement (Customer integration)	(Beck & Andres 2004), (Plattner et al. 2009), (Ries 2011)
	Design Thinking	Storytelling	Grots & Pratschke 2009, S.20), (Lindemann 2009, S.307)
	Design Thinking	5 Why	(Hilbrecht & Kempkens 2013, S.359f), (Ambrose & Harris 2010, S.16)
	Design Thinking	Brainstorming	(Plattner et al. 2009, S.121)
	Lean Startup	Context or stakeholder mapping	(Stickdorn & Schneider, 2011, S. 225)
Idea Selection	Design Thinking	Consumer Clinics	(Uebernickel et al., 2015, S. 186)
	Design Thinking	Usability Testing	(Uebernickel et al., 2015, S. 187)
	Design Thinking	Heuristic Evaluation	(Hom, 1998, S. 21)
	Design Thinking	Elevator or rather NABC Pitch	(Uebernickel et al., 2015, S. 188)
	Design Thinking	Pecha Kucha	(Uebernickel et al., 2015, S. 189)
	Lean Startup	Hypotheses	(Maurya, 2012, S. 83 & S. 101)
	Lean Startup	Interviews	(Maurya, 2012, S. 84 & S. 103)
	Lean Startup	Prototyping	(Maurya, 2012, S. 95)
	Scrum	Release Plan	(Gloger, 2016, S. 81)
	MPM	preselection	(Lindemann, 2009, S. 324)
	MPM	Weighting of the evaluation criteria	(Lindemann, 2009, S. 271)
	MPM	Advantage-disadvantage comparison	(Lindemann, 2009, S. 325)
	MPM	Pairwise comparison	(Lindemann, 2009, S. 289)
	MPM	(Simple) point rating	(Lindemann, 2009, S. 296)
	MPM	Weighted point rating	(Lindemann, 2009, S. 296)
Requirements Collection	MPM	Moderation with Cards	(Lindemann, 2009, S. 280)
	MPM	Mind Mapping	(Lindemann, 2009, S. 279)
	MPM	Research	(Lindemann, 2009, S. 299)
	MPM	Benchmarking	(Lindemann, 2009, S. 248)
	MPM	Technical evolution	(Lindemann, 2009, S. 314)

	MPM	Trend Analysis (Extrapolation)	(Lindemann, 2009, S. 316)
	MPM	Delphi-Analyze	(Lindemann, 2009, S. 256)
	MPM	Scenario-Technik	(Lindemann, 2009, S. 312)
	MPM	Gradual Consistency (German: "Stufenweise Konsistenz")	(Lindemann, 2009, S. 308)
	MPM	consistency matrix	(Lindemann, 2009, S. 276)
	MPM	Cluster Analysis	(Lindemann, 2009, S. 255)
	MPM	plausibility analysis	(Lindemann, 2009, S. 290)
	MPM	weak point analysis	(Lindemann, 2009, S. 305)
	MPM	Relation-oriented functional modeling	(Lindemann, 2009, S. 301)
	MPM	ABC-Analysis	(Lindemann, 2009, S. 242)
	MPM	SWOT-Analysis	(Lindemann, 2009, S. 309)
	MPM	Degree of freedom analysis	(Lindemann, 2009, S. 266)
	MPM	Portfolio	(Lindemann, 2009, S. 291)
	MPM	forecast	(Lindemann, 2009, S. 295)
	VDI 2221	objectives definitions (German: "Zieledefinitionen")	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	market analysis	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	competitor analysis	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	analysis of the company	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	Third-party product analysis	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	forecasting methods	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	Problem analysis (e.g. ABC analysis)	(VDI-Richtlinie 2221, S. 33)
	Scrum	Freewriting	(Gloger, 2016, S. 118)
	Scrum	Elevator Pitch	(Gloger, 2016, S. 118)
	Scrum	Market and competitor key figures	(Röpstorff & Wiechmann, 2016, S.99)
	Scrum	User statistics, survey or test results	(Röpstorff & Wiechmann, 2016, S.99)
	Scrum	Customer or client information	(Röpstorff & Wiechmann, 2016, S.99)
	Lean Startup	Strategy Canvas/Value Curve	(Kim & Mauborgne, 1997, S. 108)
	Lean Startup	Questionnaire	(Maurya, 2012, S. 89 & S. 107)
	MPM	Functional Modelling	(Lindemann, 2009, S. 267)
	MPM	Clustering	(Lindemann, 2009, S. 255)
	MPM	German: "Wirkungsnetz"	(Lindemann, 2009, S. 327)
	MPM	Dependency matrix	(Lindemann, 2009, S. 259)
	MPM	Portfolio Dependencies	(Lindemann, 2009, S. 291)
	MPM	Connection Matrix	(Lindemann, 2009, S. 322)
	MPM	Quality Function Deployment	(Lindemann, 2009, S. 298)
	MPM	Black Box	(Lindemann, 2009, S. 251)
	MPM	Kano Model	(Lindemann, 2009, S. 275)
	Lean Startup	Risk Analysis	(Maurya, 2012, S. 50)
	Lean Startup	Business Model Canvas	(Stickdorn & Schneider, 2011, S. 212)
	Lean Startup	Lean Canvas	(Maurya, 2012, S. 44)
	Lean Startup	Value Proposition Canvas	(Osterwalder et al., 2015, S. 3)

