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The role of the Maker Movement in product development

Identification of Maker Movement elements and their effects on hardware start-up's product development projects

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Zusammenfassung

Ein offener Zugang zu Wissen, Design- und Fertigungsmöglichkeiten gestattet es heute jedem nahezu mühelos, physische Produkte selbst zu erfinden und zu bauen. Dies stellt auch den Kern des sogenannten „Maker Movement“ dar. Innerhalb dieser Bewegung existieren „Makerspaces“ in denen sich Einzelpersonen mit Gleichgesinnten zum Wissensaustausch treffen, die angebotene Fertigungsinfrastruktur nutzen und von Fachleuten unterstützt werden. Viele Beispiele haben gezeigt, dass gerade Makerspaces wichtige Faktoren bei der Unterstützung neuer Hardware Start-ups sind. Als Hardware Start-ups bezeichnet man eine Gruppe von jungen Unternehmen, die sich auf die Entwicklung physischer Produkte konzentrieren. Der Konnex zwischen dem Maker Movement und den Hardware Start-ups besteht, auch wenn der eigentliche Einfluss solcher Einrichtungen auf die Produktentwicklung und insbesondere auf Hardware Start-ups noch nicht wissenschaftlich untersucht wurde. Hardware Start-ups sehen sich außerdem in der Produktentwicklung mit anderen Herausforderungen konfrontiert, als jene Start-ups, die beispielsweise Softwareprodukte entwickeln. Um diesen speziellen Herausforderungen gerecht zu werden, gibt es bestimmte Aspekte innerhalb des Maker Movement. Diese Aspekte sind allerdings den meisten Unternehmen derzeit unbekannt.

Der Zweck dieser Dissertation ist es daher, die Rolle des Maker Movement in den Produktentwicklungsprojekten insbesonders von Hardware Start-ups zu untersuchen. Es wird gezeigt, dass ein geeignetes Umfeld hilft, Herausforderungen und Probleme in der Produktentwicklung von Hardware Start-ups zu lösen. Als Startpunkt dieser Forschung wurde zuerst ein „Maker Movement Element System“ entwickelt. Dieses neu entwickelte System basiert einerseits auf einer wissenschaftlichen Recherche der Literatur und im Internet, und anderseits auf einer Reihe von Exkursionen zu verschiedenen Makerspaces. Ergänzt wird diese Untersuchung durch Interviews mit verschiedenen Akteuren innerhalb der Bewegung. Anschließend wurden sowohl qualitative als auch quantitative Daten bei mehreren Hardware Start-ups in Europa erhoben. In einer Mixed Methods Studie wird das Maker Movement Element System später mit qualitativen Motiven und deskriptiven Statistiken verknüpft.

Die Ergebnisse dienen dazu, das allgemeine Bewusstsein für die verfügbaren und unterstützenden Ressourcen innerhalb des Maker Movement zu schärfen. Sowohl Betreiber wie auch Nutzer von Makerspaces können dadurch profitieren. Hardware Start-ups können basierend auf den Ergebnissen neue Fähigkeiten erwerben, welche durch Best-Practice-Beispiele untersucht sind.

Abstract

Open access to design, prototype, manufacture and knowledge exchange possibilities enables everyone nowadays to invent and build physical products easily themselves. This represents also the core of the so-called Maker Movement. Within this movement, the institutions of Makerspaces exist. Makerspaces are locations in which individuals are able to connect to like-minded individuals, use manufacturing infrastructure provided, and obtain support from operational staff. As seen in the past few years, Makerspaces are key drivers in supporting the creation of hardware start-ups. Hardware start-ups are a distinct group of young companies with focus on the development of physical products. The connection between the Maker Movement and hardware start-ups already exists, although the influence of the movement on product development, and especially on hardware start-ups, has not yet been scientifically investigated. Hardware start-ups are more complex and face more critical challenges in product development than start-ups that focus on software products. To overcome these challenges several aspects of the Maker Movement can provide help and support, but these aspects are not widely known and not well structured for promoting the needs of hardware entrepreneurs in a more appropriate manner.

The purpose of this dissertation is to examine the cross influence of the Maker Movement and product development projects, especially in hardware start-ups. It is shown that a proper ecosystem helps to solve critical tasks in product development. In order to start this research, a Maker Movement Element framework was developed. This framework is based on desk research, field trips and interviews with various players within the Maker Movement. Then, both qualitative and quantitative data was gathered through the investigation of the local Maker Movement and 26 individual hardware start-ups in Graz, Munich, and Zurich. In a Mixed Methods study the Maker Movement Element framework is subsequently linked to qualitative themes and descriptive statistics.

The results push awareness about supportive resources for hardware start-ups within the Maker Movement and can be used by Makerspace operators, general users, entrepreneurs, and also decision makers. Hardware entrepreneurs in particular may acquire new skills based on the results and best practice examples described in this dissertation.

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1 Introduction

This section provides background information for the research study element of this dissertation. An outline for this dissertation is provided and the research problem as well as the research purpose is stated. In conclusion, the structure of this dissertation is outlined.

1.1 Motivation and research problem

Over the last decade a new movement that focused on the do-it-yourself principle, sharing economy and development of physical products has evolved in the USA. This movement is subsequently termed the Maker Movement.

A great number of Makerspaces, physical locations that are the primary source of the Maker Movement, have been established. In 2017, over 1,400 Makerspaces are in existence worldwide (Lou and Peek, 2016). According to Krzanich, these are the places where the next great hardware product innovation will occur (Dougherty, 2013a). The widespread access to capabilities for designing, manufacturing and distributing in these locations enables individuals, so-called Makers, to invent and build hardware products themselves. As a result, Makers can take their ideas from zero to market maturity. Gershenfeld(2012) stated that while personal fabrication was long perceived as science fiction, with today's digital manufacturing machines, like desktop size 3D printers, any individual can now make anything, anywhere (Gershenfeld, 2012, p. 46).

In Addition, the number of start-ups is increasing constantly. A study in 2016 assumes the existence of nearly 3m European start-ups (Thannhube *et al.*, 2016, p. 27). In 2018, a report on European Tech industry detailed that investment in European Tech reached a record of USD 23bn, up from USD 5bn five years ago (Wehmeier, 2018, p. 4). Start-ups also systematically create more jobs than they destroy and have a positive impact on country's economy (Mauldin, 2017). Based on Audretsch(2002), for example, during 1990–1995 the net employment gain in the USA is greater among smaller companies than among larger companies as well as when measured on a per-employee basis the patenting rate for small companies is higher (Audretsch, 2002, p. 13). But Ghosh stressed in 2011 that 30 to 40% of start-ups liquidate all their assets and fail, hence if failing is linked to not meeting the projected return on investment, then the estimated failure rate is as high as 70 to 80% (Nobel, 2011). One group of these small young companies are hardware start-ups that bridge the gap between the analogue and the digital worlds with the development of technology wise advanced physical and tangible products.

Anderson promotes the creation of hardware start-ups due to the Maker Movement and states: *"The shape of the 21st century's industrial structure will be very different from that of the 20th century. Rather than top-down innovation by some of the biggest companies in the world, we are* *seeing bottom-up innovations by countless individuals, including amateurs, entrepreneurs and professionals. We have already seen that it worked before in bits, from the original PC hobbyists to the Web's citizen army. Now the conditions have arrived for it to work again, at even greater, broader scale, in atoms"* (Anderson, 2012, pp. 31–32).

Hardware start-ups, like the Pebble smartwatch[1], the Nest thermostat[2], the SmartThings[3] or the littleBits[4], are positive proof that innovative hardware products will not necessarily be born within the walls of large, traditional corporations, but instead in garages, Makerspaces and start-up support centres (Geyer, 2015). Another example is a Makerspace in the Bay Area of San Francisco, in which the users catalysed USD 10bn in shareholder value, USD 2bn in annual sales and USD 200m in annual salaries (Feldman, 2015). Makers come to Makerspaces, picked up the skills and tools that they need, and then start their own company.

The Maker Movement and these Maker projects also have an impact on the venture capital market. Investment in connected device hardware start-ups reached USD 1.48bn in 2014, more than triple the amount of two years earlier (Geyer, 2015). Connected device hardware start-ups is something which is typically created by Makers.

Graham(2012c) states that there is no single factor to explain the increasing amount of hardware start-ups, but instead multiple sources such as crowd funding platforms, improved electric motors, accessible wireless connectivity of various forms, available mass production possibilities, accessible machine, tools and open-source hardware which, all-in-all, make prototyping and selling easier (Graham, 2012c). All these factors mentioned by Graham are encountered within the Maker Movement. But still and despite the current development, no clear picture of those aspects in the Maker Movement exists as yet. Various players such as MakerFaire[5], Instructables[6], TechShop[7] or Etsy[8] help to support individuals in realising their projects, and new players are evolving daily.

However, hardware start-ups tend to have significant problems. Kickstarter[9] is a crowd funding platform that also supports various hardware start-ups. According to statistics more than 84% of the most successful Kickstarter projects shipped late (Pepitone, 2012). Furthermore, 76% of all Kickstarter projects in the category "Technology" miss their financial goal, most likely due to

[1] www.pebble.com, acquired by Fitbit (Accessed: 02 June 2019)

[2] www.nest.com, acquired by Google (Accessed: 02 June 2019)

[3] www.samsung.com/at/apps/smartthings/, acquired by Samsung (Accessed: 02 June 2019)

[4] www.littlebits.com (Accessed: 02 June 2019)

[5] www.makerfaire.com (Accessed: 2 June 2019)

[6] www.instructables.com, acquired by Autodesk (Accessed: 2 June 2019)

[7] www.techshop.ws, filed bankruptcy in Februar 2018 (Accessed: 2 June 2019)

[8] www.etsy.com (Accessed: 2 June 2019)

[9] www.kickstarter.com (Accessed: 2 June 2019)

unsatisfied communication of product features to the end-customer and lack of a working prototype (Kupka, 2018). No hardware start-up wants to be in this group.

As stated later in this dissertation, hardware start-ups face more and different challenges compared with software start-ups, for example. To overcome these challenges several aspects of the Maker Movement can help and support nowadays, but these elements are rarely known by most of the entrepreneurs and are not well structured or presented in order to promote the needs of hardware start-ups in a more appropriate manner.

In contrast, operators of those Makerspaces, political decision makers and university staff want to support start-ups, but current research does not offer an adequate tool for doing so: neither the actual needs of hardware start-ups are listed nor the need for infrastructure, operations, and community can be found. The aim of this dissertation is to describe the connection between the Maker Movement and their use by hardware entrepreneurs in the product development. The research is based on a Mixed Methods study conducted at Europe's hardware start-up hotspots.

1.2 Issue in practice: data from the European Start-up Monitor

As described, many sources show that start-ups are important drivers for economic growth but face various challenges in their development. This dissertation focuses on Europe and therefor the European Start-up Monitor (ESM)[10] is an important study for this research.

The EMS is a quantitative study which focuses on entrepreneurs and the ecosystem provided for these entrepreneurs in Europe to promote transparency for the environment, to identify country-specific and common challenges of the start-up landscape in Europe, as well as to show and highlight specific developments over time (Koo, 2016). In line with person-related queries such as age, gender, and the location of start-ups, entrepreneurs are also questioned on the current three biggest challenges within their start-up (Kollmann *et al.*, 2016, pp. 5–7).

The data sets of ESM 2015 and 2016 are analysed on the question involving challenges as shown in Figure 1. In ESM 2015 and ESM 2016 the biggest challenge of all 4,615 entrepreneurs questioned is sales/customer acquisition. Product development is ranked number two in ESM 2016 and ranked number three in ESM 2015. The Austrian data for ESM 2015 and ESM 2016 has been provided and analysed by the author in more detail. The industrial technology/ production/ hardware, biotechnology/ nanotechnology/ medical technology and green technology groups of start-ups in ESM, are considered to be hardware start-ups. Those are combined and analysed again in regard to the biggest challenges. According to ESM more than 15% of European start-ups are hardware focused (Kollmann *et al.*, 2016, p. 25). This analysis shows that product development (21%) is the number one factor; second is sales/customer acquisition (19%) and third is raising capital (18%). Based on quantitative data and the findings, as well as the author's own

[10] www.europeanstartupmonitor.com (Accessed: 2 June 2019)

five years' experience at Makerspaces and in supporting hardware start-ups, it is underlined once more that hardware start-ups see greater difficulties in product development and obtaining support.

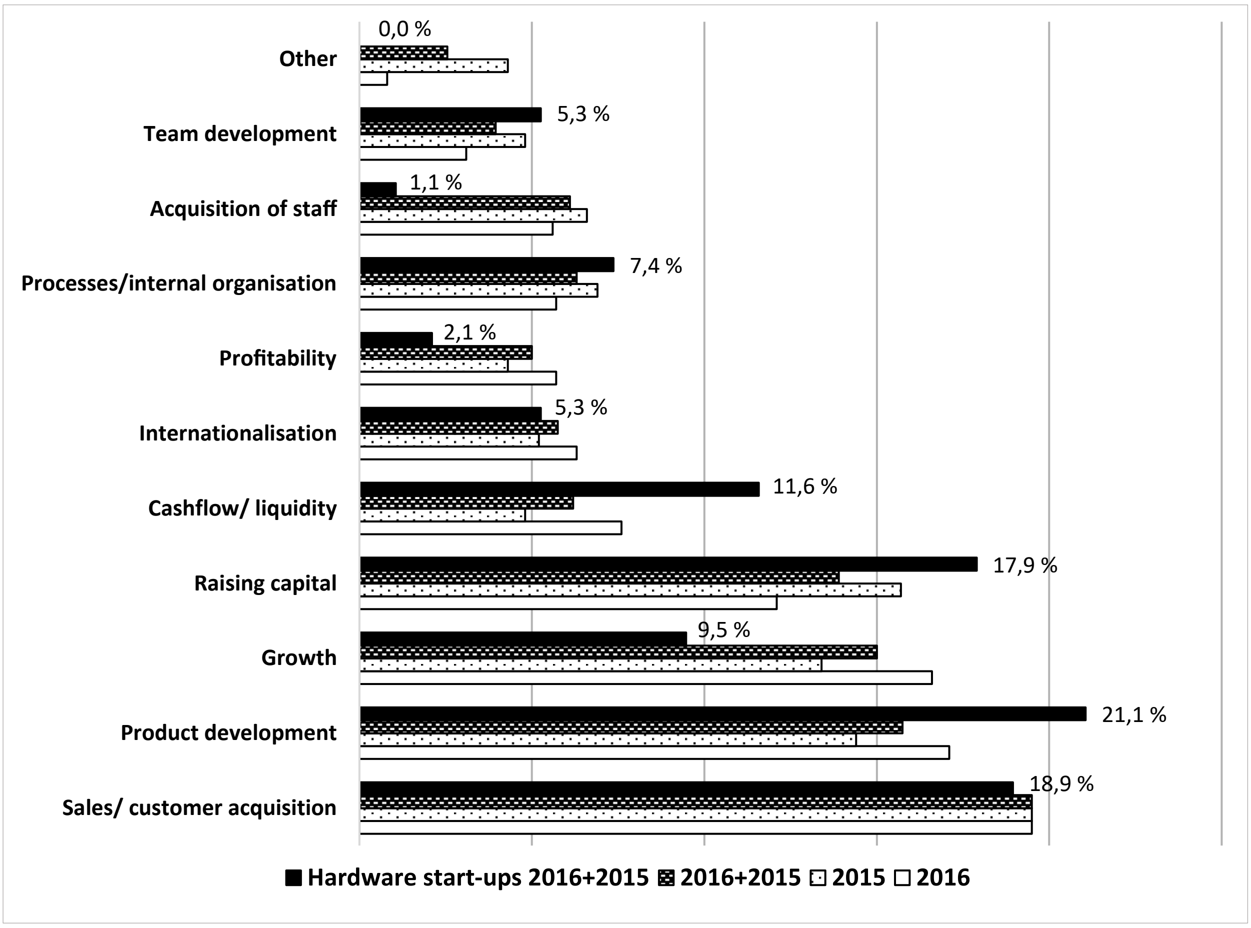


Figure 1: Overall results in terms of the current challenges facing European start-ups[11]

1.3 Issues in theory: review studies and research perspective

Three research streams have been focused in the desired field: start-ups, product development, and the Maker Movement. Product development is an important stream because every successful start-up must master the product lifecycle of its product. The aim of product development is to support the creation process by itself starting with an idea up to the time the final product reaches the market. Literature gives various models, such as Simultaneous Engineer or Design Thinking, which are mainly designed to work efficiently in large organisations but may not in new small firms like start-ups. The start-up's main disadvantage is the lack of resources. These resources, in comparison to established, large companies, may be personnel or skills and competencies on the one hand, and financial or infrastructural aspects on the other hand. Therefore, these models and processes may help these new companies but do not meet their needs adequately. Due to lack

[11] Based on ESM 2015 - 2,100 responses Kollmann, Linstadt and Kensbock(2015, p. 61) and ESM 2016 - 2,515 responses Kollmann *et al.* (2016, p. 94)

of resource and limited timeframe, entrepreneurs, especially from software start-ups, typically employ a test-driven process - build, test and iterate.

Another research stream presented in this dissertation covers the characteristics, types and challenges of start-ups in general and gives a first insight into the special circumstances of hardware start-ups. Even though the group of hardware start-ups is on the rise, the scientific literature on hardware start-ups is very limited on the whole. Various research studies have been especially carried out on start-up support programs like incubators and accelerators. But, according to Hochenberg and Fehder(2015, p. 1203), studies on accelerator programs have focused until now only on software start-ups and further research will be needed to assess new curricula to serve biotech or hardware start-ups more efficiently.

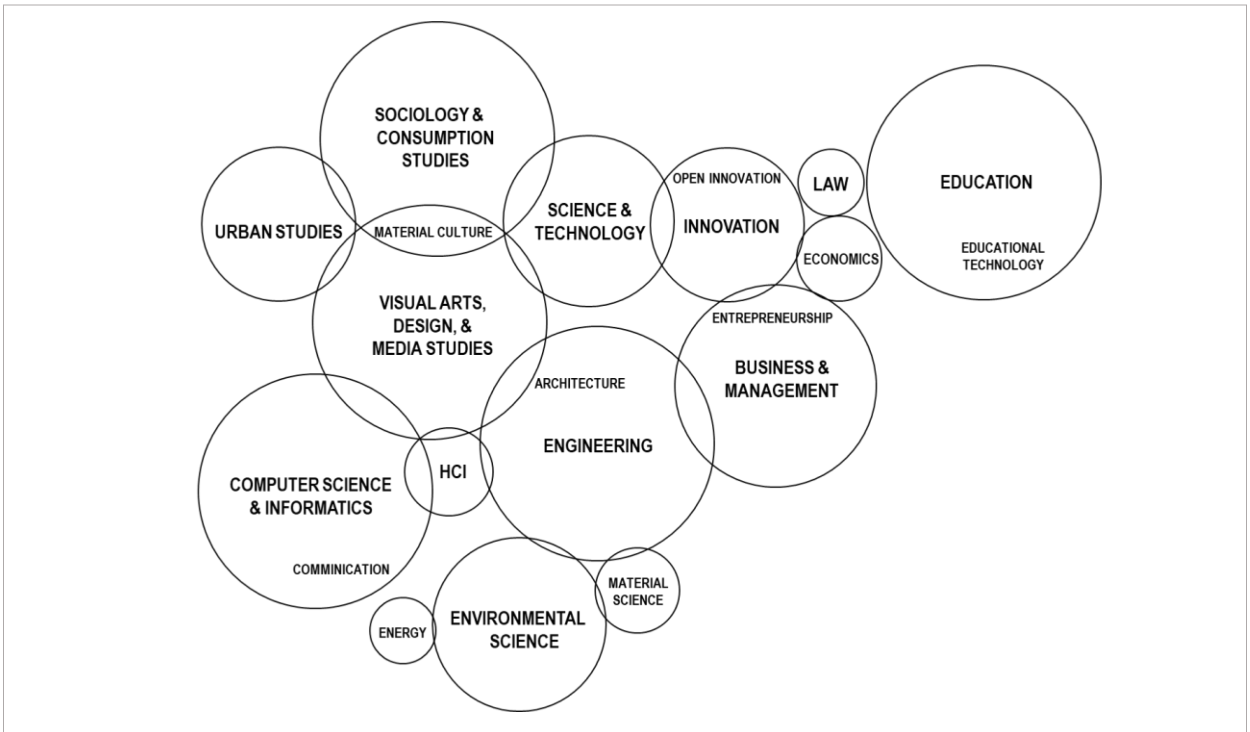


Figure 2: Research areas in the Maker Movement (circle sizes are relative to literature published in each area)[12]

A similar situation as for start-ups can be applied to the research stream of the Maker Movement. The term Maker Movement itself dates back to 2005 and only over the last couple of years has this movement caught the attention of the research community, see for instance Papavlasopoulou, Giannakos, and Jaccheri(2017), Smith et al.(2013), Toombs, Bardzell, and Bardzell(2014), Voigt, Montero, and Menichinelli(2016), Hagel, Brown, and Kulasooriya(2014), Anderson(2012), Howard et al.(2014), Schön, Ebner, and Kumar(2014) or Dougherty(2013b). Analyses based on a Google Scholar search indicate that the scholarly publishing activity on the Maker Movement began in 2012 and continues until the present date at a relatively low level of articles published per year worldwide (Hartmann and Mietzner, 2017, p. 2). Various research has

[12] Based on Kohtala(2018)

been conducted in the field of Maker Movement and education so far. However, in the field of Maker Movement and entrepreneurship, research is limited as only a small number of papers, like Holm(2015a), Browder, Aldrich, and Bradley(2017) or Scully (2018), have been published in these fields. Figure 2 gives an overview of research areas within the Maker Movement, whereas the size of each circle represents the approximate amount of publications in each area. Kohtala(2018) stated that Maker/fab education and learning is still perceived as the biggest area of interest in most scientifically studies.

The Higher Education Makerspaces Initiative (HEMI) has been launched recently to further promote research activities on the Maker Movement. HEMI(2018) is a collaboration between USA-based universities such as UC Berkeley, Case Western Reserve University, Georgia Tech, MIT, Olin, Stanford University and Yale University, which are key advocates of Makerspaces located and run by universities(*HEMI*, 2018). The annual International Symposium on Academic Makerspaces (ISAM) is also set up to connect people, to fuse knowledge and inspiration and also to catalyse higher education Makerspaces with the aim of maximising their effect on student learning experiences and alumni success (*ISAM*, 2018).

Despite an increased interest in the Maker Movement and start-ups, little empirical research has actually been conducted on the topic and particularly from the perspective of hardware start-ups in their product development projects. This dissertation contributes in this area.

1.4 Significance of the thesis

In recent years, the concept of the Makerspace has raised international awareness and various new locations are currently in the planning, construction or launch phase. This study can have a high value, particularly for initiators of a Makerspace. Due to the novelty of the Makerspace concept, these initiators only have access to a limited amount of publications, on, for instance, setting up an appropriate operational model and infrastructure for a Makerspace. Furthermore, only assumptions can be made on the use, the accurate selection of infrastructure and the operational services of a newly-opened Makerspace. This research is also of high value for people who currently operate a Makerspace as the current services and offerings can be compared and checked for completeness.

On the other hand, users of Makerspaces can profit from this research as well. In particular, persons who wish to start their own start-up based on the development of a hardware product. These persons can study the best practice examples mentioned and can gain knowledge of supportive aspects based on the Maker Movement for their hardware start-up.

From an academic research perspective, this research supports the common understanding of aspects within the Maker Movement. Researchers have often studied organisations in a single location, and either qualitative or quantitative research methods have been applied. In this research, qualitative and quantitative research are carried out based on the sample of hardware start-ups in multiple European locations currently working in a Makerspace. This design and structure have not yet been applied to the selected group and therefore new highly-relevant and scientifically-valid information is created in this dissertation.

Policy, decision makers and university management are always seeking a well-founded basis for their choices. This research provides not only best practice examples but also conclusions based on scientifically-evaluated results for the increasingly important Maker Movement field. Due to the scope of the research, which is set to university locations within Europe, university management/staff in particular can draw profound conclusion from this research. Furthermore, the approach employed can be transferred to other locations in order to assess local environments and match them with the locations described in this dissertation. These assessments can further help to detect shortcomings and result in use of new infrastructural or operational facets with the help of this study.

1.5 Purpose statement

The intent of this dissertation is to examine the Maker Movement's role in hardware start-ups' product development. Two empirical studies are carried out. First, an explorative qualitative study to structure the Maker Movement and second, a Mixed Methods research study to analysis hardware start-ups in product development. Hence, the Convergent Parallel Mixed Methods design is used. Based on Creswell(2014, p. 4), this is a design in which qualitative and quantitative data are collected in parallel, analysed separately, and then merged. The qualitative data gathered in interviews and observations will explore themes from hardware start-ups working at Makerspaces. The reason for collecting both quantitative and qualitative data is to converge the two forms of data to bring greater insights and understanding into this problem than would be obtained by either type of data separately (Creswell, 2014, p. 4).

In this context, a qualitative study is important: firstly, to develop a framework for the ecosystem of the Maker Movement and secondly to verify that the interviewees understand Maker Movement elements correctly. This is done because of the newness of the Maker Movement in general to the European region. To meet this goal, problem-centred interviews are conducted. These interviews are characterised by a variety of deductive and inductive components as well as the theoretical knowledge of the interviewer and unforeseen but relevant aspects of the interviewees need to be considered (Witzel, 2000). The information provided by the interviewee can only be collected indirectly, and due to the presence of the researcher biased answers can be assumed (Creswell, 2014, p. 191). Conducting problem-centred interviews is thus not a method for the generation of statistically valuable data, but rather to gain insight into the experience and action in the context of hardware start-ups.

In order to statistically assess elements in the Maker Movement, quantitative research is also carried out. Surveys can be used to provide a numeric description of trend, attitudes, and opinions with the purpose of generalising from a chosen sample to a global view (Fowler, 2009, pp. 3–4). A questionnaire is therefore used for data collection of hardware start-ups questioned.

1.6 Dissertation outline

Based on the guidelines given by Karlsson(2016, pp. 76–77) and Creswell(2014, p. 81), the structure of this dissertation is divided into the following sections, as also shown in Figure 3.

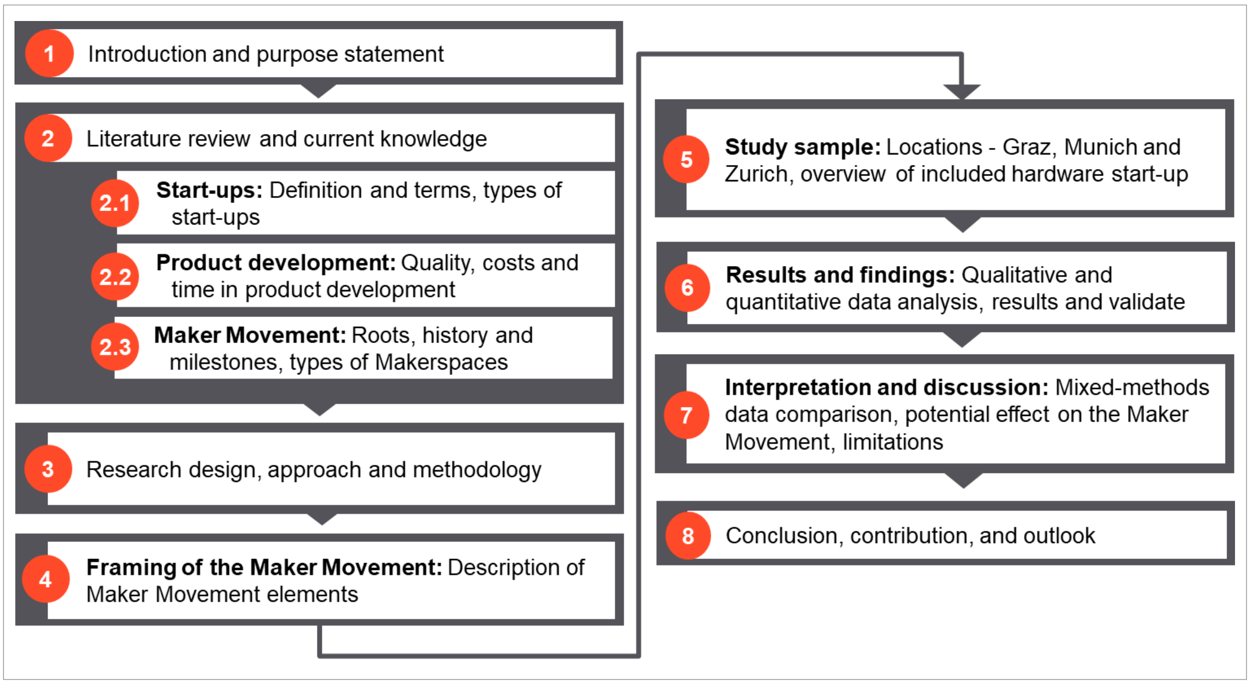


Figure 3: Overall structure of the dissertation

Section 1: The introduction describes the problem and identifies current issues in research as well in practice. Furthermore, the purpose of the intended research is given.

