Master thesis

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Makerspaces in the university community

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Master thesis

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Titel (deutsch): Makerspaces im universitären Umfeld.

Title (english): Makerspaces in the university community.

Motivation: Makerspaces are open workspaces, which offer a variety of tools and machines, supervision and classes to their users. Users work side by side on different projects within an open culture of collaboration. Makerspaces empower their users to develop, build and test physical prototypes hands-on. Prototyping is a key process of product development, especially in technology driven industries and research. A prototype serves as a milestone and can be used in various stages of the development process to improve communication and learning within a group or organization. It is also an important part of project-centered education and relevant for engineering education.

Engineering education in universities is traditionally focusing on the theory and students have little opportunities of creating physical prototypes hands-on inside the university. Many universities have recognized the value of makerspaces and introduced them into the university community. Makerspaces in universities and their implementation differ, depending on the individual university and the purpose they have within the university community. There are many benefits about giving a large portion of the student body access to: they include an increased student motivation, enhancement of learning through a hands-on approach and the promotion of interdisciplinary teamwork.

At TUM there are efforts of different departments and organizations to introduce more project-centered classes to the engineering curriculum and allow students to work in a hands-on manner. One good way to empower students and give them a space to build physical prototypes are makerspaces in the university. Especially in the US, there are many good examples of successful makerspaces in universities, which offer access to students to work on projects both in- and outside of classes. Each university and their makerspaces are different, depending on factors such as the university’s history, culture and focus. However, general lessons can be learned from existing makerspaces, which can help to better understand the implementation of makerspaces in the university. The results can be applied to improve the current infrastructure at the TUM.

Goals: The goal of this thesis is to identify how makerspaces function in the university community and how to apply the results of this analysis to the specific case of the TUM. By looking at examples from other universities, lessons about different forms of implementing prototyping into the curriculum using makerspaces and how they affect student life of technical students at the university can be learned. In order to develop implementation concepts, a good understanding of the current infrastructure at TUM and the stakeholders must be developed. The main analyzed stakeholder groups are engineering students, who are potential users of a makerspace in the university, but other stakeholders in the university community are taken into consideration as well. The final outcome of the thesis is the development of first concepts for implementing makerspaces at TUM, based on lessons learned from existing spaces and the improvement potentials analyzed at TUM. These concepts can help to build the basis for a later implementation at the TUM.

This results in the following content:

- Identification of the potential of makerspaces in universities
  - Define and categorize physical prototyping
  - Define the concept of makerspaces and relevant aspects
  - Discuss the role of makerspace the university community and engineering education
  - Predict the future development of makerspaces in universities
- Investigation of existing makerspaces to learn lessons about implementation
  - Select appropriate existing makerspaces in universities for the investigation
  - Analyze the spaces individually, using a set of parameters
  - Comparison of the spaces along measurable variables
- Analysis of improvement potentials for TUM
  - Analyze the infrastructure of makerspaces at TUM
  - Analyze the stakeholders involved
  - Derive improvement potentials
- Derivation of implementation concepts for TUM
  - Synthesize the lessons learned and improvement potentials
  - Develop and evaluate basic implementation concepts

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Content

1 Introduction

Makerspaces are community workspaces, where users have access to manufacturing tools and machines to build physical prototypes and objects. The number of makerspaces has been growing sharply over the past ten years, both in the USA and internationally (DOUGHERTY 2013). Makerspaces are also increasingly entering into universities, where they allow students to build physical prototypes *hands-on*. In universities, makerspaces have many benefits, such as increased motivation of students, enhanced learning and more possibilities for interdisciplinary teamwork and the development of an entrepreneurial spirit. As such, they have the potential to transform modern higher education – especially for engineers.

This thesis is researching makerspaces for the university, by investigating existing makerspaces in universities, as well as the potential for the specific case of the *Technical University of Munich* (*TUM*). The *introduction* chapter states the *motivation* (1.1) why makerspaces are relevant to research and application, leading to the *objectives* (1.2) for the research conducted in this thesis. Finally, the appropriate *approach* (1.3) and overall structure of the thesis is introduced.

1.1 Motivation

Technical universities play a central role in shaping our society by educating the next generation of professionals, such as engineers and scientists. This group of people will later develop new processes, products and services, which create value for society and have an impact on the world. It is the university's role to provide students with a strong theoretical background and the set of skills to apply that knowledge to become good problem solvers.

Traditionally, universities focus primarily on the theory part (SHEPPARD et al. 2009). On the other side, the industry often complains about the lacking experience and practical skills of university graduates. While many students come with great digital skills, few have worked with tools or machines and exposure to these topics often stays limited during their studies. Research from learning sciences suggests, that moving away from the traditional teacher-centered education in universities and introducing more practical applications and project-centered courses has a positive effect on learning and introduces students to new ways of thinking (GAGNÉ & DRISCOLL 1988). Especially in engineering education, letting students work on projects and building prototypes in interdisciplinary teams, proves to be a powerful tool in education to prepare engineers for the future (SHEPPARD et al. 2009).

One possibility to provide students with problem-solving-skills are makerspaces inside the university (EDUCAUSE 2013). A makerspace empowers the students to develop new ideas, build and test them. This usually involves the use of tools and machines in order to build prototypes. Building prototypes is a key part of the product development process, especially for new technologies or applications (EPPINGER & ULRICH 2014). Prototyping helps teams to communicate better, explore the design space and improve learning through hands-on application. The nature of prototyping encourages *hands-on learning*, by promoting a high level of engagement with multiple senses. Advances in the learning sciences show, that this deep level of involvement increases the learning effect and motivation of the user (GAGNÉ & DRISCOLL 1988). As such, prototyping is useful not only useful in the industry, but may be an effective tool in education as well. Project-centered classes allow students to gather experience in the processes of getting from a problem to concept ideas and finally the tangible solution – a prototype. Since the university is a place where innovations are created and the next generation of professionals who will design tomorrow's products come together, there exists a high demand in the community for a space to make ideas tangible. This can be realized in makerspaces. As the *maker movement* continues to grow internationally, it becomes important to build an understanding of the impact makerspaces have inside of universities. The motivation for writing this thesis is to explore the potential of makerspaces in universities and to apply the findings to the specific case of *TUM*.

TUM is today ranked among the top universities in Germany and has an excellent global reputation. In recent years it has gone through improvements and changes, such as building a large entrepreneurial network and turning the new campus *Garching* into a high-tech location. However, students' access to manufacturing tools and machines, which are needed for physical prototyping, is generally very limited. This is mostly due to the many difficulties associated with traditional workshops like capacity, student safety or funding. There are different models in the form of makerspaces, which could give students access to manufacturing tools and machines and empower the university to implement more project-based classes, improve engineering education and further enhance the entrepreneurial spirit of students.

1.2 Objective

The objective of this thesis is to build an understanding of how makerspaces function, the potential they have for university communities and how they can be implemented in the university. The central *research goals* for this thesis can be summarized as:

- The development a holistic understanding of makerspaces in universities
- The infrastructure analysis of *TUM* and need assessment of its stakeholders
- The synthesis of results to develop concepts how to implement a makerspace based on the *lessons learned* from existing spaces and *improvement potentials* at *TUM*

This means learning from existing makerspaces and the experience of the people who manage them. By looking at examples in other universities, lessons can be learned about the different forms of implementing makerspaces and how they affect education and student life. These learnings can be applied to the specific case of *TUM*. In order to develop implementation concepts, a good understanding of the current infrastructure at *TUM* and the stakeholders must be developed. The main stakeholder groups analyzed in this research thesis are students in technical courses (*BA/MA/PhD*), as well as the professors and staff on the teaching side. The scope of the investigation comprises mainly of facilities inside the universities.

The final outcome of the thesis are the development of concepts for makerspaces *TUM*, which can help to integrate makerspaces in the university. These concepts are aimed at increasing the access of students and other stakeholders to makerspaces, helping to integrate makerspaces into the university and improve culture and student life in the university. By identifying the improvement potentials and stakeholders, these concepts can form the basis for a later implementation at *TUM*.

1.3 Approach

In order to reach the objective of understanding the potential of makerspaces, the chosen approach is to investigate good examples of existing makerspaces. Together with an analysis of stakeholders and improvement potentials, makerspace concepts for the specific case of *TUM* are developed. The approach of this thesis consists of the following steps:

1. Identification of the potential of makerspaces in universities (*Chapter 2*)
2. Investigation of existing makerspaces to learn about implementation (*Chapter 4*)
3. Analysis of improvement potentials for *TUM* (*Chapter 5*)
4. Derivation of implementation concepts for *TUM* (*Chapter 6*)

This approach and the structure of the thesis are demonstrated in *Figure 1* together with the methods used and results. This figure will be used throughout the thesis to guide the reader through the chapters

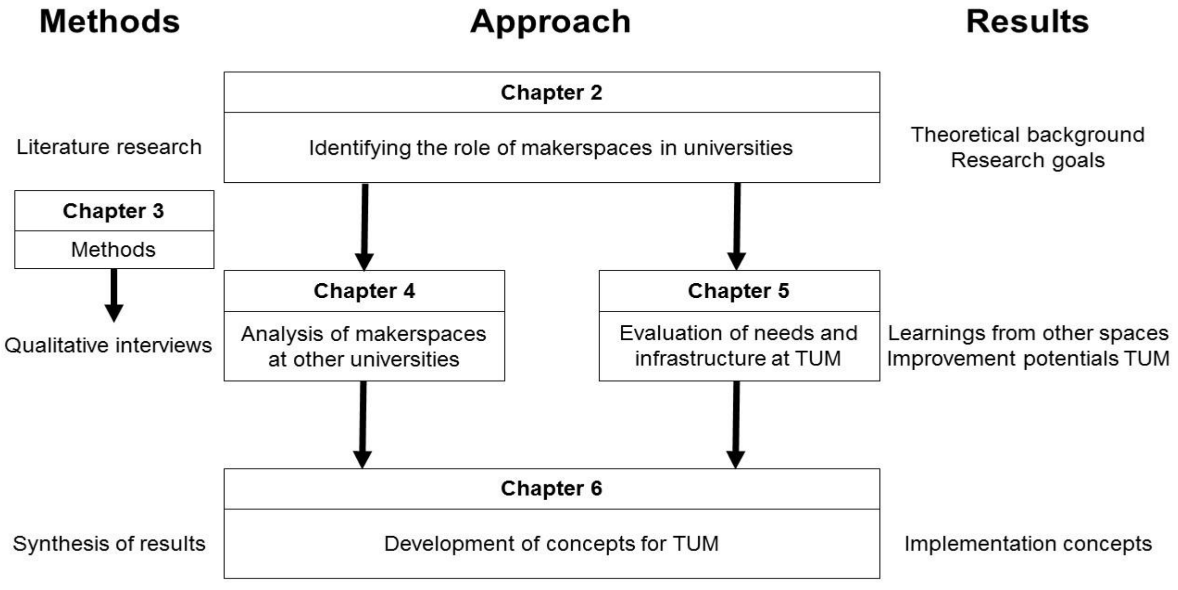

Figure 1 Approach and structure of this thesis

Chapter 2 identifies the role of makerspaces and their potential for the university community. The literature research will provide the theoretical background about prototyping, makerspaces and education, which provides the foundation for the research conducted.

Chapter 4 and *chapter 5* are dedicated to the research part, investigating makerspaces and the university infrastructure. In *chapter 4*, five existing makerspaces are investigated and compared, in order to build a deeper understanding about makerspaces in the university. *Chapter 5* consists of the infrastructure and need evaluation at *TUM*.
The main method used for this research are qualitative interviews with directors of makerspaces, university stakeholders and other experts. The quantitative data is triangulated with quantitative data gathered through other sources.

In *chapter 6* the results of the research are synthesized in order to develop concepts for makerspace solutions for the specific case of *TUM*.

2 Potential of makerspaces in the university

In the following chapter, the specific role and the according relevance of makerspaces in the context of university communities are derived from the literature analysis[1]. The underlying process of *physical prototyping* (2.1) and building is described, leading to the concept of the *makerspace* (2.2) as a potential place for these activities. The relevance of *makerspaces in the university community* (2.3) is discussed, addressing in particular the area of engineering education. Using the theory of diffusion of innovation, possible future development of the *implementation of makerspaces in the university* (2.4) is introduced.

2.1 Physical prototyping

Physical prototyping is a key activity in product development and enables hands-on learning in education (VANDEVELDE et al. 2002). The *definition* (2.1.1) and relevant aspects of physical prototyping and its *purpose* (2.1.2) are derived from literature. Potential *manufacturing methods* (2.1.3) are introduced, with a focus on rapid prototyping techniques.

2.1.1 Definition

Different definitions of the concept of a prototype exist in literature and depend on the context. The general dictionary definition is: "*The first, original, or typical form of something; an archetype*" (OXFORD UNIVERSITY 2000). In terms of engineering EPPINGER & ULRICH (2014) define a prototype as "*an approximation of the product along one or more aspects of interest*" and prototyping as "*the process of building, testing and analyzing prototypes*". These definitions illustrate the nature of prototyping as a tool in order to learn more about one or multiple aspects of a product during product design and development. It should be noted that this definition does not limit prototypes to only physical objects.

According to CHUA et al. (2010), there are three aspects of a prototype:

- *Degree of approximation:* from rough representation to exact replica
- *Form:* from virtual to physical
- *Implementation:* from entire product/system to subcomponents

These three aspects are depicted in *Figure 2*. The focus of this thesis is on the building of *physical prototypes*, which occurs in *makerspaces*, which are introduced in *chapter 2.2*. However, virtual prototyping techniques, such as sketches or CAD-models (computer aided design), can be part of the process as well.

[1] Other important concepts for analyzing the potential of makerspaces are the basic theories about success of innovation (ERNST & GEMÜNDEN 2007), (DYCKHOFF & SPENGLER 2007) and learning processes (GAGNÉ & DRISCOLL 1988), (KNOWLES et al. 2011). A further analysis of these topics would go beyond the scope of discussion for this thesis and is reserved for future research

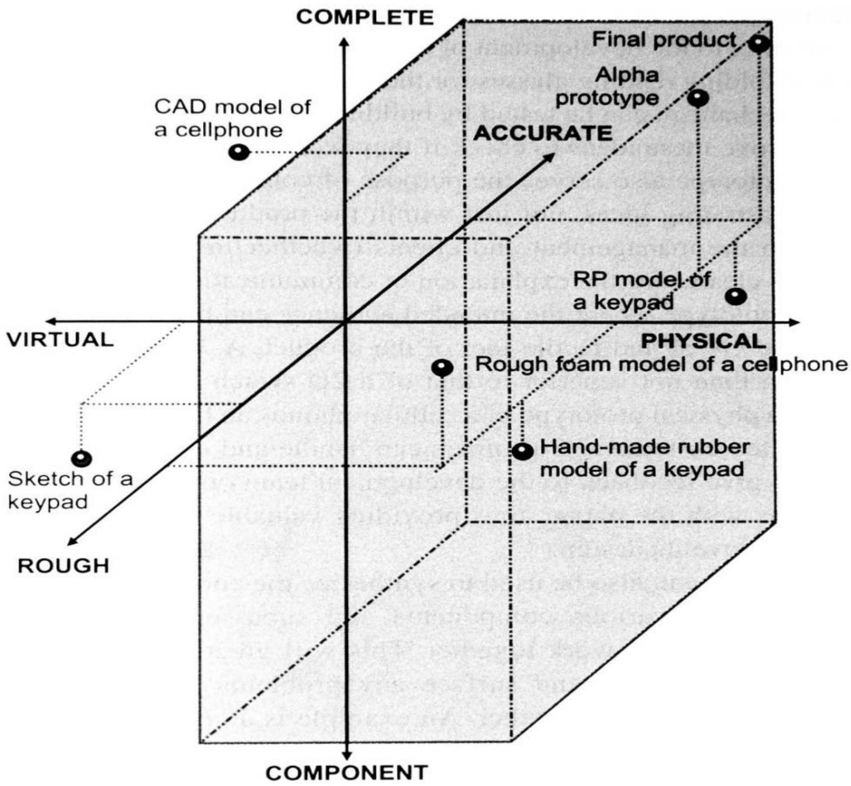

Figure 2 Types of prototypes along the three aspects approximation, form and implementation
(CHUA et al. 2010)

Putting prototypes into an educational context, DAVID BEACH the co-director of the *Product Realization Lab* (PRL), a makerspace at *Stanford University*, stated in an interview that to him a prototype is "*an object that answers questions about the design process*". He adds that "*you may not finish a prototype, but if it answers your questions that is okay and you will learn a lot*". This adds to the definition of CHUA et al., that the use of prototyping is a means of learning about the process of design and manufacturing. The goal is often not the resulting physical object itself, but the questions that are answered about product and process while prototyping.

2.1.2 Purpose

Physical prototyping plays an important role both in the product development process and in education (VANDEVELDE 2002): "*Prototypes unlock cognitive association mechanisms related to visualization, prior experience, and interpersonal communication in ways that favor iterative learning between peers in the product development community*". For engineers, idea-generation and prototyping can be combined through hands-on activities (BERGLUND & LEIFER 2013). Physical prototyping is expected to shorten the product development process (VANDEVELDE 2002). Although prototyping itself requires time as well, it can reduce the total development time because of its ability to stimulate learning and communication. This is especially true for rapid prototyping, which substantially reduces the building time of prototypes (CHUA 2010). Potential manufacturing methods, including rapid prototyping are introduced in *chapter 2.1.3*.

Physical prototyping is a craft, involving aspects, such as selecting materials and manufacturing methods, sizing and modulating interfaces. The activity of building prototypes and communicating through prototypes has a central role in all phases of product development (e.g. feasibility testing, subsystem functionality, proof of concept, and market testing) (EPPINGER & ULRICH 2014). "*Prototyping is an activity core to designing and engineering, though prototyping is an activity that has traditionally been under-examined. Developing a habit of prototyping early and often and continuously throughout the engineering design process is an approach used throughout mechanical engineering and design*" (LANDE 2012). The main roles of prototyping are identified by EPPINGER & ULRICH (2014) as:

- *Learning*: answering questions about performance and feasibility
- *Communication*: communicating ideas inside and outside the team
- *Integration*: combining sub-systems (especially in mechatronics)
- *Milestones*: developing a time schedule

Another study comes to the conclusion, that *physical prototyping* reduces the design fixation, which often occurs subconsciously. This allows to be more creative and take more alternatives into account (YOUMANS 2007). Additional studies argue, that greater attention should be paid to the functionality and role of prototyping in engineering education (CHUA et al. 2010). The role of makerspaces in engineering education will be examined in *chapter 2.3.1*.

2.1.3 Manufacturing methods

Physical prototypes are built by using different manufacturing methods. The appropriate method depends on the purpose and material of the prototype or object being manufactured. While some basic prototypes can be built with basic tools, such as paper and glue, other prototypes require high precision and more advanced techniques, such as using a water jet to cut aluminum. According to GEBHARDT (2014) there are three pillars for manufacturing technology:

- *subtractive manufacturing*: e.g. milling, turning
- *formative manufacturing*: e.g. casting, forging
- *additive manufacturing*: e.g. additive manufacturing

Subtractive manufacturing processes begin with a large quantity of bulk material and remove the excess material. The traditional techniques include milling and turning. Examples of modern techniques are water jet cutting and ultrasonic machining.

Formative manufacturing processes deform material to manufacture parts. Techniques range from handmade clay models to forging, extruding, casting and injection molding.

The third pillar of *additive manufacturing processes* is a relatively new group of techniques that produce prototypes by adding material, instead of removing or deforming it.

GEBHARDT (2014) further defines additive manufacturing as "*layer-based automated fabrication process for making scaled 3-dimensional physical objects directly from 3D-CAD data without using part-dependent tools.*" Many of these techniques are commonly referred to as *rapid prototyping*. Having no part-dependent tools is the great advantage of such rapid prototyping techniques, because they do not rely on tools, such as moulds or dies. "*Hence, rapid prototyping, and more generally, physical prototyping, are expected to hasten the development process*" (GEBHARDT 2014). Multiple aspects to classify *rapid prototyping* methods are illustrated in *Figure 3*.

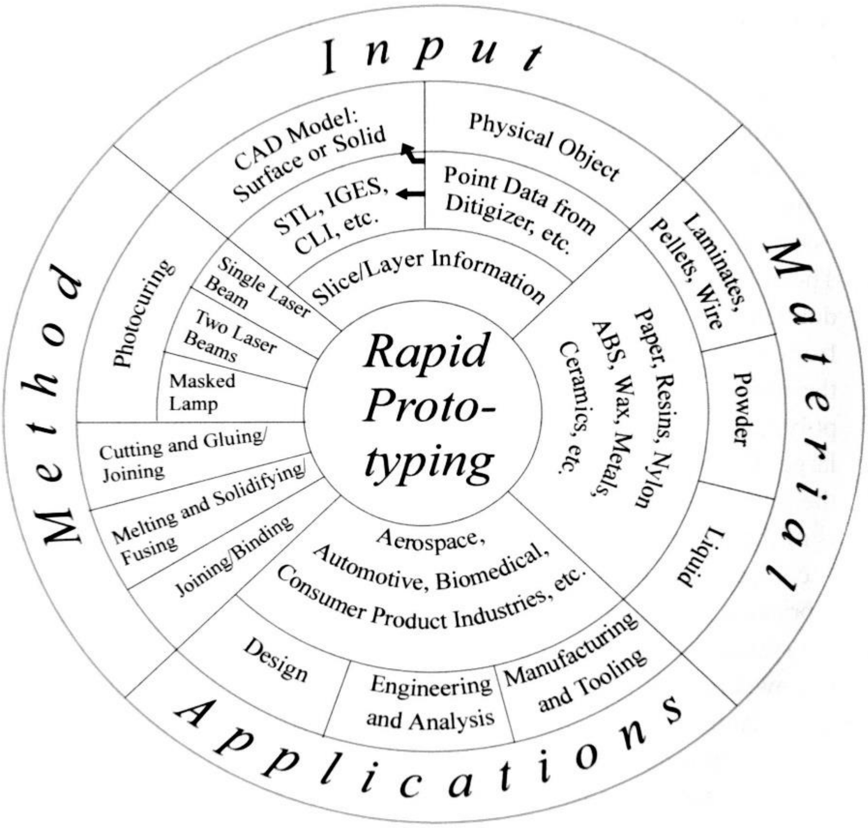

Figure 3 Wheel depicting the four major aspects of rapid prototyping (GEBHARDT 2014)

There are different examples for rapid prototyping techniques, often referred to as 3D-printing, including stereolithography, photocuring, ballistic particle manufacturing, laminated object manufacturing and laser sintering (GEBHARDT 2014).

2.2 Makerspaces

This chapter introduces the concept of a makerspace as a communal space, where users build physical prototypes in a hands-on manner. The term *makerspace*, which is used throughout this thesis, is defined (2.2.1) and different *types* of makerspaces are differentiated (2.2.2), both inside and outside of the university. Finally, the *setup* and necessary aspects of a makerspace are discussed (2.2.3).

2.2.1 Definition

Due to its origin outside of academics, there does not exist much research on *makerspaces* yet. However, its growing relevance for engineering education supports further research, such as this thesis does. The concept of makerspaces is not new, but the term itself has a recent origin and is linked to the *maker movement* (HATCH 2014). Other words commonly used to describe this phenomenon are *hackerspace*, *creative space*, *fab lab* or *makelab* (EDUCAUSE 2013). The *maker movement* is based on the idea of building and creating things, similar to the *do-it-yourself* (DIY) culture. In contrast to *do-it-yourself*, the *maker movement* also has an emphasis on community and sharing. The movement is expressed in the form of physical makerspaces, maker fairs[2] and publications both online[3] and in print media[4]. Having originally started in the USA, the *maker movement* is growing internationally in size and participation (DOUGHERTY 2013). The growth can be demonstrated with the development of the Maker Faires in the USA, which grew from 22,000 visitors in 2006 to 455,000 estimated visitors in 2013, as displayed in *Figure 4*.

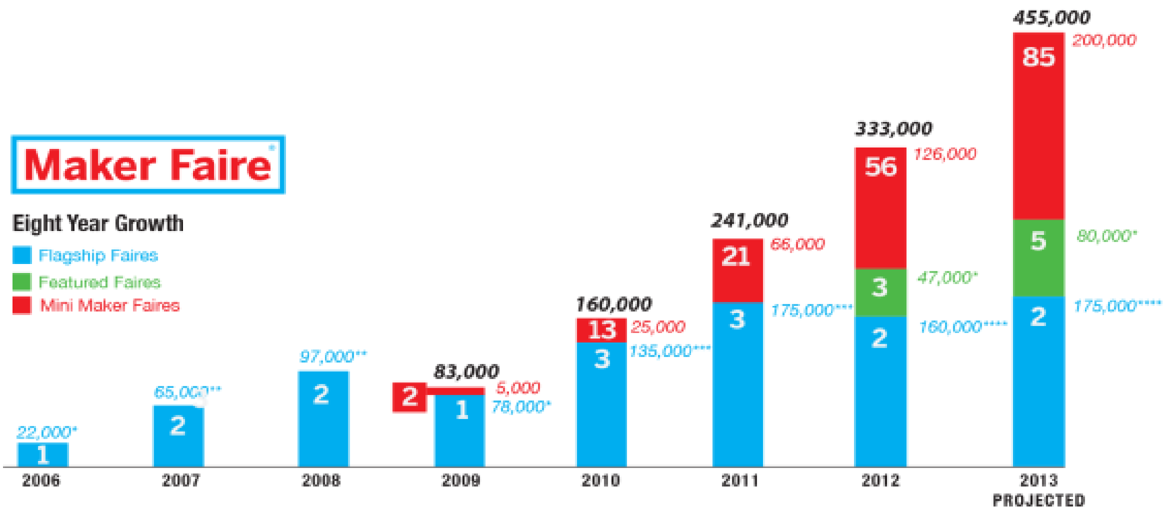

Figure 4 Growth of Maker Faires since 2006 (MAKERMEDIA WEBSITE 2014)

Since the term makerspace is used in a variety of different contexts, an exact definition is difficult. (HATCH 2014). MARK HATCH, the CEO of *Techshop*, describes a makerspace as "*a center or workspace where likeminded people get together to make things*". This illustrates

[2] Examples for maker fairs include Make Munich www.make-munich.de and Makerfaire www.makerfaire.com
[3] Examples for online publication sites are www.instructables.com and www.diy.org
[4] An example for the maker movement in print media is Makezine (www.makezine.com)

the communal and physical prototyping aspect of makerspaces. The MENTOR MAKERSPACE GROUP (2013) is describing makerspaces as "*gathering points where communities of new and experienced makers connect to work on real and personally meaningful projects, informed by helpful mentors and expertise, using new technologies and traditional tools*". Adding to the previous definition, tools and machines as an essential part of *makerspaces* are mentioned. The EDUCAUSE (2013) learning initiative further defines a makerspace as "*physical location where people gather to share resources and knowledge, work on projects, network, and build. They are primarily places for technological experimentation, hardware development, and idea prototyping*". This definition adds the aspects of a physical location and prototyping. Since there does not exist an academic definition, the term makerspace is hereby defined for this thesis.

Definition **makerspace**:

"Physical location with a community, where members build physical prototypes and objects by using manufacturing tools and machines in a hands-on manner."