	Lean Startup	Customer Segmentation	(Maurya, 2012, S. 157)
	MPM	text analysis	(Lindemann, 2009, S. 315)
	MPM	expert discussion	(Lindemann, 2009, S. 72)
	MPM	questioning technique	(Lindemann, 2009, S. 265)
	MPM	Checklist	(Lindemann, 2009, S. 254)
	MPM	cause and effect analysis	(Lindemann, 2009, S. 320)
	MPM	Reverse Engineering	(Lindemann, 2009, S. 303)
	MPM	weighting in single-stage (German: "Einstufige Gewichtung")	(Lindemann, 2009, S. 271)
	MPM	weighting in multi-stage (German: "Mehrstufige Gewichtung")	(Lindemann, 2009, S. 271)
	MPM	problem formulation	(Lindemann, 2009, S.294)
	VDI 2221	Verbal functional description	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	functional specification document	(VDI-Richtlinie 2221, S. 34)
	Scrum	MusCoW	(Gloger, 2016, S. 134)
	Scrum	1.000 Ping Pong-Balls	(Gloger, 2016, S. 134)
	Scrum	Relative weight	(Gloger, 2016, S. 137)
	Scrum	Things-that-matter-Matrix	(Röpstorff & Wiechmann, 2016, S. 147)
	Scrum	Estimate with story points	(Gloger, 2016, S. 141)
	Scrum	Magic Estimation	(Gloger, 2016, S. 143)
	Scrum	T-Shirt-Method	(Röpstorff & Wiechmann, 2016, S. 160)
	Scrum	Team-Estimation-Game	(Röpstorff & Wiechmann, 2016, S. 165)
	Scrum	Relative comparison	(Röpstorff & Wiechmann, 2016, S. 173)
	Scrum	From a single source method	(Röpstorff & Wiechmann, 2016, S. 173)
	Scrum	Laser Sword Estimation	(Röpstorff & Wiechmann, 2016, S. 174)
	Scrum	Ouija Board Estimation	(Röpstorff & Wiechmann, 2016, S. 174)
	Scrum	Text files	(Gloger, 2016, S. 127)
	Scrum	Spreadsheets	(Gloger, 2016, S. 126)
	Scrum	Sketches	(Patton et al., 2014, S. 93)
	Scrum	Story Cards	(Gloger, 2016, S. 126)
	Scrum	User Stories	(Gloger, 2016, S. 130)
	Scrum	Product Backlog	(Gloger, 2016, S. 79)
	Lean Startup	Lessons Learned	(Maurya, 2012, S. 65)
	Lean Startup	Validated Learning	(Ries, 2011)
	MPM / VDI 2221	Requirements list	(Lindemann, 2009, S. 246; (VDI-Richtlinie 2221, S. 34)
	Lean Startup	Pivot	(Maurya, 2012, S. 9)
	VDI 2221	calculation method	(VDI-Richtlinie 2221, S. 36)
	VDI 2221	Costs early detection methods	(VDI-Richtlinie 2221, S. 36)
Concept Developmen	MPM	stimulus word analysis	(Lindemann, 2009, S. 300)
	MPM	Bionics	(Lindemann, 2009, S. 250)
	MPM	Physical effects	(Lindemann, 2009, S. 257)
	MPM	Mind Map	(Lindemann, 2009, S. 379)