Section 2: The literature review maps existing knowledge. First, in the fields of start-ups, then product development and thirdly on the Maker Movement. Related work, relevant studies and basic models are mentioned for all three fields. Furthermore, the most important terms in these fields are determined. The interim conclusion provides an overview of the state of knowledge and underpins the objectives of this dissertation.

Section 3: The research design, approach and methodology actuate specific research questions and reinforces the choice of research design, approach and methods. The methods for the empirical studies are presented and the required conceptual framework, sample size and group, and principles for data collection and analysis are clarified.

Section 4: This section focuses on the development of a framework: The Maker Movement Elements framework. This framework is needed for structuring the newly arsing Maker Movement and for data collection and analysis in the empirical study.

Section 5: The study sample section describes the three locations in which the start-ups have been selected to be investigated.

Section 6: In this section, the data gathered from two different data sets are analysed separately and results are named. Furthermore, the described results are validated by results generated from a fourth location.

Section 7: The data interpretation and discussion include a report comparing outlined results from the qualitative and quantitative databases and describe whether there is convergence or divergence between the two data sources. After side-by-side comparison, qualitative data is used to either confirm or disconfirm quantitative statistical results. Additionally, potential effects on the community, operation, infrastructure and product development due to the Maker Movement elements are given.

Section 8: In the final section, the main findings are summarised, conclusions are given, the research study is evaluated and suggestions for further research fields are presented.

2 Literature and current knowledge

This section maps the existing knowledge. The most important aspects of product creation, start-ups and the Maker Movement are described. Each subsection introduces initially the most essential definitions and terms.

A deep understanding of concepts in product creation is important for this research. Therefore, the concept of the product life cycle, effectiveness and efficiency, as also quality, time, and cost aspects in product development are outlined. In addition, selected and current popular models of product development are presented. The followed subsection gives a definition and classification of start-ups in general. Furthermore, applicable business fields, branches, organisation forms and development stages are mentioned. Subsequently, the term hardware start-up as one specific group within start-ups is described. Current knowledge on hardware start-ups is gathered and specific needs and challenges are explained. Finally, the Maker Movement with its roots, facilities and players is described, and similarities and differences are elaborated. This is followed by the state-of-the-art scientific research on the role of the Maker Movement in education and product development.

2.1 Start-ups

In Austria, for instance, 10.9% of adults are currently involved in start-ups (statista, 2019a). In addition, the worldwide funding in start-ups dealing with advanced manufacturing and robotics grow between 2012 and 2017 with 1386% (statista, 2019b). Start-ups are also an important factor for economics. Those new companies provide nearly 50% of the new jobs in Europe (Kollmann *et al.*, 2016, p. 3). Considering that this is a big impact on employment, the impact on innovation makes start-ups an important driver for future growth too. These examples illustrations the growing interest in start-ups within the last years.

This section, after defining the term start-up and distinguishing between innovation-driven enterprise (IDE) entrepreneurs or small and medium-sized enterprise (SME) entrepreneurs, presents some main characteristics and a classification of start-ups in general. However, a classification is heavily dependent on which parameters are taken in account. Due to thesis focus on the development of hardware products, aspects in line with this field are considered in more detail.

2.1.1 Definition and terms

People have a specific picture in their mind when start-ups are mentioned but no start-up is like another start-up, and start-ups are different compared to established companies, so the following paragraphs highlight the main terms and definitions.

Kidder(2012, p. 13) states that the actual term start-up roots back to the dot-com boom and describes since then venture backed technology companies. They future define a start-up broadly as any company with limited operating history, in a phase of product or service and market discovery, whereas the founder/founders have no clear picture if costumer/users actually need their business idea (Kidder, 2012, p. 13).

Ries defines, *"A start-up is a human institution designed to create a new product or service under conditions of extreme uncertainty"* (Ries, 2011b, p. 27) In this definition neither the size of the start-up nor the economy sector or industry is included. He further stresses most small or large companies are not a start-up because of the extreme uncertain context in which a start-up is operating in which also most kwon management tools are not working (Ries, 2011b, pp. 28–29). In other words, start-ups are an experiment and the results are not predictable but something fundamentally new. Ries(2011a) also states that a start-up is not replication of an established company. A known business model, pricing, target customer and product may be an attractive investment in terms of economics, but in his view this is not a start-up (Ries, 2011a).

On the other side, Graham says, *"A start-up is equal to growth. Having been started recently does not make a company a start-up. It does not need to work on technology, take venture funding, or have some sort of exit. Growth is the only thing that matters"* (Graham, 2012b). In his thought every aspect related to a start-up is also related to growth and scaling.

Another definition is given by Blank(2010b). He describes a start-up as a temporary organisation used to search for a repeatable and scalable business model (Blank, 2010b). Again, time and growth play a major role.

Another important term which is often mentioned in line with start-ups is entrepreneurship. Based on Stevenson: "E*ntrepreneurship is the pursuit of opportunity beyond resources controlled"* (Eisenmann, 2013). Meaning that entrepreneurship is seen as a distinctive approach to managing rather than a specific stage in an organization's life cycle, a specific role for an individual, a guidepost for risk taken and resource related actions or a constellation of personality attributes (Eisenmann, 2013). In line with this statement, entrepreneurs can therefore be found in many different types of organizations, and not only in start-ups.

For further understanding, a definition for entrepreneurs is also important. Aulet(2016, pp. 6–7) distinguishes two distinct types of entrepreneurs: entrepreneurs in innovation-driven enterprise (IDE) or in small and medium-sized enterprise (SME). Table 1 provides a comparison of the two types and highlights the differences. Based on him, SME entrepreneurs have little drive to innovate and to bring new products or services to their mainly local market, but IDEs focus in contrast on introducing new and innovative products or services to the global market (Aulet, 2016, pp. 6–7). Herein, IDE entrepreneurs are focused within the context of this dissertation due to their characteristics of high-risk goals, innovative products or services, as well as potential for exponential growth. IDE entrepreneurs are typical the founders of start-ups as well as the main drivers.

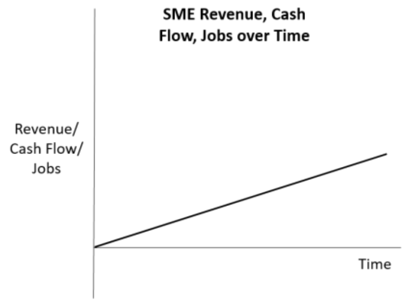
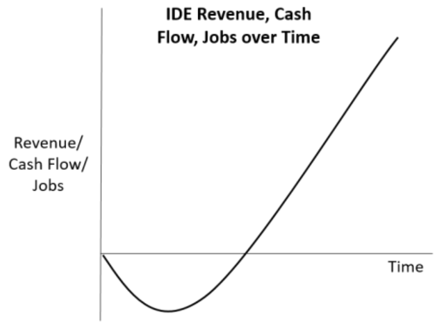
SME entrepreneurs	IDE entrepreneurs
Initially focus on addressing local markets only	Focus on global markets. The firm is based on some sort of innovation where they can go global and across regions
"non-tradable jobs" – jobs that must be performed locally (e.g. service industry)	"tradable jobs" – jobs that must not be performed locally.
Most often family businesses. People who start them seek to maintain control, not to create high growth. Likely an individual-driven founder group.	More diverse ownership base as the focus of founders is on high growth and creating company market value. More team-oriented group of founders.
The firm grows at a linear rate. When putting money into the firm, the system will respond quickly in a positive manner. 	The firm starts by losing money, but will have exponential growth. Requires investment. When putting money into the firm, the revenue/cash flow/jobs numbers do not respond quickly. 

Table 1: Comparison between IDE and SME entrepreneurs[13]

The European Commission defines a SME by staff/headcount and finical ceilings (The Commission of the European Communities, 2003, pp. 1–2). But both metrics are not appropriate to start-ups. According to Steigertahl, Mauer and Say(2018, p. 7), start-ups on the one side may have a large number of employees, but not yet a significant revenue, and on the other side their initial needed capital to grow the company is commonly much higher than for SMEs. Therefore many European studies, like the European Start-up Monitor (ESM), define start-ups by three elements characterised by Kollmann *et al.* (2016, p. 5):

- Start-ups are younger than 10 years
- Start-ups feature highly innovative and/or technology-based business models
- Start-ups have strived for significant employee and/or sales growth

Based on this view and the given statements the following definition is used hereinafter: *a start-up is a business younger than ten years and is selling a single service or product with the ability*

[13] Based on Aulet and Murray (2013, p. 6)

to scale rapidly in terms of significant employee and/or sales growth. Generally, start-ups are novel and in their early stages of development, which mean that they have been in existence for no more than ten years. As mentioned before, one common characteristic of a start-up is that it sells one type of product or service to its customers. It is not a start-up if it is offering multiple products or services. Finally, one of the most crucial elements is the ability to scale from one customer to thousands within a short period, which is difficult to achieve when relying on very limited and specific resources.

2.1.2 Type of start-ups

Blank and Dorf(2007) present a classification of start-ups based on the product and the market channel. Based on their view, a product can be characterised as either a physical or a virtual product as also the market channel: physical or virtual (Blank and Dorf, 2007, p. xxiv). For example, household goods are physical products and can be bought in a physical marketplace. In contrast Google Maps is a software product and it is accessed in a virtual marketplace.

Building on that, a hardware start-up can be defined herein as a specific group of start-ups with focus on physical products that can be bought either in a physical and/or a virtual market. Clarifications and differences to virtual products, like in software start-ups, are highlighted in the following paragraphs.

2.1.2.1 Product

A start-up varies widely based on the to be developed product. The following highlights differences based on a physical or virtual product.

Physical product

As stated, a hardware start-up is a company less than ten years old that sells a single physical product which may include a software element, and with the ability to scale rapidly.

One very distinguishing factor of hardware start-ups is that these start-ups develop a physical product while e.g. software start-ups have a virtual one (Westerheide, 2016). Various statements of hardware start-up founders indicate that physical products are more difficult and need more time to come to market than software start-ups. DiResta, Forrest and Vinyard(2015, p. 1) stress that today is most likely the best time to start a hardware start-up because of technological advances and exiting support ecosystems to master obstacles. Hardware start-up need to tackle on a tight budget and with limited resources complexities of prototyping and manufacturing, optimization of pricing and logistics, as well as correct branding and marketing (DiResta, Forrest and Vinyard, 2015, p. 1). Nevertheless, an incomplete physical product results in unfulfilled customer requirements which cannot be fixed with a software update/patch and may cause the start-up to fail (Westerheide, 2016).

Based on Crichton(2014), developing a physical product can be more complex from the beginning and more people to cover the different disciplines are needed, which results in a more expensive development and various time-consuming stages until the final product reaches the market. This results in higher risks and required investment but can lead to fast growth once the product gets to market (Crichton, 2014).

Testing physical products on users is also a big challenge. Westerheide(2016) stresses that virtual products can be tested by having a demo server or providing beta access. In contrast he clarifies for hardware product: First, you need a functional prototype and/or appropriate testing equipment. When initial testing is finished, the search for suppliers and producers needs to be started. After contract negotiation, the production time can be determined and then assembly and logistics have to be planned. After all this the series of beta testing can be started (Westerheide, 2016).

Špetič(2014), Einstein(2015) and Teel(2018) reviewed start-ups developing physical products and mentioned the following aspects which are typically not part of a start-ups with virtual products and are important on top of others to be successful:

- **Hardware engineering:** Designing hardware is a long process because, for instance, mechanical components, circuits, electronics have to be designed in the constrain of limited iteration capabilities.
- **Design engineering/industrial design:** Depending on the target market, industrial design is important. User interaction design and user experiences with a physical prototype are needed.
- **Firmware engineering:** A firmware is hidden part in any physical product that involves electronics. A hardware start-up usually builds its own computer with non-standard components.
- **Logistics:** Products cannot be distributed overseas like virtual once. Resources to take care of logistics, packaging, shipping, customs declarations, warranties, are needed.
- **Certifications:** Hardware products need certifications depending on the different markets.
- **Production/manufacturing:** Creating physical products require organising manufacturing. When a start-up is scaling, outsourcing of manufacturing may makes sense. However, outsourcing overseas is not an option when the start-up is still designing and improving the product.

The hardware start-up Pepple smartwatch can be named as a known example, they underestimating efforts needed to transform an initial prototype to a mass-producible physical product. Even with very high funding the Pepple smartwatch team encountered many problems in this stage, leading to delays in the assembly and manufacturing, and resulted in late shipment of the final products as well disappointed customers (Lindtner, Greenspan and Li, 2014).

Virtual product

Morettini(2017) clarifies that the development of virtual/software products can happen in fast iteration steps and the product can be further advanced and improved constantly. Additionally, the user/customer may not expect the product to be perfect at the beginning. As a result, software companies might reach profitability sooner if a large enough market is found (Morettini, 2017).

Moreover, starting a software start-up does not need a big team. The business can also be handled alone because a limited amount of disciplines is needed in the beginning (Westerheide, 2016).

Since creating a software start-up is faster, cheaper and sometimes simpler, there is tough competition (Crichton, 2014). Named among the main negative aspect of startup with virtual products.

2.1.2.2 Market channel

The market channel is how a company delivers its product or service to its customers. Based on Kollmann, Kirchgeorg and Krieger(2018), two major channels apart from physical and virtual are known: Business-to-Consumer (B2C) and Business-to-Business (B2B). B2C is the market in which companies offer products directly to end consumers; whereas, B2B is the market in which companies offer and provide services to other companies (Kollmann, Kirchgeorg and Krieger, 2018). Mixed groups of B2B and B2C exist but are relatively rare.

Based on Quintero(2016), three types of market access possibilities can be applied to start-ups:

- **New market:** A start-up is working on a completely new product or service type and therefore a new market segment needs to be developed. This takes the longest time to start and is therefore most expensive for a start-up, because it is not known who the customer/users might be and what the essential product features are.
- **Re-segmented market:** For start-ups, re-segmentation via low cost products and re-segmentation via a niche can be distinguished within this market segment.
- **Existing market:** Entering an existing market segment with already well-known players is hard for start-ups. However, building a premium product is usually a way to succeed.

Physical market channel

Blank and Dorf(2007, p. xxiv) point out that traditionally physical products are sold through a physical market channel, like a salesperson is visiting customers or a customer is visiting a brick-and-mortar stores. They continued that the same principle can also be applied to virtual products, which are sold to customers via specialist software stores (Blank and Dorf, 2007, p. xxv).

Virtual market channel

The Internet created according to Blank and Dorf(2007, p. xxv) a new market channel and allows the creation various new companies which have the value proportion of selling physical or/and virtual products through a virtual market channel.

The virtual market channel boosts also the creation of new start-ups, which are thus also exposed to a much more dynamic life cycle than start-ups in traditional industries (Gutberlet, 2012, p. 61). Gutberlet(2012, pp. 61–62) stresses that success factors of those start-ups are speed, direct communication, flat hierarchical and quick adjustments due to changing market channel or customer requirements.

2.1.3 Fields of business and branches of start-ups

Figure 4 shows data from the Europe and gives a good overview of various possible start-up branches. In this region over one third of the start-ups are in the IT/software development field, software as a service and mobile/app applications fields. According to 2.1.2, these categories can be termed software start-ups. Followed by industrial technology/production/hardware (8.3%), termed hardware start-ups, and then medical- (5.8%) and finance technology (5.2%).

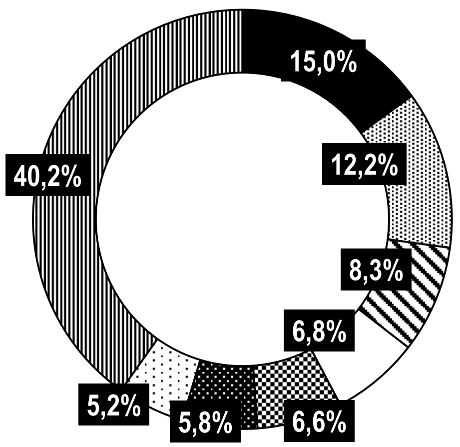


Figure 4: Branches of start-ups[14]

Virtual products are the leading field for start-up branches, however, various analysts view the hardware sector as having a high potential. For instance Geyer(2015) states that venture capital investment in connected device hardware start-ups reached USD 1.48bn in 2014, more than triple the amount of two years earlier. While there are well over a hundred incubators and accelerators for early-stage software companies, the number focusing on hardware start-ups is significant smaller (Geyer, 2015), see also 2.1.8. But these programs can play a crucial role in the development of new hardware start-ups.

2.1.4 Organisation forms of start-ups

The organisational structure of start-ups differs in most cases from established companies. Blank argues: *"a start-up is not a smaller version of a large company"* (Blank, 2010a). Blank and Dorf(2007, p. xxii) also describe that start-ups traditionally used the same tools and methodology as large companies and a significant amount of start-ups failed. It is recognised nowadays, that these tools are appropriate for execution in a known business field, hence start-ups work in unknown fields they have to iteratively build and test a new product in order to turn unknown

[14] Based on Kollmann *et al.* (2016, p. 25)

aspects in known (Blank and Dorf, 2007, pp. xxii–xxiii). Therefore, a flat hierarchy and transparency are important.

In general, start-ups are under time pressure, have to cope with limited resources and the team needs to be constantly motivated to achieve high performance. Thus, making decisions fast is essential for most start-ups. But the execution is only as good as the team's commitment (Sisney, 2013, pp. 47–53). Therefore, start-ups usually work in small highly productive teams and the founders make sure all pursue a common goal. Finette(2013) compares start-up teams with soccer teams: Eleven players all highly skilled, each with defined responsibility play on one field, pursue the same goal, trust each other, and do their best to win. This analogy fits perfect to start-ups. Start-ups can most likely only succeed when working as a united team.

That stated, the most important part of a start-up is the founder or the team of founders. Founders drive the development of a start-up, keep the team on track, carry the vision, play a big role in the entrepreneurial scene and network (Chan, 2016). One key characteristic of good founders is making the right decisions quickly, which depends on their ability to judge and leadership skills (Sisney, 2013, pp. 49–53). The main responsibility of founders is to keep the team motivated and build a spirit to drive the start-up growth.

According to the results of ESM 2016, the biggest share with 34.5% are start-ups consisting of two founders, less than one quarter of all start-ups questioned where founded by a solo founder and 77.4% founded as a part of a team, as shown in Figure 5. Founding in teams means shared risk and workload right from the beginning.

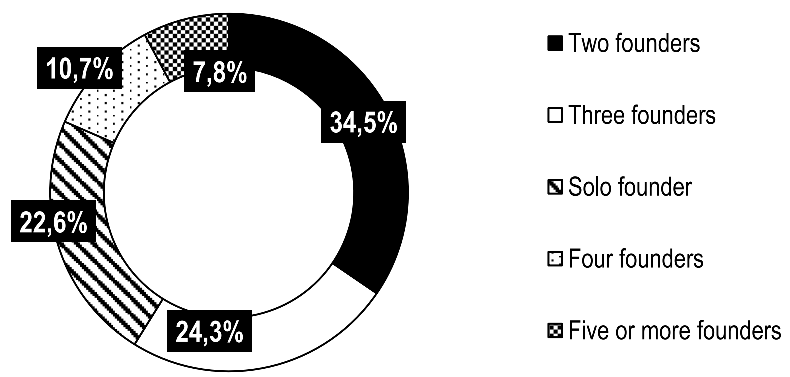


Figure 5: Start-up formation[15]

Start-ups are meant to have an agile organisation structure, meaning that such an organisation can decide fast, has short learning cycles, can react flexibly to changes, and is willing to adapt frequently. The team needs to work closely together and effectively communicate support through state-of-the-art technologies in order to share their insights. Aghina *et al.*(2018) state that in agile organisations no boundaries should exist because rapid actions are essential. Further

[15] Based on Kollmann *et al.* (2016, p. 46)

they should not be afraid to fail during the process and low hierarchy allows them to precede fast and create transparency on their workflows (Aghina *et al.*, 2018).

2.1.5 Development stages of start-ups

In literature, several different development processes, phases, or stages of start-up exist, but in general these models can be summarised into three main steps: formation, validation, and growth, as shown in Figure 6.

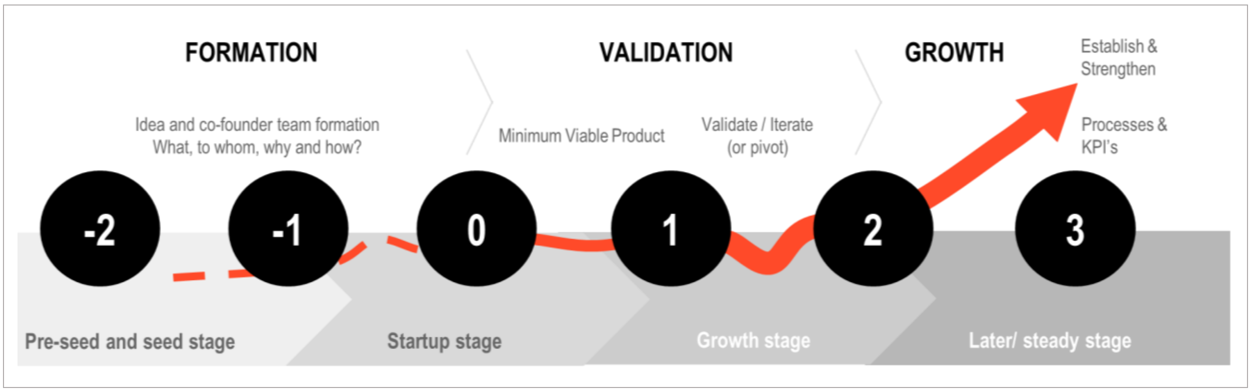


Figure 6: Start-up development phases from idea to business.[16]

2.1.5.1 Formation

In literature, a pre-seed/seed stage is often mentioned, which in this dissertation is included in the formation stage.

The pre-seed stage is about the formation of the idea which results in a first rough prototype and a need for additional capital to bring the first prototype to a working stage (Novoa, 2014). These steps may be carried out even before the start-up exists as an officially entity or the founders' team is fixed. The pre-seed stage starts when a person or a team has the intent to commercialise an idea and/or product concept that has the possibility to scale rapidly.

During the seed phase, it is important that a potential founder or team detect a possible market potential. Thus, there must be an imbalance between an expected market demand and the current market demand. Based on Pott and Pott(2012, p. 6) the market demand refers to the demand of a potential user/customer within a given market and is the basis for every start-up process, which try to exploit the existing potential through the development and implementation of a suitable business idea. Often, market potentials are detected indirectly by experiencing an unsatisfying situation, so-called accidental discovery, or by solving one's own problem, that is helpful for others in the same situation (Pott and Pott, 2012, p. 6). In brief, the seed phase ends with a developed product concept, but no revenues have yet been created by the start-up.

The capital necessary in this stage is commonly called seed capital and is necessary in order to take the first steps to forming a legal entity and build first prototypes (Novoa, 2014). Novoa(2014)

[16] Based on Startup Commons(2018)

names three main sources of financing support in this stage are: friends, family and fools (FFF), start-up pre-seed accelerators and business angels.

2.1.5.2 Validation

In the validation or startup phase, the feasibility of the business idea is tested. Pott and Pott(2012, p. 7) stress that the idea needs to be checked for profitability through estimation of a realistic level of effort needed, costs, time and possible sales. They detailed further that to examine an idea, a business plan need to be created which considers different perspectives, like skills needed, market environment, competition, and evaluates the feasibility overall (Pott and Pott, 2012, p. 7). Overall, a business plan or a Business Model Canvas[17] is usually also required by banks or support centres to get a clear picture of the expectations of a start-up.

In this phase ideas become reality or not. Often, the assessment of business ideas is also done in a so-called fast failure approach, which allows entrepreneurs to quickly evaluate many ideas with the help of rapid prototyping, trails, and small-scale user tests, with the goal to determine quickly which of the novel business ideas is optimal and useful for implementation (Shalley, Hitt and Zhou, 2015, p. 72).

If the assessment is positive, the entrepreneurial/start-up team establishes the necessary conditions to ensure that the start-up can run smoothly right from the beginning. According to Pott and Pott this include issues such as the choice of an appropriate legal form, organisation structure of the company, completion of partnership agreements and also the necessary knowledge on laws, marketing, sales, accounting, pricing of products, etc. (Pott and Pott, 2012, p. 7).

In brief, start-ups have completed this phase when a minimum viable product (MVP) exists and have created initial revenues through their first sold products. An MVP is a iteration of a new product or service which allows a start-up to collect the maximum amount of validated learning about customers/users with a minimum effort (Ries, 2009).

2.1.5.3 Growth

The growth or implementation stage involves the formal institutionalization of the desired start-up. Depending on the legal form, different requirements need to be fulfilled. Based on Pott and Pott it is important that during this stage clear structures and a good organisation forms are implemented and maintained (Pott and Pott, 2012, p. 8).

Stocks, Wilson and Mador(2010, p. 117) claim that start-ups developed in this stage are looking for a strong sales increase as well as growth in new customers/users. They see management of internal processes and employees are as critical in this phase because rapid growth may place strains on the start-up's structure and a division in teams based on the function as well as

[17] www.strategyzer.com/canvas/business-model-canvas (Accessed: 2 June 2019)

recruitment of non-owner managers are often a prerequisite to take the start-up through this phase (Stokes, Wilson and Mador, 2010, p. 117).

Some literature sources also name later stage and steady stage. Pott and Pott(2012, p. 8) stress that these stages focus mainly on the new and additional capital requirements for restructuring, and the reorganisation or further diversification into new products or services. A critical factor in this stage is often the management, which usually still just consists of the founder or the founding team, and now seeks support from experienced executives or is even replaced by them (Pott and Pott, 2012, p. 8).

The forms of financing in this stage are very different. Achleitner and Braun(2018, pp. 331–333) distinguish between turnaround, restructuring, management buy-out or management buy-in. However, financing is mainly provided by investors, outside capital, via the company's own funds, subsidies, profits or through an Initial Public Offering (IPO) (Achleitner and Braun, 2018, pp. 331–333).

In brief, this stage describes start-ups that has matured into an established market player and has no longer significant market growth or sales increase.

2.1.6 Start-up founding and funding

Ideas and initial concepts to find a start-up are derived from different sources and have an impact on the founding and funding of a new company. Kollmann *et al.* (2016, p. 20) distinguish three main different options: Independent venture foundation, spin-off from a university, and spin-off from an existing company. First, a start-up may be founded by an individual or a group of individuals as an independent venture. This is also according to Kollmann *et al.* (2016, p. 20) the most common option. Second, start-ups may be founded as a spin-off from a university or a research institute. For examples, individuals have written a final thesis and discovered in the course of this that there are certain aspects that could be better brought to market within a company than within the current institution. Third, individuals discover an interesting aspect within their normal working activities at a traditional/established company and then subsequently found a spin-off based on these activities. This is done because company representatives see a higher potential when the new product or service is marketed specifically. Start-ups founded as a spin-off either from a university or a company certainly have different constraints on the founding phases and/or already have initial founding at the very beginning of the venture.

The financing and the optimal form of financing for start-ups must be carefully, hence it has an influence on the business model and the stage of development of a start-up. Hahn(2018, p. 19) stresses that all forms of financing aim to secure a start-up's solvency at every development stage and give the possibility of indispensable growth. Especially in the early days of a start-up high investments in technology and the company structure are needed and therefore a start-up will regularly be forced to reach out to financing partners, in particular also public subsidies(Hahn, 2018, pp. 19–20).