The main aspects of this definition are:

- *Physical location* – located in one physical location, accessible by its members
- *Community* – there is a community amongst the members, which results in synergy and networking effects through interactions both in- and outside of the space
- *Physical prototypes* – the space is primarily used to build physical objects
- *Manufacturing tools and machines* – the space provides manufacturing tools and machines, which are used to build the physical objects
- *Hands-on* – the members themselves operate the tools and machines to build their parts

2.2.2 Types

All makerspaces have one characteristic in common: the intrinsic motivation of their users to build physical objects in a hands-on manner. However, there are different implementations of makerspaces, depending on their focus and user groups. Each individual space is catered to the individual needs of its users, and the purpose it is trying to achieve within the community. Makerspaces vary in size and focus, and may range from a small rapid prototyping space in a public library with basic rapid prototyping tools, to a large workshop with multiple areas and a wide range of tools and equipment. A number of examples of makerspaces in academic settings and their differences will be demonstrated in *chapter 4*. Because of the cost for room, staff and equipment, makerspaces rely on funding, which often combines membership fees and external sources. Makerspaces attract a wide range of members working in the spaces, such as artists, engineers, entrepreneurs, tinkerers and students (ANDERSON 2012). The number of accessible makerspaces around the world has been growing over the past decade, including examples such *as Makelab, Bibliolab, Fix lab, Hacklab, iFabrica, Repair Café, STGO makerspace, Technasium, Techlab* and *Techshop*.

There is often a sense of "play" involved in the building process at makerspaces (BROWN & VAUGHAN 2009). DOUGHERTY (2013), Founder of MAKE magazine, writes: "*Makers give it* *a try; they take things apart; and they try to do things that even the manufacturer did not think of doing. Whether it is figuring out what you can do with a 3D-printer or an autonomous drone aircraft, makers are exploring what these things can do and they are learning as well. Out of that process emerge new ideas, which may lead to real-world applications or new business ventures. Making is a source of innovation*."

In the educational sector, makerspaces are found in schools or universities. Whereas in schools they are usually part of MINT-education-programs, which is the German equivalent to STEM (science, technology, engineering, and mathematics), universities use them for project-work in engineering or interdisciplinary courses. MINT stands for the subjects of mathematics, computer sciences, natural sciences and technics. This thesis is focusing on makerspaces in universities, which are discussed in detail in *chapter 2.3*. One of the main challenges for introducing a makerspace into an academic setting is to avoid that the spirit of play and freedom is constrained by institutional boundaries (BROWN & VAUGHAN 2009). Examples for makerspaces in the university will be described and analyzed in *chapter 4*.

2.2.3 Setup

When setting up a new makerspace, there are certain requirements, which need to be fulfilled. According to MENTOR MAKERSPACE GROUP (2013), the following requirements are necessary in order to set up a makerspace:

1. Funding
2. Location
3. Tools and machines
4. Staff for maintenance, classes and supervision
5. Safety and liability precautions

While makerspaces are not defined by specific equipment, but by a guiding purpose to provide people with a place to experiment, create, and learn, they usually provide modern rapid prototyping equipment, such as 3D-printers and laser cutters, as well as power tools (HATCH 2014). Makerspaces are often also equipped with traditional manufacturing equipment, such as manual mills and lathes, and more advanced equipment, such as CNC-mills (Computerized Numerical Control) or a water jet. Similar to traditional workshops, makerspaces are generally divided into areas, based on the materials groups and manufacturing methods (MENTOR MAKERSPACE GROUP 2013). A makerspace should focus on fulfilling the needs of its users and hence, the setup of each individual makerspace is different. A list of areas in makerspaces from the example of *Techshop* (4.2.5) may include:

- Metal
- Wood
- Plastics
- Casting
- Welding
- Textiles
- Electronics
- Rapid prototyping

2.3 Makerspaces in the university community

The implementation of makerspaces into the university community, just like *maker movement* itself, is a relatively recent one. Within the past decade multiple makerspaces were opened at large technical universities in the USA, such as *Arizona State University* and *Georgia Institute of Technology*. At the same time there has been little research on the effects of these spaces in universities. In this chapter, the impact a makerspace has on the university community is investigated. The focus hereby is on the *relevance for engineering education* (2.3.1). There are various *stakeholders* (2.3.2) in the university affected by implementing a makerspace, which will be identified later on. Furthermore, their relationships among each other and how they are affected by a makerspace is described. Finally, the *benefits* (2.3.3) and *limitations* (2.3.4) to implementing a makerspace into the university are discussed.

2.3.1 Relevance for engineering education

The key relevance of makerspaces in engineering education is their potential to bring hands-on learning into the curriculum and enable project-centered classes. There is recent research, which compared classes from *Stanford University* and *TUM*, in order to analyze the effect of hands-on experiences on learning. JAN BERENBECK (2014) concluded that the following aspects influence learning of students positively:

1. Addressing multiple senses and involving the body
2. Creating surroundings that foster attention and concentration
3. Creating positive emotions
4. Desisting demotivation
5. Emphasizing social interaction
6. Letting students work on their own ideas and in their own interests
7. Challenging students, creating flow
8. Integrating academic content into a superior context

Universities have traditionally focused on transferring theory in the form of teacher-centered lectures. (SHEPPARD et al. 2009). While this form of lecture is addressing only a few of the aspects above, project-centered education and hands-on learning usually involve multiple aspects, if not all of them. Makerspaces can therefore improve learning for students in areas, when such an approach is applicable. Additionally, makerspaces are places where people naturally work hands-on in a community on building projects and this concept can be applied to education. FISHER (2012) states that makerspaces "*fill a variety of needs within an educational setting. Most importantly, they provide opportunities for people to learn with their hands. Hands-on learning and creation is often devalued in education and seen as meaningless play. However, play has profound educational benefits. Play aids in the development of critical thinking and problem solving skills*".

Hands-on learning combines different separated areas of knowledge that students acquire in their theoretical classes, and allows them to be creative and develop new concepts. The learning sciences have long discovered that the more a person is engaged and the more senses are involved, the more a student will learn (GAGNÉ & DRISCOLL 1988). Understanding the learning process and how it works from a practical viewpoint may substantially increase the chances of developing and applying these abilities later in life (LANDE 2012).

BERENBECK (2014) comes to the conclusion that hands-on learning "*helps students to structure the isolated academic contents from lectures and apply their knowledge creatively on new complex problems working under real life conditions*". Makerspaces provide an opportunity for exactly this type of hands-on learning. The effects of hands-on learning are demonstrated in *Figure 5*.

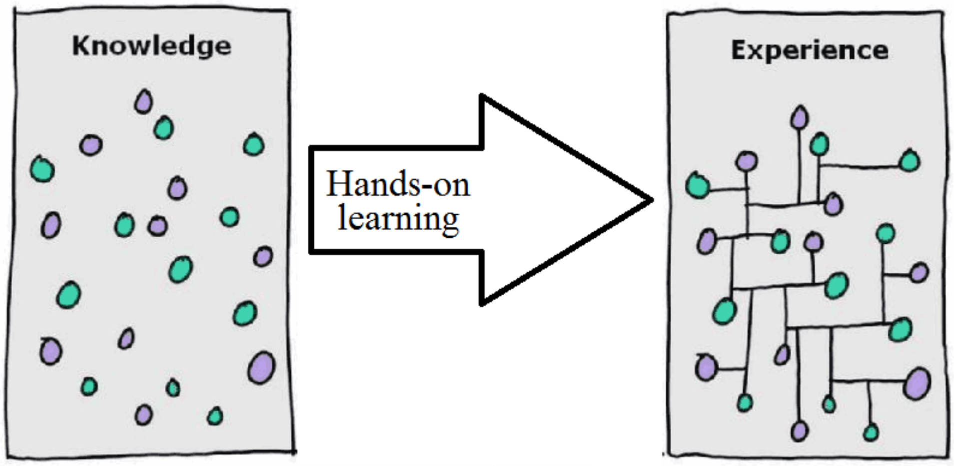

Figure 5 The effect of hands-on learning (LETKEMAN, 2014)

The danger of separating the learning of concepts from the sites of their application is that the concepts become a mere "list of disconnected facts" (BRANSFORD et al. 2002). SHEPPARD (2005) suggests, that engineering schools react by adding more to the curriculum rather than considering the overall design. "*This creates a jam-packed curriculum focused on technical knowledge*. (...) *Opportunities for the kind of deep learning and understanding that allows students to become, over time, sophisticated, independent learners are lost in the effort to teach everything*." As a conclusion, the challenge facing engineering education today is not the coverage of technical knowledge, but teaching students deep knowledge (CLIVE et al. 2005). While lectures are a key part in engineering education, there is a lack of applying the knowledge from lectures, which is known as hands-on learning.

Figure 6 shows a lecture room at the ME (mechanical engineering) department of *TUM*, where in many classes over 1,000 students listen to a single lecture.

Figure 6: Lecture room "2001" at TUM in the ME department (TUM MASCHINENWESEN WEBSITE 2014)

Universities are still mainly specialized in transferring theory. However, engineering graduates of today are expected to have a much broader skill-set. The range of personal transferable skills that students need to be able to display, include communication and presentation skills, problem-solving and organizational skills, teamwork skills, and leadership skills (SHEPPARD et al. 2009). They are often summarized as *soft skills*.

Students may learn *soft skills* in project-centered courses. Additionally to hands-on learning, project-centered work has one further characteristic: It creates an atmosphere and conditions (e.g. working in a team or with imperfect resources), which are similar to the conditions in a professional life in the working world (CLIVE et al. 2005). If organized well, design courses enable students to recognize that engineering involves much more than following a fixed process or methodology; it involves ways of thinking (NEELEY 2007). This means applying their experience to new problems in a creative manner, which is depicted in *Figure 7*.

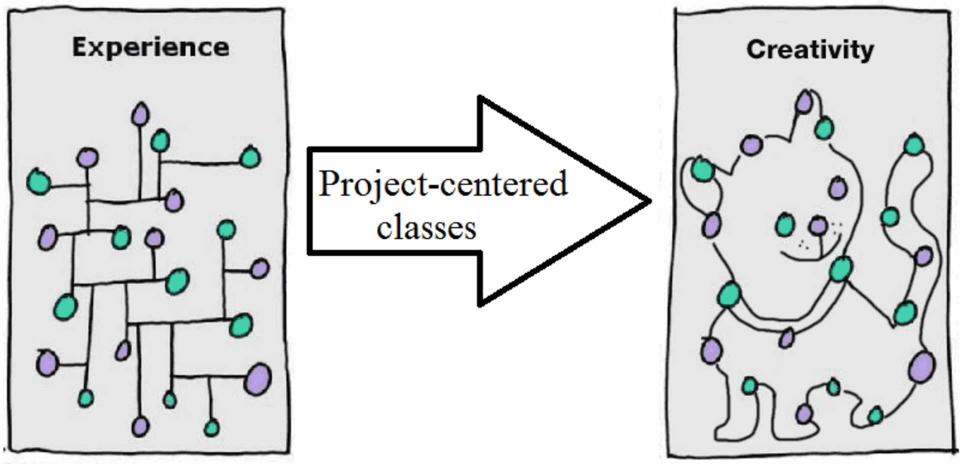

Figure 7: Creativity through the use of project-centered classes (LETKEMAN, 2014)

Motivation is another important aspect for learning, stated by BERENBECK (2014). He comes to the conclusion, that project-centered education enhances student interest in engineering. It has the effect of enhancing student retention in engineering programs, motivating learning in upper division engineering science courses and enhancing performance in capstone design courses and experiences (CLIVE et al. 2005). DAVID BEACH, who is teaching multiple project-centered engineering courses, where students build physical prototypes, described them as a great source of excitement: "*Many view their work as the first time doing real engineering*". In his classes, students go through the complete cycle of picking something they think is important, building, documenting and finally presenting it in front of a jury. *Figure 8* shows an interaction between the professor and students in a project-centered class in Stanford.

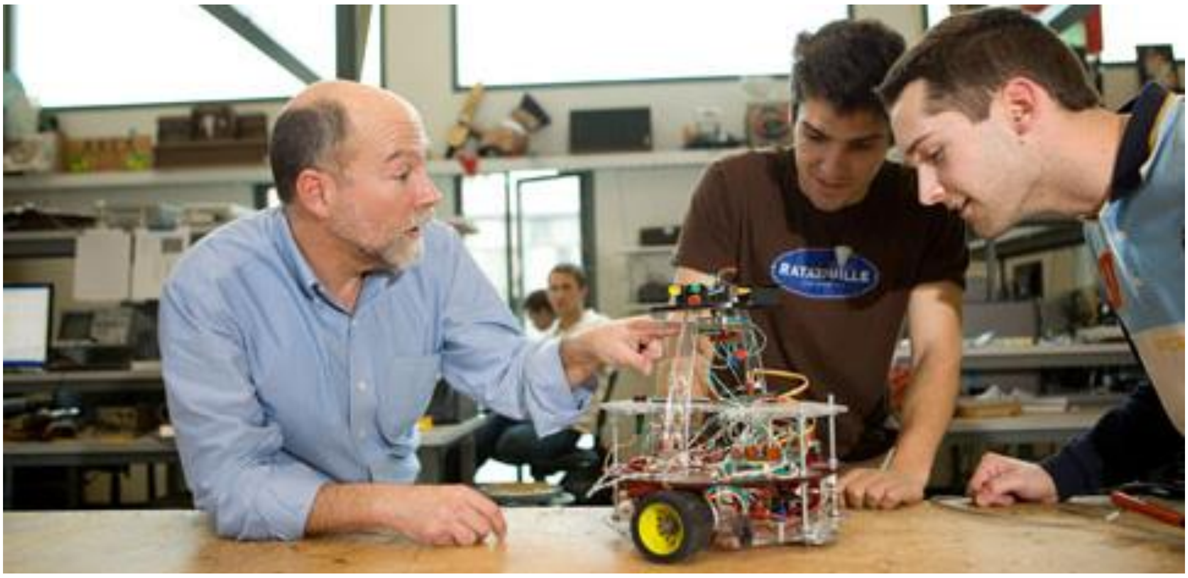

Figure 8: Professor and students in project-centered mechatronics course at Stanford University (STANFORD UNIVERSITY WEBSITE 2014)

In German higher education there are two types of educational facilities for engineers: *universities* and *universities of applied sciences* (*Fachhochschule*). This separation is uncommon in the USA and special in Germany and a couple of other nations such as Switzerland. While the *universities* are more theoretical, the *universities of applied sciences* are more hands-on and primarily designed to teach professional skills. Since the Bologna Process[5], both institutions can award equivalent Bachelor's and Master's degrees. This separation between the more theoretical *university* and more hands-on *university of applied* sciences has its tradition and advantages, such as giving students more alternatives to choose from. Some critics in traditional *universities* want to keep practical work out of universities, in order to protect the *university's* education and reputation. However, the learning sciences show that adding more practical experience in the form of prototyping and project-centered has many benefits. While the focus in traditional *universities* should stay on theory, adding more hands-on elements increases motivation, communication skills and practical experience. Universities are beginning to recognize the value of makerspaces in education. Examples of the implementation of existing makerspaces in universities will be introduced in *chapter 4*. More characteristics of German higher education will be discussed in *chapter 5*, when investigating *TUM*.

[5] For more information about the Bologna Process and the legislature, see www.europa.eu/legislation_summaries/education_training_youth/lifelong_learning/c11088_de.htm

2.3.2 Stakeholders

During this chapter the main stakeholder groups in the university are introduced, which are impacted directly or indirectly by a makerspace. The stakeholders will later on be evaluated for the specific case of *TUM* in *chapter 5.2*. A simplified and generalized university system with the stakeholders is demonstrated in *Figure 9*.

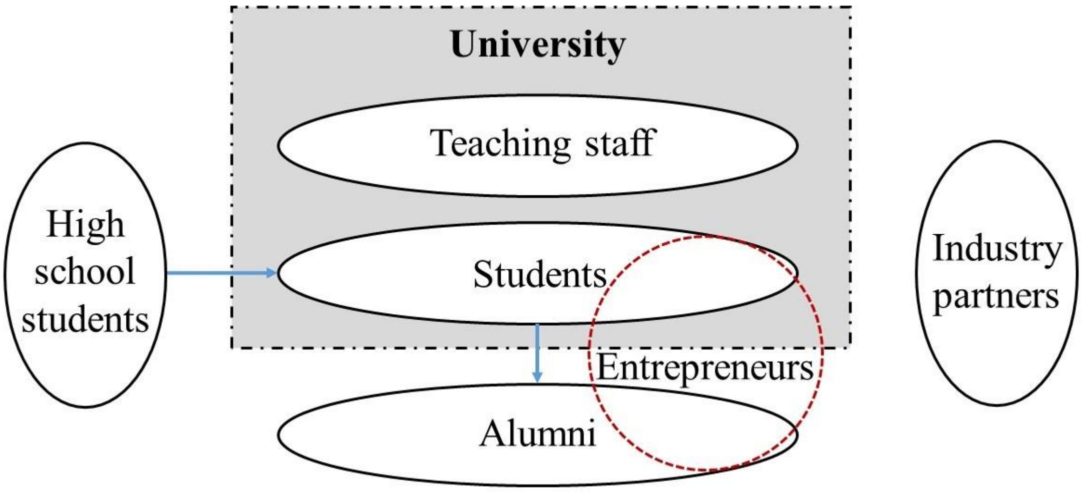

Figure 9 Stakeholders in the context of makerspaces in the university

The main stakeholder groups were identified as:

1. *University students*
2. *Teaching staff*
3. *High school students*
4. *Alumni*
5. *Entrepreneurs*
6. *Industry partners*

In the following section, each of the stakeholder groups is introduced together with their role and the impact a makerspace in the university can have on them:

1. *University students*

In general, the students are the main user group of makerspaces in the university. The primary impact of a makerspace for students is to enable them to build physical prototypes in a hands-on manner inside the university. This is something they often previously could not do, as they were not allowed to enter and use the university workshops. Students can use makerspaces either inside or outside of their curriculum for building activities. While any student may come in contact with the makerspace, the investigation of existing makerspaces, described in *chapter 4*, shows that the majority are *MINT* (mathematics, computer sciences, natural sciences and technics) students - in particular mechanical engineers or architects. The main reason for this is the fact, that product design and manufacturing are often part of their specific curriculum, including the building of prototypes or models as part of their education.

Inside the curriculum, students come in contact with makerspaces as part of their classes. Examples for such implementations in the form of existing makerspaces are introduced in *chapter 4*. The benefits of physical prototyping and project-centered education have been outlined in *chapter 2.3.1*. Makerspaces as part of education prove to be a powerful tool to teach design and manufacturing concepts in parallel, which is especially important for product designers and engineers. There are also examples of courses in disciplines other than engineering or architecture, and a majority of the courses are interdisciplinary. This helps students to develop their personal *soft skills*, such as teamwork, communication and learning to work with students from other fields. Students may also build physical prototypes for research projects and their theses. Giving students access to a makerspace, where they may build parts for their research, allows students to work more efficiently on their research and learn about design and manufacturing in the process. It can also enable new projects, which were not feasible without having access to a makerspace.

Outside of the curriculum, students are often interested in building as well. This may be in the form of personal projects, student contests or student clubs. Personal projects by students are for example the building of presents, furniture for their homes or prototypes for a business idea. A makerspace offers students the opportunity to work on a personal project and form a community of students interested in building things. In extra-curricular design projects and competitions, students build physical prototypes and compete with each other - often in interdisciplinary teams. A makerspace introduces new possibilities to participation in existing competitions and increases the potential for more advanced contests in the future. A number of students dedicate a large portion of their time outside the curriculum to student clubs, many of which are building prototypes, such as robots or model airplanes.

2. *Teaching staff*

The teaching staff inside the departments and chairs of universities generally consists of professors as well as additional scientific staff and PhD students. Their main task as teaching staff, besides their research, is education. In terms of education, a makerspace adds possibilities to teach students hands-on in project-centered classes. Makerspaces can be used as a platform for such classes, seminars or competitions. Students are usually split into teams and given the task to develop concepts and build physical prototypes. Using makerspaces to build more project-centered courses, can improve education and enhance the students' motivation.

For research, the departments generally have high-tech shops and laboratories, where they can build and test parts and prototypes related to their research. A makerspace with more of a "play" culture is therefore usually the inadequate place for advanced research. However, it is suitable for low-resolution and early-phase prototyping activities, which often have an application in university research as well.

3. *High school students*

High school students are the potential new university students. Makerspaces in the university with an outreach to high school students have the positive affect of attracting more students to pursue a career in *MINT* subjects. Furthermore, essential skills can be taught to students, which will help them later on in their university studies. Examples are *maker camps* for high school students in the *Invention Studio* at *Georgia Tech* or afterschool programs in *Techshop* at *Arizona State University*, which will be introduced in *chapter 4*.

4. *Alumni*

A makerspace presents the opportunity for alumni to stay in touch with the university, and therefore increases the university's role as an institution for life-long learning. This benefits both the alumni and also the current students, who can network and learn from the experience of former students. A strong alumni network is a powerful addition to the university. *Stanford University* recognized this value of their alumni network and is using the *PRL* as a platform to reconnect with their alumni, who return as guest speakers, and furthermore, support the space and university both in monetary and non-monetary ways. Other makerspaces, such as the *Hobby Shop* at *MIT*, allow alumni to use the space and at the *Prototypenwerkstatt* of *TU Berlin* alumni, who want to found their own business, are specifically one of the targeted user groups. These examples show that makerspaces strengthen the alumni network by reconnecting alumni to their university.

5. *Entrepreneurs*[6]

SCHUMPETER (1934) defined an entrepreneur as "*the innovator who implements change within markets through the carrying out of new combinations*". Entrepreneurs in the university can be students developing a business idea and alumni who get involved in a start-up. Entrepreneurship in the form of spin-offs can help universities to transfer technology, which will be important for economic growth of the region (SCHÖNENBERGER 2000). Especially technological start-ups need support and funding in their early phase, as they can often not afford to buy expensive machines to build their first prototypes and develop a product. This is where makerspaces in universities, such as the *Prototypenwerkstatt* at the *TU Berlin*, which is introduced in *chapter 4*, empower founders through access to space and equipment to build their first prototypes. Additionally, a makerspace and its creative environment create a community, which serves as a creative breeding ground for ideas (BOH et al. 2012). This helps entrepreneurial students and alumni with team creation and networking. Universities often act as accelerators, allowing students and faculty to meet, form teams, and experiment with the idea of bringing technology from research laboratories to the market. BOH et al. (2012) further suggest that universities effectively offer an incubation period to spin-offs, in which students and faculty have the freedom to develop the technology and form their strategic plans, reducing the venture's market and technological risk.

During their time at university, students can work on the initial stages of the start-up next to their studies. This way, there is no opportunity cost of foregoing a paid job (BOH et al. 2012). After a year or two of working on the spin-off as students, they have gathered sufficient information to determine if they will take the risk to work full-time on the spin-off following their graduation. A study, which is centered on research about university spin-offs, comes to the conclusion that university founders often meet in project-centered courses. The conclusion is that "*in about half of the investigated spin-offs, founders of a company took project-centered courses together, where they formed a team and began to develop their idea*" (BOH et al. 2012).

[6] It is important to note, that the definition of entrepreneurship varies and also has a cultural connotation, for example for Germany and the USA (VALTONEN 2007). While important to note, these differences are not further analyzed as part of the research of this thesis.

6. *Industry partners*

In general, industrial partners have two major interests for cooperating with universities – *image crafting* and *technology scouting* (CLIVE et al. 2005). *Image crafting* refers to the attraction of potential future employees. The industry also has a great interest in graduates, who fulfill their expectations. One way to come in contact with future graduates and influence their development is in the form of student-projects. This may either be in form of extracurricular student challenges or as a part of the curriculum - for example the *Capstone Design Course* at *Georgia Tech* (4.2.3). *Technology scouting* refers to the detection of new technological trends, which are developed in university and may be relevant for industrial use. Technology transfer may be facilitated in the form of university spin-offs, industry projects with university departments or projects with students. One example is the *ME310-course* at *Stanford* by *Professor Larry Leifer*, which matches student teams and companies around the world to solve real life problems.

2.3.3 Benefits

Makerspaces in the university can benefit from the university's stakeholders in different ways. The main benefits for the university community have been identified as:

1. *Improved engineering education*

Students can apply their knowledge hands-on, which has a positive effect on their learning. Within the community, they can also develop soft skills, such as communication skills and team work.

2. *Increased student motivation*

Makerspaces serve as a source of motivation, both inside and outside of the curriculum. Students see a purpose in applying their knowledge and engaging in personal projects or student clubs.

3. *Creation of communities and networks*

People from different backgrounds and disciplines come together working in a makerspace. This connects students from different disciplines, strengthening the internal networks and opening the possibilities for interdisciplinary work. It also improves the communication and network between the different stakeholder groups, such as students, alumni and industry partners.

4. *New inventions and innovations*

As a place of creative freedom, makerspaces are catalysts for new inventions and innovations. This has a positive impact on several areas, such as research and entrepreneurship.

5. *Support of entrepreneurship and technology transfer*

Entrepreneurial students and start-ups are supported through the opportunity to build prototypes and test their ideas. This improves technology-transfer from the university to the industry through spin-offs.

2.3.4 Limitations

Although the positive effects of hands-on learning in engineering education have been confirmed in research studies (2.3.1), there are several risks and limitations associated with implementing a makerspace in the university. Perhaps the biggest challenge is the traditional mind-set of universities. Additionally, there are three basic factors, which limit the implementation of makerspaces:

1. *Cost*

Implementing a makerspace requires investments in space, equipment and staff. While the cost of space and equipment is the first item that people think about intuitively, in reality the staff is usually the biggest expense.

2. *Safety*[7]

The university is liable to the safety of its students. Depending on the type of equipment, a makerspace can be a hazardous place. Especially manual machines, such as the band saw, manual lathe, or mill pose the highest threat for injuries. The university needs to be prepared for the consequences of injuries and be equipped with a good safety system, preventing injuries in the first place.

3. *Capacity*

When implementing project-centered classes, the capacity of a makerspace is often a limiting factor. In a large engineering school, such as the *TUM*, classes may consist of up to 1,200 students, according to professors from mechanical engineering. These large numbers need to be divided into smaller subgroups, if everyone should get the chance to work on the machines.

[7] Liability is an important legal aspect and there are special requirements about student safety with large differences depending on the country, such as the USA or Germany. The legal aspect is not analyzed thoroughly within this thesis, but is an essential factor for a later implementation.

2.4 Diffusion of makerspaces in universities

In order to predict the implementation of makerspaces in universities, principles from the theory of diffusion of innovations can be related to implementing a makerspace in the university. According to ROGERS (2003), innovation is an "*idea or practice new to an individual or other unit of adaption*". ROGERS (2003) identifies four elements in the process of diffusion of innovation:

- *Innovation*
- *Communication channels*
- *Time*
- *Social system*

In this case, the *innovation* are "makerspaces in universities", where students have access to tools and machines to work hands-on and build physical prototypes – something they previously did not have. This could be implemented using existing labs and spaces, or by creating a completely new space. There are different *communication channels* benefitting the further diffusion of makerspaces. Example are conferences, articles and research, such as this thesis. The universities need time to go through the process of adapting, which according to ROGERS (2003) consists of the following five stages:

1. *Knowledge* – People learn about what makerspaces are and the role they can play in universities
2. *Persuasion* – Decision makers are convinced that a makerspace is beneficial and worth the effort to implement it
3. *Decision* – The decision to implement a makerspace is made
4. *Implementation* – The makerspace is actually implemented in the university
5. *Confirmation* – Experience and results show the effect of the makerspace (success is measured)

The *social system* of universities as a large organization has special norms, and is influenced by the stakeholders, which were introduced in *chapter 2.3.2*, as well as other stakeholders outside the university, such as the government and committees. The interpersonal networks among the universities and its stakeholders should be taken into account for the prediction of the diffusion of makerspaces.