	MPM	bought-in parts (German: "Wiederhol-Ähnlich-, Zukaufteile")	(Lindemann, 2009, S. 140)
	MPM	Patents	(Lindemann, 2009, S. 140)
	MPM	Research Institutes	(Lindemann, 2009, S. 140)
	MPM	design catalogs	(Lindemann, 2009, S. 277)
	VDI 2221	Method 66	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	Method 635	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	synectics	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	mitigated synectics	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	Modest morphology	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	Systematic variation	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	blocks system	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	Morphological box	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	Property list	(VDI-Richtlinie 2221, S. 35)
	MPM	Compromise	(Lindemann, 2009, S. 149)
	MPM	concept change	(Lindemann, 2009, S. 148)
	MPM	Multidimensional ordering schemes	(Lindemann, 2009, S. 150)
	VDI 2221	product planning	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	Functional description - verbal	(VDI-Richtlinie 2221, S. 33 & 34)
	VDI 2221	Function description - Physical elementary functions and basic operations	(VDI-Richtlinie 2221, S. 33 & 34)
	VDI 2221	Function description - mathematical	(VDI-Richtlinie 2221, S. 33 & 34)
	VDI 2221	Function description - symbols or other representation	(VDI-Richtlinie 2221, S. 33 & 34)
	VDI 2221	function hierarchy	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	function network	(VDI-Richtlinie 2221, S. 34)
	Scrum	Sprint Review	(Gloger, 2016, S. 177)
	Scrum	Backlog Refinement	(Röpstorff & Wiechmann, 2016, S. 247)
	Scrum	Definition of Done	(Gloger, 2016, S. 177)
	Scrum	Happiness-Index	(Röpstorff & Wiechmann, 2016, S. 237)
	Scrum	Daily Scrum	(ScrumAlliance 2014, S.11), (Sutherland & Schwaber 2012, S.23)
	Scrum	Sprint Planning	(ScrumAlliance 2014)
	Lean Startup	Interview	(Maurya, 2012, S. 129)
	Lean Startup	User Lifecycle	(Maurya, 2012, S. 157)
	Lean Startup	Conversion Dashboard	(Maurya, 2012, S. 191f)
	Lean Startup	Pirate Startup Metrics	(Maurya, 2012, S. 40)
	Lean Startup	Sean Ellis Test	(Maurya, 2012, S. 156)
	Lean Startup	80/20 Rule	(Maurya, 2012, S. 146)
	Lean Startup	Customer Development Model	(Blank, 2013a, S. 17f)
	Lean Startup	MVP	(Maurya, 2012, S. 154; Ries, 2011)
	Lean Startup	Website	(Maurya, 2012, S. 185)
	Lean Startup	Landing Page	(Maurya, 2012, S. 185)

	Lean Startup	Five Whys	(Ries, 2011)
	XP	Daily Deployment und Continuous Deployment	(Beck & Andres 2004) (Ries 2011, S.192f)
	XP	Continuous Integration	(Beck & Andres 2004)
	XP	Pairing/Pair Programming	(Beck & Andres 2004)
	XP	Weekly Cycle	(Beck & Andres 2004)
	XP	Stories	(Beck & Andres 2004)
	XP	Root-cause Analysis	(Beck & Andres 2004)
	Scrum	Scrum, Task or Kanban board	(Epping, 2011, S. 115; Röpstorff & Wiechmann, 2016, S. 195 & 346)
	VDI 2221	3-stage selection	(VDI-Richtlinie 2221, S. 37)
Refinement and Development	MPM	Analysis planning (single, partial, full factorial)	(Lindemann, 2009, S. 245)
	MPM	Estimation	(Lindemann, 2009, S. 304)
	MPM	Calculation	(Lindemann, 2009, S. 249)
	MPM	Numeric Simulation	(Lindemann, 2009, S. 283)
	MPM	Experiment	(Lindemann, 2009, S. 323)
	MPM	Hardware-in-the-loop	(Lindemann, 2009, S. 273)
	MPM	property lists	(Lindemann, 2009, S. 258)
	MPM	result hypotheses	(Lindemann, 2009, S. 168)
	VDI 2221	Simulation and similarity calculation	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	structural mechanics	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	function structuring	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	Mathematical models	(VDI-Richtlinie 2221, S. 34)
	VDI 2221	Idea-Delphi	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	provocation	(VDI-Richtlinie 2221, S. 35)
	VDI 2221	objectives definition	(VDI-Richtlinie 2221, S. 33)
	VDI 2221	Design rules and guidelines	(VDI-Richtlinie 2221, S. 35)
	Scrum	Selected Product Backlog	(Gloger, 2016, S. 161)
	Scrum	Sprint Goal	(Röpstorff & Wiechmann, 2016, S. 215)
	Scrum	Tasks	(Röpstorff & Wiechmann, 2016, S. 224)
	Scrum	Sprint Burndown Chart	(Röpstorff & Wiechmann, 2016, S. 228)
Test and Evaluation	MPM	Negation	(Lindemann, 2009, S. 282)
	MPM	process analysis	(Lindemann, 2009, S. 202)
	MPM	Analysis of the functions	(Lindemann, 2009, S. 209)
	MPM	fault tree	(Lindemann, 2009, S. 262)
	MPM	FMEA	(Lindemann, 2009, S. 263)
	MPM	Reduce risk	(Lindemann, 2009, S. 205)
	MPM	Target Costing	(Lindemann, 2009, S. 313)
	MPM	Balanced Score Card	(Lindemann, 2009, S. 247)
	Scrum	Interactive review	(Röpstorff & Wiechmann, 2016, S. 259)
	Scrum	play	(Röpstorff & Wiechmann, 2016, S. 259)
	Scrum	Reviews on Epic level	(Röpstorff & Wiechmann, 2016, S. 259)