As stated, start-ups require funding which initiators cannot fully provide themselves. Figure 7 shows sources of financing based on Kollmann *et al.* (2016, p. 76). 84.5% of the investment comes from personal savings, 29,6% have also financial support by friends/family and more than one quarter are supported by public subsidies.

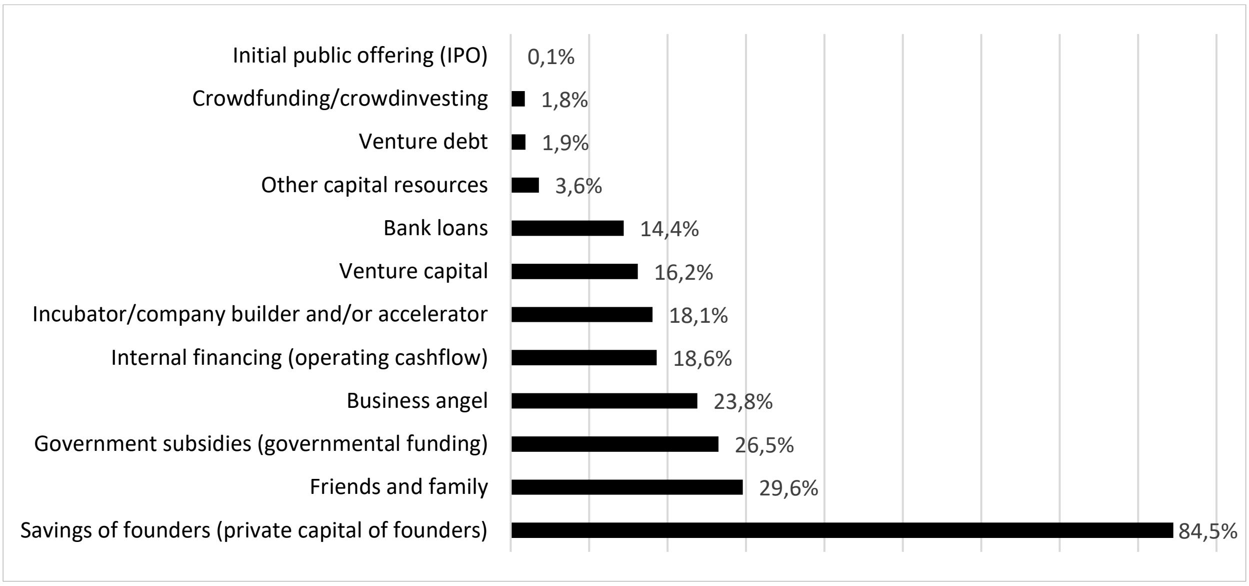


Figure 7: Sources of financing[18]

Start-up funding possibilities have recently changed significantly. According to Novoa(2014),five years ago, start-ups had only a few options, but nowadays a wider variety of funding option, such as Venture Capital (VCs), crowd funding, accelerators, business angel networks, and similar exist. However, Van Osnabrugge and Robinson (2000, p. 5) state that business angels, as also described in 2.1.8.2, are the dominate source for outside funding for start-ups. The number of potential business angels spanning form very rich to middle class individuals is at a record high but still grows significantly (Van Osnabrugge and Robinson, 2000, p. 5).

For start-ups Van Osnabrugge and Robinson(2000, p. 6) recommend to detailly investigate all available internal and outside founding option before conforming a deal. Hence, it is crucial to understand the full investment process ranging from understanding the motivation and criteria of a possible investor to considering how a deal is might structured and how the investor's intent to help a start-up growing (Van Osnabrugge and Robinson, 2000, p. 6).

2.1.7 Start-up challenges and obstacles

Start-ups face like established companies various challenges and obstacles. Especially start-ups see themselves confronted with an extremely high business failure rate and various literature sources have already pointed to the need of entrepreneurs to access supportive resources during

[18] Based on Kollmann *et al.* (2016, p. 76)

the early stages of their development to overcome some obstacles and challenges easier (Honjo, 2000, p. 558; Belso-Martinez, Molina-Morales and Mas-Verdu, 2013, p. 2079). The following section lists therefore first known challenges in theory and second challenges in practice based on surveys.

2.1.7.1 Knowledge on challenges in theory

The needs and challenges stated in literature differ widely depending on the start-up's type, market, branches, stages, product and organisational structure. Shepherd, Douglas and Shanley(2000, p. 393) argue that the mortality risk of a start-up correlates with the degree of novelty to the market, to management and in production as well as with the number of novelties in with the start-up is operating. Further they summarised obstacles a start-up is typically facing: costs of learning new tasks, characteristics of the new product, conflicts regarding new organizational roles/stability, informal organizational structures, and connections with key stakeholders (Shepherd, Douglas and Shanley, 2000, p. 394).

Many challenges are specific to one start-up. Nevertheless, certain aspects fit in general and are common among many, Newtek(2014) lists those as follows:

- **Timing:** The right moment to launch a start-up is always a balancing act of many influencing factors, the success of competitors, the start-up funding, the personal circumstances as well as the presents of skilled team.
- **Budget:** Every possible new strategy should be budgeted carefully. A proper budget and expertise in this field is essential before any money is spent.
- **Self-discipline:** Goals and milestones which are planned on a timeline are important. Checkpoints on a daily/weekly/monthly basis help to foster self-discipline.
- **Social skills:** Part of working in a start-up is networking and therefore high social skills are essential. Finding funding and people willing to invest their money and time in a start-up is important.
- **Flexibility:** Start-ups are not durable. However, start-ups need to stay focused, react flexibly and quickly to changes in order to adapt the new product.
- **Funding:** Money/funding is considered to be the most urgent need of start-ups generally have. If the start-up does not generate enough funding, it cannot develop further and will not be able to survive.
- **Team:** Even the best business plan with the most innovative product will have no chance of success if the individuals involved lack the necessary endurance, skills and knowledge to make it work.

As introduced in 2.1.2, hardware start-ups are different to other start-up groups and face therefore also different challenges. Many challenges as described by Iseman(2016) or Migicovskay(2017) are in line with the creation of the new physical product. Migicovskay(2017) stresses that hardware start-up are often challenged by building rough and unfished prototype early to do customer/users tests. Iseman(2016) claims that in the earliest stages of a start-up, nothing involving physical prototyping should take more than three days longer than by a software start-up. Both emphasize on a build, test and iterate cycle until the new product is ready for mass manufacturing. However, Kazerounian claims that the biggest issue is currently in getting those prototypes industrialized and he also supposes that this knowledge is currently far outside of the reach of any hardware start-up (Hessman, 2015).

Williams and Nadeau(2014, pp. 64–66) summarised their hardware start-up experience and conclude that today it is easier to build many prototypes of a new product, but challenges in line with mass manufacturing, like sourcing of components, managing the supply chain, designing for assembly testing, still exist.

2.1.7.2 Knowledge on challenges in practice

Figure 1 in section 1 displays overall results in terms of challenges faced by European start-ups. Sales/ customer acquisition is seen as the overall biggest challenge. Besides that, there are a few quantitative surveys specifically on hardware start-ups and their challenges. The results of two prominent surveys are mentioned below. Interestingly all the quantitative empirical studies mentioned conclude that funding, access to manufacturing resources and product development are viewed as one of the top three challenges by the persons questioned.

Analysis of "The state of hardware start-ups" survey by Fictiv[19]: in 2016, 213 responses

Fictiv, a USA-based contract manufacturer specialising in prototyping and small-batch production, asked its clients in an online survey to rank their many challenges in their product development. Fictiv's clients are mainly entrepreneurs working on hardware products. Funding and resources are perceived as the biggest challenges in bringing a product successfully to market, as shown in Figure 8.

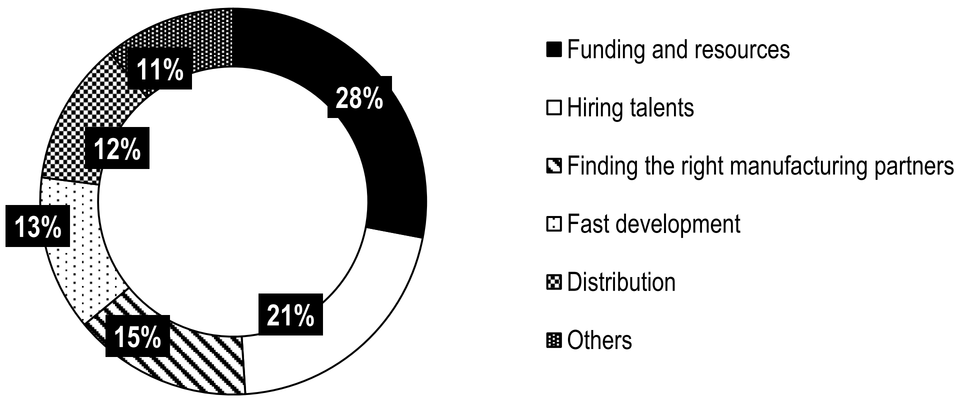


Figure 8: Challenges of hardware start-ups survey by Fictiv, 213 responses, mostly USA.[20]

[19] www.fictiv.com (Accessed: 2 June 2019)

[20] Based on Fictiv(2016, p. 13)

Analysis of "Maker Survey" by Hackster[21] in 2016, 3.139 responses

Hackster, a division of Avnet[22], which is one of the biggest electronic suppliers worldwide, is a growing developer community for learning, programming and building physical products. By bringing together a global network of nearly half a million users and hundreds of technology partners, Hackster hopes to facilitate the creation of innovative products. 3,139 responses across 104 countries were collected in 30 days in the online "Maker Survey" on the state of the Maker Movement and the results were then shared.

One question is about the biggest challenge that the persons questioned face in their current projects. 25% mention funding, 19% manufacturing and 16% engineering, as shown in Figure 9.

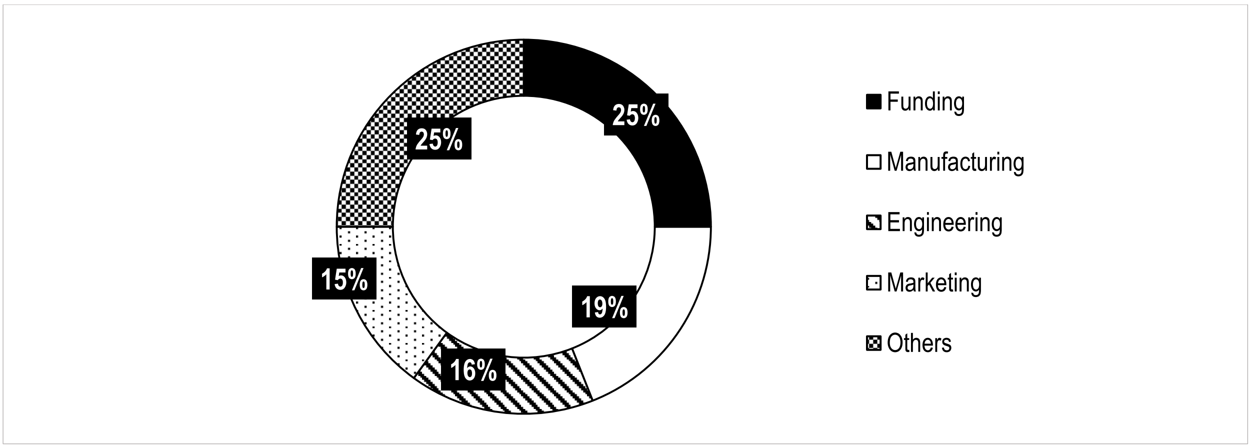


Figure 9: Challenges of hardware start-ups survey by Hackster.io, 3.139 responses, worldwide.[23]

2.1.8 Start-up support programmes

Starting start-ups can be, as described, challenging even though the entrepreneurs have a great idea. Furthermore, designing a solid business model and forming the team are difficult with limited knowledge, resources and experience. This gap may be closed through business angels, public/private incubators/accelerators or other support programmes for start-ups. Those are described in the following section.

Cohen and Hochberg(2015) concluded that incubators and accelerators in particular have become a vital resource for obtaining the missing skills for start-ups. Therefore, the first steps of many start-ups are nowadays often made in accelerator or incubator programme, which offer entrepreneurs opportunities early on and even though the company is not yet founded (Hochberg and Fehder, 2015, p. 1202). Accelerator or incubator offer often free support to grow a business quickly and can increases the chances of attracting additional investors as well as first users/customers.

[21] www.hackster.io (Accessed: 2 June 2019)

[22] www.avnet.com (Accessed: 2 June 2019)

[23] Based on Hackster(2016, p. 28)

Table 2 gives an overview of characteristics, differences and definitions between start-up support programmes. While accelerators have a defined cycle time and cyclical selection periods, incubators offer the start-ups to retain support for up to two years and the selection for the programme is ongoing throughout the year (Hathaway, 2016).

	Incubator	Business angel	Accelerator
Duration	1 to 5 years	ongoing	3 to 6 months
Cohorts	No	No	Yes
Business model	Rent, non-profit	Investment	Investment
Selection	Non-competitive	Competitive, ongoing	Competitive, cyclical
Venture stage	Early to late	Early	Early
Education	Ad hoc, human resources, legal	None	Seminars
Mentorship	Minimal, tactical	As needed	Intense
Venture location	On-site	Off-site	On-site

Table 2: Summary of the differences between incubators, business angels, and accelerators[24]

2.1.8.1 Incubator

The two known pioneer incubator programs are the Stanford Research Park, California, established in 1951 and the Industrial Center of Batavia, New York, established in 1959 (Mian, Lamine and Fayolle, 2016, p. 2). Based on Mian, Lamine and Fyolle(2016, p. 2), the first incubators aimed at economic restructuring as well as job creation and were not directly linked to start-up activities. The programs at that time provided mainly affordable office space and services. The next iteration of incubators which started around 2000 offered a more complete portfolio towards start-ups like counselling, skills enhancement trainings and networking (Mian, Lamine and Fayolle, 2016, p. 3). Since then the model has evolved constantly. In 2003 there were around 800 incubators(Wiggins and Gibson, 2003, p. 56), whereas in 2016 more than 1,400 exist in the USA (InBIA, 2018).

The general idea behind an incubator programme is to create an institutionalised environment that assists and enables start-ups with their ideas to grow based on very different processes and time spans (Grimaldi and Grandi, 2005, p. 112). In comparison to the accelerator programme, the incubator model is suitable for a large variety of different types of start-up.

Incubator focus on providing fundamentals for start-up teams. In most cases the programme costs the start-up only a rental fee which may be government subsidised. According to Lewis, Harper-Anderson and Molnar(2011, p. 6), start-ups that have participated in an incubator programme have a greater chance of success compared to those that have not done so.

[24] Based on Cohen(2013, p. 20)

Mian, Lamine, and Fayolle(2016) published a systematic analysis of the literature on technology-based incubation. They stated that a wide variety of different incubator approaches show the diverse and multidisciplinary of the field. Incubators typically include professional management, entry and exit policy, a mix of business support and professional services, networking, access to capital, as also in many cases access university resources (Mian, Lamine and Fayolle, 2016, pp. 6–7). Though this analysis reveals the need to develop a unified theory of incubation, the challenge is the tremendous variation in program grants and policy objectives.

In brief, a start-up incubator is a physical location which offers a working space with many other like-minded companies. The time the start-up teams spend inside an incubator varies depending on their needs. According to Deep(2014), most incubators offer in addition mentoring which is typically done by approved persons, such as other entrepreneurs or investors. Mentors share their experience with incubated start-ups frequently.

2.1.8.2 Business angels

Business angels, or so-called angel investors, have their origin in New York and the musical scene. Ramadani(2009, p. 249) stated that musical producers who needed founding for a new show reach out to wealthy patrons, so-called angels, to invest in the risky venture, in this context a new show. Nowadays, the term represents generally wealthy individuals who invest their personal capital typically in early stage start-ups in return for an equity stake.

Many start-ups require a substantial capital and venture capital is an option to fulfil these requirements when the first capital of a start-up is exhausted. According to Gompers and Lerner(2005, p. 267) venture capital is an independent managed and dedicated pool of capital that focus on equity or equity-linked investments in start-ups, whereas angel investors are individuals who finance start-up by putting their own venture capital to work.

Wiltbank(2009, p. 4) states among others that especially early-stage start-ups have a significant risk of failure and are therefore more difficult for investors to assess. Due to this high failure rate, most business angel expect a return on investment within three to eight years and a return of more than ten times of their initial investment as well as they take in many cases an active role as a board member or consultant in invested start-ups (Wiltbank, 2009, pp. 4–5).

2.1.8.3 Accelerator

The accelerator, also so-called business accelerator or seed accelerator, derives many characteristics from incubators.

In 2005, the famous Y Combinator[25] in Cambridge, Massachusetts, was launched which was among one of the first accelerator programmes worldwide (Graham, 2012a). The success of the Y Combinator has been a source of inspiration for many other accelerators. According to

[25] www.ycombinator.com (Accessed: 2 June 2019)

Christiansen(2009, p. 7) the most important difference between incubators and accelerators is the cycle time, meaning that a single start-up should not be longer than three months in the accelerator program. This should reflect, for instance, the rapid development cycles of mobile software applications. In addition, financial backing should help accelerated start-ups to grow faster (Christiansen, 2009, pp. 7–10). Since 2005, the number of accelerator programmes has increased and a global report counted in 2016 579 programs (gust, 2016).

Cohen and Hochberg(2014, pp. 4–5) offer the first formal definition of an accelerator program, distinguishing accelerators from other programmes that have similar or related goals, such as incubators or business angels. Later, Fehder and Hochberg(2014) investigated the regional effects of accelerators on the general equilibrium in the entrepreneurial ecosystem, rather than the effect of the accelerator on the supported start-ups.

Miller and Bound(2011) investigated the accelerator concept even in more detail. According to them, early evidence shows that an accelerator programme has a positive impact on start-ups and in particular on start-ups working with web/mobile software applications since their development costs and cycles are relatively short compared to other branches (Miller and Bound, 2011, pp. 11–12).

Miller and Bound(2011, pp. 9–10) conclude in five key aspects of an accelerator:

- An application process that is open to all yet highly competitive.
- Provision of pre-seed cash investment, usually in exchange for equity in the start-up.
- A focus on teams, not individuals.
- Time-limited support consisting of programmed events and intensive mentoring.
- Start-ups supported in cohort batches/classes.

Christiansen(2009, p. 14) studied also accelerator programmes and stated that the most important aspect of long-term success of start-ups is the connection to investors in accelerators. It is vital for every start-up to raise more cash investments after the accelerator programme is finished in order to continue development and to improve the product idea further. Based on his findings, the network and connections to investors are the most important factors for every accelerator.

Hallen, Bingham and Cohen(2014) compare accelerated start-ups that eventually raise venture capital to non-accelerated start-ups that eventually raise venture capital. They find that graduating from a top accelerator programme is correlated with a shorter time to raising venture capital, exit by acquisition, and achieving customer traction (Hallen, Bingham and Cohen, 2014, p. 5).

Another similar study, which revealed comparable results, was conducted by Winston Smith, Hannigan and Gasiorowski(2013). They compare ventures that have participated in two of the leading accelerators to similar ventures that do not participate in such programmes but raise angel funding instead. They find that start-ups that graduate from these top two programmes are founded by entrepreneurs from a relatively elite set of universities, receive their first round of follow-up financing significantly sooner, and are more likely to be either acquired or to fail (Winston Smith, Hannigan and Gasiorowski, 2013, p. 3).

In brief, many literature sources concluded that start-ups, which have participated in an accelerator, can overcome challenges more easily and are seen more successful than others. Compared to incubators especially the shorter cycle time of accelerators is seen beneficial due to the rapid changing circumstances of start-ups environments.

2.2 Product development

Newly-created products and services are an important factor for economic welfare. Schumpeter(1912) was among the first economists who pointed out the importance of the so-called new combinations of entrepreneurial activities - later termed innovation. He states that competition imposed by innovation, which results in new products and services creations, is more significant than marginal changes of prices of existing product and service aspects (Schumpeter, 1912, pp. 170–180).

The process of converting ideas into new products and services is an essential part of any innovation and individuals, who define a problem, have ideas and perform linkages, are the key components of any innovation (Trott, 2016, p. 11). However, innovation is not only about the development of a new product and service itself. Based on Trott(2016, pp. 11–12), it must also include, the economic exploitation of new products and services. Consequently, innovation is a comprehensive process including all phases of product development from idea creation to the introduction of the new product into the marketplace (Trott, 2016, pp. 12–16).

Innovation has always derived to economic changes and nowadays the time spans between fundamental innovations is also decreased dramatically. Dobbs, Manyika and Woetzel(2016, p. 35) name that more than 500 years passed between the first book printing press and the computer printer, but it then took just 30 years that the first 3D printers where introduced to the market. In the years ahead, new products and service will continue to spur growth and many new businesses will be created based on now available and affordable technologies (Dobbs, Manyika and Woetzel, 2016, chap. 2).

As stated, innovation is therefore the origin of dynamics in business ecosystem and economic development. However, those face todays many challenges. According to Schuh(2012, pp. 2–5), new developed products and services face for instance a saturated marketplace, pressure on the sales price, a high variety of offers, and interchangeability between various other products and services. Those challenges lead mostly to short product life cycles and product development cycles, a higher sensitive to product cost, and explicit customer requirements (Schuh, 2012, pp. 2–5).

Thomke and Reinertsen(2012) state that many industrial companies treat innovation and new product or service development similar to manufacturing, although those have profound differences: Manufacturing deals mainly with the creation of physical objects, repetitive tasks, predictable activities, and in one place at a time created item. In contrast, tasks are mainly unique in product and service development, project requirements constantly change, and the output is data and information, which can be created in multiple locations at the same time (Thomke and Reinertsen, 2012).

Based on the given statements, the following section clarifies the basic terms in product and service development, selected models and processes are introduced, as well as attributes of success in product development are discussed. All models, processes and concepts are selected based on known constrains of start-ups as described in 2.1.

2.2.1 Definition and terms

Before the industrial revolution, products are made entirely by one person, a process known as craft production (Russell and Taylor, 2011, p. 6). Master workmen/craftsmen possessed most of the knowledge needed for product creations and the necessary work was carried out mostly by themselves, but the industrialisation caused the separation of planning and execution tasks (Ehrlenspiel and Meerkamm, 2017, p. 226).This leads to todays recognised discipline of product development. Albers and Meboldt(2007a) stress that the last decades of research in product development were mainly characterized by specific aspects: First, a focus was given to design methodologies and later on management and economics, then the focus was switched again to the development processes and technologies. Those processes were influenced by concepts of radical or incremental innovations, market pull and technology push (Albers and Meboldt, 2007a, p. 1). In addition, many different terms for product development arose over the years.

Based on Albers and Gausemeier(2012) is the term product creation mainly used in German-speaking literature and is broken down into strategic product planning, product development and production system development. However, those sub-areas cannot be deemed to be fixed or consecutive phases (Albers and Gausemeier, 2012, pp. 17–19).

Developed subsequently and more favoured by English–speaking researchers is the concept of new product development (NPD), which is herein used for this thesis. Law(2016, pp. 415–416) defines the concept of new product development in a way that it covers the whole process of bringing a new product to market. Along with various business considerations, a central aspect is product design (Law, 2016, chaps 415–416). Broadly spoken, NPD describes the transformation of an innovative idea with market opportunity into a product available for sale.

Both terms are further clarified in the following paragraphs.

2.2.1.1 *Product creation*

Product creation includes three phases. The first phase is based on Albers and Gausemeier(2012, pp. 18–19) strategic product planning, which is characterised by a process to identify future areas of economical high potential and includes the creation of a development strategy, technology/product screening, as well as business development. Future opportunities for a company are indicated, market needs are evaluated, new market segments and emerging potential in a technological and economic perspective are described. Albers and Gausemeier(2012, pp. 18–19) name that the task of product screening is to find possible new products and services including requirements as well as given boundary conditions. Whereas, business development focuses on issues regarding economic and product strategies as well as gives the foundations for phase two and three (Albers and Gausemeier, 2012, pp. 18–19). The first phase addresses the identification of possible future areas of growth, success and the creation of action plans.

The second phase according to Albers and Gausemeier(2012, p. 20) is the product development phase which includes product concepts, technical designs, preparation tasks required as well as the integration of outcomes of individual disciplines into a holistic solution. This includes detailed and obligatory designs of the product regarding technical functions, costs, quality and time, resulting in an evaluation of feasibility based on an economic and a technological perspective (Albers and Gausemeier, 2012, p. 20). The results are a descriptions and documentations of the product or service.

The main areas of the product development phase are basically similar throughout literature and the following five core areas of product development, according to Albers and Meboldt(2007a, p. 2) and Ehrlenspiel and Meerkamm(2017, p. 199), can be named:

1. Planning of new ideas, areas and fields for activities in product innovation as well as business model innovation.
2. Concepting of a new product and service as also methods for developing new, innovative product principles. This also includes software for mechatronic products and contact with other idea providers.
3. Designing and development of a new product and service. An initial preliminary design of geometrical and material properties of a product are made. This should also include procurement, manufacturing and assembly, as well as concept of the may applied business model.
4. Driven primarily on software solutions the product is tested, and prototypes are built.
5. In production and market launch planning the final determination of the product or service are made and all functional areas merge with the design areas.

The final phase in the product creation is production system development. Albers and Gausemeier(2012, pp. 20–21) stress that this phase is the reason for mutual dependencies of product development and manufacturing. It starts with the concept creation regarding aspects of work flow planning, work equipment proposal, workshop design, production planning and logistics (Albers and Gausemeier, 2012, pp. 20–21).

2.2.1.2 *New product development*

New product development (NPD) covers the complete process from idea generation to bringing a product to market and is described very broadly in literature as the transformation of an idea into a product available for sale (Kahn *et al.*, 2013). The product can be physical and tangible or virtual and intangible, like a service. According to Amran, Committee and Jumbri(Kahn *et al.*, 2013) knowledge of customer needs and wants, as also knowhow of the competitive environment and the market are required in NPD. Whereas, cost, time and quality are the main variables that drive product development projects. Developers have to cope with many uncertainties and challenges in NPD. The use of best practices and the elimination of barriers in the development teams are seen as main concerns for the good management of NPD projects (Kahn *et al.*, 2013).

The most basic sequential NPD process has according to Ulrich and Eppinger(2016, p. 9) seven steps: idea generation, requirements definition, product concept development, system level design, detailed design, prototype testing and refinement, process design as well as production ramp-up. In a traditional view each step has been completed when all information is gained and can be passed to the next step's functions. This indicates based on Russell and Taylor(2011, pp. 160–161) also the main problem within this view: the sequential information flow from one department to another.