The Director of the makerspace *Invention Studio* at the *Georgia Institute of Technology*, FOREST NELSON, is receiving inquiries from a large number of US universities, who are interested in building their own version of the *Invention Studio*. His predicts that "*in just a few years we will see a full blossoming of these kind of spaces*".

Innovations are generally adapted over time in the form of an S-shaped curve, illustrated in *Figure 10*. There is a critical mass at about 10-20% adaptation, when interpersonal networks are activated and the rate of adaptation increases sharply. At this point a system becomes self-sustained.

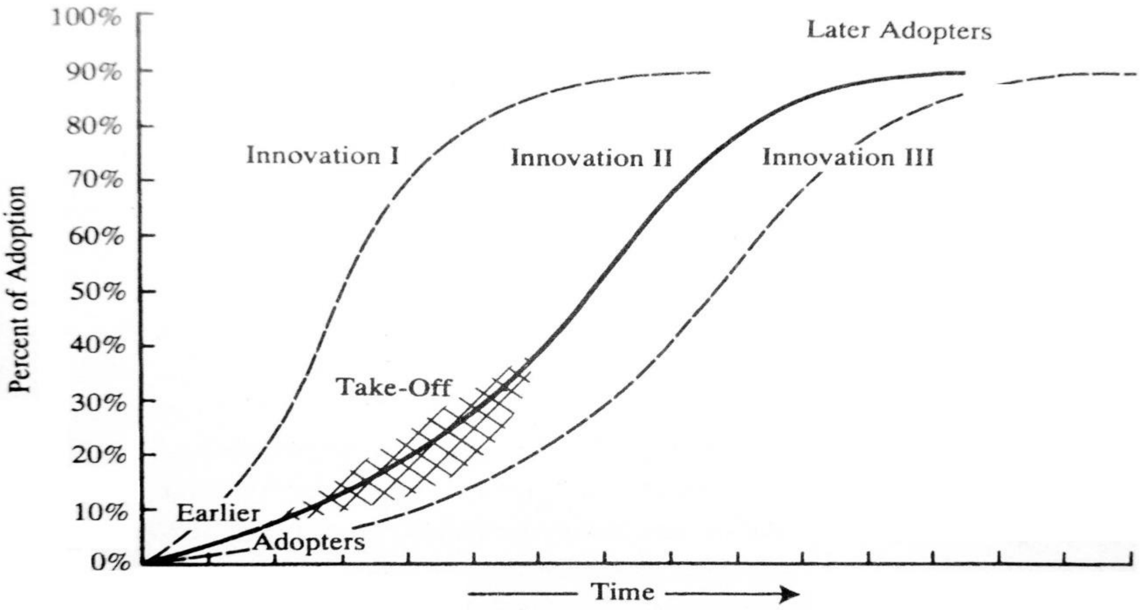

Figure 10 Adaptation process of innovations (ROGERS 2003)

The rate of adaptation depends on five factors (ROGERS 2003):

- *Perceived relative advantage*
- *Compatibility*
- *Complexity*
- *Trialability*
- *Observability*

In order to be adapted successfully, an innovation should fulfill these factors. In terms of a makerspace at *TUM*, the *perceived relative advantage* is subjective. Examples from other successfully implemented spaces, such as the ones investigated in this thesis, and advancement in learning theory can be good examples for why having a makerspace is definitely an advantage. Makerspaces are *compatible* with the infrastructure of universities, since similar setups exist in other university shops. The main difficulty, however, is that they are not always compatible with the traditional culture at universities with its focus on theory and closed shop-environments. Although the concept of a makerspace is not too *complex*, the meaning and possibilities are currently not that well-known in Germany in comparison to the USA, where more examples of makerspaces in university exist. However, as the Maker Movement increases, more people will understand the concept and potential of makerspaces. Makerspaces are inviting in terms of *trialability* and *observability*. Potential new users can visit a makerspace on campus and often get started immediately.

The important players for the diffusion process are *opinion leaders* and *change agents* (ROGERS 2003): "*Opinion leaders provide information and advice to other individuals. They generally possess the attributes of being communicators, having a higher socioeconomic status and being innovative. Change agents are individuals who are trying to influence the clients' innovation decision in a position deemed desirable by their change agency*."
Opinion leaders can be found among the departments and the administration of the university. They usually take the first step to implement a makerspace within the university. As for change agents, DALE DAOUGHERTY (2013) writes: "*The biggest challenge and the biggest opportunity for the Maker Movement is to transform education. My hope is that the agents of change will be the students themselves*."

The diffusion of makerspaces in universities is a trend, which is shown by the number of new makerspaces opening within the last decade. Some of these examples are introduced in *chapter 4* and a list of more examples can be found in the *appendix*. Based on the recent development of these makerspaces and interviews with directors, it can be assumed that the number of makerspaces in the US will further grow within the next five years. Also, the movement is predicted to further spread in other regions, such as Central Europe, East Asia and parts of South America.

The literature analysis has demonstrated the value of makerspaces as workspaces for physical prototyping within a community. The methods used for the research will be introduced in *chapter 3*.

3 Methods

The *research goals* of this thesis are to develop a holistic understanding of makerspaces in the university in general, analyze the infrastructure and improvement potentials at *TUM* and develop concepts for the specific case of implementing makerspaces into *TUM*. In order to reach these, there are two parts of the investigation:

- *Chapter 4*: Analysis of existing makerspaces – Exploring the role of prototyping and makerspaces in the university in order to *learn from existing examples*
- *Chapter 5*: Baseline evaluation of *TUM* – Identifying stakeholders and their needs in order to identify *improvement potentials* at *TUM*

Since there does not exist much research on makerspaces in the university, qualitative interviews were chosen as the primary method to gather data. In-depth interviews are a method to quickly yield data in quantity (MARSHALL 2011). Qualitative researcher GEERTZ (1973) states that "*qualitative research should be thick*", meaning that context is important. In interviews participants articulate their experiences, which can not otherwise be reached (NOHL 2009). The main objective of this methodology is to gain insight from the experience of the directors and staff in makerspaces, as well as other researchers involved in engineering education.

However, it is important to triangulate the data from interviews with data gathered through other methods. (MARSHALL 2011). Thus, properties were determined, both through in-depth qualitative interviews, as well as data from other sources, such as online resources and statistics. By using multiple sources, results supported from multiple perspectives (MARSHALL 2011).

Data collection methods

1. Visiting existing makerspaces
2. Makerspace interviews with directors and staff
3. Explorative interviews at *TUM* and *Stanford University* with stakeholders and experts in fields, such as prototyping, engineering education and learning
4. Internet and literature research for additional quantitative data
5. Existing surveys conducted by universities and makerspaces

In total, over 38 interviews were lead with participants from makerspaces and universities. Interviews generally had a duration of 30-60 min, and most of the interviews were recorded, which amounts to over 20 hours of recorded material. A list of interview partners and the used questionnaires are listed in the *appendix*. The researcher spent a total of three months at *Stanford University*, where explorative interviews were held with professors and researchers involved in engineering education, in order to better understand the role of makerspaces and physical prototyping in the university. The spaces *Techshop*, *Hobby Shop*, *Product Realization Lab* and *Prototypenwerkstatt* were visited and observed by the researcher in person and are introduced in *chapter 4*.

The results will be synthesized to develop implementation concepts in *chapter 6*.

4 Analysis of existing makerspaces

After the literary assessment of the topic of makerspaces in the context of universities in *chapter 2*, different existing makerspaces in universities are analyzed in this chapter. The goal is to learn from these real spaces and thus develop a deeper understanding how makerspaces can be integrated into universities. This understanding can later be used to develop concepts, which can be applied to new or existing spaces. The role of *chapter 4* within the thesis is demonstrated in *Figure 11*.

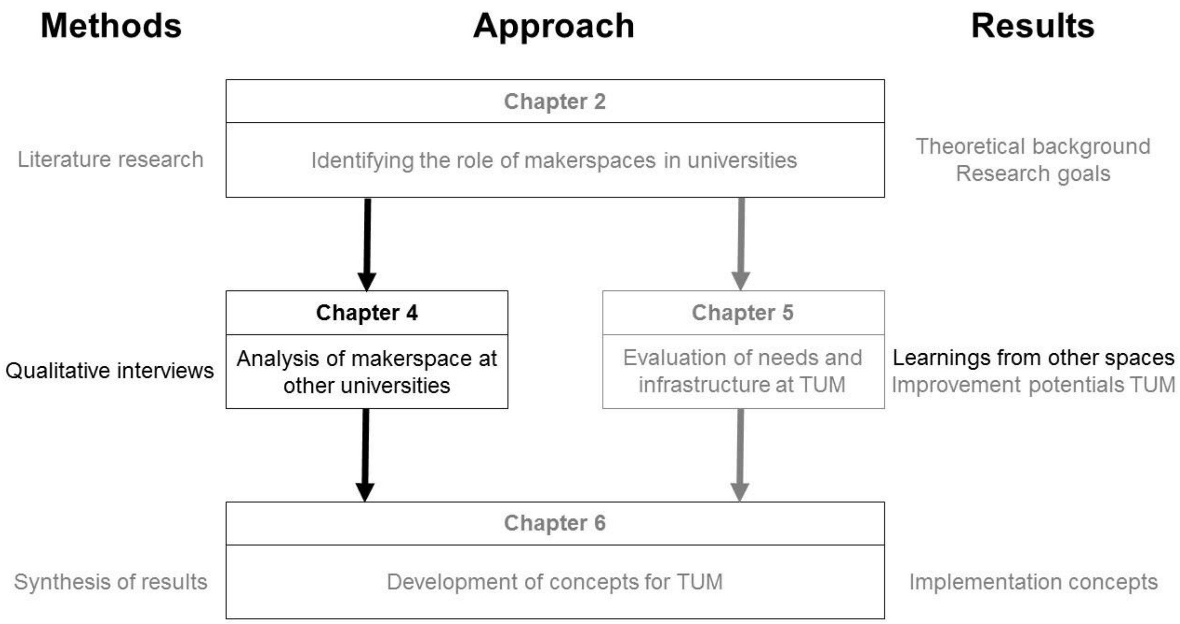

Figure 11 Chapter 4 - Analysis of existing makerspaces (see also Figure 1)

In order to show the spectrum of applications of makerspaces in the university, existing makerspaces in universities are *selected* (4.1) for the analysis. Using a set of both quantitative and qualitative parameters, the selected makerspaces are then analyzed. The results for each space are demonstrated in detail in an *individual analysis* (4.2) and finally compared and discussed during the *comparison* (4.3). Outcomes are summarized as *lessons learned* (4.4).

4.1 Selecting makerspaces

In this chapter the makerspaces, which were selected for the comparison, are introduced. In order to fully understand today's makerspaces in universities, a variety among the types of both, the selected universities and spaces, are necessary. Factors that may influence the different implementation and culture of a makerspace are:

- *University*
- *Location*
- *Focus*

University – the concept and implementation of a makerspace may vary, depending on the university and factors, such as its size and funding. A small or private university, for example, has different needs and capabilities than a larger public university. The culture within the university and attitude towards new academic concepts is another important factor to consider. There sometimes exist prejudices against makerspaces, because they have several aspects in common with machine shops. Hence, some people see them as dirty work places, which are inappropriate for an academic institution.

Location - The origin of makerspaces is related to the growing *maker movement* introduced in *chapter 2.2*, which has its origin in the USA. This is also reflected by makerspaces in universities, which are more common in the USA than in Germany. The majority of these spaces, such as the *Invention Studio* at *Georgia Tech*, have opened during the last decade. Other traditional spaces, such as the *Product Realization Lab* at *Stanford University*, have continuously been developed over decades to become the makerspace that they are today. Since this thesis is written at *TUM*, a German university, it is important to include at least one German example in the analysis. Inquiries during the selection process at all universities of the *TU9*[8] have shown, that open makerspaces in the top technical German universities are still rare. The *TU9* is an alliance of nine leading institutes of technology in Germany, including *TUM*, with more than 50% of German engineering students attending these universities.

Focus – Makerspaces in universities often focus on a user group and are trying to achieve a specific purpose with that given user group. For example: a space could focus on undergraduate mechanical engineering students with the purpose to enable them to work on class projects and apply theory hands-on. A specific focus usually depends on the champion of a makerspace and its source of funding, for example a specific department. The investigation of existing makerspaces in this thesis shows, that makerspaces are normally found in the departments of architecture, engineering or in combination with entrepreneurship programs.

There were five spaces selected based on the criteria above, which are displayed in *Table 1*:

Makerspace	**Since**	**Focus**	**Location**	**Users**	**University**
Product Realization Lab **Stanford University**	1891	Hands-on class projects combining design and fabrication	Palo Alto, USA	Students	Private
Hobby Shop **Massachusetts Institute of Technology**	1937	Possibility to work on personal projects and hobbies	Boston, USA	Students Staff	Private
Invention Studio **Georgia Institute of Technology**	2010	Early hands-on exposure to machines of undergraduates	Atlanta, USA	Students	Public
Prototypenwerkstatt **TU Berlin**	2013	Creation of early prototypes for potential business ideas	Berlin, Germany	Students Alumni	Public
Techshop **Arizona State University**	2013	Empowerment of makers - classes, machines, community	Chandler, USA	Students Makers	Public

Table 1 Selected makerspaces

[8] For more information about the alliance of the nine leading technical universities in Germany, see www.tu9.de

These spaces all have a different focus, and represent both public and private universities. They rank among the top universities for mechanical engineering worldwide, with *Stanford University* and the *MIT* consistently ranking in the top five of several university rankings, such as the *Times Higher Education World University Rankings* for engineering and technology and the *Academic Ranking of World Universities*[9].

- The *Product Realization Lab* (*PRL*) at **Stanford University** is a large and well-equipped makerspace, which is deeply integrated into the curriculum of engineering and design students in the form of project-centered classes. Students learn manufacturing and design skills in parallel by designing and building physical prototypes in a hands-on manner.
- In contrast, the *Hobby Shop* at **MIT** is a space with a large wood shop and some other machines for university affiliates, focusing more on personal projects and hobbies.
- **Arizona State University** is the first university to have a cooperation with the makerspace company *Techshop*, which is relevant to *TUM*, as there is a *Techshop*, currently being built in Munich, which will be introduced in *chapter 5.1.3*. The concept is a makerspace in the university, which is open to the public as well, providing access to a large variety of machines to build physical prototypes and work in a community of “makers”.
- **Georgia Tech** as the largest technical university in the USA is a good example of how a makerspace can be implemented within larger communities. The *Invention Studio* is a growing makerspace, which is organized by the students themselves with the university in a supporting role. Undergraduate engineering students are introduced to building activities early and build prototypes both inside of class and in personal projects.
- The **TU Berlin** represents an implementation of a makerspace at a German university. The *Prototypenwerkstatt* is a relatively small makerspace, empowering entrepreneurial students and spin-offs to produce prototypes of their business ideas in a quick and affordable manner.

For this analysis, a larger number of makerspaces was taken in consideration. The complete list of the places taken into consideration with a short description can be found in the *appendix*.

[9] The respective rankings can be found under: www.timeshighereducation.co.uk and www.shanghairanking.com

4.2 Individual analysis

The different parameters of each space are evaluated in the individual analysis. For each of the five makerspaces there exists a *summary*, a list of quantitative *facts* and an evaluation based on a list of *parameters*. The data has been collected by interviewing the staff in qualitative in-depth interviews, as well as additional quantitative data, such as existing surveys and statistics, as was introduced in *chapter 3*. The results in form of *lessons learned* (4.4) are applicable both to other existing makerspaces or the planning of new makerspaces.

In order to evaluate the selected makerspaces, a set of parameters was defined. This list of parameters has been developed while leading explorative interviews with the directors of the makerspaces and independent experts in the fields of prototyping and engineering education at *Stanford University*. Interview partners were asked, which aspects were most relevant to makerspaces, coming down to a list of parameters, which were given the highest priority among the interview partners. The parameters are divided into *external parameters*, which are user-centered, and *internal parameters*, which focus on the implementation of the space itself:

External parameters (user-centered):

1. *Integration* – How is the space integrated in the university (e.g. in the curriculum)?
2. *Classes and safety* – How are classes taught about safety and machine usage?
3. *Activities and Events* – Which regular or special events are organized in or by the space?
4. *Culture* – How can the culture among the users be described?

Internal parameters (space-centered):

5. *History and future plans* – What can be learned from the development of the original space to the current version and are there plans for future development?
6. *Equipment* – How is the space laid out and which machines and tools are available?
7. *Staff* – Who is managing the space and how is the staff organized?
8. *Challenges* – What are main challenges for the staff?

4.2.1 Product Realization Lab – Stanford University

Summary

The *Product Realization Lab* (*PRL*) is a multi-site teaching facility on the campus of *Stanford University*, used mainly for hands-on class projects by engineering and design students. The goal is to provide an experience for students that will empower them to become confident makers – and consequently better designers, engineers or artists. *Stanford's* engineering and design programs have a strong focus on classes with hands-on projects in contrast to theoretical lectures.

What makes this space unique is its long tradition, excellent staff and thorough integration into classes and curricula inside the university. It provides the basis for a large number of project-centered classes, which teach design considerations and manufacturing methods in parallel. Students from different departments can use the workspace on their class project and create physical prototypes. The *PRL* has its roots in the *Department of Mechanical Engineering* and forms many connections to the *d.school* and their design program. It is primarily focused on student education in the form of class work, but also allows students to work on personal projects. Furthermore, access is granted to any student paying the fee and passing the safety course. The space has two separate locations – main and *Room 36*. The metal shop at the main location is displayed in Figure 12.

Facts

- Users: Students
- Number of users: 1,711 (registered users in 2011 statistic)
- Size: ca. 1,000 m²
- Fee: $80 per semester (may vary, depending on how many quarters are bought)
- Opening hours: 70 hours/week; usually from 8-12 am, 1-5 pm, 7-9 pm (sometimes closed for classes)

Figure 12 Metal shop at the PRL at Stanford University (NEWS WATCH WEBSITE 2014)

External parameters (user-centered):

1. Integration

The *PRL* is deeply integrated in the academic curriculum and community at *Stanford University*. Over 20 design and engineering courses are directly linked to the *PRL*. Most of the classes require from the students to build something physical, which they can do at the *PRL* itself. Classes formed by other disciplines also rely on the *PRL*, such as the thermodynamics class which lets students build a heat sink, as well as classes in art and medical engineering. All ME (mechanical engineering) undergraduates go through the mandatory entry course *ME203* by DAVID BEACH, who is also a co-director of the *PRL*. About 90 students can take the course and learn to use machines for rapid prototyping, manual milling/lathing, welding, sandcasting and finishing in a hands-on manner within the first three weeks. Afterwards, they choose their own projects and build physical prototypes. Most students are later on taking additional classes, where they use the *PRL* and DAVID BEACH notes that the "*knowledge begins to stick in second course*". The main goal of the *PRL* is that "*we want the students to graduate, knowing they can make anything they want to and therefore can change the world*". Hence, to instill confidence, creativity and problem solving skills in *Stanford* students.

There is a strong connection between the *PRL*, *d.school*[10] and *design group*[11] at *Stanford University.* The *d.school* is teaching design principles to non-designers and offers classes for all students interested in design, regardless of major.

2. Classes and safety

A two-hour safety course is required for any student wanting to use the *PRL* – the course consists of a general discussion about safety concerns and a tour through the entire space. Afterwards, students are covered by their university insurance. Most new users have never worked with machines in a shop before and one of the most important goals is to take away the fear associated with such machines and to introduce the right mindset to future users. According to one of the teaching assistants, FOREST NELSON, the role of the staff is "*to be a mobile sentry and to correct people early, when they might be doing something wrong*". This is especially important towards the end of the semester when the space is full and things get hectic.

The basic skills for most machines are taught in *ME203*, which is the gateway-course for most users. After that, improvement is a matter of practice, and students can always ask the staff for help, when they get stuck. More advanced skills, such as CNC-machining, can be learned

[10] For more information about the d.school at Stanford University, see www.dschool.stanford.edu

[11] For more information about the design group at Stanford University, see http://me.stanford.edu/groups/design/

in additional classes. Students with previous experience are free to use any machines they are comfortable with.

3. Activities and events

There are a number of events organized by the *PRL*, including the final presentation of several classes and alumni talks. These events are opened to everyone at Stanford. In the final presentations, students generally present their final prototypes from the projects they have been working on in front of a jury and public audience – in some cases potential investors are invited as well.

The alumni network is an important factor for the *PRL* and *Stanford* in general. Alumni are invited to talk about their work and inspire current students. Many alumni also become donors and form an important part in financing the facilities.

4. Culture

The professors describe their students as smart and energetic – due to the tough selection process at Stanford, only a small and elite group of students is admitted. New users at the *PRL* generally have little previous experience in building things. DAVID BEACH describes that "*they get very excited when they build for the first time. (...) They usually have intense emotions between proud and frustrated with the outcomes and a tendency to do much more than what is realistic*." The staff is observing an increasing altruism from the student body to share ideas and work on projects to help other people, who can't afford a similar lifestyle.

In order to instil a good culture in the space, the entire staff is learning and practicing the value system of the three directors. Teaching assistants, who are supervising the space throughout the quarters, are invited two weeks earlier, in order to hone their skills and go through an intense bonding experience. Consequently, they form a tightly bonded group with shared values. One shared value at the *PRL* regarding failure, stated by director CRAIG MILROY: "*Don't wait until you have everything figured out – just start.*" Failure and iteration are seen as key factors for learning and part of the prototyping process.

Internal parameters (space-centered):

5. History and future plans

The *Product Realization Lab* first opened in 1891, originally under a different name. It has moved and expanded several times since the beginning and recently added a new location for rapid prototyping – the *Room 36*. After the Second World War, many shops in Stanford, which had been used to help the war effort were closed, but the *PRL* remained. In 1972, DAVID BEACH came to join the space and at that time there was only one full-time position, with no additional staff, and a total of about 150 students using the space. Now there are three directors, about 18 teaching assistants and over 1,700 registered students.

The space also went through a transition regarding its focus: It changed from being a very practical shop, where excellent machinists were trained, to focusing on hands-on learning in project-centered classes and teaching fabrication and design methods in parallel. Plans for the future include increasing the size of the space to allow more students to have access, as the demand is growing quickly.

6. Equipment

There are two locations of the *PRL*, which have different equipment and focus. At the main location, there are larger industrial machines. Areas include a wood workshop, metal workshop, welding and foundry. In comparison to other makerspaces, the space is well equipped, and especially the foundry used for sand casting is rarely ever found in other universities. *Room 36* focuses on rapid prototyping using tools like laser cutters, 3D-printers and materials for low-resolution prototypes, such as paper and hot glue. It is perceived as being faster, less hazardous and has a lower entry barrier for new students. Due to the wide range of equipment and special areas, such as the foundry, the *PRL* can be categorized as a makerspace with advanced equipment.

7. Staff

There are currently three directors managing the space, two at the main location and one at *Room 36*. Additionally, around 18 teaching assistants, who are still students themselves, work at the space. The teaching assistants work 20 hours per week and the job positions are very popular. Important factors next to the required technical skills, are especially the cultural fit of the supervisors and the group dynamic of the staff as a whole. The advantage of the teaching assistant, opposed to an experienced workshop manager, is that he/she is usually the same age as the users and therefore more easily approachable. Because they also may not know the right answer yet, the student and teaching assistant have to figure out a good solution together, which again has a positive impact on learning. Quarterly, every user gives direct and confidential feedback to up to three different teaching assistants, in order to help them to improve continuously.

8. Challenges

The *PRL* is facing the challenge that there is an increasing demand in the number of people who want access to the space, while the number of users is limited by its capacity in terms of size and equipment.

4.2.2 Hobby Shop – MIT

Summary

The *Hobby Shop* is a workshop with a fully equipped wood and metal working area on the campus of the *Massachusetts Institute of Technology*, used for working on personal or academic projects. The goal is to give university affiliates a place to pursue their hobbies and work on anything they want.
This makerspace is unique, because it allows students to work freely in a calm and familiar environment. The majority of students work on personal projects, but there are also people working on class projects, and occasionally smaller classes are hosted in the space. It grants access to *MIT* affiliates, such as students, staff and alumni for a membership fee. The *Hobby Shop* is linked to the department for non-academic student life and is independent of any academic departments, which results in a focus on students' personal needs and projects. The *Hobby Shop* with director KEN STONE is shown in *Figure 13*.

Facts

- Users: Students, alumni and staff
- Number of users: Over 300 users
- Size: ca. 400 m²
- Fee: students \$100/year, staff \$150/year, faculty \$250/year, alumni \$500/year
- Opening hours: 50 hours/week, about 6 additional hours/week for classes

Figure 13 Student and director Ken Stone working on spherical robot in the Hobby Shop (MIT NEWS WEBSITE 2014)

External parameters (user-centered):

1. Integration

The space is located centrally on campus and open to all *MIT* affiliates, but mainly used for personal work. Its main role is to improve student life on campus. However, some students are also using the *Hobby Shop* for class work, because they prefer the open atmosphere and personal freedom to other available shops. In some cases, professors rent the space out for a smaller class, but there are rather few cases. In those cases, the professors approach the shop director, KEN STONE, to discuss how they intent to use the space for their class. The classes, which occasionally use the space, are small and include about 12-20 students.

2. Classes and safety

There is a one-hour safety lecture to familiarize new users with the space, before being granted access. Afterwards, there exists the principle of teaching on a "need-to-know" basis from staff to the users. This means, a staff member may spend around 15 minutes to introduce a user to a new machine or teach him a new technique. Instead of teaching all the functions immediately, the information necessary for the task will be taught one at a time and the user is encouraged to come back when he/she needs additional support. Each week there is a 90-minute class for CNC-machines and the water jet. The safety policy provides that supervisors should be aware of what projects the users work on and will correct things at once, when they spot something wrong. The supervisors will normally know all the users and their projects in the space personally. The staff is trying to create a calm atmosphere and prevent accidents by students who often try to rush things.

3. Activities and events

The *Hobby Shop* is present at the *MIT Techfair*[12], but in general, there are few events organized by the staff itself.

4. Culture

The users are coming to the space voluntarily, because they have the shared interest to build things and are willing to pay for the makerspace. One result is a friendly community, where knowledge gets shared commonly. The staff is interested in what the users are working on and will give advice and assistance. Knowing what the people are working on, also helps to reduce accidents. The user groups are interdisciplinary, with the majority coming from engineering programs, such as mechanical-, aerial- and astronomical engineering. Other groups may include architecture students or even music students building their own instruments.