	Scrum	Energy pulse retrospective	(Röpstorff & Wiechmann, 2016, S. 275)
	Scrum	Health Drop Retrospective	(Röpstorff & Wiechmann, 2016, S. 280)
	Scrum	Agile values retrospective	(Röpstorff & Wiechmann, 2016, S. 285)
	Scrum	Love and hate letter retrospective	(Röpstorff & Wiechmann, 2016, S. 288)
	Scrum	Online Retrospective	(Röpstorff & Wiechmann, 2016, S. 291)
	Scrum	Sprint retrospective	(ScrumAlliance 2014)

A7.2 Prototyping Strategies

Table 11-10: Prototyping strategies, adapted from (vonUnold, 2017; Zink, 2017; Woche Buccini, 2018).

Scope	Framework	Strategy	Reference
Discovery	Prototyping Strategy	Manual	(Hallgrimsson, 2012, S. 58)
	Prototyping Strategy	Geometric Prototype	(Kampker et al., 2016, S. 67)
	Prototyping Strategy	Prototype for Desirability	(Menold, 2016)
	Prototyping Strategy	Prototyping – Explorative	(Hallgrimsson 2012)
	Prototyping Strategy	Prototyping – Communication	(Hallgrimsson 2012)
	Design Thinking	Customer Journey Map	(Meinel, et al., 2013)
	Design Thinking	Improvised Roleplay	(Meinel, et al., 2013)
	Design Thinking	User Product Box	(Meinel, et al., 2013)
	Design Thinking	Stakeholder Map	(Meinel, et al., 2013)
	Design Thinking	Process Map	(Meinel, et al., 2013)
	Design Thinking	Just Play Prototype	(Meinel, et al., 2013)
	Design Thinking	30 Second Sketch	(Meinel, et al., 2013)
	Design Thinking	Paper Model	(Meinel, et al., 2013)
	Design Thinking	Advertising	(Meinel, et al., 2013)
	Design Thinking	Iterative Prototyping	(Hallgrimsson, 2012)
	Design Thinking	Group Sketch	(Meinel, et al., 2013)
	Design Thinking	News of the Future	(Meinel, et al., 2013)
	Design Thinking	Letter to Grandma	(Meinel, et al., 2013)
	Design Thinking	Solution Image	(Meinel, et al., 2013)
	Design Thinking	Idea Panorama	(Meinel, et al., 2013)
	Design Thinking	Photo Storyboard	(Meinel, et al., 2013)
	ME310	Dark Horse	(Ge, X. and Maisch, B., 2016)
	Empathic Design	Inspiration Video	(von Unold, 2017)
	Empathic Design	What-if	(von Unold, 2017)
	Empathic Design	Asking about Bias	(von Unold, 2017)
	Empathic Design	Knowledge Transfer	(von Unold, 2017)
	Empathic Design	Peopleness Persona	(von Unold, 2017)
Enlightenment	Prototyping Strategy	Rapid Prototyping	(Hallgrimsson, 2012, S. 65)
	Prototyping Strategy	Concept Prototype	(Kampker et al., 2016, S. 67)
	Prototyping Strategy	Prototype for Feasibility	(Menold, 2016)
	Prototyping Strategy	Prototyping – Usability and Design	(Hallgrimsson 2012), (Cabage & Zhang 2013, S.120)