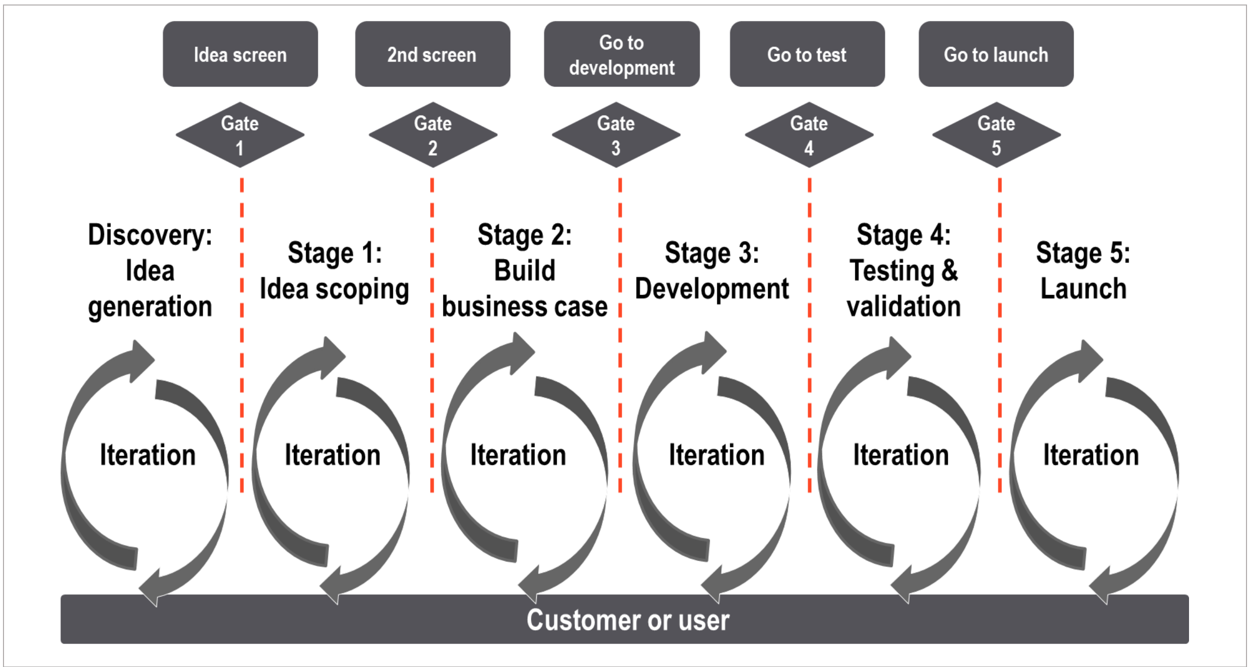


Figure 10: Steps in the idea-to-launch system such as Stage-Gate[26]

[26] Based on Cooper(2014, p. 21)

Cooper(1999, pp. 96–101) works on improvements of NPD and presented over the years various iterations of the so-called Stage-Gate processes, see also 2.2.4.3. The Stage-Gate system breaks down each NPD project into discrete stages. The number of stages is set by the NPD team itself. Each stage consists of various activities, which can be fulfilled parallel by individuals from different functional areas, who work together as a team. In order to manage risk via in Stage-Gate, the activities within a stage must be designed to gather documented and desired information to further clarify technical and business uncertainties in NDP (Cooper, 1999, pp. 96–101). Subsequently, Cooper(2014) formulated the so-called *"The next-generation idea-to-launch system"*, as shown in Figure 10, which includes the factors described above and also the main steps which should be taken in the NPD process.

Based on the given literature, the term product development is in this dissertation herein used as the overall process that takes place until a product is used by customers from idea creation up to the start of production and is a part of the product life cycle.

2.2.2 Factors to developing successful new products

One goal of the product development is to transform existing items with a set of actions into a suitable and desired object. Kern(2016, p. 458) states that this is achieved by developing a product that meets the needs of customers in a most appropriate way. In addition to the functionality of the product, its quality, time and cost aspects, as well as the flexibility with which it can respond to changing customer requirements, contribute significantly to customer satisfaction (Kern, 2016, p. 458). Other characteristics named in line with successful product development projects are environmental, health and safety concerns. A new product or service is always developed with the intend to succeed in the market. However, not all new products end in a success. At present there are several reports and scientifically studies available on performance/success factors of new product development, like Montoya-Weiss and Calantone(1994), or Cooper (2010, pp. 55–61).

Mital *et. al.* (2014, pp. 23–29) summarised several factors, which separate success form failures and mentioned the following attributes:

- Products that succeed in the selected marketplace are unique and offer entirely new benefits that existing products do not have.
- Focus on customer/market wants is critical in the development of a successful product.
- A lack of predevelopment work significantly increases chances of product failure and is therefore critical. Predevelopment work leads to a sharp and early product feature definition and is essential.
- Successful product development teams have multifunctional skills and are empowerment by management. The operative climate needs to be supportive, to recognise effort and to reward success. The primary role of management is to support the team and sufficient resources. This is critical because lack of time, money, and human resources are the main causes of product development failures.

- Many companies/employees are involved in too many projects at one time. Therefore, a project selection is important to narrow down the number of projects.
- The quickness with which a product makes it to market is an important determinant of profitability. However, this advantage is may lost if compromises on product quality or executive quality are made.
- A strict action plan/process gives the product development team many advantages, such as improved teamwork, early detection of failure, higher success rate, better launch of the product, may resulting in shorter time-to-market.
- While it is desirable to have an attractive market, the success of a new product is less sensitive to external environment than to customer needs. Therefore, an inclusion of customers into the product development is recommended.
- It is unlikely that a new product will succeed immediately in a totally new area of expertise. In general, the stronger the fit between the requirements of the new product features and competencies of the development team is, the greater is the likelihood of success.

Innovative new product may have some initial success, but costumers/users typically expect also high-quality products. Mital *et. al.* (2014, p. 29) suggest that product development can be accelerated in many ways but not at the expense of quality of execution, because a poor-quality product may capture some market initially, but the bad costumer experience associated with it can have a long-lasting negative effect. Obviously, the ultimate goal is to have an innovative, high quality product at the market first. In fact, if a new product offers an innovative feature to customers' needs, there is no reason for it to fail (Mital *et al.*, 2014, p. 29).

2.2.2.1 Flexibility

Thomke and Reinertsen(1998) stress that the term flexibility is used in various forms, hence they give a definition for product development: *"flexibility can be expressed as a function of the incremental economic cost of modifying a product as a response to changes that are external (e.g., a change in customer needs) or internal (e.g., discovering a better technical solution) to the development process"* (Thomke and Reinertsen, 1998). Furthermore, they argue that high economic costs of modifying a product, as a response to a given change, is a result of low flexibility in product development (Thomke and Reinertsen, 1998).

Kern(2016, p. 459) describes flexibility in product development as an enabler for companies to meet the evolving needs of the business environment. The flexibility potential of a company is based on accessible resources of different partners; whereby additional knowhow and additional capacities are gained during product development (Kern, 2016, p. 459). To realise these potentials, companies need to be able to work together quickly and cost effectively with different partners.

Sanchez and Perez(2003, p. 139) stress that flexibility in product development is connected with networking and the use of best practices to reduce time and cost in new product development. Those practices include open organizations, broad jobs, employee autonomy, cross-training/job rotation, standardization, group technology, computer-aided-design/computer-aided-engineering (CAD/CAE), cross-functional teams for innovation, supplier development, supplier partnership, just-in-time purchasing, benchmarking, concurrent engineering, rapid prototyping, value analysis and design for manufacturability (DFM), which can lead to faster and cheaper developed new products (Sánchez and Pérez, 2003, pp. 139–140).

2.2.2.2 *Environment, health and safety*

In product development, significant risks can arise with regard to environmental damage, health impairment, human safety and property. Oehmen(2016, p. 70) describes that product development impacts company's reputation for understanding and implementing customer requirements, product quality and environmental, health and safety risks. Depending on the industry, reputational risks can cause serious image damage and have an impact on the sales of products and the recruitment of qualified employees. However, the dominating factor is often the usage phase of the developed product and the product development process itself (Oehmen, 2016, p. 70). Environment, health and safety concerns are also important because many companies like to improve their social image based on new developed product.

2.2.3 Factors for assessing success in product development

Based on Ulrich and Eppinger(2016, pp. 2–3) results a successful in product development in a product which can be produced and sold profitably. Hence product quality, product cost, product development time, product development cost and development capabilities are the main criteria for assessing the performance of a product development effort (Ulrich and Eppinger, 2016, pp. 2–3). In addition, recommendations for successful product development project include for example approach to shortening time-to-market, reducing development costs and production costs as well as improving the product, process and planning quality (Bochtler and Laufenberg, 1995, pp. 11–12; Berndes and Stanke, 1996, p. 18).

The cost, time and quality criteria in product development/project management is in German-speaking countries in many case summarised in the Magisches Dreieck (Angermeier, 2009; Hab and Wagner, 2017, p. 10). In English speaking countries also sometimes called the Iron Triangle (Atkinson, 1999, pp. 337–338). Based on Gleich, Munck and Tkotz (2016, p. 360) certain dependencies between the factors of time, cost, and quality exist, which can be incorporated by using multi-dimensional metrics and tools, such as cost, milestone trend analysis, or the earned value method. The satisfaction of employees in the development process has also a direct impact on the set effectiveness and efficiency goals, which should be measured frequently. However, project cancellations are by no means to be considered negative but mean that for instance, future sunk costs are avoided for futile projects and the funds released are available to other new product development projects (Gleich, Munck and Tkotz, 2016, p. 360).

2.2.3.1 Product quality

Quality is generally defined as the degree in which a set of inherent features of an object meet presupposed requirements (NORM, 2015). Quality is therefore not absolute and indicates to what extent a product or service meets the defined requirements.

Kern(2016, p. 458) suggest to use the knowhow of the development partners in a targeted manner, development cooperation can lead to an increase in innovative strength, a more mature product quality and an increase in customer orientation. In addition, through learning effects and close coordination of the work-sharing processes, an improvement in process quality can be achieved. Inadequate product quality is reflected in the failure to meet the defined requirements for the functionality and durability of the product which may cause also additional costs, like contractual penalties, costs for recall and improvement of already sold products as well as costs in development and production to eliminate the root of the quality problem (Kern, 2016, p. 458).

Cheaper products, which have a low quality, tend to fail on the market and therefore product quality determines the product price customers are willing to pay as well as the market share a new product will gain (Mital *et al.*, 2014, p. 22).

2.2.3.2 Product cost and product development cost

The costs in and the budget of a development project is a critical magnitude. Kern(2016, p. 458) names personnel costs, prototype manufacturing and development costs, production as well as distribution costs as the main factors. Hence, product development costs are typically allocated to the individual product costs (Kern, 2016, p. 458). Product cost set the product price, and these determine how much profit is allocated by a company through sales (Ulrich and Eppinger, 2016, p. 2). Adherence to the product development project timeline is another key objective because it has typically direct influence on personnel expenses and can be influenced by a variety of factors such as the availability of experts or resources, or the quality of the development process and unexpected iterations and rework (Kern, 2016, p. 458). Key indicators in product development projects under cost aspects are cost-effectiveness, cost deviations and the frequency of cost overruns.

Most of the costs in product development are set very early in the process. According to Ehrlenspiel *et al.* (2014, p. 15) at a point were about 9% of costs are consumed, about 70% of product costs are already fixed. Especially in this context, it is obvious that an early integration of production process knowhow in product development is important to reduce costs (Ehrlenspiel *et al.*, 2014, pp. 14–16).

2.2.3.3 Time in product development

In today's dynamic environment, time represents a decisive competitive factor in product development. Time is central to new product development. Generally spoken, new products should be brought to market as quickly as possible. Hence, Kern(2016, p. 459) specifies average product development time and on-time delivery to the market as key figures. The project progress can be analysed, for example, via the number of completed work packages or the amount of achieved milestones, in addition development cooperation/ outsourcing can be used to reduce time (Kern, 2016, p. 459). In addition, product development time defines how responsive a company can be to competitors and technological changes as well as defines how quickly a company obtains economic returns on a product development project (Ulrich and Eppinger, 2016, p. 2).

An ambitious development project driven by time constrains ensures focus and helps to set the right priorities. Meboldt, Matthiesen and Lohmeyer(2013, p. 12) stress that companies only earn money when products are sold on the market. Furthermore, they clarify that every product development project lasts timewise exactly until the market launch date of the new product can no longer be postponed. Based on that product development is not just about bringing the best product to the market but bringing a product to the market in a given timeframe which is just good enough to reach customer's needs (Meboldt, Matthiesen and Lohmeyer, 2013, p. 12).

Also, Karlsson and Ahlstrom(1996, p. 284) stress that time is the ultimate factor to succeed in today's turbulent markets. Hence, they recommend the concept of lean product development, which can enable companies not only to develop new products faster and with less engineering hours but also emphasis on collaboration and integration in product development (Karlsson and Ahlstrom, 1996, p. 284).

2.2.3.4 Efficiency

Efficiency is an evaluation criterion, which can be used to describe useful actions to reach a set objective in a defined manner and is increased by an overlap of tasks as well as a good cooperation of all persons involved in a project (Eversheim and Schuh, 2005, pp. 1–2). Efficiency is therefore also connected to the time criterion. Berndes and Stanke(1996, p. 10) state, in addition, that optimized processes, structures and objectives which are set with the least possible resources can lead to increase efficiency.

However, recognized lately the main driving force for increasing efficiency in product development is the batch size of needed tasks and activities to finish a product development project (Thomke and Reinertsen, 2012). Thomke and Reinertsen(2012) specify that managers should ensure that the team breaks down the project in small and appropriate batch sizes of tasks to fulfil them faster and test earlier in order to increase efficiency. Software companies were the first to understand that relation, but also other companies are citied in their work which improved the efficiency by 220% and decreased defects by 33% when shrinking batch sizes (Thomke and Reinertsen, 2012).

2.2.3.5 Productivity

Productivity, in German speaking literature also called effectiveness, is link to the time and cost criteria. It describes doing useful measures to reach a set objective (Hab and Wagner, 2017, p. 26). Effectiveness is potential increase through clearly defined tasks, competences, responsibilities of the involved persons (Hab and Wagner, 2017, pp. 10–11). Conflicts should be prevented to clear and common objectives.

Productivity in product development is a critical process performance factor and can be increased when the communication is frequent, project teams become more efficient in gaining and using the information being conveyed, sufficient resources for the project exist, engagement of the management and senior management to support the project is present (Brown and Eisenhardt, 1995). Moreover, Berndes and Stanke(1996, p. 10) describe productivity as the right technology for the right products and the right allocation of resources.

2.2.4 Overview of selected models and processes in product development

Product development processes always depend, based on situation, technology and environmental, of the product to be developed, in resulting in various product development process (Albers and Meboldt, 2007b). However, the stages/steps of product development process are in fact compared even if designation differ widely as well as order and connections of each single stage/step.

Integrated product development process, in which all people involved cooperate on common objectives regarding quality, time and costs, as well as parallelisation of the required actions are state-of-the-art (Ehrlenspiel, 2009, p. 188). Ehrlenspiel and Meerkamm(2017, pp. 233–234) stress that the integration of and collaboration between humans, who are motivated and have freedom during their work, is seen as a very important aspect in product developments, because humans have the ability to solve problems creatively. Furthermore, a shared commitment, common objectives and knowhow should be set in product development projects (Ehrlenspiel and Meerkamm, 2017, pp. 233–234). Organisational/human integration and team developments are essential in product development and influence the efficiency significantly (Eversheim and Schuh, 2005, p. 1). Vajna et al. (2018, p. 422) describes the objectives as a facilitation of cooperative work and a common understanding across departments and working groups. Herein, the use of organisational integration can enable a dynamic network of individuals, who adapts itself independently to any form of process or change.

Another important aspect in integrated product development processes is technology. Ehrlenspiel and Meerkamm(2017, p. 251) indicate that technological integration enables a consistent and software supported development project from the idea to production and distribution. Hence, technological integration can be achieved by the implementation of product data management (PDM) systems, the provision of common interfaces such as computer-aided design (CAD) file standards and/or computer-aided manufacturing (CAM) interfaces as well as quality assessments using simulation tools or rapid prototyping (Ehrlenspiel and Meerkamm, 2017, pp. 251–252).

The integration of the production processes early in product development can be important too. As stated earlier, product costs are mainly determined by production costs. Eversheim and

Schuh(2005, p. 15) clarify, for instant, that a selection of test processes and applications can be set to define, tolerances, in order to evaluate them on their necessity or to develop appropriate test scenarios. Unnecessary tight tolerances might have an influence for the choice of production process itself and thus on the production cost. Revolutionary changes in production technologies may require sometimes massive adaptation of existing processes and product concepts as well as an early adjustment and selection of the production processes can support a smooth ramp up (Eversheim and Schuh, 2005, pp. 15–16).

Furthermore, a product development process should include a product definition and strategy technology planning, which needs to match rising technological innovation, market and consumer requirements (Eversheim and Schuh, 2005, pp. 13–14). It is also recommended that market and consumer requirements should be collected at an early stage and should be translated systematically into the definition of product features. Consumer Co-creation, for instance, is a relatively new research field which clarifies the in-depth integration and empowerment of consumers/users in the new product development (Hoyer *et al.*, 2010, p. 283). Another important aspect is the integration of a quality planning system, which serves as a guidance for ensuring product features, cost, and environmentally-orientated perspectives are incorporated in the early phase of product development (Eversheim and Schuh, 2005, p. 15).

The following paragraphs describe various processes of product development, which are selected on the basis of the dissertation focus, see 1, and on the stated constraints, limitations and challenges of start-ups, see 2.1. Experiences show that especially start-ups tend to choose the model of 2.2.4.4 Design Thinking or 2.2.4.5 Agile Engineering as their product development process, if any is implemented.

2.2.4.1 Simultaneous or concurrent engineering

In the past decade new products have primary focused on functionality and performance, which is no longer enough for today's competitive markets. Product developers today need to focus on aspects such as costs, timing, current state-of-the-art technologies, which are may include in the new product, and also availability of means of manufacturing technologies. Mital *et al.* (2014, pp. 15–16) suggest to meet these goals that various disciplines such as designers, manufacturing engineers and controllers must closely work together in product development process.

Concurrent engineering (CE) and simultaneous engineering (SE) are concepts for integration in product and process development (Klabunde, 2003, p. 16). CE, developed in 1986 in the USA, mainly concerns the integration of the product development and the development of the design- as well production processes. It focuses mainly on increasing the competitiveness by decreasing the lead-time and has a side effect in improving quality and cost (Sohlenius, 1992). In contrast, SE, developed in Europe, empowers the simultaneity of individual steps in the product development process (Berndes and Stanke, 1996, p. 15). Based on Berndes and Sranke (1996, pp. 18–19) ,the following three essential strategies exist for both terms:

- **Parallelisation:** Parallelisation aims at a reduction of the overall time needed for the whole product development process. Independent and partial process steps should be performed in parallel. Whereas dependencies between partial processes exist, processes must start with incomplete data and information in the parallelisation process. This must not necessarily lead to inferior quality of results, because in many cases there is no need for all results of the upstream process at the beginning.
- **Integration:** Integration is utilised through dedicated cross-functional teams who work to overcome today's departmental boundaries and therefore improve communication.
- **Standardisation:** Standardisation is the basis for all parallelisation and integration efforts. It is achieved by restructuring the processes or product. Overall, standardisation can have many different aspects depending on the field to be applied. It can be seen in technical aspects of a product (modules, components and interfaces), in the development process (phases and organisation) as well as in the organisational structure (involved departments and comparable projects). Standardisation helps to implement transparency and stability in a development project.

2.2.4.2 Design for "X"

As introduced, product developers need also to consideration the issue of mass production when designing new products. Hence, the design for "X" (DFX) describes an integration of costumer/market needs, materials, processes, assembly and disassembly possibilities, maintenance needs, as well as economic/ social needs in the product development (Mital *et al.*, 2014, pp. 16–18). Mital *et al.* (2014, pp. 16–18) stress also that DFX is an interactive process, which requires frequent expert feedback during its various stages.

Based on Huang(1996, p. 1), simultaneous/concurrent engineering embrace an ideal environment for product development, whereas DFX is an effective model to implement SE/CE. The objectives, like improving quality, reducing costs, shorting development cycle time, increasing flexibility and rising efficiency and effectiveness, of DFX are also similar to SE/CE (Huang, 1996, pp. 1–3). The "X" in DFX stands for disciplines and abilities needs, such as manufacturing, inspecting, recycling, assembling, and "Design" is interpreted as product design and development.

2.2.4.3 Stage-Gate process

According to Cooper(Cooper, 2017, p. 99), is the Stage-Gate process characterised by breaking the product development into a predetermined set of stages, each stage consisting of a set of described, cross-functional and parallel activities with gates being the entrance to each stage. These gates help to control the process, act as a progress control and management checkpoints. Hence the typical Stage Gate process includes six stages and each stage is more expensive than the previous one as well as has the purpose of generating new knowledge on the development product (Cooper, 2017, p. 99).

Various iterations of the Stage-Gate process have been developed in the last decade. However, the following six stages are commonly described according to Cooper (2017, pp. 124–128):

- **Discovery:** ideas are generated, and opportunities are discovered.
- **Scoping:** preliminary investigation of the project.
- **Building the business case:** detailed investigation of the project; business cases, product and project definition, as well as a project plan are created.
- **Development:** design and development work of the actual product
- **Testing and validation:** test runs in a laboratory and market environment with the aim of verification of the proposed product features.
- **Launch:** start of production, marketing and commercialisation.

Each of these stages are preceded by a gate. As mentioned, gates represent checkpoints where go/ no-go decisions are made by the entire team or by senior managers. Cooper(2017, p. 123) proves that the aim is to control the resource required to complete a product development project and to debate all the information obtained so far.

The third generation of the Stage-Gate processes is especially adapted based on rising circumstances in new product development projects and is characterised by so-called Fuzzy Gates (Cooper, 1994, p. 9). Cooper(1994, pp. 9–10) formulates the following key aspects to encounter arising conflicts and challenges in product development:

- **Fluid and adaptable:** Activities do not necessarily have to be connected to one phase only but can also be carried out across phases or take place completely in another phase.
- **Fuzzy Gates:** There are no absolute states in the checkpoints. This means that the development process can continue under certain conditions even though some tasks have not yet been completed.
- **Focused:** Every decision is made taking into account the entire project. May limited resources must be distributed to the existing projects in a meaningful way.
- **Flexible:** Here, flexible stands for the adaptation of the process to the dynamics of the current conditions. The development team can decide which phases are needed to develop the product and can skip to needed phases.

Based on Meboldt(2008, p. 35), the iterations of the Stage-Gate processes clearly show that today's and most likely future product development processes increase in complexity based on networking and integration of various needed field. Resulting in a high degree of management, coordination and control activities as well as a need for transparent decision-making (Meboldt, 2008, p. 35).

2.2.4.4 Design Thinking

Design Thinking is a model in product development that aims to support innovations and change by a human-centred approach. Design Thinking was first named in literature in 1987 and later elaborated and successfully applied over the years by the company IDEO[27], a global design and consulting firm founded in 1991 (Curedale, 2016, p. 62). The first Apple mouse[28] or the Palm V[29] are the stand-out innovations by IDEO and proof of the success of the company and its methods (Thomke, 2000). Historically, Design Thinking is an offspring of Thomas Edison's team-based approach to innovative product development whereas the objective was that the experimenters/developers should be supported to learn something new from each product development iteration (Brown, 2008, pp. 85–86).

Nussbaum(2004, pp. 3–5) emphasises that in Design Thinking individuals carry out the process of designing a new product or service by breaking it down into actions like observation, brainstorming, rapid prototyping, refining, and implementation. Each action is used with the intention of utilising creative problem-solving capabilities in order to achieve innovative solutions for a given problem (Nussbaum, 2004, pp. 3–5).

As already stated, Brown(2008, p. 86) describes Design Thinking as a human-centred approach for product creation which builds on designer's sensibility and methods to integrate people's needs, technological possibilities as well as requirements for business success in the process. He future states that new products or services need to be empowered by direct observation of individual's/user's wants and needs (Brown, 2008, pp. 88–89). Hence, Design Thinking is a model that imbues prototyping and.

The following general phases can be described in Design Thinking according to IDEO(2012, pp. 10–16):

- **Discovery:** The basis for generating ideas is user understanding. Discovery is the phase where empathy is employed to gain inspiration for creating innovative solutions.
- **Interpretation:** Just collecting data and gaining empathy for the user will most likely not result in a good project. Therefore, it is necessary to analyse the acquired knowledge before brainstorm sessions and idea generating are started.
- **Ideation:** Brainstorming sessions are used to create possible solutions for a specific task fast. However, a key factor is a diverse group of individuals because having different fields of expertise in the group means also having different views on a task.
- **Experimentation:** Ideas developed should be realised by prototypes. Prototypes are important to show and explain the main concept of the ideas as well as give the possibility to obtain feedback. A prototype is something that users can interact and get a feeling of what the idea looks like. Ideas should be further developed and refined based on the user's feedback.

[27] www.ideo.com (Accessed: 2 June 2019)

[28] www.ideo.com/case-study/creating-the-first-usable-mouse (Accessed: 2 June 2019)

[29] www.ideo.com/case-study/handheld-organizer-becomes-sleek-accessory (Accessed: 2 June 2019)

- **Evaluation:** A product development is not finished when the prototype is completed. It is necessary to define the next steps.

Although Design Thinking is not a skill for individuals. Based on Curedale(2016, pp. 93–95) it should be performed in groups/teams whereas a team should include members who have experience in more than one discipline and skill due to the complexity of the given task. Forming teams with the right mix of disciplines is not easy but the goal is to have a as diverse team as possible in terms of expertise and personality (Curedale, 2016, pp. 93–96). In addition, Kelley and Littman(2001, pp. 4–14) name other success factors for Design Thinking, like mind-set of the team members, focus on human values and users, and rules and a framework in which the team can independently work.

As stated, potential solution ideas are always tested through rapid prototyping in Design Thinking. Rapid prototyping must not involve complex and expensive materials. According to Brown(2009, p. 88) prototypes should demand only as much time, cost and effort as necessary in order to generate useful feedback to evolve a solution. The objective is to learn more about the strengths and weaknesses of developed solutions and to identify new directions that further development stages might take (Brown, 2009, pp. 88–89).

2.2.4.5 Agile Engineering

Based on Douglass (2016, p. 42), agile methods are characterised by lightweight and less bureaucratic processes with short iterative cycles whereas users are actively involved, knowledge is shared within the team, mainly without documentation, and the team organises itself. Processes, principles and work structures are not predetermined, but arise or change during the project (Douglass, 2016, pp. 42–43). Other aspects are a positive attitude of the developers towards changes, simplicity, rapid prototyping, and ongoing experimentations.

Beck et al.(2001) formulated the agile manifesto in response to traditional software development processes, which were considered cumbersome, lengthy, inappropriate, and neither customer- nor developer-friendly and claim that with the help of various so-called agile development methods, software should be developed which better meets customer requirements. However, Fritzsche and Keil(2007), for instance, do not see the procedure described in the agile manifesto as a process, but rather as collections of techniques, tools, and activities.

With the help of digital manufacturing tools, some aspects for agile software development can now be translated to product development of physical products, so-called agile engineering or agile product development. Individuals can develop ideas fast while testing features with users. In addition, this method encourages teams to fail quickly which gives the possibility to learn and improve products at a faster pace. Peels(2016) lists the following principles for agile product development of physical products:

- Continuous collection of customer feedback means that it is more likely that the new products meet the customer's needs.

- The interplay of design, construction, manufacturing and marketing enables teams to understand better each other's perspectives, needs and challenges.
- Each iteration gives a physical prototype to show and discuss. All individuals involved learn more easily from holding, testing and discussing a real prototype.
- Testing the physical prototype helps you to identify possible problems.
- More, faster and cheaper iterations mean that a greater number of potential solutions for the given problem can be explored.
- Continuous testing means that technical risks are more likely to be exposed throughout the process.

Rapid prototyping is often mentioned in line with agile engineering. Based on Schmutzler *et al.* (2016, p. 954), rapid prototyping describes the development of models and prototypes in the early stages of product development, whereas additive manufacturing techniques are often used to build functional/technical components. With the prototypes produced in this way, the properties of the end product can be simulated realistically, so that an early series-near functional test is possible (Schmutzler *et al.*, 2016, p. 954). Ehrlenspiel and Meerkamm(2017, p. 386) state that with the help of rapid prototyping not only haptic feedback and product handling patterns arise but it is also possible to generate fully loadable test scenarios. Furthermore, the adaptation of modular systems to meet customer-specific wishes becomes imaginable (Ehrlenspiel and Meerkamm, 2017, p. 386).

2.3 Maker Movement

Anderson(2012) started his popular book on the Maker Movement with the following saying: "*We are all Makers. We are born Makers [...]*" (Anderson, 2012, p. 10). Gershenfeld(2012, pp. 43–46) detailed that personal fabrication was long perceived as a science fiction, but with today's digital manufacturing machines any individual can now make anything, anywhere. These new capabilities are described within the Maker Movement and the following section.

In the following section, important terms and milestones in the development of the Maker Movement are clarified. Influences, on this movement come from various fields such as mass customisation, open innovation, sharing economy and digital fabrication as discussed later. The main drivers of the movement are individuals, so-called Makers, and physical facilities, so-called Makerspaces, as also clarified later. As claimed by many authors, is the widespread access to easy-to-use capabilities for designing, manufacturing and distributing an enabler for Makers to invent and build hardware products themselves. Meaning that building, testing and iterating based on a functional physical prototype got faster and simpler. As a result, Makers may become entrepreneurs and start their own hardware start-up based on their ideas and built prototypes.