[12] For more information about the MIT Techfair, see www.techfair.mit.edu

Internal parameters (space-centered):

5. History

In 1937, the vice president of *MIT* at that time gave students access to a basement room with machines. The name "*Hobby Shop*" was chosen, based on the students belief, that a "*well rounded individual pursued interests outside their profession - hobbies*" (MIT HOBBY SHOP WEBSITE 2014). Since then, the *Hobby Shop* has changed locations and directors several times, but continued with the idea of providing an independent makerspace, where university affiliates can work on anything they want. KEN STONE, who has been the *Hobby Shop* director since 1991, stated in an interview that the "*MIT had many shops when I was a student at MIT, including student shops in all engineering and many science departments. Most of these shops had been closed by 1990 and the ones that remained focused on work for specific classes. At the same time, secondary schools were closing shops and sending fewer students to MIT with hands-on experience*." Hence, the *Hobby Shop* is an exception within today's infrastructure at the *MIT*. Currently, the researcher is not aware of any future plans for the *Hobby Shop*.

6. Equipment

There is a larger variety of machines in the wood and metal shop. Especially the wood-working-shop is well equipped, compared with other spaces. In general, the equipment is older, which is also due to the fact that many of the machines are donations. The *Hobby Shop* is moderately equipped, compared to other makerspaces. While it has a large variety of basic machines and a great wood shop, it lacks certain other areas, such as welding and rapid prototyping.

7. Staff

There is one full time director, KEN STONE, of the space and two half-time supervisors and instructors. During important working hours, there are at least two people present to supervise the space and provide guidance and advice to the users. Experiments to employ a smaller staff had negative results, because especially new users got stuck and could not continue without proper advice and instructions. This experiment demonstrated that good supervision is a critical factor for makerspaces and their users.

8. Challenges

The biggest challenges appear in funding and staff. Since the *Hobby Shop* is not integrated into the curriculum or part of any department, other laboratories receive a higher priority and consequently more funding. In order to provide better supervision, it would be of great benefit to have a larger staff.

4.2.3 Invention Studio – Georgia Tech

Summary

The *Invention Studio* is a free-to-use makerspace on the campus of *Georgia Tech* with the purpose to expose undergraduate students to hands-on projects early in their studies. It provides a space for students to apply classroom theory in design, and building projects and experiment with tools and materials. The goal of this hands-on approach to education is to stimulate topics, such as innovation, creativity, and entrepreneurship at the university.
This space is unique, because it is managed and primarily maintained by an undergraduate student group, called the *Maker Club*. The university staff has a supporting role, while the students have the main responsibility for the space. Usage is free, there are no restrictions on projects and the space is integrated into the curriculum of engineering students. The *Invention Studio's* purpose and primary focus is to let students build physical models within the community, as well as to take responsibility of organizing and managing the space. It grants free access to students of any major and year. The Invention Studio is currently divided into five rooms, one of which is shown in Figure 14.

Facts

- Users: Students
- Number of users: about 500
- Size: ca. 300 m²
- Fee: none
- Opening hours: Accessible 24/7 for maker club, Mo-Fr 10 am - 5 pm for others

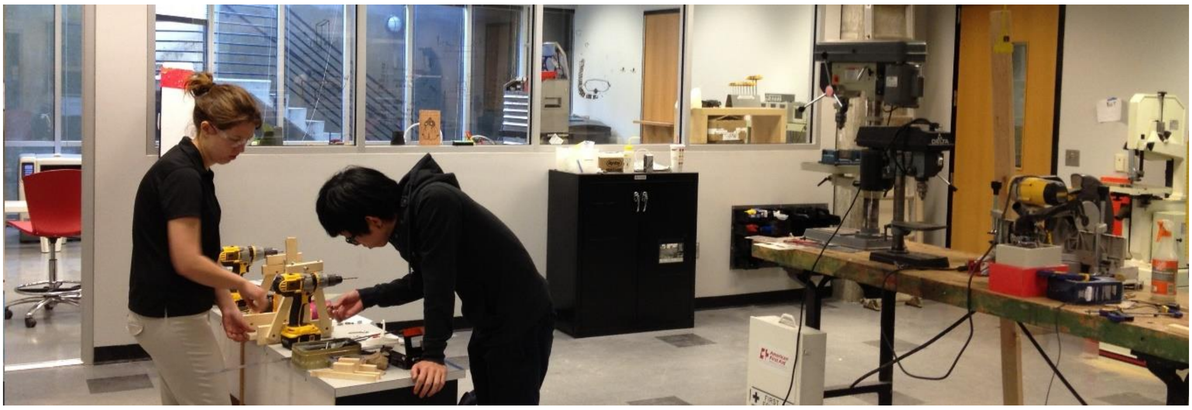

Figure 14 Undergraduate students working in one of the currently five Invention Studio rooms (INVENTION STUDIO WEBSITE 2014)

External parameters (user-centered):

1. Integration

The *Invention Studio* is currently located centrally on campus in the ME building. There are over 25 courses which are using the space, about half of which are for mechanical engineering. Especially for undergraduate mechanical engineering students, the space is embedded closely into the curriculum. Courses from other disciplines include courses in computer science or arts. Classes usually range from 30-80 students per class. With over 100 members, the large community of the student *Maker Club* plays an important role in the students' lives on campus. The *Capstone Design* classes are one central aspect, which provides students with the opportunity to work with "*real-world, open-ended, interdisciplinary challenges proposed by industrial and research project sponsors"* (GEORGIA TECH WEBSITE 2014). Students learn about and apply the different parts of the engineering design process: defining functional requirements, conceptualization, analysis, identifying risks and countermeasures, selection, and physical prototyping. Student teams need to buy and build prototypes in order to realize their ideas. Working in teams helps to develop leadership abilities and *soft skills* by dealing with scheduling conflicts, meeting weekly deliverables and deadlines, and communicating among team members, project sponsors and course instructors.

2. Classes and safety

The place is run and supervised by students. Central aspect for the safety is an ethic of responsibility, safety and ownership, which exists within the community, because the students manage the space themselves. This culture of ownership is essential for the success of the space. Peer pressure and public awareness of violations help to prevent accidents and support that students clean up after themselves. This is uncommon for universities, where shops are normally hierarchical – with the university staff supervising the students. Complex equipment is handled exclusively by *equipment masters* of the *Maker Club* or a shop professional of the university. This includes CNC-machines, which are too difficult to pass on to every new generation of students. The basic rules, according to director CRAIG FOREST are to "*clean up after yourself, don't hurt yourself or the machines, respect other people and follow the basic safety instructions."* Disrespecting these rules will mean immediate expulsion, which happens approximately once per semester.

3. Activities and events

Typical activities are freshmen orientations and daily guided tours with different stakeholders, such as prospective students, industry representatives, alumni donors or visiting professors. There is an annual *Makers Summer Camp* (peaks-ceismc.gatech.edu/content/makers-program-inventing-brand-new-world) for high school students, which allows taking courses and helps install *Junior Maker Clubs* at high- and middle schools. The goal is that university students showcase their excitement to the next generation of high-school students. The *Invention Studio* is also present at the *Atlanta Mini Maker Faire*[13] exhibition. Through these events and activities, the space is boosting public perception of *Georgia Tech* as a main driver and supporter of innovation.

[13] For more information about the Atlanta Mini Maker Faire, see www.makerfaireatl.com

4. Culture

Students are responsible for managing the space independently, which has positive effects on community and safety. Activities done by the students include: machine training, repair, giving advice about design and manufacturing methods, safety supervision and cleaning the space. The community poses as a creative facilitator of new projects and ideas - examples include evening workshops, such as 3D-printing workshops, which students host for other students. The community consists mainly of undergraduate students from the colleges of engineering, sciences and architecture and plays an important role in student life on campus.

Internal parameters (space-centered):

5. History

The original space was founded in 2009 and started out as an experiment with a small pilot study. Target was the *Capstone Design* course, where student teams work together with industry partners in a project-centered class in order to develop concepts and prototypes, which solve real-life problems. Of the 200 students in the *Capstone Design* course, a selected group of ten students were given the keys to a room with a few basic machines to work on their project. The ten volunteers who used the shop for their *Capstone Design* projects, gained a distinct advantage over the other teams in the course from their 24-hour open access. The ten students were selected because they already had existing machine shop skills. In exchange for the right to use the space, they would volunteer three hours per week helping other class mates with their projects. The results of the experiment were astonishing in terms of the final outcomes of the volunteers, and in consequence, the university became interested and encouraged a further growth of the space. The industry partners agreed to continue funding the project, helping the *Invention Studio* to further grow. Its link to the *Capstone Design* course was crucial for ensuring the necessary funding for the space and continues to play an important role for the *Invention Studio*. One more problem that needed solving, was that there was not enough funding to employ a full-time staff by the university.

As a result, the *Maker Club* was founded in order to manage the space by the student body. The *Maker Club* is responsible for maintaining and supervising the space, which also has the benefit that knowledge can be handed down through generations of students. Thanks to the funding, the space was able to grow constantly over the past five years, having moved into a new area of about 300 m² in 2013. Consequently, the students are eager to own and manage their own space and there is potential for further growth of the space and the community. The fact, that the space is located inside the department of mechanical engineering, can be intimidating for students from other disciplines. In order to make the space more open to everyone and grow further, an expansion to a new center for design and building activities on campus is a possible option for the future.

6. Equipment

There are several rooms in the *Invention Studio* with different tools and machines. They include equipment such as rapid prototyping, a metal and plastics area. Being a relatively young project, the space can still be described as moderately equipped in comparison to other spaces, but has great improvement potential for the future.

7. Staff

The space is run by the *Maker Club* with the university in a supporting role. The *Maker Club* has a president, vice president, secretary and director of programs, who are elected annually. Additionally, so called *"Masters"* are elected for each major class of equipment. They are responsible for training other students and maintaining the machines. Supervision during open hours is organized by about 70-80 undergraduate members in the *Maker Club*, who work four hours per week for free, supervising the space. In exchange, the members get a 24-hour access to the space. The *Maker Club* has spending authority on social activities, maintenance and expansion of the equipment and space-layout.
For support from the university, there is a technician who repairs machines, a machine shop professional who helps with complex training on machines, a coordinator for initiatives between university and major initiatives, an assistant for purchases and large event logistics and a faculty advisor for vision and fundraising. The university staff dedicates a certain percentage of their time to support the *Invention Studio* in addition to their other functions at the university.

8. Challenges

One of the challenges is finding the right balance between safety and individual freedom of the students, which is always a trade-off. Another point of conflict is the standard university policy of owning the space versus this new model of student-ownership.
Due to the power of the *Maker Club*, there exists a threat that an arrogant elite may emerge, which could try to exclude others. This form of possible elitism should be observed and be managed carefully.

4.2.4 Prototypenwerkstatt – TU Berlin

Summary

The *Prototypenwerkstatt* is a relatively small makerspace, close to the main campus of *TU Berlin*, used mainly by students and alumni who have a business idea and need a proof-of-concept prototype. The goal is to give students and alumni the opportunity to quickly produce prototypes and realize their ideas. After they have built a working prototype, they can look for a larger shop to start producing a series of their product.
The space is unique, because of its focus on entrepreneurial ideas with the goal to spark entrepreneurship at the university. Although there are many shops with good equipment at the university, students generally do not have access to work on their own potential business ideas. In certain cases, the *Prototypenwerkstatt* also allows students to work on class projects if they have the potential for an innovation. The majority of projects, however, are focusing on entrepreneurship not affiliated directly with the university. In theory students and alumni of any major and year, who are granted access, can use the room – in some cases people outside of *TU Berlin* are granted access as part of a team, which mainly consists of affiliates of the university. The *Prototypenwerkstatt* is linked to the *Entrepreneurship Center* of *TU Berlin*. The makerspace is essentially one larger room with a small variety of different tools and machines and a few additional rooms for team meetings, as shown in Figure 15.

Facts

- Users: Students and alumni
- Number of users: 50-100
- Size: ca. 100 m²
- Fee: none
- Opening hours: Accessible 24/7 with transponder

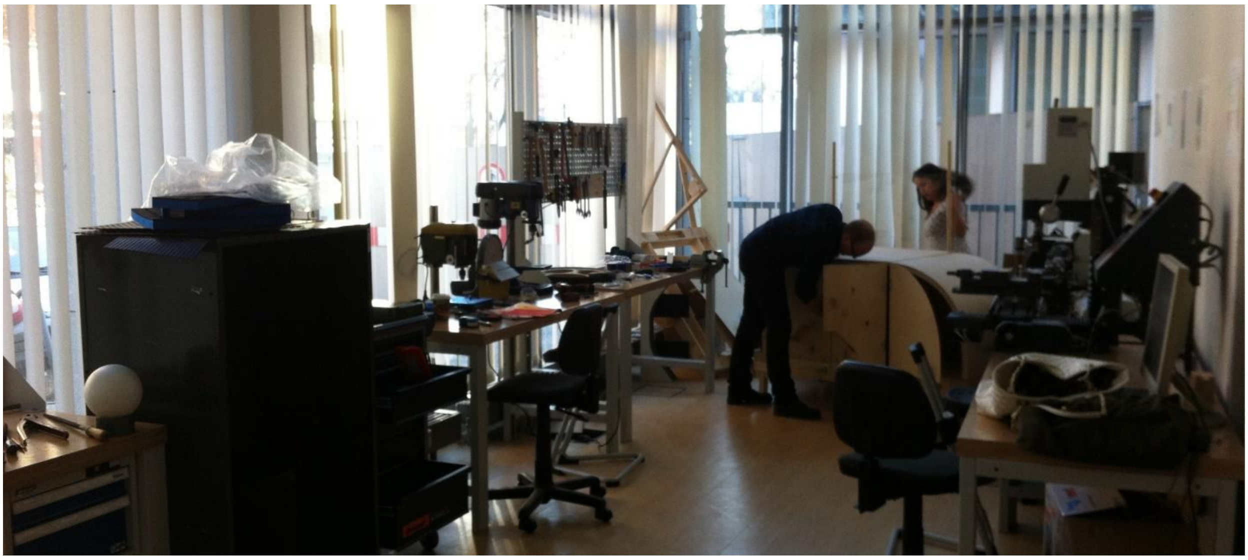

Figure 15 Students working on a project in the Prototypenwerkstatt, fotographed by author

External parameters (user-centered):

1. Integration

The *Prototypenwerkstatt* provides students and alumni with a possibility of transitioning from university to starting their own business, by allowing them to build and test their prototypes for business ideas. There is no direct connection to the curriculum, but a few students also use the space for class projects with the potential for innovations.

2. Classes and safety

It is decided for each individual case, if a person or team will be granted access. Important factors are an affiliation to *TU Berlin* and a focus on entrepreneurship of the project. There is no constant supervision, and people who work on longer projects, receive a transponder to have 24-hour access to the space. There are no official classes to learn how to use the machines either, and users are expected to know what they are doing. However, people with experience often help and teach others in the space. Occasionally, there are also organized workshops within the network of entrepreneurs, such as for 3D-printing. Regarding machine access, there is a differentiation between *TU Berlin* students and founders currently outside of university (e.g. alumni), due to safety regulations of insurance. Students are not allowed to use dangerous machines, such as the lathe, mill and band saw, because they are not covered by insurance. Others sign a declaration that they know how to run machines and are liable themselves – this way the university is not responsible for injuries. If people turn out not to know how to operate a machine they signed up for, their access to the space is revoked.

3. Activities and events

There are currently no events organized by the space itself, but rather in the user network or at the Entrepreneurship Center. Examples include workshops, such as a 3D-printing workshop, which is organized by one of the Start-Ups using the space.

4. Culture

There are constant fluctuations, as teams are normally coming to the space for one specific project and most projects are finished in about a month. In general, there can be differentiated between the two groups: founders and students. The founders who are part of the network, will normally stay longer. One of the start-up teams actually has its office within the space.

It is important, that everyone has the same rights to space and machines and this requires from the teams to communicate with each other and plan together. The people who are working on projects at the same time generally get to know each other and may in some cases help each other out, if necessary. First effects of this networking are already visible, according to the university. However, the effect is still small due to the limited number of teams going through the space.

Internal parameters (space-centered):

5. History

The space was opened in 2013, because the Entrepreneurship Center[14] saw the need of many founders to build and test viable prototypes for their business ideas. Recently, the space has begun to attract more users and to advertise itself in the entrepreneurship scene in order to slowly increase its user numbers with people who want to build prototypes with an entrepreneurial focus.

6. Equipment

The equipment inside the *Prototypenwerkstatt* consists of hand tools, a 3D-printer, electronics equipment, band saw and a small lathe and mill. The selection is limited and there is mostly only one of each machine, but it offers the necessary equipment to build different prototypes from metal, wood or plastic. The equipment is the most basic of all spaces analyzed, which is due to the relatively small size and funding of the space.

7. Staff

There is no shop leader, but a director, who is in charge of organizing the space and a teaching assistant, who is supervising the space and maintaining the machines. Most of the time, there is no staff present at the space and the teams are left to themselves.

8. Challenges

The space is small, and the number of people, who can get access is limited. Therefore, it is important to advertise the space selectively and attract the right user group – people with an entrepreneurial focus, who want to build a prototype for their business ideas. Other challenges include managing the space with the small available budget and making sure that the space is safe and the requirements by law are met.

[14] For more information about the Entrepreneurship Center at TU berlin, see www.entrepreneurship.tu-berlin.de

4.2.5 Techshop – ASU

During the time of writing this thesis, the *Techshop* had opened only recently and several parameters, such as user numbers, could not be measured yet. In order to make predictions about the *Techshop* at *ASU*, several other *Techshop* locations were investigated and numbers estimated for the new location.

Summary

Techshop is a membership-based, do-it-yourself fabrication workspace with several locations across the US and a new location on the campus of *Arizona State University* in the *ASU Chandler Innovation Centre*. *Techshop's* mission is to fuel innovation and empower people who want to build something. In the context of the engineering education, *Techshop* is supposed to empower students to work on hands-on projects, give them a real feeling for how engineering is done outside the university and provide the opportunity to work on both projects inside and outside of class.
The space is unique, because it is open to everyone, even people from outside the university, while being located on university campus. This creates a mixed community of students, entrepreneurs, artists, hobbyists and tinkerers with a lot of potential synergy effects. *Techshop* at *ASU* is working together with the university and the city of Chandler to promote innovation within the region. Its purpose and primary focus is to empower people to build what they want and to provide the necessary tools, classes and environment. It grants access to anyone older than 16, with a valid membership. *Techshop* is a for-profit organization and as such financially independent. Part of the open work area of *Techshop* is displayed in *Figure 16.*

Facts

- Users: Everyone with a valid membership
- Number of users: 1,500 (planned)
- Size: ca. 1,000 m²
- Fee: students in certain classes free, other students $995/year, others $1,395/year,
- Opening hours: 105hours/week; 9 am – 12 pm

Figure 16 - Tour through the new Techshop at ASU before the official opening (source: Techshop)

External parameters (user-centered):

1. Integration

The *ASU Chandler Innovation Centre* consists to one half of the makerspace *Techshop* and to the other half of class rooms of the university. There are several classes held in the building, which use the *Techshop* extensively to build prototypes for class projects. Furthermore, many students use the makerspace outside of university to work on personal projects and the majority of the staff working at *Techshop* are actually students.
The *Techshop* is not trying to replace university facilities, but offers additional infrastructure to supplement the theory of more hands-on experience. MITZI MONTOYA, the vice provost and dean of the *College of Technology and Innovation*, stated that "*normally labs like this aren't open to the public. I expect the crossover effect will be tremendous*" (EAST VALLEY TRIBUNE WEBSITE 2014).

2. Classes and safety

There are classes for each machine, often with basic and more advance courses. The right to use more complex and dangerous machines like the lathe or laser cutter is earned by passing these classes. Classes take about three hours, depending on the machine and cost a fee of normally $50-100 per class. Main focus of the classes are safe and proper usage of the machine, as well as teaching of manufacturing techniques. Classes always require hands-on use of the machine, and users will manufacture at least one part during the class. Only people, who pass the class, may use certain machines, which can only be activated with a personal RFID-badge. The content of individual classes are identical across all *Techshop* locations, but the type of classes offered at a certain location depend on the user demand. Users accept all liability. In order to avoid accidents in the shop, users are always encouraged to ask the staff for help, if they are not sure how to operate a machine.

3. Activities and events

Depending on the *Techshop* location, there are varying programs, such as afterschool programs with non-profit organizations or art projects with local artists. Additionally, there are regularly networking events, and companies or individuals may rent the space to host an event. These events act both as attraction of potential users and also as a part of the funding.

4. Culture

Techshop users usually have an intrinsic motivation in common to build physical objects. The company is closely linked to the *Maker Movement* and communities across the USA, as already described in *chapter 2.2*. User groups include students, entrepreneurs or artists – all ages and professional levels are represented. This is a main difference in comparison to other makerspaces in the university, where only students, and in some cases university affiliates, have access. Opening the makerspace to the outside world, creates a more diverse culture with creative potential. Each *Techshop* represents the community of its location. For example, according to RAFFI COLET, the General Manager of San Jose, "*there exists a large entrepreneurship culture in San Francisco and a more artistic culture in San Jose, where several artists are involved at the Techshop*".
In Chandler at *Arizona State University*, a majority of the users will be students and with more time it will become more apparent how this affects the culture within the *Techshop* compared to other locations.

Internal parameters (space-centered):

5. History

The *Techshop* at *ASU* opened in 2013 in Chandler, in order to spark innovation in the region and improve cooperation between university, city and industrial partners. While this location is new, the history of *Techshop* began in 2005, when the first *Techshop* opened in Menlo Park, California. At *ASU*, plans for the partnership began after a panel discussion about the DIY and maker movement, when dean MITZI MONTOYA of *ASU* and CEO MARK HATCH of *Techshop* discussed how to implement a makerspace at *ASU*. *ASU* wanted to introduce a makerspace to their university, but realized that they would not have the proper infrastructure, such as equipment, classes and supervisors to implement one with the available funding. By cooperating with *Techshop*, the university is outsourcing the job of setting up, running and maintaining the makerspace. At the same time, the infrastructure is available for university stakeholders and several classes are using the space. Future plans at *ASU* are to build a strong community of members and work on improving models to cooperate with the university. The company itself has plans for further expansions both in the US and internationally. One of them is the planned *Techshop* in Munich at the *TUM*, which will be discussed in the outlook in *chapter 8*.

6. Equipment

Techshop has a large variety of tools with individual areas for metal, wood, rapid prototyping, welding, plastics, basic electronics, large work tables to work on individual projects, computers with CAD-software and even textiles. This wide range of equipment is suitable for building prototypes of nearly any material. While the machines are not comparable to the high precision machines normally found in university shops, they serve most building purposes and prototyping activities of its users. Due to the large variety of different machines, compared to the other selected makerspaces, the equipment at *Techshop* can be described as advanced.

7. Staff

Each *Techshop* has a small management team with the *General Manager* as director of the space. Additionally, there are supervisors, called "*dream consultants*", whose tasks include supervising the workshop and teaching classes. At *ASU*, a large portion of the *dream consultants* are students, working part-time. Additional instructors are employed, whose only task is teaching classes. The most important factors for new *Techshop* supervisors are a technical background, great social skills and wanting to help other people how to learn and build things.

8. Challenges

The challenge for the new shop will be building a large user base of over 1,000 members from nothing in the beginning, which will take some effort and time. Other challenges are adapting the existing *Techshop* model to the special needs and demands of the university community. This includes cooperating closely with the university, helping to give students access to the space and facilitating an implementation of the makerspace into the curriculum of *ASU* students.

4.3 Comparison

After the *individual analysis* of each space (4.2), a *comparison* of the spaces will demonstrate the difference in implementation of the selected makerspaces. This allows a more thorough analysis of the effect certain aspects have on the nature of the spaces. The overview of the quantitative data is displayed in *Table 2*.

Parameters	***PRL***	***Hobby Shop***	***Invention Studio***	***Prototypen-werkstatt***	***Techshop***
User numbers	1,700	300	500	50	1,500
Size [m²]	Large: 1,000	Medium: 400	Medium: 300	Small: 100	Large: 1,000
Ratio [users/m²]	1.7	0.8	1.7	0.5	1.5
Total hours supervision T [h/week]	480	80	280	20	470
Ratio [users/T]	0.28	0.27	0.56	0.4	0.31
Staffing	3 Directors 16 Supervisors	1 Director 2 Supervisors	80 Student Supervisors	1 Organizer 1 Supervisor	1 Directors 16 Supervisors 20 Instructors
Open publically [hours/week]	70	50	35	Only open transponder	105
Open with special access [hours/week]			168	168	
Age [years]	122	76	3	1	0
Funding	1. University 2. Donations 3. Fees	1. University 2. Fees 3. Donations	1. University 2. Industry Partners 3. Donations	1. University	1. Fees 2. Events 3. Industry partners
User groups	1. Students	1. Students 2. University affiliates	1. Students	1. Students 2. University affiliates	1. Students 2. University affiliates 3. Outsiders
Equipment	Advanced	Moderate	Moderate	Basic	Advanced
IP	Depends	Depends	Depends	No	No
Classes	Yes	Yes	Yes	No	Yes
Organizing events	Yes	No	Yes	No	Yes
Plans to expand	Yes	No	Yes	No	Yes

Table 2 Overview of the comparison of selected makerspaces

The outcomes from *Table 2* are based on the qualitative interviews, as well as other sources of data - using the methods introduced in *chapter 3*. In this chapter, the quantitative data will be interpreted in order to categorize the different spaces and discuss advantages and disadvantages of the different models. The selected makerspaces are compared regarding the following aspects, based on the data presented in *Table 2*:

1. Focus
2. Size
3. Funding
4. Access vs. Integration
5. Staffing

4.3.1 Focus

The focus of a space influences most other *parameters* and has a large influence on its implementation in general. Three major categories were identified for the focus of the spaces:

- *Education*
- *Community*
- *Entrepreneurship*

Each of the five spaces fits into one major category and some also belong to a second minor category, as demonstrated in *Figure 17*.

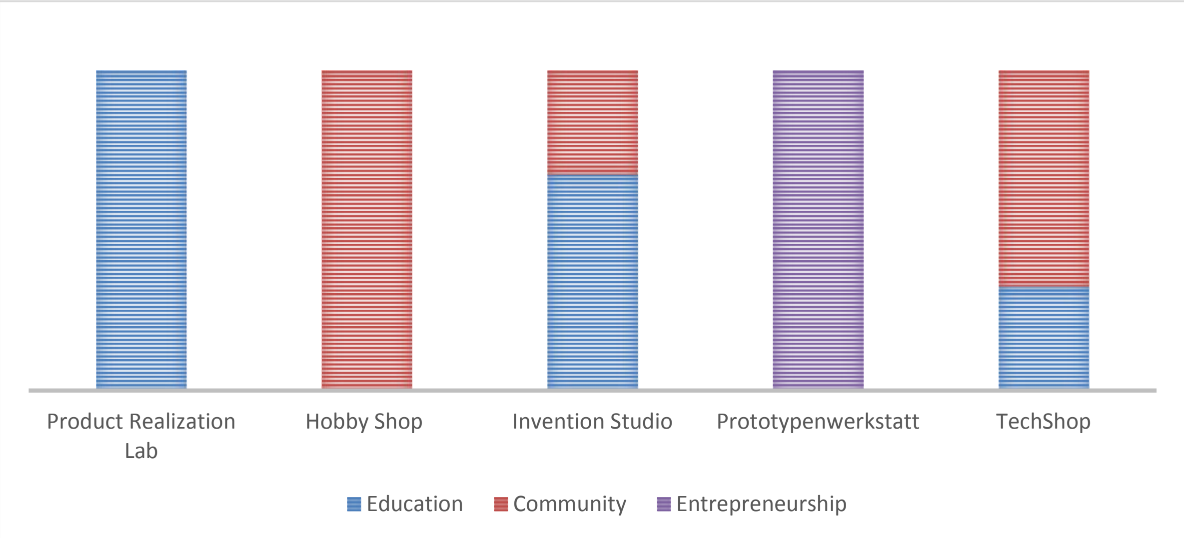

Figure 17 Focus of the selected makerspaces

A focus on *education* means that the primary role of the makerspace is its usage as a learning platform for students, and to incorporate it into classes and the curriculum. Both the *PRL* and *Invention Studio* have education as their main focus in common and use the space primarily for classes. The *Techshop* is also focusing on education in the form of many classes, but only as a secondary priority.