	Design Thinking	System Map	(Meinel, et al., 2013)
	Design Thinking	Rough 3D Prototype	(Meinel, et al., 2013)
	Design Thinking	Team Product Box	(Meinel, et al., 2013)
	Design Thinking	Video	(Meinel, et al., 2013)
	Design Thinking	Comic Storyboard	(Meinel, et al., 2013)
	Design Thinking	Service Blueprint	(Meinel, et al., 2013)
	Design Thinking	User Story Map	(Meinel, et al., 2013)
	Design Thinking	Informative Roleplay	(Meinel, et al., 2013)
	Design Thinking	Paper Wireframe (Prototype)	(Meinel, et al., 2013)
	Design Thinking	User Integrated Roleplay	(Meinel, et al., 2013)
	Design Thinking	Digital Wireframe / Blended Prototype	(Meinel, et al., 2013)
	Design Thinking	Click Dummy (Wizard of Oz)	(Meinel, et al., 2013)
	Design Thinking	Digital Click Dummy	(Meinel, et al., 2013)
	Design Thinking	Service Wizard of Oz	(Meinel, et al., 2013)
	Design Thinking	Tangible User Interfaces	(Meinel, et al., 2013)
	Rethink! Prototyping	Digital Mockup	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Clay Modelling	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Smart Hybrid Process Planning	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Full-Scale Prototyping	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Physical Mock-Up	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Small-Scale-Prototyping	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Expert Estimation	(Ängeslevä et al., 2016, p. 207)
	ME310	Funky	(Ge, X. and Maisch, B., 2016)
	Empathic Design	Generalize Insights	(von Unold, 2017)
	Empathic Design	Age-Man-Suit	(von Unold, 2017)
	Empathic Design	Role Playing	(von Unold, 2017)
	Empathic Design	Experience Prototyping	(von Unold, 2017)
	Empathic Design	Playbook	(von Unold, 2017)
	Empathic Design	4D Persona	(von Unold, 2017)
	Empathic Design	No User Available	(von Unold, 2017)
	Empathic Design	5 Dim of Culture	(von Unold, 2017)
	Empathic Design	Co-Creation Workshop	(von Unold, 2017)
	Empathic Design	Diary	(von Unold, 2017)
	Empathic Design	Real-Scale Prototype	(von Unold, 2017)
	Empathic Design	Emotion Timetable	(von Unold, 2017)
Integration	Prototyping Strategy	CNC machining and laser cutting	(Hallgrimsson, 2012, S. 74)
	Prototyping Strategy	Technical Prototype	(Kampker et al., 2016, S. 67)
	Prototyping Strategy	Prototype for Viability	(Menold, 2016)
	Prototyping Strategy	Prototyping – Verification	(Hallgrimsson 2012)
	Design Thinking	Variation Prototype	(Meinel, et al., 2013)
	Think.Make.Start.	Hack Existing	(Böhmer, et al., 2017)
	Design Thinking	Critical Function Prototype	(Meinel, et al., 2013)
	Design Thinking	3D Prints	(Meinel, et al., 2013)

	Design Thinking	Pre-Production Prototype	(Meinel, et al., 2013)
	Design Thinking	CAD Model	(Meinel, et al., 2013)
	Design Thinking	Alpha Version	(Meinel, et al., 2013)
	Design Thinking	Beta Version	(Meinel, et al., 2013)
	Rethink! Prototyping	Arduino Prototype	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Functional Mock-Up	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	CAS	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Service Prototyping	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Smart Hybrid Prototyping	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Hybrid Product-Service Prototyping	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Simulation Modelling	(Ängeslevä et al., 2016, p. 207)
	Rethink! Prototyping	Virtual Clay Modelling	(Ängeslevä et al., 2016, p. 207)
	ME310	Functional Prototype	(Ge, X. and Maisch, B., 2016)
	ME310	X-Finished	(Ge, X. and Maisch, B., 2016)
	ME310	Final Prototype	(Ge, X. and Maisch, B., 2016)
	Empathic Design	Theme Mind map	(von Unold, 2017)
	Empathic Design	Requirements Translation	(von Unold, 2017)

A7.3 Mind-Set Cards

Table 11-11: Overview of mind-set cards, adapted from (vonUnold, 2017).