2.3.1 Definition and terms

The Maker Movement is prompted by the convergence of several trends. The introduction of new machines and tools, like consumer 3D printers and open-source microcontrollers, access to fabrication tools, easier sourcing of parts, as well as the possibility of online direct distribution of physical products are promoting the movement's growth (*The Economist - Technology Quarterly*, 2011, pp. 1–2). Makers are inspired by the work of others and share their own work. Makers learn to create their own procedure to build innovative products, hence there is a likelihood that the Maker Movement will transform education significantly (Dougherty, 2013b, pp. 10–11).

One of the first clarifications for the Maker Movement was given by Hatch(2013). In his book he tried to describe the values and sprit of Makers. Hatch(2013, pp. 1–2) formulated the following nine principles as main pillars of the movement:

- **Make:** This is fundamental to what it means to be a human.
- **Share:** Makers feel wholeness when they share what has been made and what has been known about making with others.
- **Give:** There are few things more selfless and satisfying than giving away something you have made.
- **Learn:** Makers seek always about learning to make something.
- **Tool up:** Makers must have access to the tools and machines for their projects at hand; therefore, they invest in and develop local platforms to access tools they need to make.
- **Play:** Makers are playful with what has been made, and be surprised, excited, and proud.
- **Participate:** Makers join the movement and reach out to those who want to discover the joy of making.
- **Support:** Emotional, intellectual, financial, political, and institutional support is required.
- **Change:** Makers embrace the change that will naturally occur as they go through.

Anderson(2012, pp. 55–59) stresses that the Maker Movement shares three main characteristics: First, usage of digital desktop tools to design and create new prototypes and products; Second, a culture to share those designs and prototypes in order to collaborate with others in online communities; Third, usage of common design file standards that allow anyone, if desired, to submit designs to commercial manufacturing services to be produced in any number. According to him all are transformative for society and can radically foreshorten the path from idea to product, just as the Internet did in software development.

Gandhi *et al.*(2013, p. 2) describes the goal of mass customisation in providing individualised/customised products at mass production prices which will increase the competitiveness of companies via on-demand production. The key driver to realise such a profitable small-batch production is a flexible manufacturing process (Gandhi *et al.*, 2013, pp. 2–3). Such small-batch production systems can be found within the ecosystem of the Maker Movement.

The term sharing economy/collaborative consumption describe a peer-to-peer-based action made possible by activities of sharing, exchanging and rental of resources without owning the good (Hamari, Sjöklint and Ukkonen, 2016, p. 2047). Comparing to Hatch and Anderson, this view is also true for the Maker Movement. A Makerspace is a great example for sharing, exchanging and commonly used resources.

The growth of the Maker Movement is also based on a new set of attitudes. The Economist summarised those: released open-source hardware rely on open-source software that turn simple code into actions; digitally-designed physical objects are shared based on the STL file standard[30]; 2D/3D modelling software can be downloaded and used for free; sharing of work in online communities such as Thingiverse[31] or YouTube; and exchange of knowledge and discussions in communities (*The Economist - Technology Quarterly*, 2011, p. 2).

Lindtner, Hertz and Dourish(2014, p. 440) report that the Maker Movement is no longer just a hobbyist movement driven by a loose collective of computer enthusiasts, artists, designers, geeks, and developers. Fundamental to this development is the confluence of crowd funding websites such as Kickstarter[32], the existence of Makerspaces on a global scale and publications such as Make: magazine[33]. The combination of new financial funding models, physical spaces and publications is crucial, while magazines help to spread an understanding of making projects, Makerspaces provide the physical space and tools to bring people together in implementing these ideas in practice (Lindtner, Hertz and Dourish, 2014, p. 440).

Furthermore, it is likely that making will promote also a shift in the manufacturing scene, which will allow both large and small companies to function concurrently and fruitfully. Participants at the Maker Impact Summit claim that the Maker Movement provides individuals with access to the tools that allow them to manufacture on a smaller scale which makes the boundary between product makers and product sellers more and more blurred (Media Maker and Deloitte Center for the Edge, 2014, pp. 16–18). Consumers want increased personalisation, customisation, and a human aspect to the product they are purchasing, and people now expect products to provide distinct services: both can be provided within the Maker Movement.

2.3.2 History and milestones

Making is not new, but new technologies, globalisation, and cultural shifts have positively influenced the Maker Movement. Major milestones are shown in Figure 11.

[30] According to Burns (1999) is the digital STL (Stereo Lithography) file a triangular representation of a 3-dimensional surface geometry.

[31] www.thingiverse.com (Accessed: 2 June 2019)

[32] www.kickstarter.com (Accessed: 2 June 2019)

[33] www.makezine.com (Accessed: 2 June 2019)

According to Holman(2015, p. 4) the roots of the Maker Movement date back to the mid-19th century. At that time, a global effort emerged, initially in Scotland, which revolved around foundation of the Mechanics' Institutes, which had libraries, lecture halls, and laboratories in an era before artificial lighting or reading rooms were available, combined (Holman, 2015, p.4).

In the 1970s, Hess described a network of what so-called shared machine shops in the neighbourhood of Adams-Morgan, in Washington, D.C. (Holman, 2016). While his vision never materialized, he laid groundwork for today's Maker Movement: open source, community-based, and welcoming to all were his key elements of those shops. Later the Greater London Enterprise Board (GLEB) built on these ideas and implemented in the mid-80s five so-called Technology Network Centres in which unemployed workers could retrain for a new job (Holman, 2016). Grounded on the believe that workers would also use the facilities to invent new products and companies. However, it did not succeed, and the project was cancelled later, but the GLEB and Hess experiments were both may hampered by the technology available to them at the time (Holman, 2016).

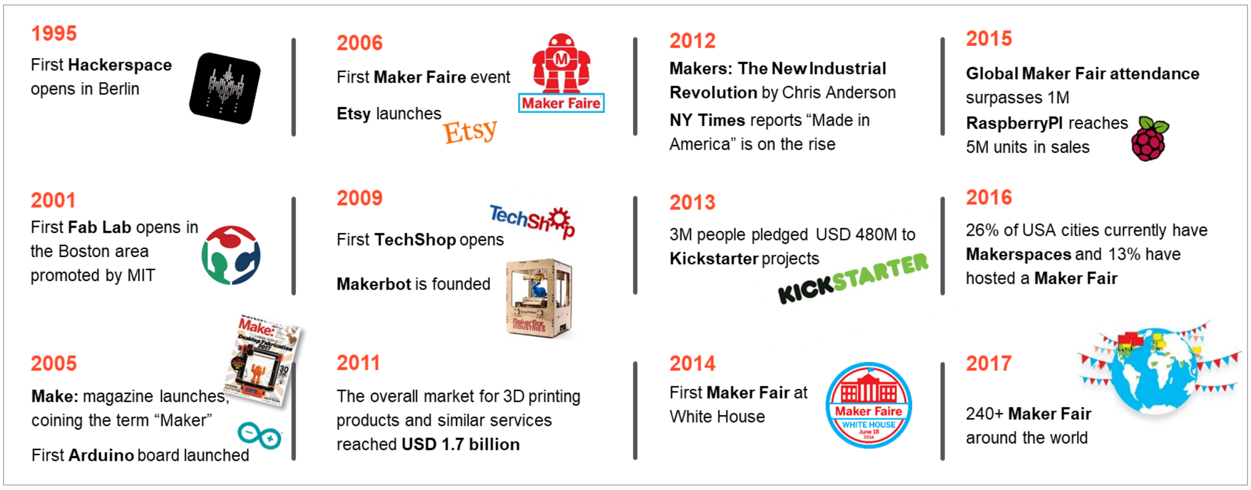


Figure 11: Milestones in the rise of the Maker Movement[34]

However, the Maker Movement gains momentum due to increasing emphasis on new technologies for manufacturing and production. Forerunners of today's Makerspaces included the labs of Thomas Edison and Alexander Bell, both of whom recognised the value of collaboration in new product development (Holman, 2015, pp. 4–5). The role of technology as an invaluable component of the movement became even more evident.

Besides these developments, in the 1950/60s a so-called hacker culture also emerged. Its members were committed to peer production, the open sharing of knowledge, and to designing technologies that were open and modifiable by users (Levy, 2010, pp. 3–6). Based on new digital technologies collaborative workspaces, like the Xerox Palo Alto Research Center (PARC)[35] emerged in the 1980s (Holman, 2015, p. 5). Roughly fifty years later, a new hacker movement is

[34] Based on Maker Media(2018)
[35] www.parc.com (Accessed: 2 June 2019)

present that both draws from this history and departs from it in significant ways which is rooted in a growing network of Makerspaces that expand the ideas of the Web generation into the hardware world (Lindtner, Hertz and Dourish, 2014, p. 441).

In 1998, Gershenfeld(2005, p. 5) started a course, in which he focused on the new possibilities for digital fabrication. This course should enables the possibility of producing one customised product for just one person (Gershenfeld, 2005, pp. 5–6). In 2003, the same group of people set up the first Fab Lab, a franchise of Makerspaces, short form of fabrication laboratory, with the intention of offering a facility to development physical products, to learn and to innovate (Gershenfeld, 2012, p. 47). As discussed in section 2.3.4.1, Fab Labs provide easy-to-use and mostly digital production machines for individuals. The success of the Fab Lab initiative is exemplified in the impressive and rapidly rising list of more than 1,000 registered labs worldwide (fablabs.io, 2018).

The current iteration of the Maker Movement, the branding has been credited to the 2005 founding of Make: Magazine, can be largely attributed to the new-found accessibility and affordability of technologies such as the Internet and 3D printers. According to O'Reilly(2013) Make: marks a broader transition from hacking to making. The magazine's founder Dale Dougherty had initially proposed to name the magazine "hack" to reflect on earlier days, but Dougherty described when he proposed the name "hack" that people were not convinced and suggested calling it "make" instead (O'Reilly, 2013).

Another important aspect about the Maker Movement is the Maker Faire[36], also started by the publisher of Make: in 2006. Maker Fairs are a place for Makers to present their work and skills: more than 200,000 people visited the two major Maker Fairs held in the Bay Area and New York annually and 190 Maker Fairs were held around the world in 2017 (Maker Media, 2017). Overall, Maker Fairs can be viewed as places where physical products and inter-disciplines meet.

Today, digital fabrication along with the rising number of Fab Labs, Hackerspaces, or in general Makerspaces are the main drivers of the Maker Movement. Gershenfeld(2012, p. 57) claims that these initiatives share the goal of democratising the manufacturing process. This gives every individual the chance to invent and build physical products themselves, a situation which was impossible in the past without organisational support (Gershenfeld, 2012, p. 57).

Former United States President, Barack Obama, encouraged in 2014 people to become *"Makers of things, not just consumers of things"* (Fried and Wetstone, 2014) at the White House Maker Faire.

[36] www.makerfaire.com (Accessed: 2 June 2019)

2.3.3 Community and individuals within the Maker Movement

Based on Hagel, Brown and Kulasooriya(2014, p. 3) is a distinction of Makers to similar terms, such as inventors, entrepreneurs, developers or designers, is nowadays blur due to modern technologies and a worldwide connected ecosystem. Today, Makers invent and build hardware and software products without traditional organisational/institutional backing and facilities and can solve essential problems (Hagel, Brown and Kulasooriya, 2014, p. 3). Furthermore, Makers can connect also with other individuals in real or virtual. According to Gauntlett(2011, p. 2), making is not only about connecting materials but also entails the connection of people by sharing problems, products and ideas.

According to Peppler, Halverson and Kafai(2016, p. 2), the term Maker denotes anyone who builds or adapts objects by hand, mainly without any business context but the interest in finding out how things may work. Based on them, making is an alternative to the consumer culture and seeks to hack, mod, tinker, create, repair, and re-use tools and materials (Peppler, Halverson and Kafai, 2016, p. 2).

Makers are a very diverse group of individua. They include for example 3D printing enthusiasts, tinkerers, crafters and mechanics. All like to customize objects for instance by equipping them with sensors and Internet connectivity as well as prefer to design their own items which are manufactured on demand and were turned into the Maker Movement because of the commonly used infrastructure available in well-equipped spaces (Morozov, 2014).

An online survey in 2016 questioned over 3,000 people in over 100 countries, who identify themselves as Makers and highlights main characteristics of Makers (Hackster, 2016): The majority of the interviewees are male and between the ages of 26 and 48, 71%. They consider themselves as hobbyists, followed by students/educator and professionals. Home automation (68%), robots (56%), wearables (35%), or drones (33%) are the main fields of interest. Their expenditures on self-owned hardware and components are mostly between USD 11-25 (25%) and USD 25-50 (29%). Based on the survey results a typical Maker spends between 2-3 hours (35%) on building physical products each week. 56% of all respondents would like to sell what was made and 6% already do so. Overall 90% of all Makers interviewed do not earn a living from the projects they have created. (Hackster, 2016, pp. 4–24) Based that, the most common Maker architype is a hobbyist who spends roughly USD 25-50 on home automation/robotics projects whereby this activity requires less than three hours a week.

Makers are interested in selling their products and becoming professionals. Hagel, Brown and Kulasooriya(2014, pp. 6–8) therefore classifies three evolution steps of Makers: To become a Maker in the first step, so-called **Zero to Maker**, an ability to learn new skills and access to tools and machines are needed. The second evolution step, called **Maker to Maker**, is based on communication and collaboration with other like-minded individuals in order to gain more expertise and skills, which can be carried out either in physical locations or by exchanging in online communities. In their view, the final evolution step is **Maker to Market**. In this step, Makers take the risk to introduce their developed products to the market, in various cases via crowd funding or peer-to-peer e-commerce platforms (Hagel, Brown and Kulasooriya, 2014, pp. 6–8). This is also the step where hardware start-ups may be born, but only a few Makers will manage and are willing to reach this step. In section 4 of this dissertation the ecosystem of Makers is in depth described and structured as well as various representative elements and examples are named which may support the evolution from Zero to Maker towards Maker to Market.

Based on those broad definitions and statement, Lou and Peek(2016) assumption become clearer. They assume that around every second adult in the USA calls him/herself a Maker (Lou and Peek, 2016), which proves also how broad making is understood and how inclusive the Maker Movement is.

2.3.4 Infrastructure and types of Maker Movement-related facilities

The recent standing of the Maker Movement has arisen for several different reasons. Firstly, the availability of information via the Internet. Secondly, increased access to high- tech machines and thirdly, human desire to be engaged in production. All these facets coalesce in so-called Makerspaces, Hackerspaces, Techshop or Fab Labs. These are generally spoken workshops where members share tools for professional gain or hobbyist pursuits.

The most common denominator of all the above-named facilities is that they are driven by the Internet, as a network and place for exchange, and they also make substantial use of digital fabrication machines, which are an interface between digital and physical production (Gershenfeld, 2005, pp. 11–17). According to Mota(2011, p. 279), all facilities have in addition the common goal of democratising the manufacturing itself. All facilities offer, based Hlubinka *et al.* (2013, pp. 5–8), dedicated locations for Makers to work on physical and tangible products, on their own or together in teams.

In 2005, the Make: magazine was published the first time and the term Makerspace was created by them (Holm, 2015b, p. 3). As described in 2.3.2, Makerspaces in other forms may already existed before 2005, but the main differences are now the unifying platforms of the spaces and the given support of the community.

Makerspaces are tight connected with Makers and their activities. Peppler, Halverson and Kafai(2016, p. 4) stress that there are no minimum requirements in terms of infrastructure, equipment or size to open a Makerspace. Every facility can be as individual as its initiator wishes and are typically fuelled with the ideas and the desire of its local community (Peppler, Halverson and Kafai, 2016, pp. 4–6). However, Hlubinka *et al.* (2013, p. 1) describes areas in addition, to technology offerings, which should be addressed in order to establish a Makerspace successfully:

- **Knowledge** The community generates a large body of content, providing this content in an appropriate way for other learners to discover and access is a key aspect.

- **Network:** Concepts for permanent access to a collaborative network of educators and users worldwide who share ideas, insights, and best practices need to be considered.
- **Train and support:** Ongoing feedback, support, and workshops need to be provided to users. The goal is to cultivate a vibrant community of best practices.
- **Project library:** A library provides knowledge and information on what users are doing in the space. This allows like-minded individuals to filter projects based on their own interests, abilities, and available equipment.
- **Tools:** Easy access to pre-packaged kits with standardised sets of tools and advanced kits are important.

Van Holm(2015b, p. 12) illustrates that the terms Makerspace, Hackerspace or Fab Lab are interchangeable. May the largest difference relates to diverse operational models. Smith(2013, pp. 3–4) also stated that Makerspace is used in literature as a generic term. In the past decade the number of these has increased fourteen-fold on a global basis (Lou and Peek, 2016). For instance, a recent report by the Joint Research Centre (JRC) identifies 826 Makerspaces in the EU28 region alone, whereas 397 are named Fab Lab, 327 Hackerspace and 102 are other types of Makerspaces (Rosa *et al.*, 2017, p. 14).

A Google search terms trend analysis shows the interest in the terms Makerspace, Fab Lab, Hackerspace and Techshop over time, see Figure 12. In line with the statements above the relative new term Makerspace raised popularity over the last couple of years and the other terms decreased in their popularity.

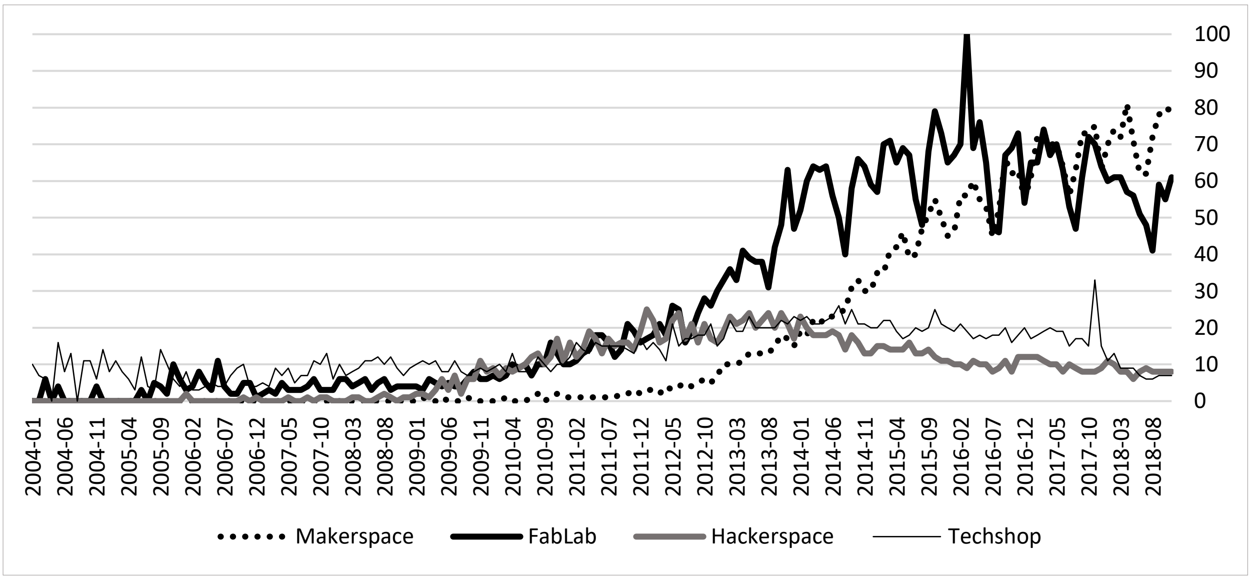


Figure 12: Interest over time on Google search terms for Makerspace, Fab Lab, Hackerspace and Techshop over time.[37]

[37] Based on Google Trends(2018)

As concluded in an early study by Böhm, Friessnig and Ramsauer(2015), Makerspaces exist with different operational models and sizes, but in general every space serves as a gathering point for tools, self-made projects, mentors, and expertise. However, the equipment is seen by Böhm, Friessnig and Ramsauer(2015, p. 4) as the most important aspect of a Makerspace and a clarification of typical Makerspace equipment[38] was given:

- **Basic digital prototyping equipment:** different technologies such as 3D-printers (FDM, SLA), laser cutters, vinyl cutters and 3D-scanners
- **Wood shop equipment:** CNC milling machines for wood, table and band saws, sanders, planers, drill presses.
- **Metal shop equipment:** welding tools, turning lathes, hand metalworking, sheet metal forming, band saws for metal, CNC milling machines, plasma or laser cutters, waterjet cutter.
- **Electronics:** circuit board production tools, PCB milling machine, soldering irons.
- **Textiles/handcraft area:** sewing machines, glue guns, pliers, T-shirt presses, vinyl cutters.

Lately, various Makerspaces also evolved which not only focus on easy-to-use and desktop-sized tools and machines but also on industrial-graded equipment. Industrial-graded equipment is for example: injection moulding presses, automation robotics, automatic electronics assembly equipment, automated measurement equipment, and process control equipment. Those industrial-oriented Makerspaces enable more ambitious objectives and allow Makers to focus also on production in addition to prototyping (Brateris and Kam, 2017, p. 3).

In this dissertation, those different Makerspace concepts are discussed in the following and the term Makerspace is herein used as a generic term. However, there are some Maker-related facilities that are not dealt with in this dissertation, such as Biolabs or artisan-labs, because digital manufacturing only plays a minor role within these types.

2.3.4.1 Fab Labs

The first Fab Labs originated in the Boston area promoted by Gershenfeld and the MIT in 2003 (Gershenfeld, 2012, p. 47). A Fab Lab offers easy-to-use and computer-guided prototyping/manufacturing infrastructure for learning and product innovation to individual (Thompson, 2018). All Fab Labs together constitute a global network, the so-called Fab Foundation (*Fab Foundation*, 2018b). The success of the Fab Lab initiative is evident in the impressive amount of 1,299 active locations worldwide (fablabs.io, 2018).

There are four main criteria, which are defined in a so-called Fab Charter(2012) that must be fulfilled in order to qualify for a Fab Lab title: First, Fab Labs provide public access at least once a week to democratise fabrication by machine use for individuals. Second, Fab Labs have to

[38] An in-depth analyis of typical Makerspace equipment is discussed in the supervised thesis by Karre(2015)

express the commitment to be part of the global network and visualise the Charter. Third, all Fab Labs share a basic core set of tools and machines. Fourth, Fab Labs should actively participate within the global network by knowledge sharing (*The Fab Charter*, 2012).

Stated by Van Holm(2017, pp. 4–6), each Fab Labs has its own culture, specific activities, interests, goals and focus in particular on educational aspects. Therefore, they are located in many cases at educational institutions such as schools or universities (Holm, 2015b, p. 5).

The Fab Foundation(2018) organisation was formed in 2009 in order to cope with the massive growth in numbers of Fab Labs which like to join the network. The Fab Foundation mission is: "to *provide access to the tools, the knowledge and the financial means to educate, innovate and invent using technology and digital fabrication to allow anyone to make (almost) anything, and thereby creating opportunities to improve lives and livelihoods around the world"* (Fab Foundation, 2018a). In order to support this the Fab Foundation(2018b) offers several programmes:

- **Fab academy:** Provides training in digital fabrication for new Fab Lab operators, and educators.
- **Fab research:** Research activities in the Fab Lab network, such as educational outreach programmes.
- **Fab education:** Presents and supports digital fabrication education.
- **Fab project:** A platform to gather together a large number of projects developed in Fab Labs which may benefit local communities.
- **Fab conference:** An annual event where the global Fab Lab community gathers.

Troxler(2018) summarised the most important Fab research works lately. He concluded that across the seven past Fab conferences, research has been mainly carried out in four areas: education, technical projects, analyses of local, national and regional Fab Lab networks, and the social aspects of digital fabrication, as well as that the Fab research stream at the Fab conferences is up to now the only places where transdisciplinary encounters are systematically curated (Troxler, 2018, p. 9).

2.3.4.2 Hackerspaces

According to Schön, Ebner and Kumar(2014, p. 4), the first Hackerspaces, c-base[39] and C4[40], evolved in Germany and had once the aim to provide physical public meeting rooms for individuals/groups of programmers to engage in software developments. The concept of Hackerspaces spread soon thereafter to the USA (Schön, Ebner and Kumar, 2014, p. 4). Later Hackerspaces emerged and started focusing also on electronics and physical products as well as

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[39] www.c-base.org (Accessed: 2 June 2019)
[40] www.koeln.ccc.de (Accessed: 2 June 2019)

fabrication, hence these spaces offer sometimes also classes (Cavalcanti, 2013). Most Hackerspaces are member-driven.

While Hackerspace exist today in many types, the typical Hackerspace is an organisation, like a club, founded by its members for their mutual interests and benefit as well as collects duties to rent a storefront/warehouse and to buy insurances (Baichtal, 2011, p. 3). Based on Baichtal(2011, p. 3), the most fascinating aspect is the collaboration aspect in those spaces: people are continuously working together and discussing issues.

2.3.4.3 Techshops

Techshop was a trademarked name and was a USA-based for-profit organisation that provided high quality machine, tools, as well as associated classes in return for paid memberships and fees. Founded in 2006 by Jim Newton and Ridge McGhee, Techshops were typically huge locations of more then 1,500m^2 and offered industrial-grade machines for wood, metal, textiles, welding, and electronics (Dickinson, 2011).

The Techshop locations were equipped with tools worth a total of more than USD 1m in which individuals could also attend paid classes and use tools as well as professional software (Newton and Woods, 2017, p. 4). The Techshop company was the largest public access workshop network and computer-enabled manufacturing platform in the world.

Members of Techshop have also good business success. Hatch stated that the members of the Bay Area Techshop catalysed USD 10bn in shareholder value, USD 2bn in annual sales and USD 200m in annual salaries. Based on him members have come in and picked up skills that they need to start their own business or to start an educational institution or to pursue their dreams (Maker City, 2017b).

Since founding, Techshop has expanded not only nationally and internationally, but also with institutional and corporate collaborations. Ford, GE, the U.S. Department of Veterans Affairs Center for Innovation, Lowe, and Arizona State University were the main partners of Techshop (Maker City, 2017b).

Even though Techshop had a premium offering, it went bankrupt in November 2017 and had at its peak ten locations in the USA, as well as four international locations in France, United Arab Emirates and Japan (Newton and Woods, 2017, p. 2). Some spaces have been re-opened by the lively community created. However, the Techshop concept and operational model acted as a pioneer in this field and influenced many other professional Makerspace worldwide, which are still in existence, like NextFab[41] or UnternehmerTUM MakerSpace[42].

[41] www.nextfab.com (Accessed: 2 June 2019)

[42] www.maker-space.de (Accessed: 2 June 2019)

2.3.4.4 Makerspaces at a library

A field of increasing importance is the establishment of Makerspaces at public libraries. A recent survey in the USA of 143 librarians noted that 41% of respondents currently provide a Makerspace in their library (Price, 2013).

Barniskis(2014, p. 836) reviewed qualitative studies on Makerspaces at public library and identified four key elements:

- Freely access to tools and machines, community and knowledge is actively facilitated by many librarians and is considered as intellectual freedom.
- Librarians describe commonly the Makerspace as a social place. Makers are can share discoveries, support each other and engage socially.
- The library becomes a place for creation, education and economic impacts. Hence, people are attracted that would never enter a library.
- Individuals can broaden their horizons in a Makerspace and can be empowered by doing something new that is out of their comfort zone.

Noenning, Oehm and Wiesenhütter(2014) stated that libraries are already centres for research and knowledge, in addition they are now hosting manufacturing capabilities and new technologies with a collaborative exchange of knowledge to complement their classical field of experience. The Helsinki central library[43], which opened in December 2018, can be named as an example of this new type of libraries. Based on Rogers(2018), it was the result of nearly two decades of planning and public consultation and each floor was built to fulfil a different purpose. The ground floor includes a restaurant, movie theatre, an information centre and several areas suited for concert and events. The second floor holds electronic/digital equipment and workshop rooms for Maker activities, and the top floor holds books and reading room (Rogers, 2018).

2.3.4.5 Academic Makerspaces

Makerspaces at higher education organisations, so-called Academic Makerspaces, can transform learning experiences for students (Linsey *et al.*, 2016). Academic Makerspace can serve different roles on campus. Some exist to support optional/extracurricular clubs and adjacent to the student experience or others integrate into the curriculum (Wilczynski, O'Hern and Dufresne, 2014, p. 3). Both types have the potential to reach and positively impact a larger amount of students.