The *community* focused spaces are building a platform, where a community of people with the shared interest of building something can work together. These places feature a larger amount of personal projects on a voluntary basis, which generally are not related directly to university work. Main examples for the *community* category are the *Hobby Shop* and *Techshop,* and with a secondary focus the *Invention Studio*. The *Hobby Shop's* main purpose is giving students a possibility to work on their hobbies and *Techshop's* business model, besides its cooperation with *ASU*, is building a strong community of makers, who use the space to realize their ideas. The *Invention Studio* has a large *community* aspect as well through the existence of the *Maker Club*, which forms an important part of undergraduate student life, thus having a minor focus on *community*.

The *Prototypenwerkstatt* is the only one focusing mainly on *entrepreneurship*, by actively recruiting founders who want to use the space to build prototypes for their business idea. Although there are several examples of businesses being launched from the other spaces, these examples were due to the effects of *community* and empowerment of using a makerspace, but not because the spaces were focusing mainly on supporting founders.

4.3.2 Size

Besides the focus, the size of a space is a key factor, as it shows the potential effect the space has within the university community. A larger space can reach more users and thus has a larger impact. The size of the spaces can be described both by area of the space and the amount of users. The size of a space strongly depends on funding, because a bigger space requires a larger staff and is more expensive in general. The size of the makerspaces is demonstrated in *Figure 18*.

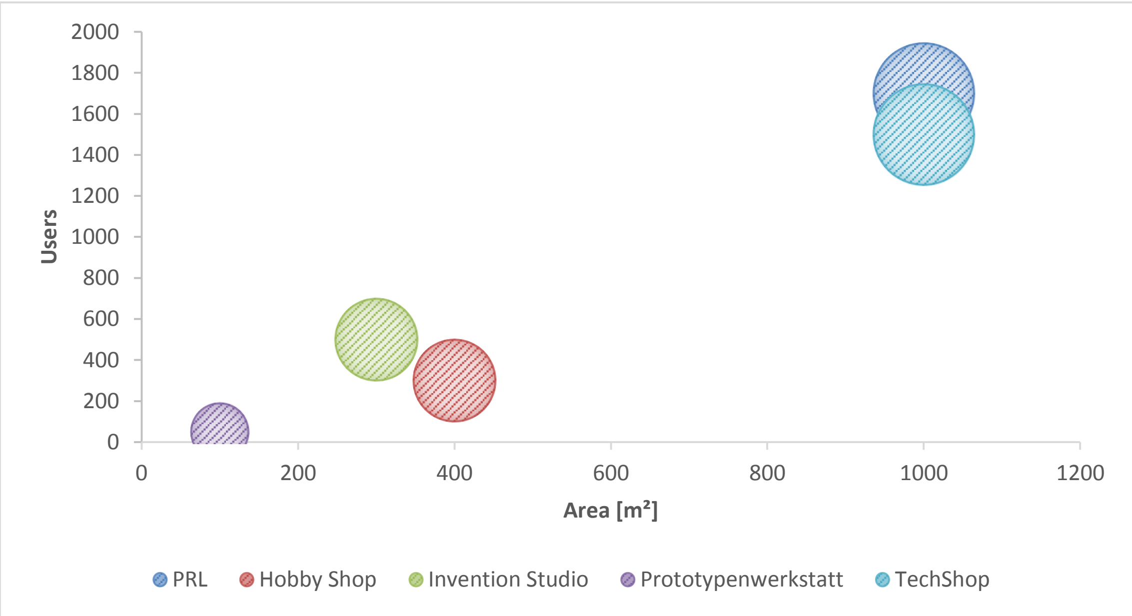

Figure 18 Size of selected makerspaces

The data demonstrated in *Figure 18* allows to identify three different sizes among the spaces:

- *Large* (Over 1,000 users): *PRL* and *Techshop* (The amount of future *Techshop* users is predicted based on data from the other *Techshop* locations)
- *Medium* (Over 200 users): *Invention Studio* and *Hobby Shop*
- *Small* (Less than 100 users): *Prototypenwerkstatt*

The ratio of users per area for each selected makerspace is demonstrated in *Figure 19*. Ratios for users per square meter in the selected spaces are ranging from 0.5 users/m² at the *Prototypenwerkstatt* to 1.7 users/m² at the *PRL* with one user per square meter as good estimate. This is an important value when planning a new space.

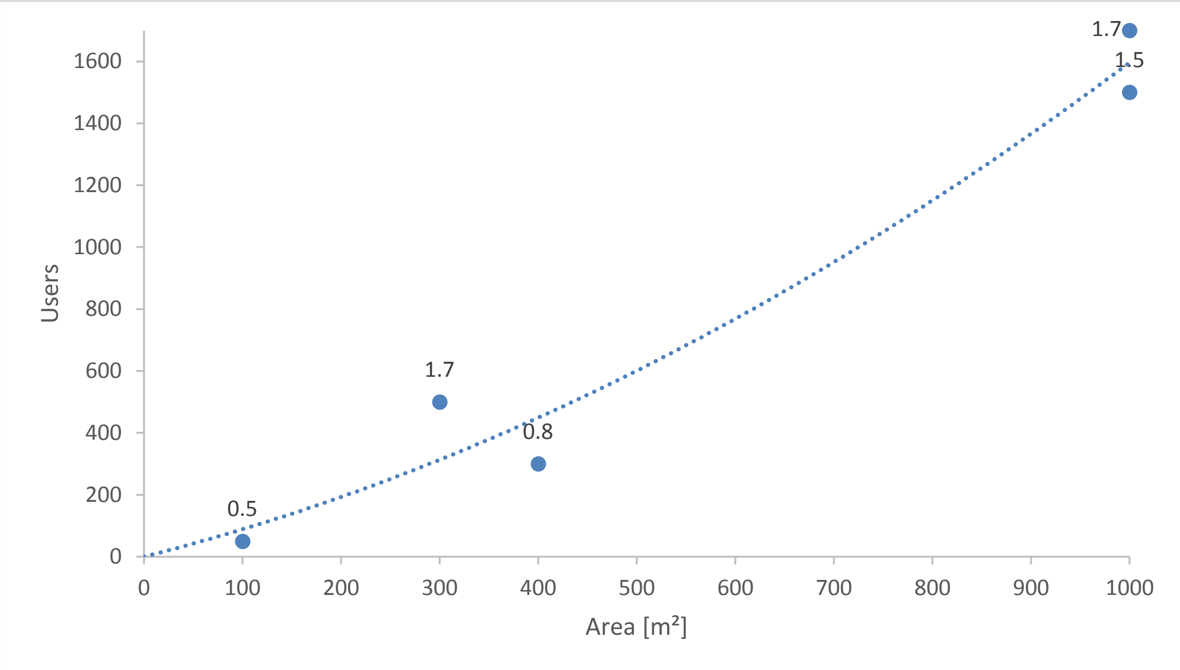

Figure 19 Users per area of selected makerspaces

There also appears to be a trend that the ratio of users per area is increasing exponentially with the area of the space, which is illustrated in *Figure 19*. However, the data is not consistent enough and further makerspaces need to be analyzed in order to investigate this possible trend.

When looking at the focus of the spaces in relation to size, it becomes apparent that the *small* space *Prototypenwerkstatt*, has a niche focus on entrepreneurship as a subset of other maker activities. In the other spaces all making activities are welcome, including education and personal projects. The researcher’s interpretation is that while *larger* spaces are supporting more maker activities and have a broad focus, a *smaller* space with limited capacity may be focusing more on one specific area and user group – in the case of the *Prototypenwerkstatt* on *entrepreneurship*. Again, additional *small* spaces would need to be investigated to confirm if this is indeed a general trend.

4.3.3 Accessibility and intellectual property (IP)

The accessibility of a space determines the range of people who have access to a space. The higher its accessibility, the more user groups have access to a space. Three levels of accessibility can be identified at the selected makerspaces:

- Basic accessibility – Students only (*PRL* and *Invention Studio*)
- Medium accessibility – Students and other university affiliates (*Hobby Shop* and *Prototypenwerkstatt*)
- High accessibility – Everyone (*Techshop*)

Limiting a makerspace only to students, as in the case of the *PRL* and *Invention Studio*, may have benefits for the educational focus of a makerspace. As demonstrated in *chapter 4.3.1*, both of the spaces' aim is education. Since only students are using the space, the makerspace can concentrate on creating an environment that supports learning. However, allowing different user groups, such as alumni and university staff in the makerspace, appears to be more beneficial for the community aspect of makerspaces, such as the *Hobby Shop* and *Techshop*.

In terms of intellectual property (IP), the makerspaces are divided into universities, where the rights of inventions, created in the space, belong to the university and makerspaces, where the IP belongs to the creators:

- IP restrictions – Inventions of graduate students are owned by the university (*PRL* and *Invention Studio*)
- No IP restrictions – Inventions are owned by the creator (*Hobby Shop*, *Prototypenwerkstatt* and *Techshop*)

An IP restriction may have a negative effect on the creation of innovation and entrepreneurship. Students, who are serious about commercializing their idea, may have to find a different space to work on their ideas. In the case of the *Hobby Shop* there is a non-defined area, because in theory the university might have a right to own the innovations, but due to the focus on personal ideas, this was never enforced and there is no interest in doing so. The data shows a correlation between the accessibility and the IP restriction. Both the *PRL* and *Invention Studio* limit access to students-only in order to focus on education and at the same time, enforce IP restrictions on the users. In the case of *Techshop* and the *Prototypenwerkstatt*, many users work in the space in order to invent things and work on business ideas, hence an IP restriction would limit the users significantly. Hence, if entrepreneurship is part of the focus of a makerspace, there should be no IP restrictions, which limit the inventors.

4.3.4 Funding

Funding plays another important role for the makerspace, because it is often a limiting factor for the size, staff and equipment. The source of funding also generally determines how the money is used. For example: if a source of funding was from a certain department in the university, the given department would assumingly have a large interest, that the makerspace will support the specific department by hosting classes or allowing access for research projects. Among the spaces investigated, there are five different major sources of funding:

- *User fees*
- *University*
- *Donations*
- *Industry partners*
- *Events*

Each space has one or multiple sources of funding among the five major sources, which are demonstrated in *Figure 20*.

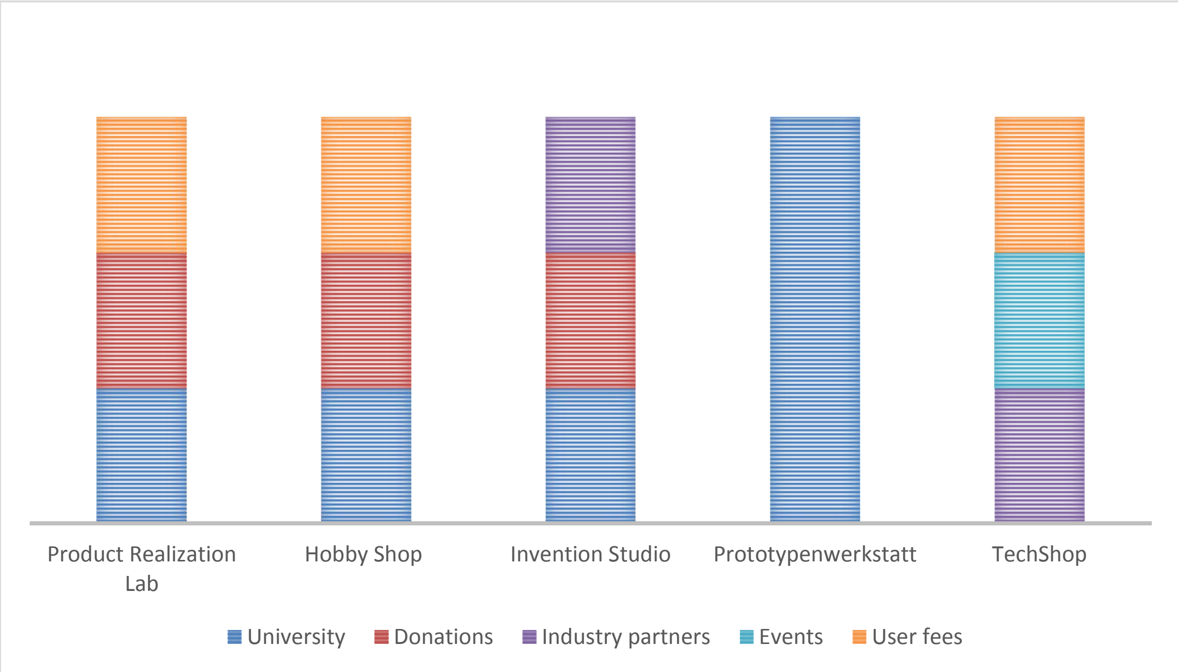

Figure 20 Funding sources of selected spaces (not in proportion)

Apart from *Prototypenwerkstatt*, each space has multiple sources of funding. As a small space, which does not require as much funding as the larger spaces, a single source is enough for the *Prototypenwerkstatt*. Private *donations*, which usually come from university alumni, are an additional source of funding for the *PRL*, *Hobby Shop* and *Invention Studio*. *User fees* are supplementing the funding of the *PRL*, *Hobby Shop* and *Techshop*, but to a different extent – while the user fees make up a major part of the funding at *Techshop* and about 30% of the funding at the *Hobby Shop*, fees at the *PRL* only cover less than 10% of the total funds. Both, the *Invention Studio* and *Techshop*, are free for users. The users only need to cover the cost of the material they require to build their prototypes. *Invention Studio* and *Techshop* are also cooperating with industry partners for funding. In the case of the *Invention Studio*, the partners fund the *Capstone Design Course*, where they work together with the students, and *Techshop* is cooperating with several industry partners such as non-profit organizations, the city of Chandler or *AutoDesk*.

Techshop as a for-profit organization is different from the other spaces, because it is the only space not funded directly by the university, which is the major source of funding for the other makerspaces. In contrast, it is relying more on the other sources of funding, predominately member fees for memberships and classes. However, *Techshop* is funded indirectly by the university, as they are providing the rooms and infrastructure for *Techshop* and agree to purchase a certain amount of memberships for students, who are taking classes in *Techshop*.

4.3.5 Staffing

This *staffing* section is focused on the staff, who is supervising and supporting users in the shop. Other tasks, which are not scope of the investigation may include repair, outreach or facility management. The models of how the spaces are staffed vary both, in the amount, and in the positions of the staff working at the space. In the following section, the different positions will be explained in more detail. This includes an estimation of the average hours spent in the space per week, based on the input of the qualitative interviews with the program directors. For reasons of simplification, an average amount of hours is estimated to be identical across shops for each function.

The positions of staff working in a makerspace can be summarized by four general types:

- *Director*

The *directors* manage and organize the space, and lead the other staff members. They generally have a strong technical background and can usually be compared to a head of a workshop in their task. However, they often take on additional activities, such as teaching. The average hours in the shop per week for *directors* are estimated to be 40 hours, which is a typical working week.

- *Supervisor*

Supervisors are trained staff, who supervise the space and help the users in the space. They had a special training and are familiar with all machines in the space. In the cases of the *PRL* and *Hobby Shop*, the *supervisors* are students, working half-time in the space. At *Techshop,* they are employees, but at *ASU* a majority of the supervisors, called "*dream consultants*", are also students working part-time. Since in most cases the supervisors work part-time, the average hours in the shop for *supervisors* per week are estimated to be 20 hours.

- *Student supervisor*

Student supervisors are *Maker Club* members at the *Invention Studio*, who are supervising the space as part of their dues to being part of the club. One of the benefits they get in exchange is a 24/7 access to the space. The *student supervisors* are generally not as well trained as regular supervisors, but have the distinct advantage of working voluntarily. Since staffing is generally the most expensive part of a space, this model is essential also in financial terms to how the *Invention Studio* functions and is able to exist. The average hours in the shop for *student supervisors* per week are estimated to be three hours per week, which is the policy for club members.

- *Instructor*

Instructors are working at *Techshop* and their job is to teach classes in safety and the handling of machines for users. The average hours in the shop for *instructors* per week are estimated to be six hours.

In each of the spaces the staff working in the space consists of a combination of the different staff positions *Figure 21*.

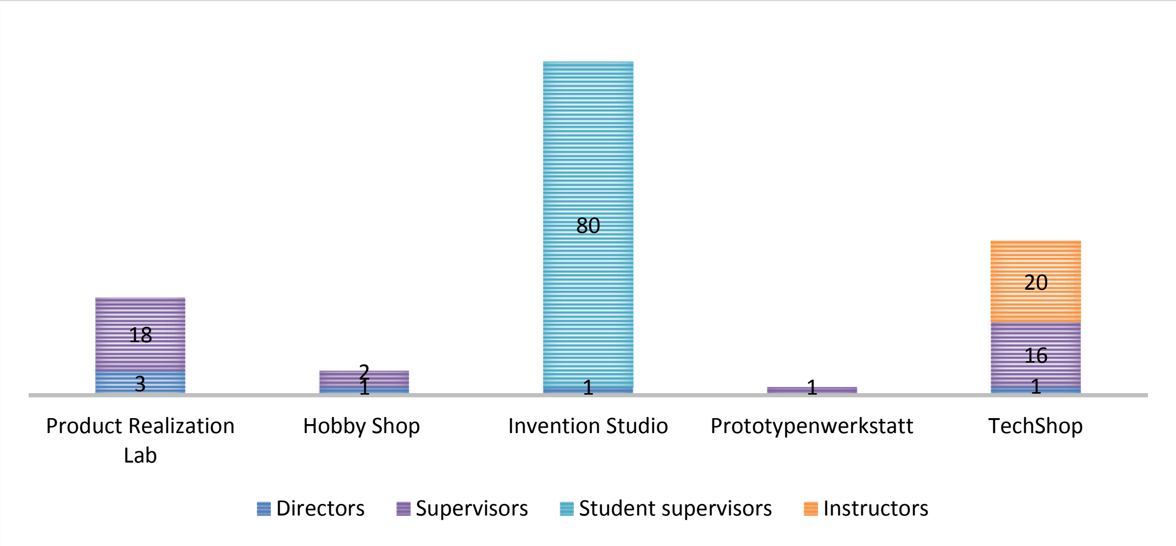

Figure 21 Staffing in selected makerspaces

The average total amount of hours spent by the entire staff per week is estimated by the following formula:

$$T = \sum_i^4 (P_i \cdot t_i) \qquad (4.1)$$

T : amount of hours spent in space by entire staff per week

P_i: amount of staff members working in position i
(1 = director, 2 = supervisor, 3 = student supervisor, 4 = instructor)

t_i : average hours spent in shop by person working in position i

The staffing in hours per week for each space is displayed in *Figure 22*.

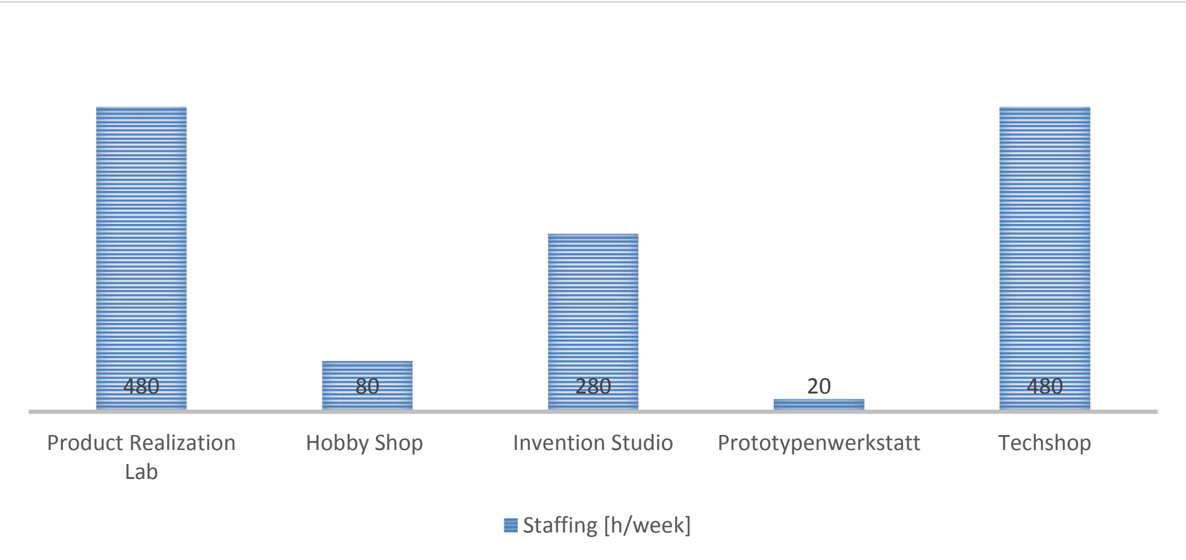

Figure 22 Estimated average amount of hours per week spent in space by entire staff

Based on these results, the ratio of hours of supervision per week available per user was calculated, and the trend is demonstrated in *Figure 23*. This shows how much supervision hours the staff is investing per user in a given week.

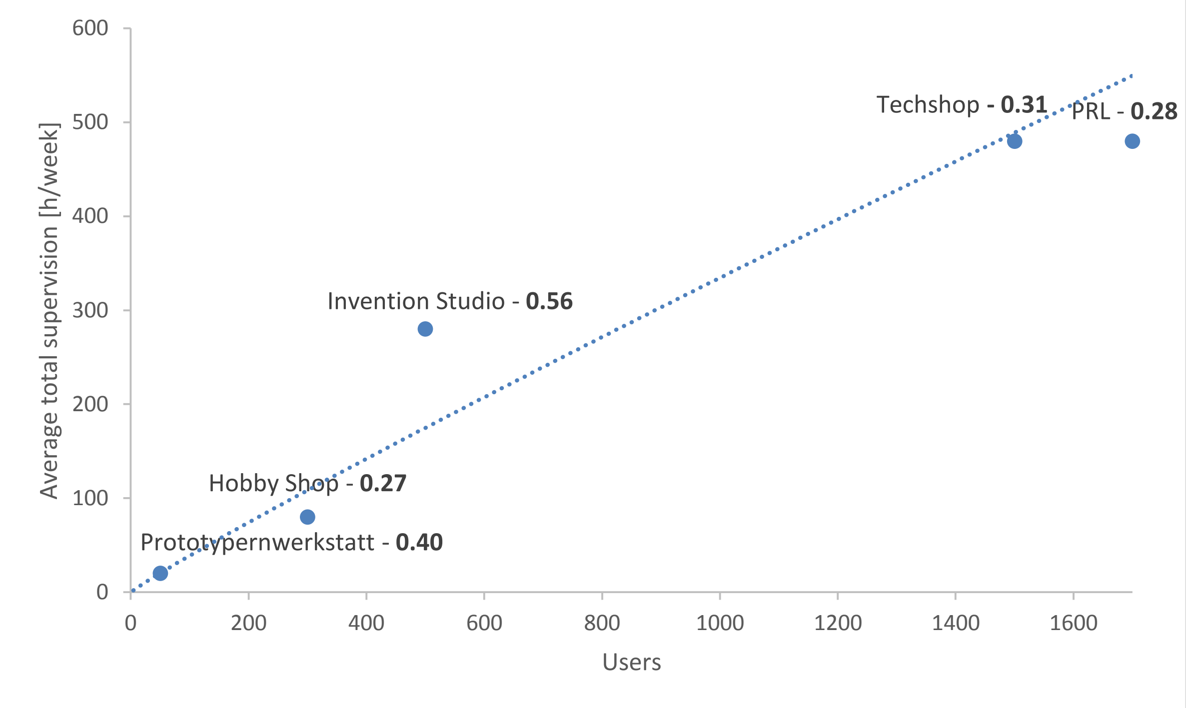

Figure 23 Trend of users to supervision ratio for selected makerspaces

The values range from 0.27 weekly hours per user in supervision for the *Hobby Shop* and 0.28 weekly hours per user for the *PRL* to 0.56 weekly hours per user for the *Invention Studio*, which is about twice as much. Again, this is an important value for planning a new space. One of the reasons, why the *PRL* and *Hobby Shop* are investing less hours per user, could be, because in comparison to the other examples they have been around for a long time and might be more efficient with their supervision. While the *Invention Studio* is putting in a lot of supervision hours in total, the staff consisting of student volunteers is not as well-trained and a larger staff may result in a loss of efficiency.
There does not appear to be a significant correlation between the ratio supervision per users to size of the space.

4.4 Lessons learned

The *individual analysis* (4.2) and *comparison* (4.3) have led to insights about many aspects of makerspaces in the university. Important feedback and advice from the different selected spaces was summarized in this chapter in the form of *lessons learned*. These lessons come mainly from the interviews with the directors of the makerspaces and can be divided in the following different areas:

1. *Communication*
2. *Funding*
3. *Users*
4. *Entrepreneurship*
5. *Supervision*
6. *Equipment*
7. *Community*
8. *Safety*
9. *Continuous improvement*

These areas are summarized by using examples from the different makerspaces. This section is structured in the way that the individual bullets are always related to one of the analyzed makerspaces. They showcase specific aspects of makerspaces in universities, which come from the experience of existing spaces. *Table 3* demonstrates how the different makerspaces contribute to the lessons learned.

	PRL	***Hobby Shop***	***Invention Studio***	***Prototypen-werkstatt***	***Techshop***
Communication	**X**		**X**		
Funding	**X**				**X**
Users	**X**	**X**	**X**		
Entrepreneurship		**X**		**X**	
Supervision	**X**	**X**	**X**		**X**
Equipment	**X**	**X**			**X**
Community	**X**		**X**	**X**	**X**
Safety			**X**		
Continuous improvement	**X**		**X**		

Table 3 Dependency matrix between lessons learned and selected makerspaces

The list of *lessons learned* is relevant for the creation of new makerspaces in universities, as many of the findings are the result of experience of the individual directors and can be applied to the creation of new makerspaces as well. Results are used later in *chapter 1* to develop implementation concepts for *TUM*.

1. *Communication*

(*PRL*)

Different shops and makerspaces, even when they are inside the same university, are usually not aware of each other. Even if they are aware of each other, they do not interact frequently or work on projects together. Although more exchange could be beneficial, joint initiatives are difficult to realize and there is no additional capacity to realize such projects.

(*Invention Studio*)

It is important to have an independent employee on university side, who is responsible for the communication between the makerspace and university, facilitates the organization and implements classes, events and other shared initiatives. A coordinator can also help with implanting a makerspace into the curriculum and to build a deeper connection between the space and other parts of the university.

2. *Funding*

(PRL)

The most important numbers for convincing the university that additional resources are necessary, are the growth in demand and enrollment of users in the space. Money from different sources is important as well: the reliable "*hard money"* from the university is used to plan the basic budget for running the space and the "*soft money"*, such as donations, can be used to try out new things and make unforeseen changes.