Number	Slogan
#1	“pretend before you spend”
#2	“fake it until you make it”
#3	“build to learn and not to last”
#4	“get out of the building”
#5	“fail fast, cheap, and early”
#6	“failure is success if you learn from it”
#7	“Build to think, don’t think to build”
#8	“if you are not ashamed of your first prototype, you have waited too long"
#9	“Done is better than perfect”
#10	“Start small and scale fast”
#11	“Hack or build upon existing”
#12	“if I`d asked my customer they`d say faster horses”
#13	“Show me don’t tell me”
#14	“build right products before building it right”
#15	“Needs over whishes - Focus on what creates value”
#16	“Be stubborn on your Vision, but flexible on your Journey”
#17	“Yes, and – not yes, but”
#18	“Tell me HOW it works, not why it doesn’t work”
#19	“Fail Forward - Keep up the good work”
#20	“Keep it simple and focus on the main feature set”
#21	“Break down big tasks into small steps”

#22	“Embrace Change and Don‘t hold on to the old plan”
#23	“Acquire Feedback and Challenge your ideas and progress with others”
#24	“Try soon, fail sooner, learn even faster”
#25	“Dream Big - Explore.Dream.Discover.”
#26	“If you're to have a chance at succeeding, you have to stay excited in the face of failure”
#27	“Don’t ask your user what they want they want, engage the user in the design process”
#28	“Don’t ask user once, build partnership with users to do interviews and user testing on a regular basis“
#29	“Ask more users. Ask different users.”
#30	“Don’t stay at home, go to the user environment”
#31	“Get out of the Building”
#32	“Don’t think others see the world you see it, make yourself aware of your biases.
#33	“Your perspective is just a representation created and processed by your senses and brain”
#34	“Don’t just consider your user, take a look at involved stakeholder”
#35	“Don’t (unconsciously exclude stakeholder from your design, ask yourself how can it be more universal?”
#36	“Enable an easy usage of your system, so that a lot of people can use it”
#37	“Don’t tell arguments, tell stories”

A8 Think.Make.Start. Templates

Relevant templates are illustrated in Figure 11-1 and Figure 11-2.

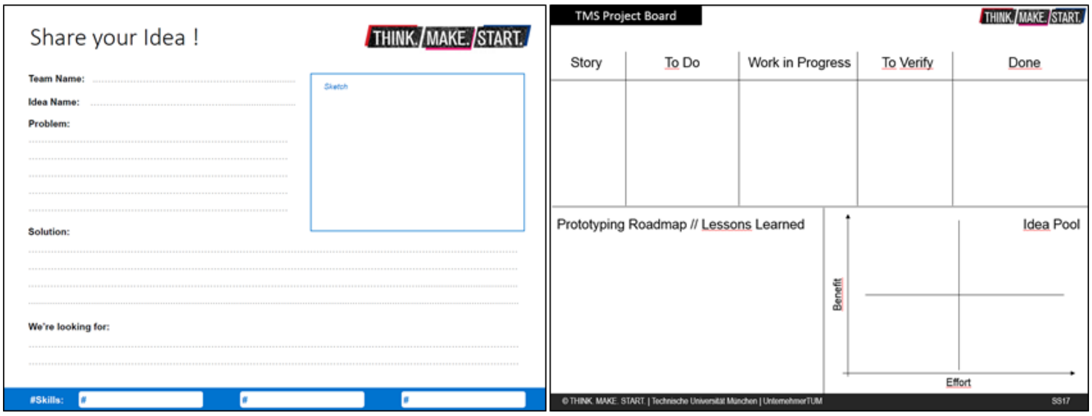


Figure 11-1: Ideation Board (left) and Project Board (right).