According to Wilczynski, O'Hern and Dufresne(2014, p. 3), integration of hands-on activities and Makerspace resources into the curriculum can strengthen the academic experience of students overall by exposing them to experiential, inquiry-driven learning experiences. Students learn skills that may not be emphasized in more traditional coursework like collaboration, design synthesis, and iterative problem-solving (Wilczynski, O'Hern and Dufresne, 2014, pp. 3–4).

[43] www.oodihelsinki.fi (Accessed: 2 June 2019)

Overall, this gain in popularity of Makerspaces is merging with the efforts to increase active learning. Forest *et al.* (2014, p. 4) names the intention as fostering talented, creative engineers and obtaining a richer, practice-based curriculum. Furthermore, the faculties desire to connect their research in Makerspaces to real-world problems and industrial needs (Forest *et al.*, 2014, p. 4).

In 2015, a research project was conducted on 127 universities and colleges in the USA to investigate the different operational models of at that time known Academic Makerspaces. Three different operational models, as shown in Figure 13, were identified: student-run, specific-support-staff, and faculty-run. According to Barrett *et al.*(2015, pp. 9–10), 35 of the 127 investigated organisations are running an Academic Makerspace. The most common model is a combination of faculty-run and specialised personnel (26%). However, some appear to be student-run/driven-only (13%) and are organised as student clubs. But most spaces are operated by or with staff, various have a combination of all three models, whereby only 9% are for and run by once faculty only (Barrett *et al.*, 2015, pp. 9–13).

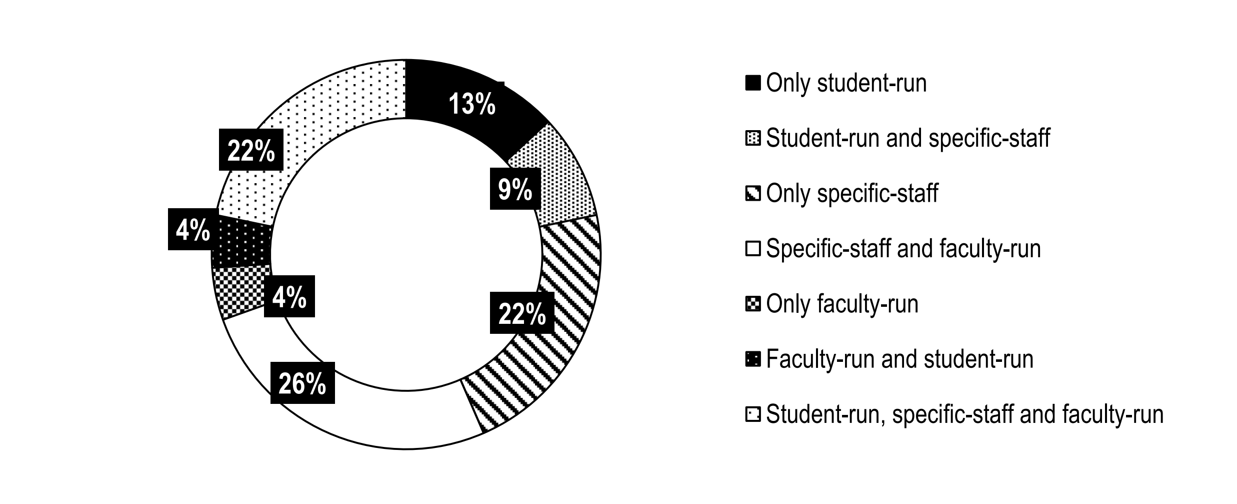

Figure 13 : Themes for operational models of Academic Makerspace.[44]

Once again, MIT is the forerunner in the fields of Academic Makerspaces and launched the Manus project[45] in October 2015 with the aim of creating the gold standard in Makerspace. According to the project website, several goals should be achieved within the projects: First, over 45 Makerspaces on the campus should be operated and connected through a smartphone application to support MIT's Maker ecosystem. Second, a state-of-the-art Makerspace with around 1,800m^2 should be established. Third every new MIT student should be trained to safely use MIT's Makerspace on his/her own (MIT Project Manus, 2018). The project is also leading an effort in partnership with peer universities in the so-called HEMI programme[46], which includes Stanford, Berkeley, Georgia Tech, Yale, Georgia Tech, CWRU and Olin.

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[44] Based on Barret *et al.* (2015, p. 11)

[45] www.project-manus.mit.edu (Accessed: 2 June 2019)

[46] www.hemi-makers.org (Accessed: 2 June 2019)

Wilczynski(2015) reviewed eight USA-based universities with an Academic Makerspace and defines unique attributes for each space. As an overall recommendation, Wilczynski(2015, pp. 15–16), similar to Kurti, Kurti and Fleming (2014), concluded the following best practices: First, a Makerspace must be designed around a clearly defined mission. Second, a Makerspace must be properly staffed with educators, manufacturing and design experts, as well as should have administrative support. Third, a Makerspace should be an open environment to promote collaboration and idea exchange. Fourth, access times to a Makerspace need to be aligned with student work schedules/curricula in order to increase utilisation. Fifth, user trainings for methods, tools and machines need to be provided to increases individual's productivity. Sixth, attention must be devoted to the location of a Makerspace on campus to attract more users and establish a greater community.

Academic Makerspaces need to be installed with and for students who are the main target group/costumer. Kurti, Kurti and Fleming(2014, p. 11) claim that Makerspaces can act as modern centres of education; combining theoretical inputs and hands-on experience with the innovative potentials of students. In order to attract users, it is necessary to catch their attention and to inspire them (Kurti, Kurti and Fleming, 2014, p. 11).

2.3.4.6 Makerspaces at established companies

As claimed by Chesbrough(2012, p. 20) basically two innovation models exist: First, the traditional closed innovation model, which describes a company's innovation strategy in which employees develop new products through internal research and resources; second, the open innovation model, which involves external sources in the product development. Makerspaces can support the open innovation model and can reduce the complexity encountered in integrating external sources in a company's product development environment. According to Piller, Ihl and Vossen(2011, pp. 21–22), Makerspaces can also be adopted to create new products together with customers and established company employees.

Leading technology companies adopted already the Makerspace concept and it became core to their corporate values. Build Space by Autodesk provides access for employees and highly talented users/costumers (Autodesk, 2018), Google let its engineers hack their workplaces (Stewart, 2013), NASA invites the public to co-create physical objects (Lewis, 2017), Facebook opens the Makerspace Area 404 for its employees (Constine, 2016), or for instance, Stanley Black & Decker encourages its employees to learn new skills and develop new expertise in their own Makerspace (Van de Castle, 2018). In addition, European companies like Adidas (Hofer, 2017), Airbus (Stephens, 2016), Bosch (Ziegler, 2015), Siemens (von Karczewski *et al.*, 2015, .p 42) and Renault (Passbon, 2014), have also started Makerspaces. Some mentioned Makerspaces reported first successes of the concept. Böhm(2018) concluded in his dissertation that Makerspaces foster product development not only due faster prototyping, but additionally in the sense of user driven product innovations.

2.3.5 Operations in the Maker Movement

As described previously, a wide variety of Makerspaces exist and thus there is also a wide range of operational models. However, many Makerspace operational models indicate that success is directly related to the establishment and preservation of an active and living community.

Holman(2016) analysed Makerspace in the USA in 2016 and described four basic models:

- **Institutional:** The Makerspace is supported by a company or an educational organisation, like a university or school. Therefore, it can offer free or nearly free access to the Makers. Almost all academic Makerspace fall in this type.
- **For-profit:** Here highly professional Makerspaces provide well-maintained infrastructure, workshops and trainings, as well as support for Maker's projects. The business model is based on selling memberships and classes to users. Techshop was an example for this model.
- **Club:** The Makerspace is initiated by a vivid community of Makers with social contract membership or pay-as-much-as-you-can principle. Sometimes a new Maker has to be voted in by existing members. The social aspect here is more important than the availability of high-tech digital manufacturing technologies. This model applies for many Fab Labs and Hackerspaces.
- **Non-profit:** Makerspaces are set up as a non-profit and running on a combination of grants, public money, and low user fees. Makerspaces at libraries fall often in this model.

Furthermore, Troxler and Wolf(2010, p. 8) defines two generic types of Makerspaces, which can be applied to all four models named by Holman: First, the Makerspace as a facility and second, the Makerspace as an innovation space. Makerspace as a facility focuses only on users' access to tools and machines as well as gives little support in the manufacturing processes, whereas the Makerspaces as an innovation spaces provide in addition service and consulting offerings to increase the effectiveness of Makers' innovative projects (Troxler and Wolf, 2010, p. 8).

For the development of a sustainable operations model, a closer look at the Makerspace ecosystem is also needed. The requirements of relevant stakeholders have to be taken into account, such as companies, educational institutions, students, artists, non-profit organisations, available staff, funding agencies, regional governments and society in general (Troxler, 2010, pp. 2–5). Guthrie(2014, p. 7) stresses that much effort is therefore necessary to build up and maintain a model which meets the requirements of the local Makerspace ecosystem and created enough revenue to compensate the running cost of Makerspace.

To run a Makerspace sustainable Troxler and Schweikert(2010, pp. 4–7) named the following key aspects: First, the ultimate goal of the Maker Movement is the democratisation of manufacturing meaning that open source thinking, commons-based knowledge, open learning environment, and a community of best practices exchange should allow Makers to develop mastery in Makerspaces. Therefore, openness and accessibility are an important aspect. Second, interdisciplinary collaboration in projects should be fostered. More innovative products are likely to be developed when Makers are connected on an equal level. Third, Makerspace operators should exchange experiences, models, formats, issues and solutions in a global network. Based on such activities the own Makerspace operational model can be developed further.

However, generating revenue is also fundamental for some Makerspace operational models. Eychenne(2012, pp. 12–13) postulates therefore the following principles to create income in a Makerspace:

- **Fees:** Besides membership fees and machine rental fees, also project space rental fees are possible.
- **Contract work:** Contract manufacturing and on-demand work for companies or individuals with limited skills/time create income.
- **Training, workshops and seminars:** Paid knowledge transfer from experts to individuals.
- **Product innovation project, feasibility studies:** Makerspaces host typically experts who are willing to work together with individuals on their projects. Experts give paid guidance and recommendations in the product development process.
- **Publicly-funded research projects:** National/international publicly-funded research projects generate on the one side additional revenue and on the other side foster the knowledge exchange and network among Makerspaces.
- **Start-up incubation:** Expertise in various fields such as prototyping, production, intellectual property rights, and communication can be provided paid to start-ups.
- **Consulting:** Short term one-on-one knowhow transfer from a Makerspace expert to an individual on a specific issue in their project.
- **Sponsoring:** Makerspaces receive financial support from industry partners in term of cash or goods.

Expiries show, see also 2.3.4.3, that especially for-profit Makerspaces struggle in generating revenue and therefor those spaces combine several principles for generating income. However, many Makerspaces relay currently on funding by public institutions but share the objective of becoming self-sufficient within the coming years.

2.3.6 Role of the Maker Movement in education

The USA based National Academy of Engineering(2004, pp. 53–57) noted that curricula in the USA mainly focus on theory, but creating, inventing and innovating are essential skills for engineering profession in 2020 and beyond. Therefore, hands-on and active learning should increasingly be focused in technology education. The NMC Horizon Report - Higher Education Edition stated in 2016 that educational organisations are in the process of changing their course programmes towards hands-on and active learning as a means of fostering creation, design, and entrepreneurship, which matches perfectly with the concept of the Maker Movement (Johnson *et al.*, 2016, pp. 1–2).

Educational programs in the Maker Movement reach across formal and informal learning, and lead to a more openly thinking where and how learning happens. Such a situation occurs for instance at Maker Fairs: participants rang from adult Makers to kids, but both work together in for example robotics clubs and share what they have created (Halverson and Sheridan, 2014, p. 498). Also, Gershenfeld(2005, pp. 11–13) set up the first Fab Lab as pedagogical environment where his students can solve everyday problems by producing items rather than purchasing or outsourcing.

Martin(2015) promoted three elements within the Maker Movement which are critical for learning experiences:

- Digital tools, including 3D printing, laser cutting and low-cost microcontroller for rapid iterations should be used in projects.
- Community infrastructure, including online resources, in-person spaces and events.
- The Maker mind-set of sharing, values, beliefs, and dispositions that are commonplace within the community.

As described earlier, Makerspaces are either independent organisations or embedded in institutions such as schools, universities, and other public organisations. Children, students, private individuals, company employees and others are users of those spaces and will be educated based on their project work. Furthermore, informal learning environments such as public libraries, museums, and independent non-profits use the knowledge of Makers in Makerspaces and convert this into learning experiences of young people. However, most Makerspaces have likely included the newest technologies and tools, but the focus in education programs should be set to processes and products produced and not to tools (Halverson and Sheridan, 2014, pp. 499–500).

According to Weiner, Lande and Jordan(2018, pp. 10–11), Makerspaces can either be consider as spaces of traditional educational programs, led by top-down teaching, or as spaces for peer-supported and interest-driven exploration steered by a bottom-up community driving learning environment. Given the current state of the research, the establishment of Academic Makerspaces is an opportunity to revaluate existing educational practices and implement curricular changes towards making (Weiner, Lande and Jordan, 2018, p. 11). However, Makerspaces can only fulfil this role when a community exits.

Forest et al. (2014) conducted a survey at the Academic Makerspace at the Georgia Institute of Technology: 90% of the responding students reported an impact on their design skills as a result of activities in the Makerspace. Additionally, 80% of the respondents confirmed that the space had a positive impact on their manufacturing skills (Forest *et al.*, 2014, p. 22). In 2018, Hilton, Forest and Linsey(2018) continued the research on the impact of this Academic Makerspace. They concluded that students who spend more time in the space develop higher confidence, have a higher expectation of success when conducting engineering design projects and have therefor a higher self-efficacy to conduct product development projects. But they stated also that still more studies need to be conducted on identifying the students who may most benefit from Makerspaces and how to even more promote them (Hilton, Forest and Linsey, 2018, pp. 3–4).

Shank, Bermann and Macpherson(1999, p.172) stress that learning by doing/experience is the most effectiveness way to learn. This way of learning can be applied to Makerspaces. A Makerspace can help Makers to use their own skills and experiences in order to solve problems and to achieve goals.

Kurti, Kurti and Fleming(2014, p. 8) address that within education, the learning process is viewed as a highly personal endeavour that requires the student's initiative rather than the teacher's support, hence an active learning environment is a characteristic for constructionism. The Maker Movement is built upon this. Thinking outside the box is often complicated; today's conformities have been imposed by many aspects of modern education (Kurti, Kurti and Fleming, 2014, p. 8). Learning, though, is an individual process and does not follow a uniform standard.

Makerspaces have demonstrated that they are modern centres of learning and knowledge transfer. These new opportunities in Makerspaces offer great possibilities for educators to become more collaborative and extend the learning beyond the walls of the space itself (Noenning, Oehm and Wiesenhütter, 2014, p. 45). Overall, the Maker Movement is seen to have the ability to transform education into a system that cultivates individuals who adopt habits and become engaged adults (Hlubinka *et al.*, 2013, pp. 3–4). Increasingly, technology has given individuals more control over their lives and hence they can be the initiators of such a change.

As stated above, to create a new product not only a sufficient infrastructure for building prototypes is necessary, but also the developer needs profound knowledge on the process and methodology of product development. Most due to giving opportunities within the Maker Movement arising educational programs, deal with hands-on product development tasks and projects. These taught skills are essential for each hardware start-up.

2.3.7 Role of the Maker Movement in cities

Over the past decade, the Maker Movement has developed into a global ecosystem for prototyping of software/hardware products. Started as an informal testing ground for digital production methods it has become a movement for individuals to developed innovative products and some Makerspaces are places where everything from Internet of Things devices to renewable-energy power stations can be produced, tested and refined. On the other side, Makerspaces in cities help to develop skills of local individuals, bring state-of-the-art production technologies back, and offer the opportunity to individuals to make items needed on themselves (Ermacora, 2018).

To further promote the development of Makerspaces in cities the Fab City[47] initiative was launched in 2014. Cities participating committed to the goal of producing everything consumed in the city itself by 2054 and enhance a shift from the current industrial paradigm, by enabling the return of manufacture to cities supported by modern technologies (Diez, 2015).

This new paradigm should allow consumers to become Makers of the design, prototypes, production processes, and products at a local scale, while sharing knowledge globally. *"The ambition is to pave the way for locally productive and globally connected cities, that foster social cohesion and well-being."* (Diez, 2017). Based on Diez(2017), the Fab City prototypes aims to be an accelerator for other cities towards European Union strategies and directives around circular economy, waste management and smart specialisation.

The Maker City[48] is comparable to the Fab City initiative and was started in 2016 in the USA. A bestselling book was published then to give Makers, community organizers, business leaders, policy makers, and city leaders a practical guide to reinventing cities based on new possible exiting within the Maker Movement. The book describes how the Maker Movement can help to close the gap between the skills available in the local workforce and explains how to increase job and economic opportunity available in cities (Maker City, 2017a).

In the Maker Movement various activities are happening through the efforts of individuals that are committed to change and mainly without support of other organisations. Based on that, Hirschberg, Dougherty, and Kadanoff(2016, chap. 7) concluded to the following aspects which can foster the development of the Maker Movement in cities:

- Access for young people to modern tools of production should be given.
- Cross-sector collaboration between public, private, and non-profit sectors which engage to solve a city's problems is transformative and an enabler.
- Co-creation, crowd sourcing, ecosystems of local manufactures and prototyping are fostering the creation of new products and can later be produced inside cities.
- Engage researchers and Makers to work together on project.
- Embrace and support urban manufacturing and advanced manufacturing initiatives.
- Keep Makers thinking local first when getting an experiment our new product off the ground and later they can scale up.
- Community meetings on a regional basis create competitive advantage and greater economic opportunity.

As stated earlier, cities host Makerspace. It is beneficial for each Maker when a big community is present in a Makerspace in order to get fast and easy support in product development projects. Cities are beneficial for each hardware start-up because potential customer can be reached, and

[47] www.fab.city (Accessed: 2 June 2019)
[48] www.makercity.com (Accessed: 2 June 2019)

user tests can be conducted easily, as well as with the development of Fab/Maker Cities prototypes and parts can be sourced to local manufactures with ease.

2.3.8 Role of the Maker Movement in product development

As stated in 2.2.1, the term new product development is herein used as the overall process that takes place until a product is used by customers from idea creation up to the start of production.

Based on Hartmann and Mietzner(2017, p. 2), the Maker Movement is until now neither fully understood nor the full potential on product development and production was scientifically explore. This results in unclear implications of the Maker Movement on current practices in production or the impact on social economic situation (Hartmann and Mietzner, 2017, p. 2).

In 2014 nevertheless, Mortara and Parisot(2014) interviewed twelve entrepreneurs who used Makerspaces during their product development projects intensively. They break down the supportive function of the Makerspace into three stages: ideation, development and commercialisation. Development and commercialisation were identified by them as the stages in which the Makerspaces can support most. However, the ideation process takes in the case of the interviewed entrepreneurs not place in the Makerspace. Therefore, they concluded that Makerspace supports most in converting ideas into prototypes and commercialisation (Mortara and Parisot, 2014, pp. 31–32). Besides, entrepreneurs interviewed benefitted from the expertise/knowledge of the Makerspace staff and agreed that the knowledge available at a space is even more valuable than the offered tools and machines.

Hlubinka(2013, pp. 33–40) argue that a Makerspace can play multiple roles in product development. It allows, for instance, opportunities to speed up prototyping, to source parts more easily and gives opportunities for the direct distribution of built products.

Many Makerspaces can be seen in which prototyping support and methodical expertise are offered which go far beyond basic activities. Furthermore, web communities facilitate access to professional knowledge for everyone at any time. Based on Walter-Herrmann, Büching and Corinne(2013, p. 124), Makers from different fields are in general fascinated by the idea of knowledge exchange and contribute actively to online communities. The access to manufacturing technologies enables a faster conception and realisation as well as an improvement in the product development can be seen (Walter-Herrmann, Büching and Corinne, 2013, pp. 124–125).

Makerspaces serve as drivers for the local hardware start-up scene. The founder of the Makerspace in Shenzhen describes their concept as a place where people exhibit and even sell their products (Lindtner, Greenspan and Li, 2015, pp. 9–10). FirstBuild[49] in Louisville has an online platform for product ideas and a Makerspace for the development and production for new product for household appliances. Venkatakrishnan stated: *"At FirstBuild, we not only design*

[49] www. firstbuild.com (Accessed: 2 June 2019)

*products but also build products and sell products. We do all three. We are now convinced that the future of product development will be similar to the way we are doing thing*s" (Hirshberg, Dougherty and Kadanoff, 2016, chap. 2).

2.3.9 Role of the Maker Movement in entrepreneurship

Literature sources assume that with the help of the Maker Movement, it has never been easier to become an entrepreneur and launch a start-up. Pool(2017, p. 1), for instance, stated that entrepreneurship aligns perfectly with the Maker's behaviours in terms of resources and spirit. In his view, Makerspaces are locations for democratization of resources, exploration, experimentation, interaction and empowerment and are therefore ideal vehicles to disrupt the status quo.

Also, Maycotte(2016) describes the potential of Makerspaces similar. In an ideal scenario, it always starts with access to technologies for getting the first idea produced and then the support and the collaboration provided in a Makerspace may advance the development of the product (Maycotte, 2016). Subsequently, the community can facilitate funding and help to recruit talented employees.

Hui and Gerber(2017, pp. 2024–2025) conclude after analysing a Chicago based Makerspace that a successful development of Makerspace for entrepreneurs goes beyond just inviting people with entrepreneurial goals. Moreover, opportunities offline and online to develop skills, projects to increase once self-efficacy in entrepreneurial, manufacturing and marketing tasks, as well as an engaging social context need to be provided (Hui and Gerber, 2017, pp. 2024–2025).

Zwilling(2014) concluded that the Maker Movement and start-ups can work hand in hand. He mentioned in his work seven positive aspects of a Makerspace from start-up's perspective: Frist, time and cost for a first/rapid prototype are reduced due low-cost design and fabrication tools. Second, prototypes for analysis can be physically built with ease. Third, networking possibilities with potential co-founders, strategic partners, investors and support organisations. Fourth, innovations become real and tangible when low-cost design and fabrication tools are available. Fifth, Makerspace machines are designing to build customised products, which matches customers demand. Sixth, available fabrication capabilities and low entry costs give solutions a chance that have a positive impact on society. Seventh, entrepreneurs collaborate and work in a Makerspace with other Makers so that both can benefit from other cultures (Zwilling, 2014).

2.3.9.1 Makerspaces and hardware start-up incubators

In general, incubators, as examined in 2.1.8.1, support the development of new companies and help start-ups to survive and grow. In most cases this help comes in when start-ups are most fragile and tailored support, services and resources are needed.

Incubators for hardware start-ups need slightly different objectives and a deeper focus on mentoring and product development. According to Berchon(2001, p. 9), hardware incubators typically offer funding, office space, prototyping facilities, mentoring, networking, as well as support in financial, technical and strategic issues, hence start-ups are incubated typically between six to twelve months, or the time it takes to get the product idea ready for the next step.

In general, there is a large number of similarities between the incubators and the Makerspaces, like administrative structure. Incubators provide work areas, infrastructure and mentoring whilst Makerspaces might also provide work areas, infrastructure and mentoring (Lahr, 2013). According to Scully(2018, p. 159), some Makerspaces for example in the UK can therefore be seen as an incubator and have very specialised and highly technical assistance as an offering. However, one strength of Makerspaces as incubators is the emphasis on a wider inclusivity, which might is beneficial to entrepreneurs, especially those who were limited due to a lack of access to manufacturing resources (Scully, 2018, pp. 159–160)

2.3.9.2 Makerspaces and hardware start-up accelerators

Accelerators overall offer very similar services to incubators, but usually the services are consumed in a much shorter period of time and they also follow a stricter curriculum, see also 2.1.8.3. Most accelerators do not accept new start-ups during the year because they select a batch of fresh start-ups per session instead. The aim here is to create a large and powerful network of alumni.

Hardware accelerators offer various workshops and training opportunities. Because of the limited time, hardware accelerators usually focus only on one specific aspect or problem in start-ups, such as venture capital pitching, branding, crowd funding campaign, supplier network, manufacturing or product testing (Berchon, 2001, p. 10).

2.3.9.3 Makerspaces with focused offering for hardware start-ups

In general Makerspaces offer various possibilities to support a hardware start-up. Therefore, Makerspace are an attractive alternative to joining an incubator or accelerator programme. However, not all Makerspaces are suited to provide the facets required by hardware start-ups (Berchon, 2001, p. 11). Berchon(2001, p. 11) clarifies that most Makerspaces offer infrastructure, mentoring, workshops, events, and a community, but they rarely provide funding and a paid membership is usually required. The major advantages of Makerspaces are the freedom and the existing community of experts (Berchon, 2001, p. 11). On this basis, hardware start-ups remain in full charge and control of their company.

Rarely Makerspaces provide the possibilities to offer exclusive work areas to hardware start-ups. However, they often organising start-up related events such as hackathons, meaning that a Makerspace can also be a good entry point to start one's hardware start-up (Lindtner, Hertz and Dourish, 2014, pp. 146–147).

2.4 Conclusion: literature and current knowledge

This dissertation covers three research streams start-ups, product development and the Maker Movement. All three have high relevance for economic welfare: First, start-ups create more jobs than they destroy as well as public interest and investments in start-ups is constantly growing of the past years; second, innovations and new products are always the reason for business success and economic development; and third, the newly arising Maker Movement enables everyone to develop and sell innovative physical products.

A start-up is this dissertation defined as a business not older than ten years, selling a single service/product and has the ability to scale rapidly. Building on this definition, a hardware start-up is a business that is developing physical products. These products can also include software aspects and connectivity features, such as Internet of Things devices. A hardware start-up brings its products either to a physical and/or a virtual market. Venture capital investment in hardware start-ups totalled USD 1.48bn in 2014, more than triple the amount of two years earlier and positive proof that this group of start-ups is on the rise (Geyer, 2015). Furthermore, famous examples from this group demonstrate that the next great hardware products might not be born within large, traditional companies, but in garages, Makerspaces and start-up support centres. Examples also demonstrate the inherent connectedness of hardware and software product development as well as the Maker Movement and hardware start-ups.

As also described in section 2.1, Achleitner and Bassen(2003, pp. 9–10) summarised known characteristics of start-ups: First, start-ups are typically managed by the founder him/herself, who has a dominate role in the new company. Second, start-ups are in existence for a very short period of time like months/years. Third, start-ups work in a dynamic environment and have flexible internal structures. Fourth, start-ups face shortages in line with every resource involved, like funding or human resources. Fifth, start-ups work in competition-intensive markets on in many cases highly innovative products, with leads to high development costs. Sixth, start-ups invest in the beginning all financial resources in the product development and therefore have a negative cash flow. Seventh, to keep the product development running and to ensure growth, start-ups always seek for external funding.

Hence, start-ups face various challenge during their product development process and have specific needs. Start-up support centres, like incubators or accelerators, have specialised in meeting these needs in order to further promote the development of rapid scalable high-technology start-ups. Hardware start-ups face even more and different challenges in contrast to e.g. software start-ups. This is based on the fact that a physical product needs to be developed with limited resources, in a short amount of time, and customers expect a similar quality to that of established companies. For instance, in contrast to software start-ups, aspects like material/component suppliers, manufacturing partners and distributor are needed to consider. Various literature sources exist describing challenges and obstacles of start-up in general but up to now hardly any study exist dealing with challenges of hardware start-up. However, reviews from hardware start-up and hardware start-ups mentors indicate that it is today easier to build many prototypes of a new physical product, but challenges in line with mass manufacturing, sourcing of components, managing the supply chain, designing for assembly testing, still exist.

As described in 2.2, the term product development includes, in the context of this dissertation, ideation, creation of product concepts, technical designs, necessary preparations for manufacturing and the integration of the outcomes of individual disciplines into a holistic solution. The outcome of new product development project is a definition, design and documentation of a new product or service, which includes a clarification of technical functions, product costs, quality and timing as well as an evaluation of economic and technological feasibility. One described aim in product development is to transform something with a set of actions into a suitable and desired object. This is mainly achieved by developing a product or service that meets the needs of customers in the most appropriate way. In addition to the functionality of the product, its quality, time-to-market and cost aspects, as well as the flexibility with which it can react to changing requirements, contribute significantly to success.