(Techshop)

"*As a for-profit organization, a profit is a sign that we are doing a good job, because it means we have many members using our space and taking our classes in order to build the things they want."* (RAFFI COLET 2014)

3. *Users*

(PRL)

Many users associate machines with fear when they enter a workspace for the first time. Therefore it is important to not only teach them the necessary skills, but also give them the confidence to start working and to build things with the right mindset.

(Invention Studio)

The earlier students begin using a makerspace, the longer they can profit from it throughout their studies. It takes time to master the technique of using different manufacturing process and prototyping skills.

(Hobby Shop)

The amount of users coming into the space fluctuates throughout the season and reaches maximum capacity towards the end of semester, when the final student projects are due.

4. *Entrepreneurship*

(Hobby Shop)

A makerspace should empower users, who are working on business ideas, to build prototypes of their product. As soon as they have finished the prototyping phase and want to start producing, it is important that they look for a different place.

(Prototypenwerkstatt)

Start-ups generally need to save money whenever possible, and especially hardware start-ups often need more support and funding and therefore benefit immensely from a free-to-use space to build their prototypes. Besides the physical prototyping facility, they benefit from a strong network, which an entrepreneurship center provides.

5. *Supervisors*:

(PRL)

Young supervisors are easily approachable for same-aged students and are therefore great for the culture within a makerspace community. By spreading their shared among the users, the working atmosphere improves. This allows for better collaboration and a reduced number of accidents among the users. During an introductory course, the values of the directors can be instilled in the young supervision staff. By taking time to prepare the staff and performing team building exercises, a strong bonded team with a shared value system and vision is formed.

(*Hobby Shop*)

The staff is usually the most expensive factor and it can be difficult to receive the necessary funding from the university. However, experience has proved that staffing is critical, not only to safety, but to the community in general. An attempt at the *Hobby Shop* to run the space without supervision, showed that more inexperienced people would get stuck and the effect on the community was very negative. The consequence of the small *Hobby Shop* staff was to help the users as much as needed without letting them become dependent. Director KEN STONE stated in an interview that "*the key is to empower them on a need-to-know basis*".

(*Invention Studio*)

Student supervisors can pass their knowledge on to the next student generations easily. This helps to maintain the system, even though there exists a high level of fluctuation among *student supervisors*.

(*Techshop*)

The main criteria for staff, besides a technical background, are social skills. Supervisors and instructors should be extroverted and wanting to help users build the things they want by learning how to use the machines.

6. *Equipment*:

(*PRL*)

The purpose of a makerspace in the university is not to train perfect machinists, but engineers and designers, who know how to build things. The essential basis for empowering students is teaching the designing and manufacturing considerations in parallel. Equipment is not the critical factor to building a successful makerspace and as co-director CRAIG MILROY put it: "*When people from other universities pay a visit, they often want a list of equipment and I tell them it has nothing to do with the equipment*". In Stanford, the *PRL* may not be as well-equipped as trade schools, where professional machinists are trained, but it serves its educational purpose very well.

(*Hobby Shop*)

There are often complex and expensive machines in university shops, which few people know how to use (e.g. 5-axis-mill). In contrast, the low resolution machines are often much more effective for the users. They challenge design decisions and might require the users to think outside the box and find alternative ways of manufacturing their parts with the available equipment, which can be a great source of learning. In the end, most parts can often be designed cheaper and easier, when precision is not the key factor. The equipment is almost never the limiting factor, but the design.

(*Techshop*)

The most used equipment in *Techshop* are the rapid prototyping machines, such as the laser-cutter and 3D-printer.

Users, who are building physical prototypes in a makerspace need materials and sometimes a space for storage. It is beneficial, if basic materials can be bought or even received for free at the location, which saves the users' time and money. In the case of *Techshop*, many materials can be bought at the location through a partnership with reseller. Additional services, such as storage or private rooms, are available for a fee.

7. *Community*:

(*PRL*)

Creating and maintaining a strong alumni community is an important part for aspects such as community, passing knowledge to the next generation, and gaining support (e.g. donations). It takes effort from the university and a platform to help alumni to get involved.

(*Invention Studio*)

A neutral location is important to attract different disciplines and make students from every discipline feel welcome.

The student ownership of the *Invention Studio* has led to an unexpectedly large community and multiple spontaneous initiatives. For example, the students regularly run evening workshops on topics such as microcontroller programming, motorized scooter design, book binding, kitting, and other examples. The director CRAIG FOREST states: "*We have been truly amazed by the initiative, independence, and resourcefulness of the Maker's Club. All this results from trusting and empowering the students."* The empowerment of the students is essential for the success of the *Invention Studio*. He adds: "*When I talk to other universities, that's the number one thing I say – you have to give the key to the students*."

(*Prototypenwerkstatt*)

In order to form a good culture and community in the makerspace, it is important to get the right user group into the space. In the case of a small makerspace with limited capacity, this is especially important. The *Prototypenwerkstatt* is focusing on creating advertisement for the makerspace, which is specifically aimed at entrepreneurs in the university community.

(*Techshop*)

Building a great community is the key activity to building a great makerspace. While the equipment needs to be good enough to empower users to build the prototypes they need, the true value of a makerspace is its community.

8. *Safety*

(*Invention Studio*)

There is always a trade-off between the freedom of access and the safety of the users. It is important to keep a balance, which neither prevents creativity, nor endangers the students. In cases where students are disrespectful to the basic rules, the space should have the right to expel them – the usage of a makerspace is a privilege and not a right. Additionally, safety can be enforced through the sense of ownership, which the students experience. This results the in self-enforcement of safety rules among the students themselves.

9. *Continuous improvement*:

(*PRL*)

In order to improve the makerspace continuously, success should be defined and measured. According to co-director David Beach of the *PRL*, the following steps are suitable for measuring success of a makerspace:

- Reconnect with alumni and let them share their stories of how the makerspace helped them get to where they are in life
- Growth in number of users (memberships)
- Growth in number of classes, which use the space as part of the student curriculum
- Number of different majors represented in the space
- Amount of money raised through funding
- Inventory of tools and equipment
- Safety records
- Teaching ratings from students
- Review from special committee
- Expansion of space over time in terms of size and facilities
- Publicity, such as citations, studies and media coverage

It takes time to build a working system like the *PRL*, which is deeply connected within the curriculum of students and university as a whole. The classes are consecutive with introductory and advanced courses. Developing this infrastructure took decades and is still an ongoing process of adapting and improving. Creating such an educational makerspace in the university is a continuous process. Successful spaces may need to change their size, location and even basic goals and values over time to adapt and improve to the university's needs.

(*Invention Studio*)

It is important to grow slowly and create a good reputation. There will always be people who criticize and poke holes into something that challenges the status quo, such as introducing a makerspace in the university. However, it is also important to just start - if there would have been long planning and meetings with all lawyers and administrators at *Georgia Tech*, the *Invention Studio* project would probably never have started.

5 Baseline evaluation at TUM

After having developed a better understanding of how makerspaces can be implemented in *chapter 4*, the improvement potentials for the specific case of *TUM* are assessed in a *baseline evaluation*. The baseline evaluation consists of two parts: an *infrastructure analysis* to better understanding the current situation of makerspaces at *TUM* (5.1) and a *stakeholder analysis* (5.2) to identify their needs and predict how a makerspace would influence them. Combining the existing infrastructure and needs, the baseline analysis will expose the specific improvement potentials for *TUM* (5.3).

The analysis was carried out by visiting existing facilities, and by conducting qualitative interviews with stakeholder groups triangulated with quantitative data, such as statistics and online resources. The research methods were introduced in *chapter 3*. The role of *chapter 5* within the context of this thesis is to identify improvement potentials at *TUM*, which is demonstrated in *Figure 24*.

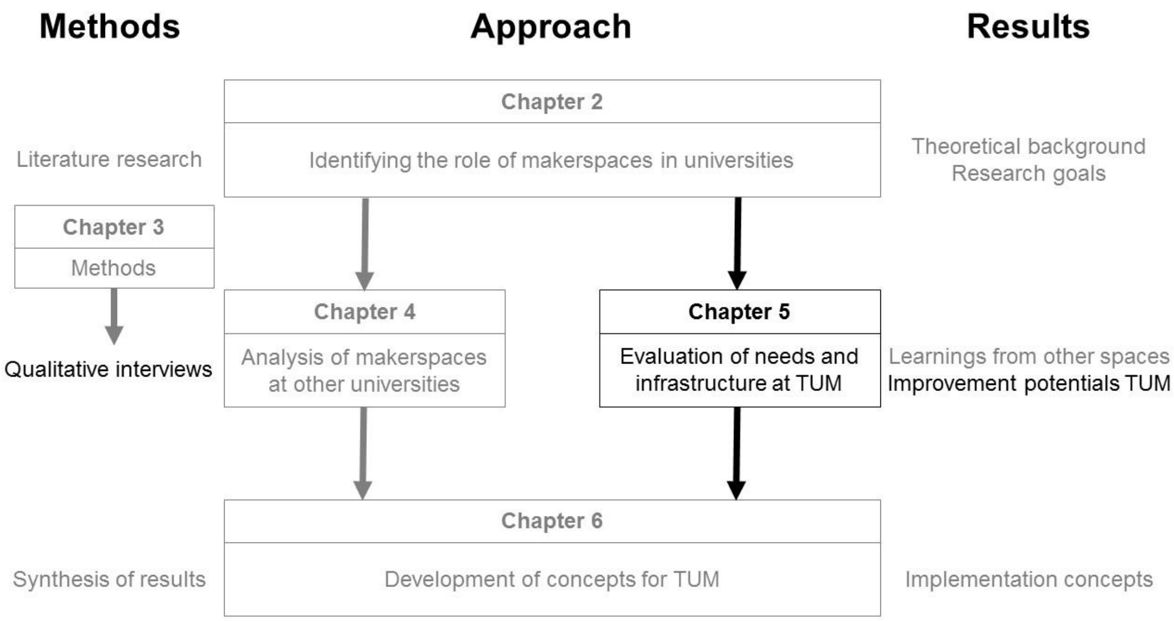

Figure 24 Chapter 5 - baseline evaluation at TUM (see also Figure 1)

5.1 Infrastructure analysis

The infrastructure analysis is revealing the current situation of makerspaces at *TUM*, with a focus on mechanical engineering. First, the *TUM* as a whole is represented with quantitative data (5.1.1) to give an overview of the current state of the university. Next, the *infrastructure of laboratories and shops*, where physical prototyping and building is happening is outlined (5.1.2). Finally, existing makerspaces in the university environment both, *inside the university* (5.1.3) and *outside the university* (5.1.4), are identified.

5.1.1 TUM in numbers

In total, the *TUM* had a budget of over 1.17 billion Euro and over 10,000 employees in 2012 (TUM WEBSITE 2014), (TUM DATEN UND FAKTEN 2013). The university is divided in the three locations Munich, Garching and Weihenstephan with 13 different departments and over 32,500 students in total were registered at TUM in 2012[15]. While architecture, economy, electrical- and civil engineering are located at the main campus in Munich, the departments for mechanical engineering, computer science, physics, chemistry and mathematics are located at the technical campus in Garching. The campus in Garching is also the largest one of the three, with about 13,000 students. The most relevant departments for physical prototyping and building are usually the departments of architecture, engineering and natural sciences. The primary focus of the investigation is placed on the department of mechanical engineering, shown in *Figure 25*, as the largest department at *TUM* with over 4,300 enrolled students (TUM WEBSITE 2014).

Figure 25 TUM campus in Garching with the department of mechanical engineering on the right (TUM WEBSITE 2014)

5.1.2 Infrastructure of laboratories and shops

There are 13 departments at *TUM*, which in turn are divided into institutes and chairs. The institutes and chairs within the departments, such as the department of Mechanical Engineering, each have their individual laboratories and shops. During the evaluation of *TUM*, several of these shops and laboratories were visited and investigated, conducting interviews with the shop staff and the responsible personnel from the chairs. The places where physical prototyping is happening in the department of mechanical engineering, range from small shops with a single shop leader and two journeymen at the mechanical shop of the *FTM* chair (Chair for Automotive Technology), to the largest shop floor at the *IWB Institute* (Institute of Machine Tools and Industrial Management).

The main focus of these spaces is research application for the chairs and institutes, in high-tech shops and laboratories. The spaces are generally under the administration of a single institute or chair and build and test prototypes, depending on demand and orders from the chair. They have professional machinists and staff managing the space and the access for outsiders is limited. People who do not have a special permission to do so, are not allowed to

[15] See also www.tum.de/en/about-tum/our-university/facts-and-figures

operate any machines. This affects the staff working at the departments, as well as the students. Students can rely on the service of the shop only, if what they are working on is in relation to the chair. In that case, students ask the professional staff working in the space, to build the necessary parts for them. Usually students will create and turn in a technical drawing or CAD-file, which the shop then builds. However, while this is a possible way to get the parts, for example, for the thesis they are working on, they currently can not get access to any shop, where they are allowed to build their prototypes hands-on by operating the machines.

There are a few exceptions, such as the *Technisches Zentrum* for architecture, which is introduced in *chapter 5.1.3*. Therefore, most existing spaces at *TUM* in the form of labs and shops can not be classified as makerspaces, because there is no hand-on building for students and no community involved. The result is, that students miss out on the learning experience associated with hands-on building and have to generally wait a long time until required parts are produced.

The complex infrastructure organization of spaces with the examples of two spaces at the chair of Product Development is demonstrated in *Figure 26*.

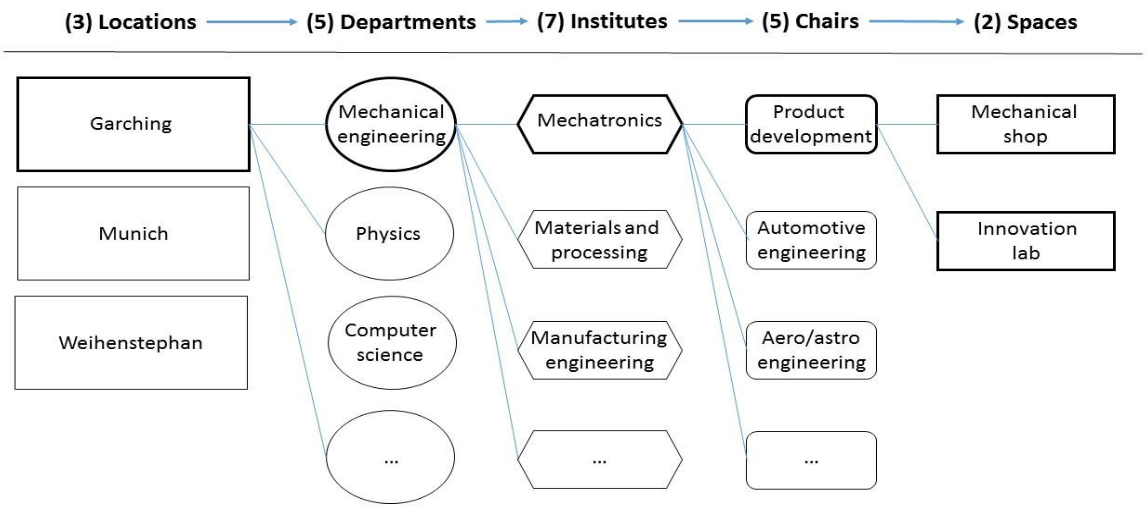

Figure 26 Infrastructure organization of spaces at TUM, graphic by author

This hierarchy with multiple levels is beneficial for the organization of large departments, such as the ME department with around 5,000 students. Some of the consequences of this infrastructure organization, however, are a strong specialization and separation of the individual modules, especially at the level of the individual spaces. This results in a weak connection between different spaces and there does often not exist any communication between the shops even within the same department. This makes a thorough investigation of the entire infrastructure difficult. Further effects of the infrastructure on the individual stakeholders is assessed in *chapter 5.2*.

5.1.3 Makerspaces inside of TUM

One of the main goals of the baseline investigation was to find existing makerspaces at *TUM*.

In each of the three locations of *TUM* makerspaces were identified, which are introduced in this chapter. The best examples for makerspaces found at *TUM* are the *Techshop* (Garching), the *Technisches Zentrum* (Munich), the *UnternehmerTUM shop* (Garching) and the *Modelmaking shop* (Weihenstephan).

- *Techshop* (under construction)

There is currently being constructed a large *Techshop* makerspace at the technical campus in *Garching*, which will open in early 2015. In its setup and size of about 1,800m² it is similar to the *Techshop* at *ASU*, which was analyzed in *chapter 4.2.5*. There is a strategic partnership with BMW and the *UnternehmerTUM* and in the official press statement it is declared: "*The new high-tech workshop will be open to the public, targeting, in particular, creative types, business founders, start-ups and employees of the BMW Group and other companies*"(BMW 2013).

One key difference to the makerspace at *ASU* is, that up to now there are no existing plans to include the *Techshop* into the engineering curriculum yet. It will form as an accelerator for innovation and startup culture without the restriction of IP and its proximity to the *TUM*, mainly the department of mechanical engineering, provides the opportunity to realize a variety of concepts at *TUM* to empower university affiliates. Since this is a completely new makerspace, lessons learned from other spaces can be applied for a successful implementation. A main challenge for creating a good cooperation between the *TUM* and *Techshop* are the acceptability of the university's departments and its administration. This raises the question of "*if you build it, will they come?"*

While this thesis is not focusing on *Techshop*, but makerspace implementation in general, it will certainly be the major source of potential makerspace usage at *TUM* in Garching for the future.

- *Technisches Zentrum (TZ)*

The *TZ* is part of the Department of Architecture at the main campus in Munich and is a makerspace for research and other projects of architecture students. The director ERIC BARTH described in an interview, that until about ten years ago, there were several divided shops in the architecture department, which belonged to the different chairs, as it is typical for the infrastructure at *TUM* departments described in *chapter 5.1.2*. The chairs decided that a shared space would be more beneficial and created the new *TZ* over the course of five years, by combining the existing shops to build a central makerspace for architects.

The outcome is a well-equipped space, which fulfills all aspects of the definition of a makerspace stated in *chapter 2.2.1*. The community of architecture students is able to build physical prototypes and models in a hands-on manner, using the provided tools and machines in this physical space. There are areas for wood, metal, rapid prototyping and plastics. In the center of the makerspace are tables, where users can work, which is displayed in *Figure 27*. Access, however, is limited to the around 1,300 architecture students and other students, such as engineering students, are not officially allowed to use the space. Sensitive research is conducted in separate rooms, which solves the problem of IP, which was described in *chapter 4.3.3*. In conclusion, there already exists a great makerspace for architecture students, but others do not have access.

Figure 27: Technisches Zentrum at TUM (main space on the left, rapid prototyping room on the right), pictures by author

- *UnternehmerTUM Shop*[16]

The *UnternehmerTUM Shop* is part of the entrepreneurship center *UnternehmerTUM* and located at the *gate 8*-building on the Garching campus. The idea behind the space is, that entrepreneurial students can use the makerspace hands-on to build prototypes for their business ideas, similar to the *Prototypenwerkstatt* at *TU Berlin*, which was introduced in *chapter 4.2.4*. It includes some basic equipment and students interested in using the space need to ask the entrepreneurship center to be granted access for their project. One of the main users of the space is actually the student club *TU-Fast*, which is building small race cars inside the shop. The needs of the student clubs as stakeholders will be assessed in detail in chapter *5.2.1*. The *UnternehmerTUM* has big future plans and is building a large *Techshop* makerspace on the campus Garching, similar to the *Techshop* at *ASU*, which is introduced in the outlook in *chapter 8.2*.

- *Model Making Shop*[17]

On the campus Weihenstephan, the students of landscape architecture have their own makerspace to build models. While it is smaller than the *TZ* in Munich, the space can also be identified as a makerspace where students can work hands-on using the machines. The focus is on building architecture models for university projects. Students have the possibilities to work with wood, metal, plastics and paper to build their models.

5.1.4 Makerspaces outside of TUM

There exists an active maker movement in Munich outside of *TUM*. There is a regional maker fair Make Munich[18], which was first held in 2013 and is planned to become an annual event. There exist some smaller public makerspaces as well, which are generally funded by foundations. Two examples are *Haus der Eigenarbeit* and *FabLab München*, which are introduced to include alternatives to makerspaces at *TUM*.

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[16] For more information about UnternehmerTUM, see www.unternehmertum.de
[17] For more information about the model making shop, see www.lai.ar.TUM.de
[18] For more information about the Make Munich faire, see www.make-munich.de

- Haus der Eigenarbeit[19]

The *Haus der Eigenarbeit* (house of do-it-yourself) is a voluntary space of the foundation *anstiftung&ertomis*, which was founded in 1987. Their goal is to spread do-it-yourself ideas and mentality in society. The space has a great wood workshop and other areas for metal, ceramics or textiles as well. There is a user fee to use the space, which includes support and supervision while working on the machines. The layout of the main space is illustrated in *Figure 28* and is similar, but slightly smaller than the *Hobby Shop* at *MIT*.

Figure 28 Makerspace "Haus der Eigenarbeit" in Munich (ANSTIFTUNG ERTOMIS WEBSITE 2014)

- FabLab München[20]

FabLab München is a makerspace focusing on rapid prototyping, such as 3D-printing and laser cutting, as well as some other basic tools and machines. The goal is to spread new technologies to all groups of society, independent of age or occupation. The *FabLab München* serves as a meeting and building spot for a community of makers in Munich. Additionally, there is a strong focus on educating students as well and partnerships with high schools in Munich.

5.2 Stakeholder analysis

The stakeholder groups that are affected by makerspaces in the university were introduced in *chapter 2.3.2*. During this baseline analysis the stakeholder groups are analyzed for the specific case of *TUM*, identifying the relevant organizations and programs inside and outside of the university. The data was collected from qualitative interviews with stakeholders at *TUM* and additional resources such as literature, websites and official statistics.

[19] For more information about the Haus der Eigenarbeit, see www.hei-muenchen.de
[20] For more information about the FabLab München, see www.fablab-muenchen.de

The six defined stakeholder groups are:

1. *University students*
2. *Teaching staff*
3. *High school students*
4. *Alumni*
5. *Entrepreneurs and start-ups*
6. *Industry partners*

5.2.1 University students

The prototyping spaces analyzed in *chapter 4* demonstrate that students can be identified as the key user group for makerspaces in universities. They come in contact with makerspaces either as part of their curriculum, especially in the fields of architecture and engineering, or outside of the curriculum in the form of personal projects and student clubs. One key difference between the USA and Germany is that students in Germany begin their studies with a major, while in the USA there is usually an orientation phase before one or multiple majors are chosen. Since the Bologna Process in Europe, university students in German universities are usually pursuing a three-year *Bachelors*, followed by a two-year *Master's* program.

High dropout rates are a problem for universities and students in engineering programs in Germany. Comparing students of mechanical engineering to other students, statistics show that the dropout rate for engineering students is much higher. The dropout rates in German universities for *Bachelors* and *Masters* are illustrated in *Figure 29*.

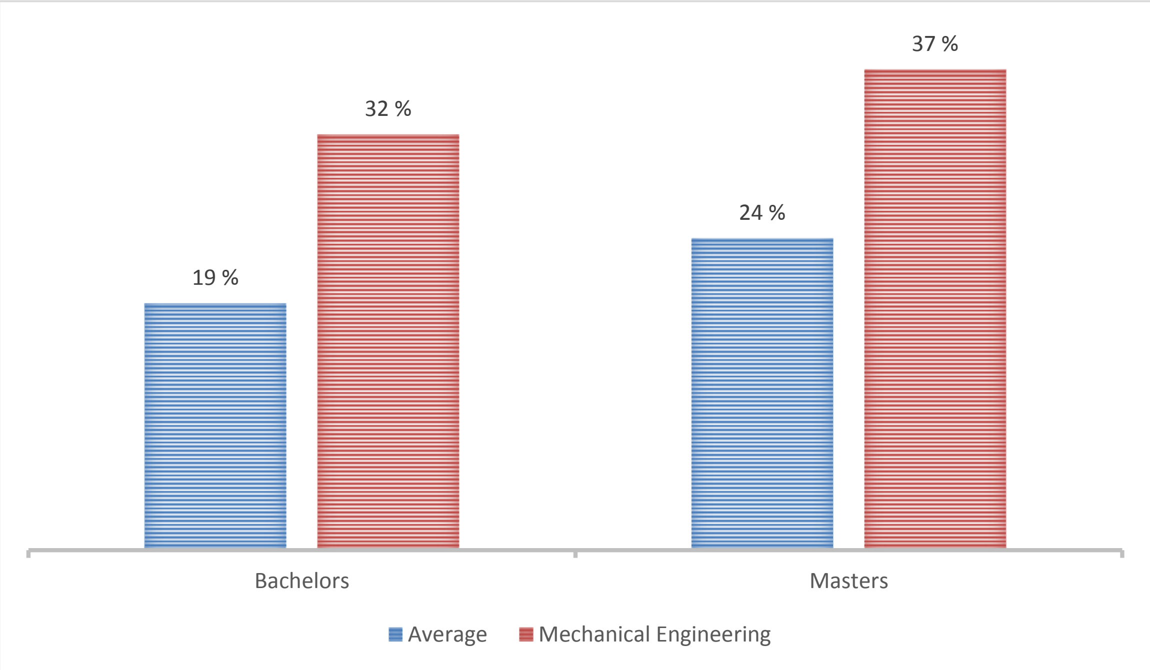

*Figure 29: Dropout rates in German universities for Bachelors and Masters students (*HIS 2012*)*

One of the benefits of makerspaces is that can may increase motivation through hands-on projects, as was introduced in *chapter 2.3*. Hence, makerspaces can have the positive effect of lowering dropout rates of ME students.

A makerspace in the university can empower students to build physical prototypes in a hands-on manner, which is currently limited at *TUM*, and thus improve education and motivation. The infrastructure analysis in *chapter 5.1* has demonstrated that students at *TUM* currently lack the opportunity to build physical prototypes with an exception of subgroups, such as architecture students at the *Technisches Zentrum*. Since *Garching* is the largest technical campus at *TUM* and Mechanical Engineering the largest department at *TUM* with over 4,000 students, the ME students are the first group, which should be analyzed for the impact of a makerspace. Therefore, this analysis is focusing mainly on ME students in *Garching*. When analyzing the impact on students, there should be a differentiation between the impact makerspaces have *inside of the curriculum* and *outside of the curriculum*.

- *Inside of the curriculum*

Internships in the industry are an essential part of studying mechanical engineering at *TUM* and part of the curriculum. Throughout their Bachelors, ME students are expected to work a total of 18 weeks in internships and at least half of the time hands-on in manufacturing. Eight weeks are to be completed before the beginning of studies at *TUM*. In theory, this system is great for teaching skills on manufacturing and how to operate machines. Furthermore, there is an important social lesson to be learned for working side by side with workers of different backgrounds. However, the university is “outsourcing” this part of education to external shops and companies, thereby losing the ability to control the quality and outcome of these internships. While there are some great examples for these internships, there also exist many reports of negative experiences as well. In some cases students are seen as a cheap source of labor and given mundane work for weeks, just to fulfill the university requirement. A makerspace can not replace this part of ME education, but performing a part of this education would guarantee that more students learn the basics of hands-on manufacturing and physical prototyping.