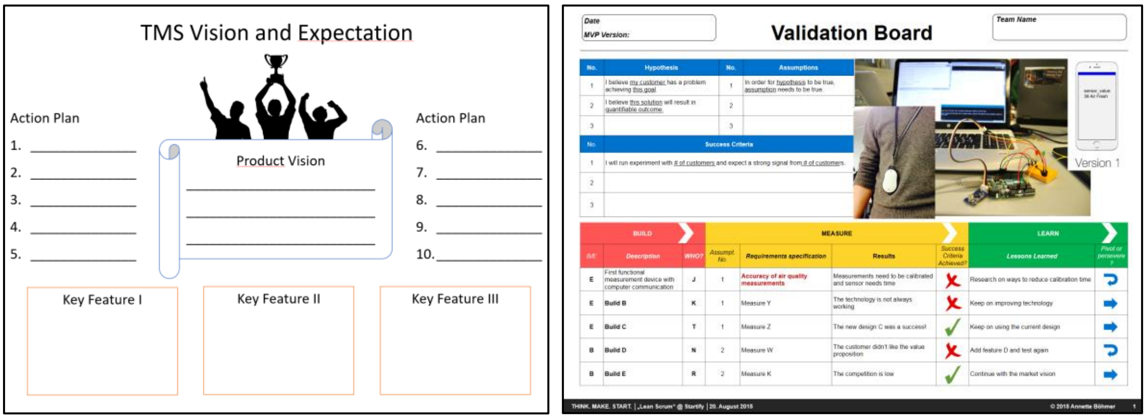


Figure 11-2: TMS Vision (left) and Validation Board (right).