Literature cited mention the so-called Magical Triangle of product development including cost, time and quality. Every optimisation should achieve a shortening of time-to-market, reducing development costs and production costs as well as improving the product, process and planning quality. In the context of this dissertation also various product development models and process are investigated. Due to rapid changing environments and tough international competition many models and process are centred-on customer needs, adapt quickly based on changing conditions and recommend early prototypes, tests and iteration cycles. However, Mital *et al.*(2014, pp. 28–29) names lack of time, money and human resources as the main cause of failures in product development.

Section 2.2 describes also success factors of new products as well as product development and Ulrich and Eppinger(2016, p. 6) mentioned challenges in product development: First, many trade-off decisions between higher quality and costs have to be made. Thus, mastering, understanding, and managing such decisions in way that the success of the new product is maximized is challenging. Second, due to dynamics of today's markets customer expectation change, new technologies evolve, and new competitors establish quickly. This leads to challenges line with fast decision making. Third, due to high complexity in product development small decision in product development can have a great implication on product costs. Third, time pressure in product development results in quick decisions and with an incomplete set of necessary information. Fourth, high investment costs are associated with the development, manufacturing and marketing of a new product and therefore a reasonable return on investment is seek.

Based on the prior described literature, Table 3 summarises known challenges and supporting factors in product development and for hardware start-up in product development in particular.

Supporting factors in product development of hardware start-ups

Office space and resources: Support programmes dedicated to hardware start-up offer not only office space but also resources for building prototypes (Berchon, 2001, pp. 9–11).	**Colocation:** Development teams are typically highly motivated and colocation raises their collective energy on creating the new product (Ulrich and Eppinger, 2016, p. 6).	**Team diversity:** A divers, multiskilled and empowered by the management development team may lead to success in product development (Mital *et al.*, 2014, pp. 25–26; Ulrich and Eppinger, 2016, p. 6)
Funding: Start-up funding possibilities have recently changed, nowadays a wider variety of funding option, such as Venture Capital, crowd funding, accelerators, business angels exist (Novoa, 2014).	**Cocreation:** An inclusion of customers early into the product development is favourable (Mital *et al.*, 2014, p. 24).	**Networking:** A key aspect for joying a start-up accelerator or incubator is networking (Cohen and Hochberg, 2014). Hence, business networks help to meet potential customers, investors or partners.
Skills enhancement trainings: e.g. in the fields of business model design or marketing (Deeb, 2014; Mian, Lamine and Fayolle, 2016, p. 3).		

Challenges in product development of hardware start-ups

Timing: The right moment to launch a new product is always a balancing act of many influencing factors (Newtek, 2014) and the quickness with which a new product reaches the market is critical (Mital *et al.*, 2014, pp. 26–27).	**Time pressure:** In product development decision usually have to be made quickly and with an incomplete set of necessary information, due to a time pressure(Ulrich and Eppinger, 2016, p. 6).	**Prizing, branding and marketing:** Start-ups have to deal with prizing, branding and marketing of new product even though they have limited human resources (DiResta, Forrest and Vinyard, 2015, p. 1; Hackster, 2016).
Trade-off decision: Decision in product development can have a great implication on product costs and quality. Thus, understanding and managing such decisions in way that the success of the new product is maximized is important (Ulrich and Eppinger, 2016, p. 6).	**Flexibility:** Start-ups need to stay focused, react flexibly and quickly to changes (Newtek, 2014), in order to adapt the new product to changing customer expectation, new technologies, and new competitors (Ulrich and Eppinger, 2016, p. 6).	**Funding:** Money is considered to be the most urgent need of start-ups generally have (Newtek, 2014; Fictiv, 2016; Hackster, 2016). In addition, high investment costs are associated with the development, manufacturing and marketing of a new product (Ulrich and Eppinger, 2016).
Self-discipline: Goals/milestones which are planned on a timeline are important and checkpoints on a daily/weekly/monthly basis help to foster self-discipline (Newtek, 2014).	**Resources and fast development cycles:** Building fat rough and unfished prototype early to do customer/ users tests is challenging (Iseman, 2016; Migicovsky, 2017).	**Skills and knowledge:** Start-ups have no chance of success if the individuals involved lack the necessary endurance, skills and knowledge to make it work (Newtek, 2014; Fictiv, 2016).
Industrialized and manufacturing: Getting prototypes industrialized (Hessman, 2015) and challenges solved in line with mass manufacturing is difficult (Williams and Nadeau, 2014, p. p.64; DiResta, Forrest and Vinyard, 2015, p. 1), as well as finding manufacturing, distribution partners and suppliers is important (Fictiv, 2016; Hackster, 2016).	**Networking:** Part of working in a start-up is networking and therefore high social skills are essential to find funding and people willing to invest their money as well as time (Newtek, 2014; Fictiv, 2016).	

Table 3: Overview of known supporting factors and challenges in product development of hardware start-ups

As stated in section 2.3 , the term Maker Movement and Makerspace were coined in 2015. Doing yourself, sharing, producing mostly customised and physical products are essential aspects within the Maker Movement. As examined in this dissertation, the core of this new movement are individuals, so-called Makers, a community of sharing and a communal high-tech workshop, so-called Makerspace. The ultimate goal of the Maker Movement is democratisation of the means of manufacturing in order that everyone can produce his/her own products. The current rise of the Maker Movement is promoted by various enablers: the introduction of new machines types, access to infrastructure, open-source hardware and software, easier sourcing of parts as well as the possibility of direct distribution of physical products are among the most important ones, as summarised in Table 4. Many different names, notations, and types of Makerspaces have emerged and exist. The most important types such as Academic Makerspaces, Makerspaces at a library, Makerspace at established companies, Techshops, Hackerspaces and Fab Labs are described. However, the term Makerspace is, and also in the context of this dissertation, used as a generic designation.

Demand for personalization Consumers want increased customization, and a human aspect to the product they are purchasing like fitness trackers or smart thermostats (Hagel, Brown and Kulasooriya, 2014, p. 12).	**Seed capital from crowdfunding** Existence of crowdfunding websites such as Kickstarter (Lindtner, Hertz and Dourish, 2014, p. 447).
Open-source soft- and hardware “Tools to innovate” like CAD programs, prototyping equipment and simulation software are much more affordable today (Piller and Ramsauer, 2014, p. 30).	**Inexpensive manufacturing hubs** Existence of physical space where people get together and turn their ideas in reality. Technologies and tools of today are typically easy to use, relatively inexpensive, and more accessible on a global scale to wide audiences than in the past (Piller and Ramsauer, 2014, p. 30).
Common design file standards Standardization (e.g. stl-files) for easy cross-platform data exchange. Open access databases allow the use of designs from others (Piller and Ramsauer, 2014, p. 30).	**International shipping** Globalization leads to cheaper international shipping and access to international vendors (Anderson, 2012, p. 207).
Sharing economy with online repositories Inspirations from Make: magazine, Instructables etc. helps spreading an understanding of making as a form of creativity and innovation (Lindtner, Hertz and Dourish, 2014, p. 445).	**E-commerce distribution** Boundary between product makers and product sellers is becoming more and more blurred with e-commerce. People build and sell products themselves at quick turnaround times (Hagel, Brown and Kulasooriya, 2014, p. 12).

Table 4: Overviews of enablers of the rise of the Maker Movement[50]

[50] Based on Ramsauer(2017, p. 12)

The Maker Movement is no longer just a hobbyist movement. New financing possibilities and the existence of Makerspaces on a global scale with a rich and professional offering of machines, tools and support along the product development process, further empower the creation of start-ups. Three development stages of individuals towards a hardware start-up are known: First, zero to Maker as individual's first step in the Maker Movement; second, Maker to Maker describes that individuals share their knowledge, learnings and projects with others; and third, Maker to market shows the final step and likely the most challenging step towards converting an idea/prototype into a marketable product and a hardware start-up.

The Maker Movement can have, based on the analysed literature, importance to various fields and disciplines. In the Fab/Maker City project the Maker Movement might change today's institutional and global connected manufacturing landscape to local, decentralised and flexible offerings. On the other hand, the Maker Movement in education promotes hands-on learning experiences, out-of-the-box thinking, learning by doing and postulates a new approach for engineering education. The role of the Maker Movement in education receives also the highest attention in the scientific community. Both can also promote the development of hardware start-ups. Another role of the Maker Movement is seen in a paradigm shift in product development. In traditional view, individuals started to work for companies and these companies pushed new product and services based on general specifications towards the users/customers. A new postulated view places the users/consumers at the centre of the product development process, which can also produce in e.g. Makerspaces their specific needed products themselves. In general, collaboration between Makers, start-ups and established companies is encountered in Makerspaces. Based on cited studies, it can be stated that in product development knowledge transfer and expertise support is currently seen as the main benefit of Makerspaces. Since literature gives no clear structure nor key support functions of the Maker Movement in product development a need for further research is clarified. Lastly, some researcher tries to compare a Makerspace to known start-up support centres like incubator or accelerators. They see many similarities but up to now no common agreement is reach on a concrete operation model of a Makerspace in this specific setting.

3 Research design, approach and methodology

As described in the introduction, the intent of this dissertation is to examine the Maker Movement's role in hardware start-ups' product development projects. The influence of the Maker Movement and product development, especially in hardware start-ups, has not yet been investigated scientifically and it is assumed that a proper set of Maker Movement elements helps to solve critical challenges in the product development of hardware start-ups.

The above described intent is translated in a conceptual framework of this dissertation and is shown in Figure 14. A conceptual framework represents an overall visual representation of the concept of the research study and the connections between research areas (Karlsson, 2016, p. 17). Overall three streams are merged and evaluated in this dissertation. First, the Maker Movement, which evolved lately and can play according to 2.3 several roles in product development. Hence, the literature reveals several support factors within the Maker Movement. Second, the product development stream gives characteristics to evaluate success in development projects and provides several aspects as well as recommendations to develop new products successfully. Those are herein used to evaluate the Maker Movement in the context of hardware start-up's product development projects. In the third stream start-ups and hardware start-ups are investigated. Based on current knowledge several hindering factors and challenges are described as well, which herein are used as a guidance for the to be conducted study. With respect to the current knowledge of the three research streams a research study is conducted to evaluate the effect of the Maker Movement on product development projects in the context of hardware start-ups. This may result, in reveals focuses areas within the Maker Movement and may clarifies if challenges in product development of hardware start-ups can be solved based on those areas.

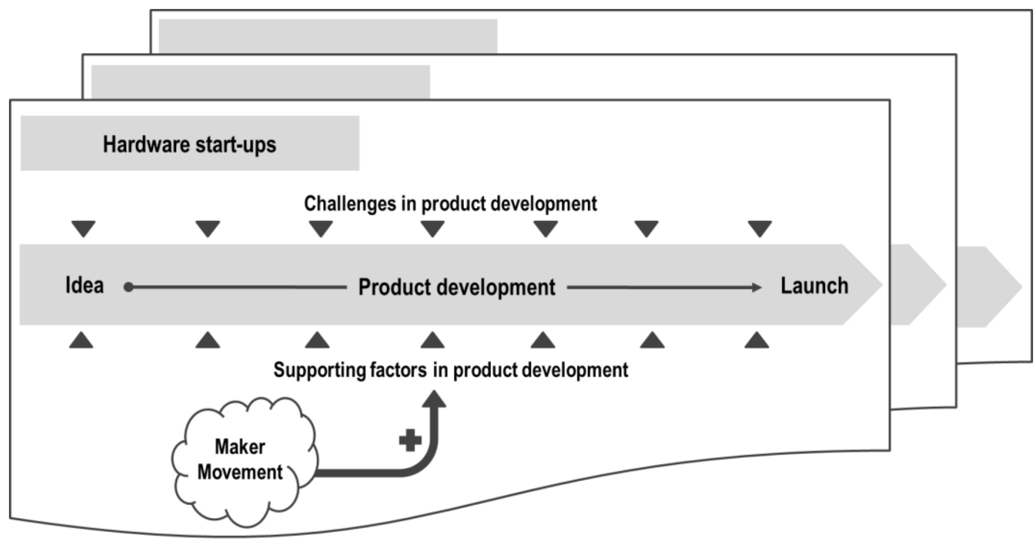

Figure 14: Conceptual framework

In general, the philosophical assumption behind the conducted study is the worldview of pragmatism. Creswell(2014, p. 6) sees the worldview as a general philosophical orientation about the world and the nature of study that a researcher brings in a study. According to Tashakkori and Teddlie(2003, p. 17) pragmatism itself as a worldview arises out of actions, situations and consequences rather than antecedent conditions. Furthermore Creswell and Clark(2011, pp. 41–42) stress that pragmatism, which employs diverse approaches, values both objective and subjective knowledge as well as practical and applied research, should guide methodological choices and findings are integrated by merging them in the discussion, which are typical pragmatic stances.

The following section also describes the research question, the research design, the empirical approaches, and the methods in order to contribute to the stated purpose of this dissertation.

3.1 Research questions

A research design derives from the chosen research questions. Creswell(2014, pp. 139–140) points out that research questions that aim for a qualitative design must be exploratory and not specific to a research scope or hypothesis. In addition, another key factor in formulation of the research questions is the ability of the researcher to control the behaviour of the subjects. Yin(2011, pp. 77–78) clarifies, that the researcher in historical events relies on existing data, while in current events, surveys or observations can be used but active intervention of the research might influence the behaviour of the subjects.

The following research questions were derived based on the current knowledge in literature and analysis of the data from ESM[51]. Three central research questions are formulated.

The first and second research questions lead to a qualitative research method. The third is the so-called Mixed Methods research question where qualitative and quantitative data is combined in order to answer the question. The formulation is based on guidelines given by Creswell(2014, pp. 148–151).

1. **What elements exist in the Maker Movement?**

Since literature gives no clear structure for the ecosystem of the Maker Movement, a framework should be derived to discover certain Maker Movement elements. Herein, the term “element” is used as a collective term for a role or a player within the ecosystem of the Maker Movement. Qualitative research is used to clarify and to develop an element framework.

2. **What influences viewed by hardware start-ups exist on product development at Makerspaces?**

It is essential in the context of this research to lay down the characteristics, needs and challenges in the view of hardware start-ups in product development at Makerspaces. Summarised in this research question in term “influences”. Based on qualitative research, knowledge of the

[51] See 1.2 and Kollmann, Linstadt and Kensbock, 2015; Kollmann *et al.*, 2017

current/past product development project by the selected hardware start-ups as well as their connection to Makerspaces is shown, discussed, and themes are described.

3. **How do the themes mentioned by hardware start-ups help to explain why the Maker Movement and product development matches?**

A more detailed description which helps to clarify the connection of qualitative and quantitative research can be see with the following formulation of the query: How does qualitative interview data on hardware start-ups further explain why the Maker Movement, as measured quantitatively, tend to support product development based on cost and time reduction in product creation, quality increase and cost reduction of the product itself, as well as hardware entrepreneurs' network effects? In general terms, it is clarified how the Maker Movement supports product development projects of hardware start-ups in the given scope.

3.2 Research design

Overall, the research design is split up in three blocks: Intro and plan, framing of the Maker Movement, which is the first empirical study, and Mixed Methods research study, which is the second empirical research study in this dissertation. Figure 15 shows the procedure in detail as well as the sample size, the technique of how data is gathered and analysed.

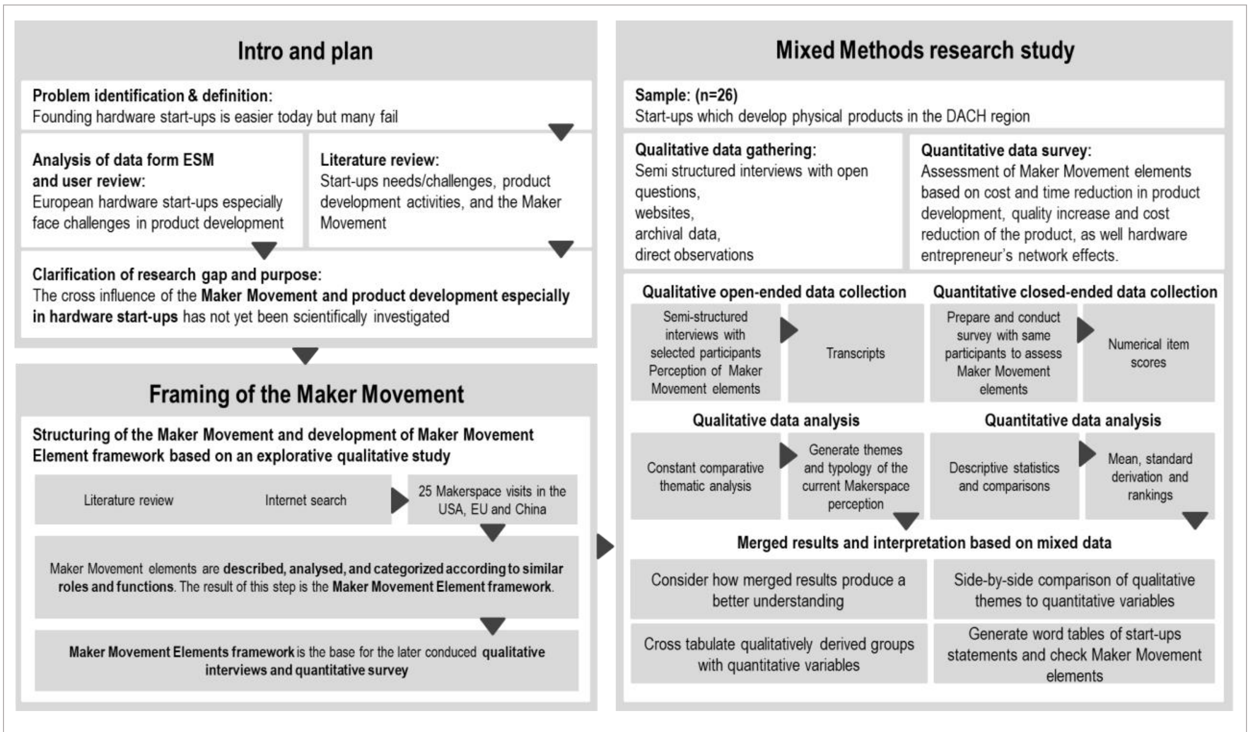

Figure 15: Overall research design

In literature three general research approaches can be distinguished: qualitative, quantitative, and Mixed Methods. There is very limited knowledge and scientific empirical studies available on the connection between the Maker Movement, hardware start-ups and product development so it is appropriate to base the research in the first stage on qualitative methods. Therefore, the first study has the intent to reveal a framework for structuring the ecosystem of the Maker

Movement. This derived framework should provide a lens for the subsequently conducted Mixed Methods design. Specifically, the Convergent Parallel Mixed Methods design is chosen for this research as clarified in section 3.5. Based on Creswell(2014, p. 4), the Mixed Methods research is in general an approach to analysis an involving collection of both quantitative (closed-ended) and qualitative (open-ended) data, to integrate those two forms of data, and to use distinct designs that may involve philosophical assumptions and theoretical frameworks. The core assumption of this form of research is that the combination of quantitative and qualitative approaches provides a more complete and clearer understanding of a research problem than either approach alone (Creswell, 2014, p. 4).

The Mixed Methods approach is selected because of its strength in drawing positive aspects of both qualitative and quantitative research and reducing the limitation of both research approaches. Mixed Methods is an ideal approach in line with this research because the Maker Movement is a relatively new field to the scientific community and the author has the possibility to gain access to both quantitative and qualitative data.

3.3 Research scope

The issue to be analysed is the connection between the Maker Movement and hardware start-ups' product development projects. The existing knowledge on start-ups, hardware start-up, product development, Maker Movement and Makerspaces indicates various issues, needs and challenges. Clarifications given there are used as a guideline for the research scope. Therefore, the scope of the research can be split into two parts: locations at which Maker Movement-related offerings exist and start-ups who developed physical products and may already use Maker Movement-related offerings in their product developments, even though they do not know that these offerings are related to the Maker Movement itself.

The first study on framing the Maker Movement focuses broadly on an identification of so-called Maker Movement elements and the focus is also broad to worldwide locations and information. However, the second study, Mixed Methods research study, focuses narrowly on locations within Europe and explicitly within the DACH (Germany, Austria, Switzerland) region only, due to accessibility. Based on the below defined criteria, the following spots were selected within the DACH region: Graz University of Technology (Austria), Technical University Munich (Germany), and Swiss Federal Institute of Technology in Zurich (Switzerland). The locations are described in more detail in section 3.5.2 and 5.

Focusing on a certain region is important in the Mixed Methods research study because a homogeneous group of start-ups needs to be investigated to generate in depth understanding of the issue. Start-ups in the same region tend to have the similar mind-set, have the same compulsory legislation to comply with, and have the same funding and subsidy possibilities. For the selected DACH region in particular, funding tends not to be a primary issue for start-ups because various public funding possibilities are available. This is in contrast to the USA or Asia where public funding is limited, which might result in different start-up challenges and needs. Furthermore, another peculiarity for the DACH region is high labour cost. It can be assumed that a Makerspace is used in a high labour-cost country differently. When the labour cost is low, people might tend to outsource parts or the whole product development. Another criterion for the selection of the right research spot within a country of the DACH region is the existence of start-ups and a local start-up ecosystem, which can typically be found at universities. Hence, the existence of a Makerspaces is also used as a criterion. With the presents of a local Makerspace, the likelihood is higher that start-ups know players within the Maker Movement and may have already gained there first work experiences in a Makerspace.

On the other hand, the scope in the Mixed Methods research study is limited to start-ups developing physical products. Service provider-only and software start-ups are excluded. Start-ups and hardware start-ups are already defined in section 2.1. Based on the stated definition, technology-focused and scalable young companies concentrating on the development of a physical and tangible product are considered. The location specific ecosystems are used to search for to be investigated hardware start-ups. Many of the selected start-ups work in a highly dynamic environment and have strong pressure to bring their product to market. Persons in charge of the selected hardware start-ups, like the CEO, have been interviewed. Those entrepreneurs should already have working experience in a Makerspace, such as an entrepreneur from the start-up Kewazo[52]. Kewazo is creating a robotic system for autonomous scaffolding transportation and installation. The Kewazo team has already used various offers and services of a Makerspace and has developed several prototypes.

3.4 Framing the Maker Movement

Despite the rapid growth of the Maker Movement, no clear picture of the players in the Maker Movement ecosystem exists as yet. Various players support individuals in realising their projects and new players are evolving on a daily basis. To clarify the view of the ecosystem, the first empirical study of this dissertation develops a framework based on so-called Maker Movement elements. A Maker Movement Element is a collective term for players that hold a supportive role within the ecosystem of the Maker Movement. Several Maker Movement elements can be categorised in subsystems. On this basis, a Makerspace is a physical location with the purpose of offering a decent amount of Maker Movement elements to individuals.

The aim of the framework development is to discover, identify, describe and structure the Maker Movement in order to conduct the following Mixed Methods research study and evaluate the results.

[52] www.kewazo.com (Accessed: 2 June 2019)

Creswell(2014, pp. 185–186) mentions the following key characteristics of qualitative methods that are taken into account in the process of the Maker Movement Element framework development:

- **Natural setting:** In qualitative research, the collection of data needs to take place in a natural environment rather than in a laboratory. This leads to a personal interaction between the interview persons and researchers.
- **Key instrument is the researcher him/herself:** The researcher plays a major role in qualitative research because the data is collected personally.
- **Multiple sources of data:** Qualitative research uses multiple data sources, such as interviews, observations, documentation, or audio-visual information. Following the data analysis, organisation and categorisation of the data is required.
- **Inductive and deductive analysis:** Deductive and inductive elements need to be composed. This means that jumps are made between topics and data as well as going back deductively to individual topics in order to reinforce evidence-based statements.
- **Participants' views:** Special care is taken throughout the research to bring in the views of the researcher and not defend knowledge from the literature or the researcher himself.
- **Emergent design:** A hallmark of qualitative research is that the research process can be adapted during the research itself. This means that questions can be adapted, and the form of data collection can be changed.
- **Reflexibility:** Researchers reflect on their own role. This means that the sequence of personal experiences or even the culture of the researcher feeds into the interpretations of the data.
- **Holistic account:** Qualitative research is holistic. A holistic overview of the researched facts is created taking into account various perspectives.

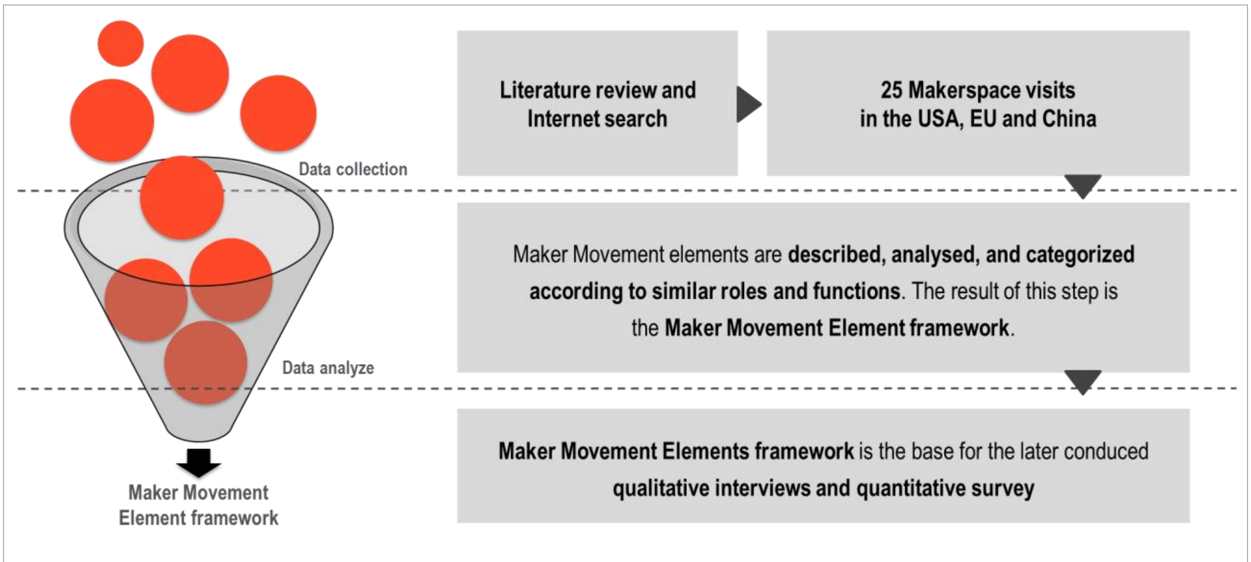

Figure 16: Flowchart of Maker Movement Elements framework development

The research for identification and classification of Maker Movement elements is based on several data sources and structured in two main segments, as shown in Figure 16. In the first segment, Maker Movement elements are identified based on a literature review (e.g. scientific publications) and an Internet search (e.g. company websites) with the keywords “Maker Movement”, “Fab Lab”, “Makerspace”. For the desk research, the Maker Movement-related roles and players, such as organisations, companies, platforms, etc. are tracked down. The second segment presents all the information gathered in various field trips to Makerspaces in the EU, USA, and China. Interviews with Makerspace managers and observations of various Makerspaces are performed. In addition, local Makerspace websites, relevant blogs as well as other available materials are studied. Due to the fact that the Maker Movement is a global phenomenon the sample of this study is also worldwide. The collected data is synthesised to the desired framework. Based on the data, all Maker Movement elements are described, analysed, and categorised according to similar roles and functions. The result of this study is the Maker Movement Elements framework.

3.5 Mixed Methods research study

Mixed Methods studies are used in general to explore and understand a complex real-world phenomenon. This research is conducted at three locations and the Convergent Parallel Mixed Methods is used as the research approach. Each location is situated in Europe and has a lively hardware start-up ecosystem as well as a technology-focused university, a start-up support organisation and a Makerspace.

The Mixed Methods approach is viewed as a new research methodology and therefore has a short historical background. Creswell(2014, p. 217) states that it originated around the late 1980s and early 1990s based on research work conducted by individuals in fields such as education, sociology and health science. Several development phases have been carried out, including the formative stage, philosophical debates, procedural developments, and more recently reflective positions and expansion into different disciplines (Creswell, 2014, pp. 217–218). Today Mixed Methods are on the rise, which is seen in federal funding initiatives, discipline-specific discussions in various journals across social and health sciences, as well as increase amount of publications (Creswell, 2014, pp. 216–217; Flick, 2016, p. 51).