The first two years for ME students at *TUM*, which are called “*Grundstudium*” (basic studies), focus heavily on theory in classes, such as mathematics, natural sciences and mechanics. There is little possibility to apply knowledge hands-on and work on practical projects inside the university. The Product Development chair of Professor Lindeman has recognized this problem and recently made a change to the course “*Grundlagen der Entwicklung und Produktion*” (basics of development and production), by introducing a project-centered project. The project part of the class is in the form of a contest, where teams of students develop and build physical prototypes. The class and project are mandatory for all ME students. Teams assigned to different shops around the entire department of Mechanical Engineering can build their prototypes. The problem, however, is that for liability reasons the students themselves can not operate the machines. Instead of working on the parts by themselves, they receive their finished parts from the shops in exchange for drawings and CAD files. This lowers the potential results the teams can achieve, because the parts are often not on high priority for the busy shops and take a long time to produce. Students also miss out on learning about design and manufacturing in the process. The supervisors of the class were interviewed and are aware of the problem, but due to the size of the class of around 1,000 students and limited capacity of machines in the shops, there currently does not exist a better option. An optimal solution was described by the teaching staff of the class in interviews as a makerspace to which the students would have access in order to build their prototypes hands-on.

After their two-year basic studies, the closest that mechanical students come to this kind of hand-on project work is in seminars, which are called "Hochschulpraktikum", where groups of around 10-20 students are doing project-centered lab work. There is a list of currently 121 available seminars on a large variety of technical topics, many of which could benefit from access to a more open lab environment in the form of a makerspace (TUM MASCHINENWESEN WEBSITE 2014) .

For research projects and theses there is another area, where students may build physical prototypes. During their typical five-year studies for a combined Bachelors and Masters, ME students at *TUM* are writing a total of three theses – the bachelor-, semester- and master thesis. A majority of topics has a design component, where students need to build and test physical prototypes. Currently these parts are usually built by the professional staff in the shops of the departments, as students are not allowed to operate the machines. Again, the disadvantage prevails that students have to wait for the finished parts, which in some cases may take weeks and that they miss out on the benefits of hands-on learning. A shop staff member of the automotive *FTM Chair* shop at *TUM* stated in an interview that over 75% of all parts could easily be built by the students themselves, but policy does not allow them to. Giving students access to a makerspace, where they may build parts for their research, would allow students to learn more about the design process, work more efficiently on their research and possibly allow them to work on projects, which simply were not feasible due to the restrictions of the current infrastructure. Additionally, it would allow the university shops to focus on their primary task, which is building parts for the department or chair.

- *Outside of the curriculum*

Students outside of the curriculum usually participate in the form of personal projects, student contests or student clubs. Currently, there does not exist a makerspace at the *TUM*, where all students are officially allowed to build things outside the curriculum. Interviews with students have shown, that in some cases the shops make an exception, but this is not the norm. Student contests, such as the water recycling contest of the thermodynamics chair[21], are asking students to build physical prototypes and compete with each other. A makerspace would give new possibilities for participation to students and could increase the potential for more advanced contests in the future.

At *TUM* student life outside the curriculum for a large number of ME students revolves around student clubs. Some examples for student clubs at *TUM* are *TUfast*[22], who are building light weight race cars to compete in races with other universities, *TUM Phoenix Robotics*[23], who work on different robotic themes like autonomous vehicles, *AkaModell*[24], who are building

[21] For more information about the sea water contest, see www.mehrwasser.de
[22] For more information about TUfast, see www.tufast.de
[23] For more information about TUM Phoenix Robotics, see www.phoenix.stud.tum.de
[24] For more information about AkaModell, see www.akamodell.vo.tum.de

model airplanes. These clubs are well financed and receive funding from the university and industrial partners. *TUfast* is using the space in the shop of *UnternehmerTUM,* and *TUM Phoenix Robotics* and *AkaModell* are allowed into the shops of the departments for control systems engineering and aerospace respectively. In an interview MATTHIAS HOELZLE, former leader of *TUM Phoenix Robotics* club, has described that what they, as a student club, lack most is access to a space and machines to quickly build parts. They mainly need rapid prototyping tools and manual mills or lathes to build their parts, and while they have their own 3D-printer, they are not allowed access to the other machines and need to make a request from the professional staff of the shop every time they need a new part. The student association for mechanical engineers, called *Fachschaft Maschinenbau*[25], have recognized these problems as well and commented in an interview that there have even been plans of building a makerspace just for student clubs. The main problem, however, was not the funding, which would be sufficient to finance such a project, but the planning and execution.

5.2.2 Teaching staff

The university departments[26] have the tasks of education and research in the university. At the ME department of *TUM*, each chair generally has its own shop, as was introduced in *chapter 5.1.2*. The focus of the shops is building and testing parts and prototypes related to research. Interviews with professors, PhDs and shop staff at different ME departments have shown that there is a skepticism towards creating makerspaces. Part of the reasons is that the chairs fear to lose funding and power of their individual shops. However, a makerspace is not meant to replace a professionally run shop with high-end equipment. The machines in makerspaces are focused on lower-resolution prototyping and can not match the precision of the equipment in other university shops. In certain cases a makerspace may actually enhance the spectrum for existing shops. One of the points shop workers at *TUM* mentioned was the need of a paint shop, which is present in some of the analyzed examples like the *PRL* and *Techshop*. Having a makerspace available would also give benefits to the BA/MA students, PhDs and professors with research projects and theses when they need to build a part quickly. The shops stated, that they are often asked by researchers if they were allowed to use the machines. Due to official policy, however, they can not grant them access to the machines.

5.2.3 High school students

High school students become potential new university students after they graduate. As such, it is important to both show them the possibilities that a university education can offer and help prepare them for the university. In 2010, over 1,300 new students registered for the major of mechanical engineering at *TUM*, with a total of around 5,200 students in ME (TUM WEBSITE 2014). The Federal Ministry of Education and Research in Germany states that although numbers of students in MINT (German equivalent to STEM) courses have increased,

[25] For more information about the student association for mechanical engineering students at TUM, see www.fsmb.de
[26] A complete list of the chairs at the TUM departments can be found at www.mw.tum.de

there are still not enough professionals in the fields of science and technology (FEDERAL MINISTRY OF EDUCATION AND RESEARCH IN WEBSITE 2014). The amount of women in technical subjects is still low with 11% women in ME, as compared to 33% women in total at *TUM* in 2010 (TUM GLEICHSTELLUNGSPLAN 2011). A number of initiatives is trying to get more girls interested in studying *MINT* subjects, such as the federal program *Girls Day*[27], which is offering field trips for school girls to technical companies and institutions in order to introduce them to the fields of science and technology. A makerspace in the university with an outreach to high school students could be integrated in existing programs and have the positive affect of attracting more students to pursue a career in MINT subjects.

5.2.4 Alumni

The *TUM* alumni network currently comprises of over 45,000 alumni (TUM ALUMNI WEBSITE 2014). Theses graduates are spread internationally and have the potential to form a powerful and influential network. Examples from *Stanford University* and *MIT* show, that many alumni would like to keep in touch with their universities and are glad to appear as guest speakers, mentors or support the university in other monetary on non-monetary ways. One of the existing ways that alumni can support *TUM* after graduating, is by taking on a mentorship of a university student for a year in the *TUM Mentoring* program[28].

Allowing alumni access to a makerspace may also have positive networking effects and increase the university's role as an institution for life-long learning. Both, the alumni and the current students, can benefit from such an exchange. A strong alumni network is a powerful addition for the university. *Stanford* is reaching out to its alumni using the *PRL* as a platform to reconnect, where alumni can come in as guest speakers and support the space and university. Other makerspaces, such as the *Hobby Shop* at *MIT*, allow alumni to use the space and at the *Prototypenwerkstatt* of *TU Berlin* alumni who want to found their own business are specifically one of the targeted user groups. By creating an open space, where alumni are welcome, the network and exchange between the university, its alumni and current students is strengthened with positive networking and learning effects for everyone involved.

5.2.5 Entrepreneurs and start-ups

Traditionally, Munich is a city of high-tech startups, which need above average funding and support due to their technical complexity (HAHN 2014). The cooperation with universities in the region are an important factor for theses start-ups. *TUM* has recognized the importance of entrepreneurship and adopted the mission statement of "entrepreneurial university" together with a reform process, which improves infrastructure and education in the entrepreneurial sector[29]. Since 1998, the university has carried out a plan, called *TUMentrepreneurship*, to develop and support technological spin-offs from the university. Part of it were the creation

[27] For more information about Girls Day, see www.girls-day.de
[28] For more information about the TUM Mentoring program, see www.mentoring.tum.de/tum-mentoring
[29] For more information about the reform process of TUM to the "entrepreneurial university", see www.portal.mytum.de/tum/unternehmerische_universitaet/index_html

of the *TUMTech GmbH*, which helps with technology transfer from the university to the industry, and of the *UnternehmerTUM*, which educates students to think and act entrepreneurial. Among other activities the *UnternehmerTUM* is encouraging entrepreneurship in students through motivational lectures with guest speakers, such as innovative entrepreneurs, seminars, such as the business plan seminar, and an extracurricular entrepreneurship program called *Manage&More*, where selected students are educated hands-on about entrepreneurship by working on innovative industry and start-up projects.

Especially technological startups need support and can not afford to buy expensive machinery to develop a product and develop their first prototypes. This is where the *TU Berlin* is positioning itself, by empowering founders in their early phase to have access to machines and tools for building their first prototypes. A makerspace at *TUM* could support students and alumni, who lack funding, but need access to manufacturing equipment. Currently, the *UnternehmerTUM* shop, which was introduced in *chapter 5.1.3*, is filling this role, but there still exists potential for improvement. A makerspace and its members should create a community, which serves as a creative breeding ground for ideas. The positive outcomes of the community for entrepreneurs are in terms of team creation and networking effects, which are an essential part in early-phase entrepreneurship (BOH et al. 2012).

5.2.6 Industry partners

The main research partners of *TUM* are large technical companies, such as *Siemens*, *General Electric*, *BMW* and *Audi*, and research institutes, such as *Max Planck Institute*, the *Fraunhofer Society* and the *Helmholtz Zentrum* (TUM WEBSITE 2014). Industrial partners of universities generally have two major interests for cooperating with university – *image crafting* and *technology scouting* (CLIVE et al. 2005). *Image crafting* refers to the attraction of potential future employees. The industry also has an interest that the graduates are suitable for their expectations. A 2011 survey from the *Association of German Chambers of Commerce and Industry* (DIHK) about the expectations of the industry towards university graduates, came to the conclusion that graduates often lack practical experience and *soft skills*. In order to improve these abilities, the study suggests the implementation of more project-centered work into the curriculum, from early on in the studies as a possible solution. Makerspaces can be integrated into the curriculum in the form of hands-on projects, as in the examples of the *PRL*, *Innovation* Lab and *Techshop*, which were introduced in *chapter 4*. In terms of *technology scouting*, the companies develop technologies, which are not yet market ready together with university departments and chairs. This type of research is usually done in more enclosed laboratories and workshops, but makerspaces may begin to play a larger role in areas of open innovation in the future.

5.3 Improvement potentials

Makerspaces empower students to build physical prototypes parts within the university in a hands-on manner. Providing a makerspace would have an impact on academic and non-academic student life and create opportunities, which affect the other stakeholders, such as alumni and entrepreneurs as well. The analysis of the infrastructure and stakeholders at *TUM* demonstrates, that the majority of students currently lack the possibility to access manufacturing equipment with some exceptions, such as architecture students. Hands-on activities and projects are currently rare in the engineering education of ME. The main improvement potentials for *TUM* are identified as:

1. Attracting more high school students and preparing them for *MINT* programs
2. Enhancing engineering education and increasing student motivation through hands-on learning in project-based classes
3. Creating a more interdisciplinary community in the university, which serves as an incubator for innovation
4. Enriching student life outside the curriculum, by supporting student clubs and personal projects
5. Supporting entrepreneurial students and university spin-offs, who need to build physical prototypes

6 Concepts for TUM

Based on the analysis of existing makerspaces in *chapter 4* and the baseline evaluation of *TUM* in *chapter 5*, concepts to implement a makerspace successfully at *TUM* are introduced in this chapter. The idea is to give an overview of some of the possibilities for *TUM*.

First, the process of *synthesis* (6.1) of the previous results in order to develop the concepts for *TUM* is explained. The concepts suggest to implement a makerspace at *TUM* to solve problems of existing stakeholders. Each of the concepts is targeting different stakeholder groups or subsets of the university community. The *potential implementation concepts* (6.2) are then introduced together with their benefits and challenges. Finally, important factors for an actual *implementation* (6.3) at *TUM* are discussed.

6.1 Synthesis

The analysis in *chapter 5* has shown, that the opportunity for students to work hands-on to build physical prototypes at *TUM* are currently limited. In order to develop concepts, how to introduce a makerspace to *TUM*, it is helpful to define subsets of the university community and their needs, as has been done with the stakeholder groups. The main stakeholder group relevant for makerspaces are the students themselves, especially students in the departments of mechanical engineering. Hence, when looking at the infrastructure of *TUM*, a primary focus should be placed on implementing a makerspace at the technical campus in *Garching*. In order to develop ideas for potential implementation concepts, the *lessons learned* from existing makerspaces in *chapter 4.4* are applied to the *improvement potentials* for *TUM*, identified in *chapter 5.3*. While the improvement potentials are showing which areas and stakeholders at *TUM* need improvement, the lessons learned from existing makerspaces make for great examples how to implement concepts, which target these groups. The outcome is a list of 8 potential implementation concepts, which are demonstrated in *Figure 30*.

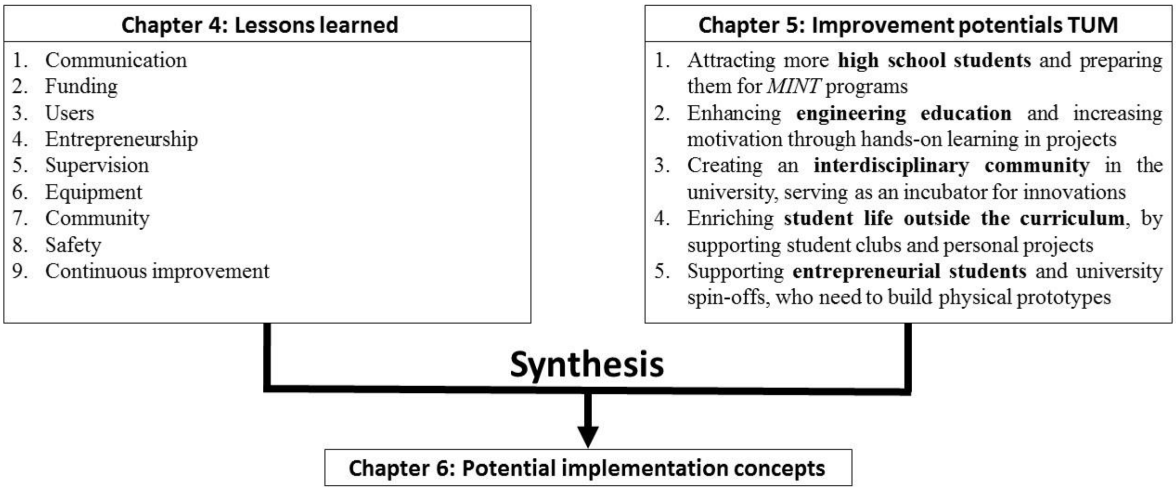

Figure 30 Synthesis of the lessons learned (chapter 4) and improvement potentials (chapter 5) to form potential implementation concepts for TUM

There developed concepts represent ideas, which could potentially be implemented at *TUM*. These concepts will be introduced in detail in *chapter 6.2* and include:

1. Space for project-centered classes in the *MINT*-curricula
2. Project-centered Master in Product Development
3. Student Club makerspace
4. Prototyping space for entrepreneurial students and spin-offs
5. Libraries as rapid prototyping hubs
6. Pre-university course for high school graduates
7. *MINT* programs for high school students in university makerspaces
8. Platform to reconnect with alumni

Each of the concepts targets one or multiple different stakeholder groups. Most concepts, with the exception of the pre-university course for high school graduates, target university students. The relationship between the concepts and the stakeholder groups is illustrated in a dependency matrix in *Table 4*. The crosses illustrate which stakeholders are affected by the different concepts.

Concept number:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
University students	**X**	**X**	**X**	**X**	**X**		**X**	**X**
Teaching staff	**X**	**X**				**X**		
High school students						**X**	**X**	
Alumni								**X**
Entrepreneurs and start-ups				**X**				
Industry partners	**X**							

Table 4 Dependency matrix between potential implementation concepts and the stakeholders affected

6.2 Potential implementation concepts

In this chapter the implementation concepts for makerspaces at *TUM* are introduced. The concepts are catered to the individual needs of the existing stakeholders at *TUM*, which were analyzed in *chapter 5.2*.

The following aspects are described or each concept:

- **Problem** – Which current problem do *TUM* and its stakeholders face?
- **Target group** – Who is affected by the concept?
- **Concept** – What does a possible implementation look like?
- **Benefits** – What are the benefits for the university and its stakeholders?
- **Challenges** – What are some of the challenges for implementing this concept?

6.2.1 Space for project-centered classes in the MINT-curricula

Problem
- Lack of hands-on application in *MINT* education
- High dropout rates in engineering programs
- Graduates in Germany lack practical experience and soft skills

Target group
- University students in *MINT* (BA/MA)
- *MINT* departments
- (*optional*): Industry partners

Concept
A large makerspace inside of a *MINT* department could allow the teaching staff to develop project-centered classes for students, in which student teams work on an open ended problem set. This could be in the form of a new class or as part of of an existing class. The project-centered nature of the class lets students gather practical experience and allows them to develop their soft skills in team activities. The final outcomes will be the documentation, presentation and prototypes built by the student teams. Such a class would be most appropriate in the engineering curriculum, but other departments or an interdisciplinary project are imaginable as well. Industrial partners may get involved in order to offer students to work on real-life problems, to receive mentoring from an industry expert and to finance prototyping costs and activities. The industrial partners benefit from the cooperation through *image crafting* and *technology scouting* (see *chapter 5.2.6*).

Examples: ME310 - Stanford University, Capstone Design course – Georgia Tech

Benefits
- Improved education through hands-on activites
- Dimished dropout rates through increased motivation
- Develop practical experience and soft skills

Challenges
- Finding professors and departments as champions to build an educational makerspace
- Managing the large number of students in *MINT* subjects with space and staff
- Changing the traditional teaching style

6.2.2 Project-centered Masters program for product development

Problem
- Many students are interested in product development and design, but there is currently little hands-on application in engineering eduaction
- The industry criticizes a lack of practical experience in *MINT* students

Target group
- ME university students (MA)
- ME Chair for product development

Concept
The idea of developing a project-centered Masters program in product development was mentioned in an interview with professor Lindemann. There exists a demand from the part of the industry to prepare engineers to be innovators of new physical hardware and products. One way to prepare students for product development is a project-centered curriculum, where students build multiple prototypes for products over their two-year Masters program. Students get to know the product life-cycle process, and experience the

different phases of product development from concept development to building a final prototype, applying the tools of project management in the process. As a small program, it would target those students, who want to learn hands-on and build innovative products. While there already exists a similar Industrial Design Masters program in architecture, this focusses more on the design and less on the manufacturing process.

Examples: Product Design Program – Stanford University, Capstone Design course – Georgia Tech

Benefits

- Students gather practical experience
- Parallel teaching on design and manufacturing
- Incubator for development of innovative products and entrepreneurship in engineering

Challenges

- Finding a professor and chair as champion
- Convincing university administration
- Developing a completely new curriculum

6.2.3 Student Club makerspace

Problem

- Student clubs need to build multiple prototypes each year
- They lack access to necessary space and equipment
- Support from university shops is limited and time-consuming

Target group

- Student clubs (e.g. *TUfast*, *TUM Phoenix Robotics*, *Akamodel*)

Concept

Giving student clubs access to a makerspace allows them to work and build their own physical prototypes. They can thereby work faster, build better prototypes and increase the learning of student members through more hands-on experience. There would currently exist sufficient funds among the clubs to create a student club makerspace in the department of mechanical engineering. The makerspace does not have to be limited to student clubs. Bringing students of different student clubs and people working on personal projects together, who share the interest of building, would create a strong community with synergy and networking effects. An important part is to transfer responsibility to the students and let them manage the space with the university in a supporting role.

Example: Maker Club – Georgia Tech

Benefits

- Empowering and supporting existing student clubs
- Allowing the foundation of new student clubs
- Freeing capacity for departments and university shops

Challenges

- Acquiring free space, which student clubs can transform into a makerspace
- Establishing equality and fairness amongst different clubs in the space
- Space design according to existing needs

6.2.4 Prototyping space for entrepreneurial students and spin-offs

Problem
- Technical startups need access to tools to prototype ideas
- Entrepreneurial students with early-phase start-ups usually have little or no funding
- Access to university shops only, if linked to the department

Target group
- Entrepreneurs and start-ups
- University students
- *UnternehmerTUM*

Concept
The growing number of entrepreneurial students at *TUM*, the entrepreneurial university, are trying to realize their business ideas. A dedicated makerspace for entrepreneurship would empower students and create a powerful network, which helps with important aspects such as team creation. Many students at *TUM* are working on technical ideas and need access to a makerspcae to develop their physical prototypes. University spin-offs are in a similar situation and while they often receive funding, such as the *EXIST* scholarship, a makerspace would significantly increase their potential and reduce time-to-market. The *UnternehmerTUM*, which is the center for entrepreneurship at *TUM* would be a perfect partner to realize such a concept.

Example: Prototypenwerkstatt – TU Berlin

Benefits
- Supporting and empowering entrepreneurial students and early-phase university spin-offs
- Strengthening entrepreneurial network at *TUM*

Challenges
- Build strong partnerships, for example with the *UnternehmerTUM*
- Establish awareness in community

6.2.5 Libraries as rapid prototyping hubs

Problem
- Traditional role of libraries in the New Media Age is decreasing
- Students are interested in using rapid prototyping
- Access to equipment in the university is limited with a few exceptions (e.g. architecture)

Target group
- University libraries
- University students

Concept
University libraries are a suitable place to establish small makerspaces for rapid prototyping. Makerspaces as facilitators of knowledge and builders of community fit well into the context of libraries. University libraries usually already have the necessary basic infrastructre and are well equiped in terms of space and computer pools. The only thing missing is the rapid prototyping equipment, such as 3D-printers and laser cutters, which could be placed in a small separate room with exhaust fans. As FISHER (2012) states: "*By bringing makerspaces into libraries, we can adapt to changing student needs and supporting knowledge creation in addition to knowledge consumption.*"

Example: Westport Library – Westport (www.westportlibrary.org/services/maker-space)

Benefits
- Facilitation of knowledge and community at libraries
- Bringing more students in contact with rapid prototyping technologies

Challenges
- Acquisition and installing of proper equipment, adjustment of infrastructure
- Educating staff about the new technologies and offering support to students

6.2.6 Pre-university course for high school graduates

Problem
- High dropout rates in engineering programs
- Practical application late in engineering studies

Target group
- Teaching staff
- High school students

Concept

The idea is to offer a pre-university crash-course about design and manufacturing to high school graduates, who begin studying *MINT* subjects, such as mechanical engineering. Students can gather practical experience hands-on as preparation for their university studies and learn hands-on. A makerspace is a perfect setting to introduce such a course, which would ideally take between one to three weeks. There already exist a two-week introductory mathematics courses for engineering students. However, the first real practical projects, apart from external internships, come much later in the studies. The product design course *ME 210* at *Stanford University* shows, that within two weeks students can be introduced to manufacturing techniques, such as welding, milling, turning and rapid prototyping. Size and relevant departments should be chosen carefully. Due to the large numbers of over 1,000 ME students per year, the course could either be made optional with limited participants or spread out into different groups throughout the first two semesters.

Examples: Introductory mathematics course – TUM, ME 210 – Stanford University

Benefits
- Increasing motivation of new university students
- Better preparation of high school students for engineering programm
- Teaching practical prototyping skills from the very beginning of university studies

Challenges
- Course is resource- and time consuming
- The number of new students is too high to teach everyone simultaneously
- Liability issues

6.2.7 MINT programs for high school students in university makerspaces

Problem
- Not enough students in *MINT* programs
- An exceptionally low percentage of girls chose to study *MINT* subjects
- University facilities are often empty during semester break

Target group
- High school students
- University students

Concept

A *MINT* program for high school students in university makerspaces is designed to introduce high school students to building activities in the form of hands-on projects early on. This will both interest more students to study *MINT* subjects and help prepare them for the university. During the semester break, the university is mostly empty and many locations can be used to invite students and to evoke an interest in *MINT* programs at the university. At the same time, high school students are on summer vacation and could visit a makerspace as part of a program to learn about manufacturing and work on projects. Additionally, the program could be supported by motivated university students, who help creating interest for *MINT* topics and help to teach prototyping skills. Possible implementations are in the form of afterschool programs, summer camps or special events.

Examples: Makers Summer Camp – Georgia Tech, Girls Day – Ministry of Education and Research

Benefits

- Facilitation of knowledge and community at libraries
- Bringing more students in contact with rapid prototyping technologies

Challenges

- Acquisition and installing of proper equipment
- Educating staff about the new technologies and offering support to students

6.2.8 Makerspaces as a platform to reconnect with alumni

Problem

- Alumni are an often underused resource of universities
- Life-long learning becomes more important
- Many alumni want to stay in touch with their alma mater

Target group

- University alumni
- University students

Concept

Makerspaces in the university, which are open to alumni, allow them to use the facilities and work on projects or entrepreneurial ideas. By giving them access to such a platform, alumni can additionally share their experience in talks to current students and stay updated about ongoing research. This strengthens the network between alumni, university staff and current students. Further, it offers new possibilities for colaboration, such as the improvement of the mentoring program, which already exist at *TUM*. In recent years the trend of life-long learning has increased and universities, including the *TUM*, have recognized the importance staying in touch with their alumni. There are many options to reactivate alumni, for instance in the form of workshops or projects, where they can get involved.

Examples: Hobby Shop – MIT, Prototypenwerkstatt – TU Berlin

Benefits

- Closer connection of university to its alumni
- University as institute for life-long learning
- Strengthening of exchange between students and alumni

Challenges

- Maintaining good contact with alumni
- Create open space, which welcomes alumni and satisfies existing needs

6.3 Implementation

In order to implement a makerspace, there needs to be a champion inside the university, who implements the space and helps acquire the necessary requirements. Champions have a certain vision for the role and impact of the space, and as such usually define the stakeholders and focus of the makerspace. Champions are *opinion leaders* at the university and can thereby convince the necessary *decision makers* to provide the requirements for the makerspace. These champions are often chair professors, as in the example FOREST NELSON *Georgia Tech* and DAVID BEACH at *Stanford University*, or part of the university administration, such as the president at *MIT* or the dean and vice provost MITZI MONTOYA at *ASU*.
In the case of *TUM*, possible champions are the chair professors, especially Professor UDO LINDEMANN at the chair of Product Development, the *UnternehmerTUM* with CEO HELMUT SCHÖNENBERGER and the university administration. Several different kinds of implementations are possible, such as the ones introduced in *chapter 6.2*. The requirements depend on the stakeholders, focus and the model of implementation.

Additionally to the champion, a space and infrastructure is necessary. There are multiple possibilities to create and improve makerspaces at TUM. One opportunity is to develop concepts, which connect the large *Techshop* makerspace, which is currently being built in Garching (see *chapter 5.1.3*), closer to the university. Other possibilities are the creation of new spaces. The *TZ* of the engineering students (see *chapter 5.1.3*) is a great example how university workshops can be transformed into makerspaces and give access to a large number of students.