A9 TAF Agile Framework

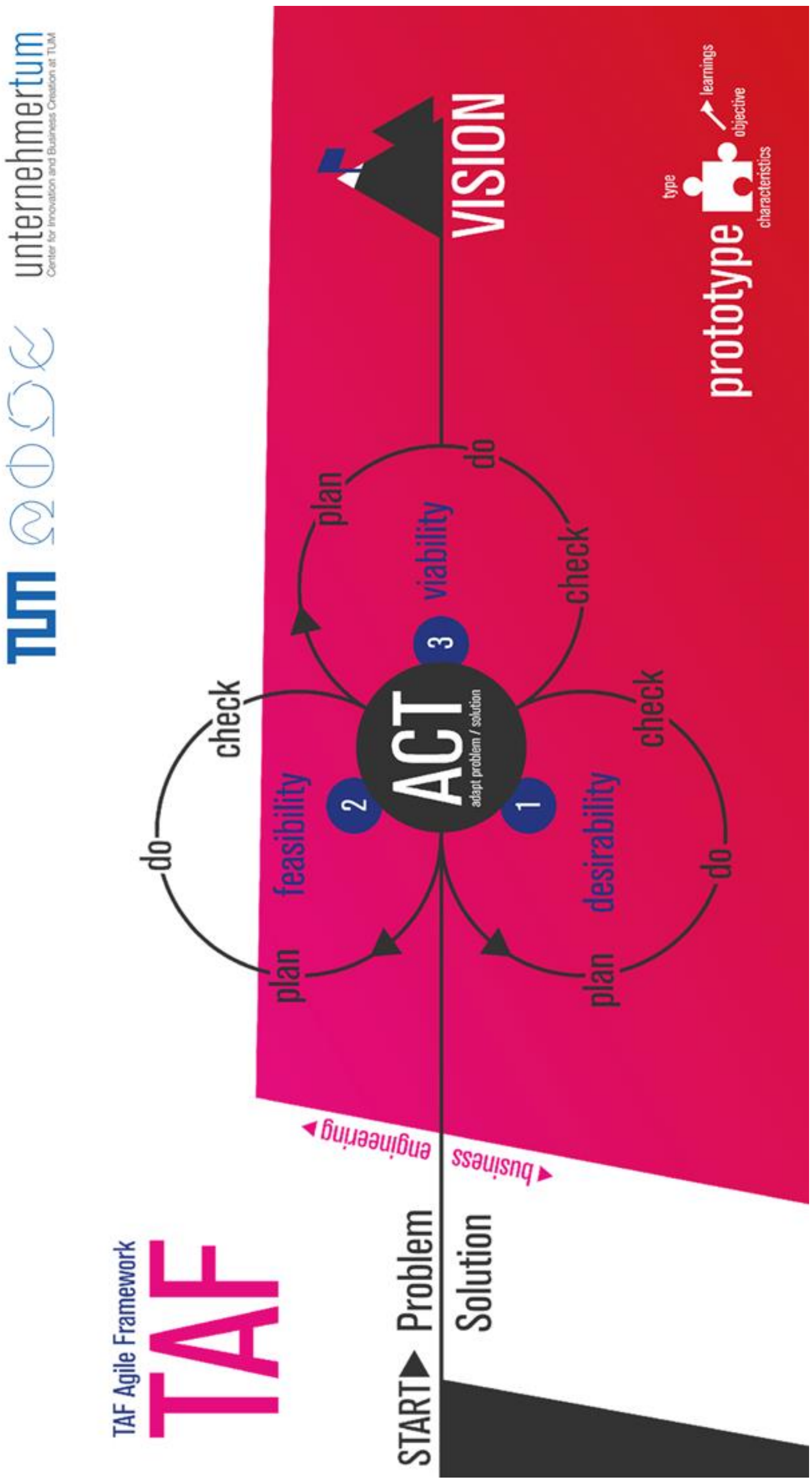


Figure 11-3: TAF Agile Framework, referring to (Hostettler et al., 2017).

A10 Agile enabler for physical products

Table 12: Agile enabler for physical products, adapted from (Mollbach and Bergstein, 2014, p. 9; Adam, 2017, p. 108).

Category	Enabler
Organization	Top management and leadership as engines of change
Organization	Learning and innovation culture
Organization	Problem-solving and decision-making behavior of the organization that focuses on flexibility, speed and implementation
Organization	Market and customer orientation of the overall organization and continuous development of the core competences
Organization	Participation of employees in terms of strategy and product development
Organization	Culture of trust and empowerment
Organization	Management structures and processes, designed for flexibility and speed
Organization	Systematic and consistent human resource processes
Organization	Orga-driven: Slicing is done by team size, and similar factor
People	Openness of the employees for changes and new things
Process	Variable sprint length: Short iterations at the beginning of the project and expand sprint length as time to produce increments increases.
Process	Time based estimation
Process	Commercial off the shelf (COTS): Increased usage of "Of the shelf" parts to have them readily available
Process	Scale with LESS / SAFE: Use existing scaling approaches such as SAFE or LESS to coordinate efforts on the higher levels
Process	Agile Front-end, and V-scale-up: Use agile to define the product, then switch to a V-Model approach to industrialize production
Process	Agile “supermarket”: Decompose product into separately agile developed modules that are at all times potentially shippable
Process	Water-SCRUM-Fall: Use the SCRUM Framework to reach the milestones in a Stage-Gate Macro Model
Product	Prototyping
Product	Desirability, feasibility, and viability (focus on user, technology, and market)
Product	Virtualization product increment
Product	Backlog items with broader scope / higher level: Backlog items cover only higher-level system functionalities.
Product	Adapted level of product backlog: Backlog items cover only higher-level system functionalities
Product	Adapted level of increments: Use increments only on a higher hierarchical level (e.g. Main module), while subsystems are being built in a non-incremental manner
Product	Broader scope of “Definition of Done”: Use Definition of Done to cover test cases and constructive standards that must be met by the final product.
Product	No factual customer integration, artifact is shown to higher level system responsible (internal customer)
Product	Decoupling of subsystems with less interfaces: Choose a product architecture with a minimum of dependencies between modules to reduce second order effects of changes
Product	Structure-driven: Functional or physical structure for slicing increments

Product	Predefined product architecture: The architecture of the product is predefined and should not be subject to change
Product	Customer value driven: Define modules derived from user perception of value
Product	Overbuild interfaces: Overbuilding interfaces between parts of the product to accommodate for e.g. later updates of one modules as a measure of precaution not due to anticipated changes
Product	Product-specific: The product breakdown cannot be done following a specific paradigm, the managers and old developers must decide on a base by case basis
People	Interdisciplinary team (Product-Team Fit)
People	Max. 6 persons per team that is highly communicative and collaborative
People	New technologies for cooperation and communication internally and externally
People	Reducing meeting frequency of the "stand-up" meeting, sprint retrospectives, backlog refinement efforts, etc.
People	Shared backlog across domains or multiple teams
People	Additional coordination roles: Introduction of new team roles with the purpose to facilitate inter team cooperation
People	Direct Communication between Teams: Let teams communicate with each other informally and trust them to do so effectively
People	Cross-functional teams: Efforts to keep teams a multifunctional as possible to break up siloed informational structures

12. List of Dissertations

Lehrstuhl für Produktentwicklung
Technische Universität München, Boltzmannstraße 15, 85748 Garching
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Prof. Dr.-Ing. W. Rodenacker,

Prof. Dr.-Ing. K. Ehrlenspiel und

Prof. Dr.-Ing. U. Lindemann

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