Regardless of how a makerspace is implemented, the champion needs to allocate and provide the requirements introduced in *chapter 2.2.3*, which include:

1. *Funding*
2. *Location*
3. *Tools and machines*
4. *Staff for maintenance, classes and supervision*
5. *Safety and liability precautions*

A makerspace does not have to be a perfect solution affecting every student right from the beginning. The examples analyzed in *chapter 4* show that makerspaces often grow from a small group or subset of the stakeholder group. A perfect example is the case of the *Invention Studio* at *Georgia Tech*, where the champion FOREST NELSON started the makerspace as a small pilot project with only 10 students. The group was so successful that the makerspace was able to grow over the past four years and is continuing to do so. According to FOREST NELSON, an implementation of the current size and impact would have been nearly impossible, as the voices of criticism towards the positive affect of a makerspace and possible dangers are initially strong. Success helps to spark further growth. Strong partners help to finance and support the makerspace – in the case of *Georgia Tech* those are the industry partners from the *Capstone Design* course and the student club initiative *Maker Club*. Likewise, strong partners are necessary to build a strong makerspace at TUM, such as the *UnternehmerTUM*.

The ME department at TUM is dealing with a capacity problem, as there are over 5,000 mechanical engineering students. CRAIG MILROY, the co-director of the *PRL* at *Stanford University*, suggests that this mass problem can be conquered by choosing just a small subset of the students, who are really eager to work in such a space. This would create a pull effect, where the students attracted to space will be intrinsically motivated to work on great projects, which can turn into lighthouse projects.

KELLY SCHMUTTE helps manage the "*@Stanford*" project[30], which developing and testing ideas of how the role and shape of the campus will change until 2020. The outcomes of this projects are important lessons, which are relevant to implementations of makerspaces at *TUM* and in general. In an interview KELLY SCHMUTTE stated that the most important factors to introduce change to the structure of a university, such as introducing a makerspace, are in her experience:

- *Take action* – In order to change things, something has to be done, which goes further than talking and sometimes it is necessary to take some steps, which initially are "under the radar" and seem "unofficial"
- *Take small steps* – It is best to show people real demonstrations of ideas, which can be implemented in small experiments, in order to convince them of the advantage of change
- *Pull-effect* – Show empathy for people in their workplace and the problems they have – changes should go in accordance to the problems of the actual people in the university environment

[30] For more information about the @Stanford program, see www.stanford2025.com/about

7 Discussion

In this chapter the significance and limitations of the results presented in this thesis are discussed. The objective of the thesis is to demonstrate an understanding of how makerspaces function, the potential they have at universities and further investigate how they can be implemented in the university community. In order to do so, a broad scope of investigation is necessary. This means involving multiple areas, such as the nature of prototyping, insights about engineering education and the organization of universities, makerspaces and their stakeholders. In the following section, the different aspects of the thesis are discussed:

- *Selection of makerspaces and interview partners*

The potential results, which was obtained from the qualitative research in this thesis, depend first of all on the *selection of makerspaces and interview partners*. The selected makerspaces should be best-practice examples, which represent working models worth studying, and the interview partners need to be experts in their fields, who are willing to share their experiences. After the pre-selection, five makerspaces in universities in the USA and Germany with different parameters were chosen for the research in this thesis. The goal is to identify similarities and differences and to develop an understanding how the makerspaces can be integrated. The interview partners are the directors of the makerspaces and other staff or users of the spaces, which have experience with managing a makerspace. It is important to note, that there also exist other examples of makerspaces and stakeholders, which might represent different models and views. In further research, other examples of makerspaces and interview partners should be chosen, to verify if they correspond with the results of this thesis.

- *Qualitative research methods*

In order to conduct research according to the objective, the primary data collection method in this thesis is to perform qualitative interviews with the directors of makerspaces, university staff and other experts in the field of prototyping, engineering education and hands-on learning. The method of qualitative interviews allows to quickly gather data in quantity (MARSHALL 2011) and that participants articulate their experiences, which can not otherwise be reached (NOHL 2009). The nature of qualitative research is that the results are subjective and based on context, as the data are linked to the experience and insights of individuals. Hence, the results can not be replicated and represent a moment in time. They convey insight into the current state of the selected makerspaces and the infrastructure at *TUM*. This applies to the results from the “analysis of existing makerspaces” in *chapter 4* and the “baseline evaluation at *TUM”* in *chapter 5*, which were obtained using mainly qualitative research methods. Therefore, it is important to note, that the results are subjective and should be treated as such. Especially for specific numbers, a further investigation would be necessary to validate the results obtained in this thesis.

- *Users of makerspaces*

For feasibility reasons, the focus of the thesis was on the staff side of the makerspaces and less on the user side. While the important stakeholder groups were identified and in some cases interviewed, there is much more which can be learned about the user needs and habits. Therefore, future research should further investigate the user side of makerspaces. Possible topics of investigation are the motivation for using a makerspace, the projects they work on, the amount of time spent in the makerspace and the effects of hands-on learning.

- *Comparability of makerspaces*

The selected universities and makerspaces, including *TUM*, are different regarding size, focus, funding, location and culture. Different spaces were chosen on purpose, in order to show a broad spectrum of makerspaces in universities, but it also complicates the comparability of makerspaces. Especially large makerspaces, such as the *PRL* and *Techshop*, function different from small spaces, such as the *Prototypenwerkstatt*. Another major point of discussion is the difference between German and US universities, which affects the organization, educational models and culture. It also limits the significance of the examples from makerspaces in the USA towards creating makerspaces in Germany. This problem was attempted to be solved, by applying the interim findings of this thesis to the specific infrastructure of *TUM*. However, future research should analyze the differences further, also including cultural differences between the universities in USA and Germany.

- *Legislation*

Laws regarding the safety of students and other stakeholders in the university, are an important aspect when planning to implement makerspaces in the university. The legislation regarding liability is different in the USA and Germany. While the topic was introduced in the context of the existing makerspaces, a thorough investigation of the legal consequences of accidents by students in university makerspaces is not part of the scope of this thesis. However, it is an important aspect, which needs to be further investigated for implementing makerspaces in universities. This is especially true for Germany, where there are few existing examples of makerspaces in universities up to today.

- *Benefits of makerspaces in universities*

Basis for the proposition, that makerspaces have a positive impart, are the examples of the investigated university makerspaces and the statements of their directors and other stakeholders. However, since they represent opinions of stakeholders associated with makerspaces, they might be biased. Hence, further research to investigate the effects of makerspaces is necessary to validate the propositions in this thesis. It is important to note that implementing makerspaces and more hands-on and project-centered classes result in less theoretical lectures, given that the curriculum is not expanded. Therefore, makerspaces are also a trade-off between the teaching of theory and practical application. The effects on what students learn in makerspaces and how makerspaces may synergize with their more theoretical classes should be further investigated.

- *Synthesis and potential implementation concepts*

The potential implementation concepts in *chapter 6* demonstrate different possibilities to implement makerspaces for the specific case of *TUM*. They represent first drafts of ideas, to show what is possible and need a more careful planning in the future. If *opinion leaders* and a champion decide to implement a makerspace, more precise planning is necessary for the actual implementation of concepts. This includes a more thorough analysis of stakeholders, decision makers, funding and the university rules and regulations.

8 Conclusion and outlook

Makerspaces motivate and empower members of the university community to build prototypes by themselves and have the potential to transform university education. This thesis has investigated the effect of makerspaces on the university community and the practical relevance it has for engineering education. In this final chapter, the results and their consequences will be summarized as *conclusion* (8.1). Research results of this thesis include *lessons learned* from existing makerspaces, *improvement potentials* for the specific case of *TUM*, and *potential implementation concepts* of makerspaces.
The implications of these outcomes and the potential for future research are outlined in the *outlook* (8.2). This includes predictions about the future development of makerspaces at *TUM* and other universities in Germany, the USA and internationally.

8.1 Conclusion

The implementation of makerspaces in universities is a growing trend, both in the USA and internationally. Makerspaces promote interdisciplinary work, help to form communities and enhance education, especially when integrated in the students' curriculum. Students are empowered to apply their knowledge hands-on, which they previously couldn't, and work under real-life conditions inside the university. Makerspaces can also be seen as a motor for innovation by giving students access to a workspace, where they can realize their ideas and build physical prototypes hands-on. This concept of makerspaces in the university was explored throughout this thesis. A makerspaces was defined as a "physical location with a community, where members build physical prototypes and objects by using manufacturing tools and machines in a hands-on manner."

The underlying concept for the success of makerspaces results from the positive effects of *physical prototyping*. Prototyping is an important tool in product development and improves communication and learning through its hands-on nature. The motivation and effectiveness of learning increases through the involvement of multiple senses and the application of knowledge. Hence, prototyping is useful in education as well, especially in the field of engineering. In the context of the university, the main user group of makerspaces are the students, who can use makerspaces as part of their classes or outside of the curriculum in student clubs, personal projects or to realize ideas for entrepreneurial endeavors. By working on projects in university makerspaces, students learn design and manufacturing skills in parallel and in a hands-on manner. Makerspaces also empower the teaching side and other stakeholders, by offering new possibilities to implement project-centered classes and enhancing research possibilities.

The central research goals in this thesis are:

- The development of a holistic understanding of makerspaces in universities
- The infrastructure analysis of *TUM* and need assessment of its stakeholders
- The synthesis of results to develop concepts how to implement a makerspace based on the *lessons learned* from existing spaces and *improvement potentials* at *TUM*

An understanding was developed about the different forms of implementing makerspaces and the impact they have on the university community. This was realized by selecting five existing makerspaces and analyzing them using qualitative methods (see *chapter 4*), such as interviews with experts in the fields of makerspaces, prototyping an engineering education. The comparison of these different spaces demonstrates, that makerspaces can be implemented in different ways, depending on a variety of factors and ultimately on the purpose they have within their community. Examples range from the small *Prototypenwerkstatt* at *TU Berlin* with a focus on entrepreneurship to the much larger *PRL* at *Stanford University* and *TechShop* at *ASU*, which are deeply integrated into the university curricula and are an important part of students' lives. These five makerspaces show a spectrum of what is possible, including the *Invention Studio* at *Georgia Tech*, with its unique sense of student ownership, and the *Hobby Shop* at *MIT*, which focus on private projects. The comparison of these spaces highlights similarities and differences in the areas *focus*, *size*, *accessibility/IP*, *funding* and *staffing* of the selected spaces. While larger makerspaces affect a great portion of the student population, smaller spaces appear to focus more on a specific user group, such as entrepreneurs, student clubs or hobby tinkerers. The lessons learned from the experience of the directors of the spaces were summarized and can be used to improve existing makerspaces or implement new concepts. These results indicate, that the key aspects to implement a good makerspaces is to form a great community and to encourage and support the users through classes and supervision. Having expansive equipment for high precision work is often overrated and not essential for a successful makerspace. The variety of implementation possibilities suggests, that there is no single perfect solution for implementing a makerspace in the university. The individual concepts depend first and foremost on the purpose of the makerspace within its individual community, as well as the framework conditions of the university and its stakeholders.

In the specific case of the German university *TUM*, access to makerspaces for students is currently limited to small groups, such as architecture students at the *TZ*. The infrastructure of existing spaces and the different stakeholder groups were analyzed in order to find improvement potentials for *TUM* (see *chapter 5*). Especially in the engineering departments, most existing shops do not allow students to use the machines and can therefore not be categorized as makerspaces. However, there are attempts to introduce more makerspaces, such as the *Techshop* which is currently being built in Garching. The chair of *Product Development* is also interested in implementing more physical prototyping and project-centered classes into the engineering curriculum. The improvement potentials identified for *TUM* are:

1. Attracting more high school students and preparing them for *MINT* programs
2. Enhancing engineering education and increasing student motivation through hands-on learning in project-based classes
3. Creating a more interdisciplinary community in the university, which serves as an incubator for innovation
4. Enriching student life outside the curriculum by supporting student clubs and personal projects
5. Supporting entrepreneurial students and university spin-offs, who need to build physical prototypes

Based on these previous findings, eight *potential implementation concepts* for makerspaces at *TUM* were developed (see *chapter 6*). These concept ideas are a synthesis of the previous findings and are based on the *lessons learned* and *improvement potentials*. The following concept ideas were developed and assessed for a potential implementation at *TUM*

1. Space for project-centered classes in the *MINT*-curricula
2. Project-centered Master in Product Development
3. Student Club makerspace
4. Prototyping space for entrepreneurial students and spin-offs
5. Libraries as rapid prototyping hubs
6. Pre-university course for high school graduates
7. *MINT* programs for high school students in university makerspaces
8. Platform to reconnect with alumni

The eight concepts are targeting different stakeholder groups at *TUM* and range from easily implemented solutions, such as turning libraries into rapid prototyping makerspaces, to large concepts, which aim to introduce project-centered classes in makerspaces to a large portion of the student body. These concepts build a basis, which can to be developed further in order to implement makerspaces at *TUM* and give more students the opportunity to build physical prototypes hands-on inside the university.

In conclusion, makerspaces enable the university community to realize their projects under real-life conditions and can be implemented in a variety of ways. Makerspaces help prepare students for their professional future, by teaching them soft skills and practical experience in addition to their already strong theoretical knowledge. As such, they have the potential to transform and enhance education. The number of makerspaces in universities will increase internationally, as universities are beginning to realize the potential of makerspaces.

8.2 Outlook

The outcomes of this thesis created a basis for future research in related areas. There are several aspects, which were not part of the scope of this thesis and should be investigated further. This includes:

- An investigation of a larger makerspaces with quantitative metrics, to make more accurate statements about the effects of the parameters of makerspaces. Additionally, more examples from different regions on a global scale could be taken into account.
- The benefits of makerspaces, which are currently based on the statements of the interview partners should be further investigated. This could be done by focusing more on the user side of makerspaces and research their behavior, projects and the effects of learning in makerspaces. The potential of innovation and entrepreneurship sparked by makerspaces could also be investigated evaluate the success of makerspaces.
- A comparison of cultural differences of makerspaces and their users in different types of institution and regions could be one more interesting aspect of investigation. The comparison of different countries, such as Germany and the USA, should also include a more in-depth analysis of the differences in legislation.

Related research areas include the effect of hands-on learning, prototyping and project-centered classes on engineering education.

Makerspaces increasingly enter educational institutions and in the process are transforming university education for *MINT* students, as was demonstrated throughout thesis. This is happening alongside of the *maker movement*, which is a growing trend in the USA and globally. The movement results in the creation of new makerspaces, growing communities of builders and the occurrence of maker fairs. There are several examples of makerspaces in universities, which have been opened during the last decade, such as three of the makerspaces, which were investigated in this thesis and examples from the *appendix*. Successful models of makerspaces, such as the *PRL* at *Stanford University* or the *Invention Studio* at *Georgia Tech*, receive request from other universities who want to visit and learn to build their own makerspaces. Research about this topic, such as this thesis, can support these universities to implement their individual solution of a makerspace. While the diffusion of makerspaces in the USA is growing fast, makerspaces in German universities are currently still the exception and university students generally do not have access to work in open workshops.

However, large technical universities in Germany, such as *TUM*, are recognizing the value of makerspaces and have begun to create new makerspaces. Examples include the *Technisches Zentrum* for architecture students at *TUM* (see *chapter 6*), which has existed since 2005, or the first German *FabLab* at *RWTH Aachen*, which was opened in 2009. At *TUM*, there is a makerspace being built on the Garching campus, which has an area of over 1,000 m². The space will be opened in 2015 and is operated by *Techshop*. It will be the future task of the university and students to provide access to existing or new spaces, create a community of "makers" and implement the makerspaces into the curriculum of students to improve education. The implementation concepts developed in this thesis are demonstrating what kind of ideas are possible. Based on the current development of makerspaces and the growing interest of universities, it can be assumed that interest in this topic and the number of makerspaces in German universities will increase significantly in between the next ten years.

9 Abbreviations

3D	Three dimensional
ASU	Arizona State University
BA	Bachelors
CAD	Computer aided design
CEO	Chief executive officer
CNC	Computerized numerical control
DIHK	Deutsche Industrie- und Handelskammer
e.g.	Example given
FTM	Institut für Maschinen- und Fahrzeugtechnik
IP	Intellectual property
IWB	Institut für Werkzeugmaschinen und Betriebswissenschaften
MA	Masters
ME	Mechanical engineering
MINT	Mathematik, Informatik, Naturwissenschaft, Technik (mathematics, computer science, science, technology)
MIT	Massachusetts Institute of Technology
PE	Produktentwicklung (product development)
PhD	Philosophiae Doctor
PRL	Product realization lab
STEM	Science, technology, engineering, mathematics
TA	Teaching assistant
TUM	Technical University of Munich
TZ	Technisches Zentrum (technical center)

10 Figures

11 Tables

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13 Appendix

A1 Interview List A-1
A2 Questionnaires A-3
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A2.2 Explorative Questionaires *TUM* and Stanford A-6
A3 Additional prototyping spaces in universities A-8

A1 Interview List

	Name	Position	Organization
1	Prof. Baier, Horst	Chair holder at "Lehrstuhl für Leichtbau"	*TUM*
2	Barth, Eric	Leader of the model making shop at „Lehrstuhl für Landschaftsarchitektur und industrielle Landschaft“ and contructor of the technical center (workshop) at „Fakultät für Architektur“	*TUM*
3	Barton, John	Lecturer and Director of the Architecture Program	*Stanford University*
4	Beach, David	Teaching Professor and Director of the Product Realization Laboratory (*PRL*) and Co-Director of the Stanford Alliance for Innovative Manufacturing	*Stanford University*
5	Beiker, Sven	Lecturer and Executive Director of the Center for Automotive Research at Stanford (CARS)	*Stanford University*

6	Biechl, Florian	Master mechanic at „Lehrstuhl für Fahrzeugtechnik“	*TUM*
7	Carryer, Ed	Consulting Professor and Director of the Smart Product Design Laboratory (SPDL) in the Design Division of Mechanical Engineering	*Stanford University*
8	Chan, Brian	Instructor of the *Hobby Shop*	*MIT*
9	Chen, Helen L.	Director of ePortfolio Initiatives at the Office of the Registrar and Research Scientist at the Designing Education Laboratory	*Stanford University*
10	Colet, Raffie	General Manager at *Techshop* San Jose	*Techshop*
11	Cutkosky, Mark	Professor and Director of the Biometics and Dexterous Manipulation Laboratory (BDML)	*Stanford University*
12	Darnhofer, Erwin	Master mechanic at „Lehrstuhl für Fahrzeugtechnik“	*TUM*
13	Dr. Diermeyer, Frank	Senior engineer at „Lehrstuhl für Fahrzeugtechnik“	*TUM*
14	Distel, Fabian	Research assistant at „Institut für Werkzeugmaschinen und Betriebswissenschaften“	*TUM*
15	Dreissigacker Kohn, Marlo	Lecturer and manager of the Product Realization Lab's Room 36 student workspace and project laboratory	*Stanford University*
16	Forest, Craig	Director of the Invention Studio	*Georgia Tech*
17	Glasl, Franziska	Trainer at „Zentrum für Sozialkompetenz- und Managementtrainings“	*TUM*
18	Hatch, Mark	CEO of *Techshop*	*Techshop*
19	Hoelzle, Matthias	Mechanical engineering student at *TUM* and former president of the *TUM Phoenix Robotics* student club	*TUM*
20	Jenna Rodriquez	Student and Researcher at the Designing Education Laboratory	*Stanford University*
21	Lande, Micah	Assistant Professor Department of Engineering College of Technology & Innovation Arizona State University	*ASU*
22	Leifer, Larry	Professor and Director of the Center for	*Stanford*

		Design Research (CDR)	*University*
23	Prof. Lindemann, Udo	Chair holder at “Lehrstuhl für Produktentwicklung“	*TUM*
24	Michailidou, Ioanna	Research assistant at „Lehrstuhl für Produktentwicklung“	*TUM*
25	Miller, Brogan	Stanford graduate student involved at the Fab Lab	*Stanford University*
26	Milroy, James Craig	Senior Lecturer and Manager of the Product Realization Laboratory (*PRL*)	*Stanford University*
27	Münzberger, Christopeher	PhD student at the *Product Development* chair at *TUM*	*TUM*
28	Nelson, Forest	Teaching assistant at the PRL and graduate student at Stanford University	*Stanford University*
29	Rencke, André	Student assistant and supervisor of the *Prototypenwerkstatt* at *TU Berlin*	*TU Berlin*
30	Schar, Mark	Lecturer and Researcher at the Designing Education Laboratory	*Stanford University*
31	Schönenberger, Helmut	CEO of the *UnternehmerTUM* entrepreneurship center	*UnternehmerTUM*
32	Schmutte, Kelly S.	Lecturer at the Hasso Plattner Institute of Design	*Stanford University*
33	Seelig, Tina L.	Professor of the Practice and Executive Director of the Technology Ventures Program	*Stanford University*
34	Sheppard, Sheri	Professor, Director of the Designing Education Laboratory (*DEL*) and co-director of the Center for Design Research (*CDR*)	*Stanford University*
35	Sinner, Klaus	Consultant at *UnternehmerTUM* and manager of the shop	*UnternehmerTUM*
36	Smith, Robert Emery	Director of Technology Service	*Stanford University*
37	Stone, Ken	Director of the *MIT Hobby Shop*	*MIT*
38	Wong, Andrew	Account Manager of *Techshop* San Jose	*Techshop*

A2 Questionnaires

There were two types of questionnaires used during the research. The makerspace questionnaires were used for the analysis and comparison of existing makerspaces. Interviews were led with directors and staff of the makerspaces. The explorative questionnaire for *Stanford University* and *TUM* was used to identify stakeholders, the infrastructure analysis at *TUM*, as well as the use of prototyping, in universities and its potential.

A2.1 Makerspace Questionnaires

In-depth Interviews with Makerspaces

Goals of interviews:

- Define and describe each space and their focus/category
- Make spaces comparable through quantitative data and categories
- Show the spectrum of what spaces are possible in universities and their differences
- Identify strengths/weaknesses of the different types of spaces
- Derive learnings which can be applied to *TUM*

Questions

General questions:

1. Based on the information we could gather from the internet and other sources we came up with a short summary about your space. Would you agree with the text or is there anything important missing or perhaps wrong information?
2. What was the main motivation for introducing this space to the university? Who had to be convinced and what was the biggest challenge?
3. Can you also give me a number of goals the space is trying to achieve in the university? What are the key activities, which help reach these goals?
4. Who has access to the space and what are the requirements to get access?
5. Who is staffing the space?
6. How do the users hear about the space? Outreach
7. Can you give some examples of typical projects which are done in the space?

Specific:

8. What is the size of the space in feet or meters squared and its maximum capacity for people?
9. How many users in total are using the space per semester/quarter?
10. Which user groups come to space and could you make a guess on the ratio?
11. What are the policies on safety and classes?
12. Who is funding the space and what is the cost for the users?

13. What is the policy on IP of things created in the lab?

Culture:

14. What is the culture among the people in the space? What are the important factors that help install this culture?
15. Are the special events held at the place?
16. How does it differ from other shops and spaces at this university? Are there collaborations with other similar spaces?
17. How do you measure success? What metrics do you use and how often? Is there a documentation/numbers we could see?
18. What makes this space special and what is its strength?
19. If you had a wish for improvement of the space, what would it be?
20. What are the main lessons that can be learned from this space and applied to other similar spaces?
21. Ranking the importance of factors: space, machines, supervisors?

A2.2 Explorative Questionnaires *TUM* and Stanford

Questionnaire Stanford University

Goals:

- Definition of Prototype
- Role, function, methods and examples of physical prototyping in industry and at university (research and education)
- Goal, Content/Structure, Facts (time, number of students), teaching methods (theory, practical application, intent) of classes
- Needs for courses (facilities, TAs, coaching …)
- Facilities for practical application in Stanford
- Pros/Cons of the current educational system / lessons learned and experiences
- Wishes for the future
- Differences between Stanford and other universities in the US
- Find out the role of Techshop
- Further contacts to programs/facilities and literature

Questions:

Introduction:

- Few sentences: Who are you? What is your background?
- What is your current position and task at Stanford? (Education/Courses? Research?)

Basic understanding of prototyping:

- Can you give us a short personal definition of a prototype?
- Which role does prototyping in general and physical prototyping play in your field - both in industry and university?

Education and university:

- Can you give us a short summary of the goals, content and teaching methods of your classes?
- Which resources do you need for your classes (human, facilities)? Who is in charge of the facilities and who has access to them?
- What is the role of the d.school (Hasso-Plattner Design School) and PRL (Product Realization Lab) in engineering education at Stanford?
- What are the advantages of the teaching methods and infrastructure at Stanford? Do you see any disadvantages?
- If you had a wish for improving education and infrastructure at Stanford, what would it be?
- Is it possible to observe your facilities?

Others:

- Where do you see the main difference between Stanford and other universities?
- Is there any connection between Stanford and Techshop?
- Do you have further contacts or literature for us?
- What is your mission?

Questionnaire TUM

Goals:

- Raising awareness of our work and create possible collaboration
- Definition of Prototype
- Role, function, methods and examples of physical prototyping in industry and at university (research and education)
- Goal, Content/Structure, Facts (time, # students), teaching methods (theory, practical application, intent) of classes
- Needs for courses (facilities, TAs, coaching …)
- Detailed information about conditions (accessibility) and equipment of the used facilities
- Pros/Cons of the current educational system / lessons learned and experiences
- Find out if and how Techshop can fit into the current concept
- Further contacts to programs/facilities and literature

Questions:

Basic understanding of prototyping:

- What are physical prototypes in your field and how are they used in your program/workshop?

Education and university:

- How is physical prototyping used in education for students?
- What are the facilities/shops used for prototyping in your program?
- What equipment is available?
- Who is in charge of the facilities?
- Which groups are using them (students, staff, firms, founders)?
- What are the conditions for students (accessibility)?
- Who is running and financing them and what is the connection to the department?
- Are students working in teams/on projects?
- How do you grade your students?
- How is the relation between theory and practical application in your program?
- What is good/bad about the current system?

Improvement possibilities for the department:

- How could the program be improved (e.g. by Techshop)?
- Which requirements had to be fulfilled, that you use the prototyping center in your program?

Next steps:

- Are you interested in the outcome of the thesis and want to get involved in possible collaborations with the new Techshop?
- Do you have any further contacts/material that could be valuable to us?

A3 Additional prototyping spaces in universities

There were additional prototyping spaces, which were taken into consideration for the *analysis of existing makerspaces* in *chapter 3*. They can be taken into account for future research and review. The list includes:

1. Learning Factory, Penn State - real world industry projects for students
   http://www.lf.psu.edu/
2. FabLab, Aachen - Germany's first FabLab
   https://hci.rwth-aachen.de/fablab
3. Integrated Teaching & Learning Program and Laboratory, University of Colorado at Boulder http://itll.colorado.edu
4. Design Lab, Rensselear
   http://eng.rpi.edu/mdl
5. Entrepreneurs' Garage, NC State University
   http://ei.ncsu.edu/wp-content/uploads/2011/garage_phase_ii.pdf
6. DMC Makerspace, John Hopkins University
   http://digitalmedia.jhu.edu/makerspace/
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8. Maker Lab, University of Victoria
   http://maker.uvic.ca/
9. Maker Lab, Australian Catholic University
   http://blogs.acu.edu/makerlab/