Recent writing tends to use the term Mixed Methods, but many different terms are used for this research approach, such as integrating, synthesis, quantitative and qualitative methods, multimethod, and mixed methodology (Kuckartz, 2014, pp. 30–56). In addition, several types of Mixed Methods are classified, identified and described. However, Creswell(2014, pp. 219–228) mentioned three basic Mixed Methods designs: Convergent Parallel Mixed Methods, Explanatory Sequential Mixed Methods and Exploratory Sequential Mixed Methods.

As stated, the in this study used Convergent Parallel Mixed Methods design is a form of Mixed Methods in which the researcher converges quantitative and qualitative data in order to provide a more comprehensive analysis of the stated research problem. Creswell(2014, pp. 219–223) describes that in this design, the research typically collects both forms of data at roughly the same time, analyses them separately, then integrates the collected materials in the interpretation of the overall results and contradictions or incongruent findings are explained or further probed in this design. The key assumption is that both qualitative and quantitative data provide different types of information and combined they yield the results (Creswell, 2014, pp. 219–223).

Integrating the qualitative and quantitative data in Mixed Methods is most important and difficult. Tariq and Woodmann(2013, p. 6) explain one approach for integrating as first to analyse the two data types separately and then second to mix, compare and combine the two data types and findings. An important aspect is that the quantitative and qualitative data are kept analytically separated and analysing techniques which are usually associated with that type of data are used. Meaning that statistical techniques are used to analyse quantitative data whilst a thematic analysis is used to examine qualitative data, hence the integrity of each data type and the potential for enhanced understanding of the research issue from combining the two data types and findings need to be preserved (Tariq and Woodman, 2013, p. 6). The described approach and recommendations are used in this research study.

3.5.1 Procedure

As stated, this study has three content-wise guidelines. Hardware start-up and their known challenges and supporting factors give first indications for the study. Another guideline is given by the literature review for product development, such as factors to product development, cost, time and quality. The third guideline is given by the reviewed literature on the Maker Movement and the developed Maker Movement Element framework. Those guidelines form the basis for the interviews and survey and also influences the procedure for this study.

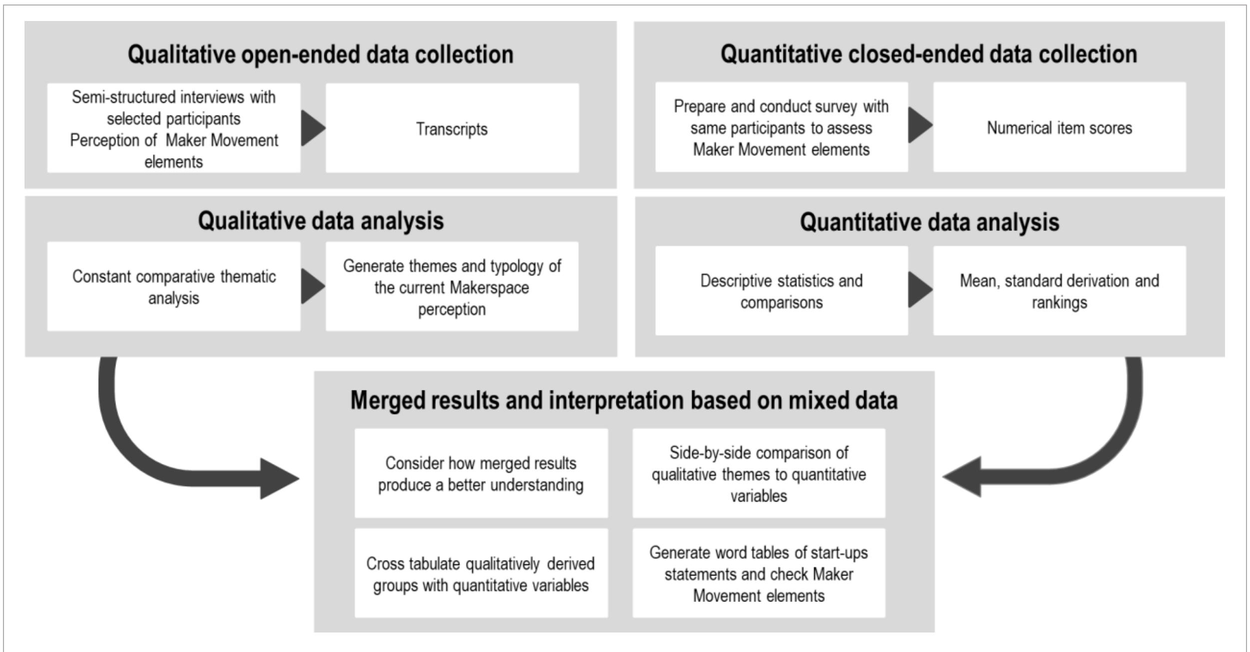

Figure 17: Flowchart of Convergent Parallel Mixed Methods design[53]

[53] Based on Creswell and Clark (2011, p. 118)

Figure 17 shows the flowchart of this research study, based on an example given by Creswell and Clark(2011, p. 118) and a study conducted by Wittink, Barg and Gallo(2006). As indicated, there are four steps in Convergent Parallel Mix Methods: collect, analyse, merge, and interpret. As stated earlier, both datasets are collected and analysed separately, but in parallel. Qualitative data is collected in semi-structured interviews, which result in transcripts. For qualitative analysis, comparative thematic analysis is used to create themes. In the quantitative strand, a survey for collection, and descriptive statistics and group comparisons are used for analysis. As shown in Figure 17, both strands have an equal emphasis within the study and their results are merged at the same stage with a side-by-side comparison matrix into an overall interpretation.

3.5.2 Sample

The sample for this study consists of hardware start-ups affiliated to Makerspaces and universities in different locations within the DACH region in Europe. During sampling and in line with the scope of the research, some considerations were taken in account when searching for appropriate start-ups: first, start-ups need to fit the given definition stated in section 2.1; second, availability and access to entrepreneurs and data of start-ups due to personal contacts, and third, the proximity of the start-up to a Makerspace as mentioned in section 3.3.

As explained, the three most prominent locations for hardware start-ups within the DACH region, one per country in the region, are chosen: Graz University of Technology (Austria), Technical University Munich (Germany), and Swiss Federal Institute of Technology in Zurich (Switzerland). All three fulfil the described criteria for the research scope. Graz is chosen because this location hosts the oldest academic Makerspace in Austria, which is also located on the campus of Graz University of Technology (TU Graz) and has an important entrepreneurship centre. In contrast, at the time of writing, Vienna still has no Makerspace promoted or located near a university. Munich is chosen as has the most prominent hardware start-up ecosystem in Europe and all constraints are fulfilled with the Technical University Munich (TUM), UnternehmerTUM and UnternehmerTUM MakerSpace. Zurich is chosen because of its world leading university, the Swiss Federal Institute of Technology (ETH). Hence, a local start-up ecosystem is in existence and an Academic Makerspace was recently opened.

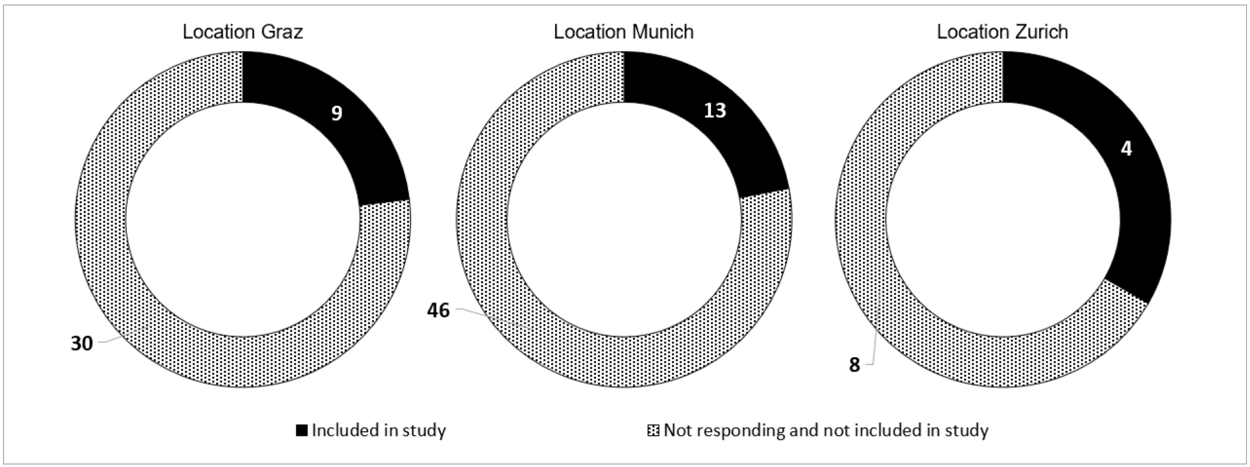

Figure 18: Overview of hardware start-ups at each location

Hardware start-ups are investigated in these three locations. This means that the operative staff of Makerspaces and entrepreneurship centres at each selected location are asked to list start-ups that suit the stated definition. Furthermore, university websites, Makerspace websites and websites of the entrepreneurship centres are reviewed in order to create a comprehensive list of possible start-ups to be interviewed at each location. The listed start-ups are structured and entrepreneurs, who may be the founder, CEO or CTO of a hardware start-up, are then selected and contacted. Figure 18 shows on the one hand the number of hardware start-ups discovered per location and on the other hand, the hardware start-ups interviewed. A total of 29 hardware start-ups have been investigated. More hardware start-ups have been contacted but some have not replied while others seem to be completely inactive. Three hardware start-ups have been questioned but have then been omitted because they do not match the defined constrains fully.

3.5.3 Data gathering and collection

As stated, data is collected qualitatively mainly through interviews with open-ended questions, and quantitatively, based on a survey, using the same variables, which is the so-called Maker Movement Elements framework. As presented in detail in section 5, the research collects qualitative and quantitative information from the same number of individuals. This means that the qualitative sample is included in the quantitative sample. Based on Creswell(2014, p. 222), the ultimate goal is a comparison between these two datasets and the more they are similar, the better the comparison is. This goal is attained in this research study.

3.5.3.1 Conducted semistructured interviews

Based on Yin(2009) a qualitive research study employed several data sources. In this dissertation the collection of data followed the principle of triangulation and saturation and includes the following data sources according to Yin (2009, pp. 101–113):

- Qualitative semi-structured interviews with Makerspace staff and hardware start-ups with different perspectives and involvements
- Internal documents provided by Makerspaces and business start-up centres
- Publicly-available information on e.g. start-up websites
- Informal discussions and exchange with Makerspace staff and hardware start-ups
- Non-participant and participant observations in the selected Makerspaces
- Field notes and photos

All qualitative semi-structured interviews are conducted by the author in person, by phone, or via a videoconference call during the period from April 2017 to July 2018. The guideline used in the interviews is composed of several subject areas and related questions but has the primary goal of serving as a point of support for the author in carrying out the interviews. It is based on exiting knowledge, see section 2.1.7, 2.2.2, as also 2.2.3, the earlier carried out EMS surveys by different and the developed Maker Movement Element framework, see 4. If necessary, it was possible to deviate from the guideline in order to ask intermediate or comprehensive questions. Interviewees were encouraged to expand on their answers, thoughts, and opinions when necessary. All interviews were recorded by the researcher with the prior consent of the interviewees and then transcribed. The duration of the interviews ranged from just over 45 minutes to around 90 minutes. Furthermore, field and observations of hardware start-up working in Makerspace were noted and later digitised as well as organised for analysis purpose.

Each interview was separated into three sections: general questions on and challenges as well as supporting factors of the hardware start-up of the entrepreneur concerned; detailed questions on the current experiences with Makerspace use; knowledge and usage of player/elements within the Maker Movement. The full guideline for the interviews can be found in the appendix.

General questions, challenges and supporting factors of hardware start-ups

Some aspects for the creation of the questionnaire to be used for the semistructured interviews were drawn from the ESM survey. As already mentioned, the ESM is an annual study to promote transparency for the start-up environment in Europe, to identify country-specific and common challenges of the start-up landscape and also projecting beyond that to show and highlight specific developments over time (Kollmann *et al.*, 2016, pp. 5–11). In line with person-related queries such as age, gender, and location of the hardware entrepreneur/start-up, the following open-ended questions are used to describe the entrepreneur's hardware start-up in more detail:

- What is the current development stage of your start-up?
- How can your start-up product be categorised and best described?
- What customers and/or users does your start-up address?
- Through which customers does your start-up generate revenue?
- What types of organisation have you already cooperated with and why? What are supporting factors of those organisations?
- What are the three biggest challenges your start-up is currently facing?
- What challenges do you may face/did you face during product development in your start-up?

The hardware start-up's experiences in a Makerspace

The second part of the interview asked about the current experiences in a Makerspace. The interviewees were specifically encouraged in this to think broadly and not only about specific Makerspace offerings or services. Furthermore, the interviewer stresses that term Makerspace can also be understood more broadly as an organisation which support the whole product development process. The following set of open questions was used to start discussion in this section of the interviews:

- Could you briefly describe what experience you already have with Makerspaces in general?
- Which machines/tools do you mainly use in your product development project?

- Do you face any restrictions when working on your product development project in a Makerspace?
- How can/should Makerspaces support you in the development of innovative products?
- What could be the main reason you chose to realise your project in a Makerspace?

Knowledge and usage of Maker Movement elements

The set of questions for the third part of the interviews is based on the knowledge and usage of certain player/elements within the Maker Movement, which are described in 4.3. After an open discussion of such player/elements the entrepreneurs are confronted with the concept of the Maker Movement Element framework for the first time. Each there named element was qualitatively discussed, a common understanding was reached, and it is noted whether a specific element used in their product development. When a certain element was used follow up questions were asked to learn more about the frequency of usage, the experience and benefits. Furthermore, the interviewee is questioned on the inclusiveness of the discussed Maker Movement Element framework.

3.5.3.2 Survey of Maker Movement elements by hardware start-ups

The quantitative questionnaire prepared by the author derives from characteristic in successful product development projects, see 2.2.3, and the developed Maker Movement Element framework, see 4.3. The survey is cross-sectional, which means that all data is collected at one point in time. The form of quantitative data collection is paper based. A pilot testing of the survey is carried out in the Graz location with two entrepreneurs, who are not included in the sample of this research. Their comments resulted in a revision of the survey. The full and final questionnaire can be found in the appendix.

The choice to use a paper-based questionnaire is underpinned by the following, based on Kuß(2012, p. 126) or Bruhn(2016, p. 98):

- A paper-based questionnaire can be used very flexibly.
- Written surveys are cost-effective, because no or minimal infrastructure is needed.
- There is no influence from interviewers due to individual paper-based survey and greater openness not biased responses can be assumed.
- The spatial and temporal flexibility of the survey situation makes it possible to reach even difficult-to-reach interviewees.

Those benefits are contrasted, according to Berekoven, Eckert and Ellenrieder(2009, pp. 110–111) or Bruhn(2016, p. 99), by the following disadvantages:

- The fact that the interviewee actually filled out the survey himself cannot be guaranteed.
- Motivation of respondents to complete the questionnaire can only be achieved through the questionnaire itself. This leads to limitations in the questionnaire design.
- Surveys can lead to incomplete or inappropriate answers.

When time-wise the qualitive interviews were finished, each interviewee was immediately confronted with a survey to assess quantitively the developed Maker Movement Element framework. For the survey, the following questions, based on criteria in product development as described in 2.2.3 and the importance of network within the Maker Movement see 2.3.3, are used to carry out this assessment:

- Which Maker Movement elements are unknown, known or already used in your start-up life?
- Which Maker Movement elements can be used to shorten product development time?
- Which Maker Movement elements help to save costs in product development?
- Which Maker Movement elements help to reduce product costs?
- Which Maker Movement elements increase product quality?
- Which Maker Movement elements support enlargement of your network?

Each element is evaluated for each question based on a Likert response items, see Likert(1932, pp. 25–35). For instance: *Can community order platforms be used to shorten product development time? [5-point Likert: 5… extremely likely, 4… likely, 3…neutral, 2… unlikely, 1… extremely unlikely]* The survey is done paper-based and is handed out to the hardware start-up entrepreneur after completion of the qualitive interview. After a certain timespan ranging from hours to several days, the completed survey is returned to the researcher. 100% of interviewees return the completed paper-based survey. After completion of the survey, each interviewee has given a total of 165 answers to the five question groups each containing 33 different elements.

3.5.4 Data analysis and interpretation

Comparative thematic analysis is used to create themes for the analysis of the qualitative data. In the first step, a general sense of the collected data is created, and general thoughts are recorded. The coding breaks up the qualitative data in chunks and words are used to label these chunks (Rossman and Rallis, 2017, p. 237). In the case of this research study, the coding items were deducted from literature, which are characteristics of hardware start-ups, challenges and supporting factors for hardware start-up and in product development as well as elements within the Maker Movement Element framework. The implemented coding is subsequently used to describe certain themes named by the interviewees. These themes are the ones that appear as key findings in qualitative analysis and are highlighted in section 6.1.

In the quantitative strand, descriptive statistics and group comparisons are used for analysis. The analysis indicates the means, standard deviations and ranking of scores for the variables. The quantitative study focuses only on a descriptive analysis because the sample size is too small for more advanced inferential analysis. The author aims for the same sample size for the qualitative and quantitative strands in order to reach validity. In addition, it is possible with a small quantitative sample to ensure that the interviewees understand the up to now relatively unknown Maker Movement elements in a correct manner and to motive the interviewees to participate in the study. All interviewees return a completed survey. The threat of response bias, which is the effect if non-responses had responded in the survey and their responses had substantially changed the overall result (Fowler, 2009, pp. 66–67), is counter to an instantaneous analysis of the responses and no significant change of responses has been detected during the conducted survey period.

One challenge in Convergent Parallel Mixed Methods design is also how to actually merge the two datasets. As stated, the two datasets are first analysed separately and then brought together. Creswell and Clark(2011, p. 223) mention several ways to merge the data: side-by-side comparison, data transformation, or joint display of data. In this research, the side-by-side comparison approach with a comparison matrix is used. In this comparison, the researcher first reports the quantitative statistical results and then discusses the findings based on the qualitative themes mentioned, which either confirm or disconfirm the quantitative results (Creswell and Clark, 2011, p. 223).

The interpretation in Convergent Parallel Mixed Methods design is based on the comparison of these two datasets and notes whenever there is a convergence or divergence. When divergence exists and is detected, follow-up steps need to be taken, and the research can return to the analysis phase to further explore the datasets and collect more relevant data in order to resolve the differences or discuss the results as a possible limit of the research (Creswell and Clark, 2011, p. 223).

3.5.5 Challenges in using Mixed Methods designs

In general, the Mixed Methods procedures induce specific challenges for the researcher. The need for extensive and time-intensive data collection and analysis and the prerequisite that the researcher is familiar with both qualitative and quantitative methods, are the challenges most commonly mentioned (Creswell, 2014, p. 218).

Creswell and Clark(2011, p. 239) stress also when merging the two datasets, different sample size can be challenging. In this study, this is countered by choosing an equal sample size for both qualitative and quantitative data. Furthermore, it can also be challenging when merging very different data and results in a meaningful way (Creswell and Clark, 2011, p. 239). This is encountered by using the same metrics, like the Maker Movement Elements framework, for both data collection and analysis. Finally, contradictions between qualitative and quantitative data can be difficult to resolve (Creswell and Clark, 2011, p. 239). In this case, more data needs to be collected to overcome this issue.

3.5.6 Validity and Mixed Methods designs

Quantitative and qualitative research have different criteria for assessing validity. Validity using the selected research approach can therefore only be established when both qualitative and quantitative database are valid (Creswell, 2014, p. 225).

For the qualitative study, validity is attained through the triangulation of data, which is collected through multiple sources, long-term and repeatable observations at the research locations, peer examination in a research group at Graz University of Technology, as well as clarification of research bias, as presented in section 3.6. For the quantitative part of the research study, validity is attained through the match to a fourth comparable location. The conclusions, themes and scores will be tested against the location of Helsinki. In total six interviews with hardware start-ups were conducted in Helsinki. Helsinki itself is comparable to the chosen DACH locations: a university and several academic Makerspaces.

Potential validity threats	**Strategies for encountering threat in this study**
Selection of inappropriate individuals for data collection	Individuals are carefully selected, and samples are drawn from same group of individuals
Obtain unequal sample size for the data collection	Same sample size for both; use larger qualitative sample and smaller quantitative sample then common
Collecting types of data that do not match the same topics	Use of the same Maker Movement Element framework and similar questions are addressed
Potential bias is introduced through while data collection	Use of a separated data collection procedure; quantitative data is collected paper-based at the end
Use of inadequate approaches to converge the collected data	Use of side-by-side comparison tables based on the quantitative findings and qualitative themes
Illogical comparison of the results	Find quotes to underline quantitative results
Use of inadequate data transformation approaches	Transformation is kept clear based on counted themes; a clear procedure is described and used
Use of inadequate statistics to analyse results	Consideration of descriptive and nonparametric statistics only; distribution of scores are examine
Divergent findings are tried to solve	Current data is reanalysed, and more data is gathered
More weight is given to one form of data	Procedure are used to present equally the results
Not discussing the Mixed Methods research question	Mixed methods question is intensively addressed
Multiphase study: stages are not relating each other	Stages are connected based on problem, theory, design and the Maker Movement Element framework
Different skills and perception among different research in a team	The whole research study is conducted by a single researcher

Table 5: Potential validity threats in Convergent Parallel Mixed Methods design and strategies to overcome those[54]

[54] Based on Creswell and Clark(2011, pp. 240–241)

Because the sample size of the qualitative and quantitative groups is the same, a deviation to one side or another can be addressed. The use of the same metrics, like Maker Movement Element framework, for the qualitative and quantitative research section may result in comparable and mergeable findings. A summary of various other validity threats for a Convergent Parallel Mixed Methods study is given in Table 5.

3.6 Further contemplation and authors' roles

Tracy (2010, p. 842) stresses that in qualitative research transparency is required as well as a description of an author's involvement is needed, in order for readers to understand their roles and assess whether the roles add or detract from the richness of data collection and assessment. However, the investigator's assumptions, biases, and personal values can be positive and useful rather than unfavourable (Wood, Mento and Locke, 1987, pp. 420–421).

This study started in 2014 and was concluded in 2018. During this study, the author has been a facilitator of a Makerspace and a faculty member of a university. The author started the first academic Fab Lab in Austria, FabLab Graz, in 2014 and managed this institution for around three years. In addition, a new research group at Graz University of Technology focusing on the Maker Movement was initiated. At the time of writing, the author was the Deputy General Manager of UnternehmerTUM Makerspace. This understanding of the context and role enhance the awareness, knowledge and sensitivity to many challenges and issues encountered by individuals working and developing products in a Makerspace. In addition, the author has a deep understanding of start-ups because he supports numerous start-ups in his current and former work, many of which come to or from a Makerspace. This unique role provided access to principals, discussions with principals, internal data of start-ups, interaction with Makerspace users, observation of Makerspace users, internal documents on Makerspaces, and connection to the worldwide Makerspace and Fab Lab network. As a result of the author's previous and current experiences as a manger of a Makerspace, he certainly brings biases to this study. However, every effort is made to certify objectivity, these biases may shape the way the author understand and interpret the collected data.

3.7 Conclusion: research design, approach and methodology

The research approach applied for this dissertation has three stages: first, the intent of the research and a conceptual framework based on current knowledge is given; second, an empirical study is conducted to structured and framed the Maker Movement in order to provide a lens for the further stage; and finally a Mixed Methods research study is carried out to examine hardware start-ups product development projects. This Mixed Methods research study is developed in line with the Convergent Parallel Mixed Methods design. Hence, qualitative data is collected and analysed separately as well as chronologically parallel, quantitative data is also collected and separately analysed. Both datasets are later merged and interpreted with the aim that the quantitative results help to explain the qualitative themes and findings.

The first empirical study has a broad scope to discover as many elements within the maker Movement as possible and the latter consist of qualitative and quantitative datasets created with hardware start-ups working at three locations in the DACH region. For qualitative data collection, various sources are used such as websites, semi-structured interviews, available documents and observations. A paper-based survey is used for quantitative data collection. The qualitative data is transcribed, analysed and themes are created. The quantitative dataset is analysed based on descriptive statistics and group comparisons.

Finally, the validity of the research study and the author's role is reflected on.

4 Framing of the Maker Movement

A large number of Makerspaces have been established in the past decade. Over 1,400 Makerspaces were in existence worldwide in 2017 (Lou and Peek, 2016). The widespread access to capabilities for designing, manufacturing, and knowhow in these locations enables so-called Makers to invent and build hardware products themselves. As a result, Makers can bring their ideas from zero to market maturity. Various players such as MakerFaire[55], Hackster[56], Arduino[57] and Etsy[58] support Makers in realising their projects within the Maker Movement and new players are evolving daily. Despite this development, as yet there is no clear picture of the players in the Maker Movement. However, a framework or a taxonomy is a central aspect to support the conceptual and scientific discussion of an emerging phenomena like the Maker Movement (Voigt, Montero and Menichinelli, 2016, pp. 190–191).

To clarify the view of the ecosystem, this research study introduces Maker Movement elements. A Maker Movement Element is a collection of players such as activities, companies, non-profit organisations or platforms that hold a supportive role within the Maker Movement. Several Maker Movement elements can be categorised in subsystems. On this basis, a Makerspace is a physical location with the purpose of offering a decent amount of Maker Movement elements to individuals. The proposed Maker Movement Element framework is based on work presented by the author, see Friessnig, Böhm and Ramsauer(2017), at the ISAM 2017 and was further developed since then.

The aim of this section is to describe and structure the Maker Movement. Based on the data gathered, Maker Movement elements are identified, described, analysed, and categorised according to their similar roles and functions. The result of this empirical study is the developed Maker Movement Element framework.

4.1 Data collection for the framework

The empirical study for the development of Maker Movement element framework relies on the identification of players within the Maker Movement, which is based on several data sources. A player is an activity, company, non-profit organisation or platforms that hold a supportive role within the Maker Movement. First, players within the Maker Movement are identified based on a literature review (e.g. scientific publications) and an Internet search (e.g. company website) with the keywords such as “Maker Movement”, “Fab Lab”, “Makerspace”. The desk research was conducted from March 2016 to October 2016. Second, observations and interviews of more than

[55] www.makerfaire.com (Accessed: 2 June 2019)
[56] www.hackster.io (Accessed: 2 June 2019)
[57] www.arduino.cc (Accessed: 2 June 2019)
[58] www.etsy.com (Accessed: 2 June 2019)

25 Makerspaces in the USA, the EU and China were done. Based on the data collected, all players were described, analysed, and later categorized to Maker Movement elements according to similar roles and functions. Having a worldwide focus for data collections should lead to a collection of as many different players and Maker Movement elements as possible.

4.1.1 Desk research with literature review and Internet search

As laid out in 2.3, Hatch(2013, pp. 1–2) described the Maker Movement with the following nine principles in his work: make, share, give, learn, tool up, play, participate, support, and change. These nine principles give this research study a first structure.

Hagel, Brown and Kualasooriya(2014, pp. 6–11) conducted a study of the Maker Movement from the perspective of a Maker's product development process. They split up the creation process into three steps: Zero to Maker, Maker to Maker and Maker to Market. Different players in the Maker Movement ecosystem are described in line with these three steps e.g. reinforcing partners and centralised platforms. According to their study, the Maker Movement itself could not have had a great impact without supporting these elements (Hagel, Brown and Kulasooriya, 2014, pp. 6–11). All by them described players were recorded for the to be developed Maker Movement Element framework.

Van Holm(2015a, pp. 29–30) mentions that especially Makerspaces can offer multiple resources, like coworking spaces, open access of tools and skills, with the potential for impact on the quantity and nature of entrepreneurship. He believes that the costs for prototyping in particular can be cut significantly due to the access to manufacturing facilities provided (Holm, 2015a, pp. 29–30). Also Hlubinka *et al.* (2013, pp. 33–40) argue that Makerspaces and certain elements grant the opportunity to speed up prototyping in addition to easier sourcing of parts and the direct distribution of physical products online. Those resources are documented as players and Maker Movement elements.

Many Makers and Makerspaces serve as active agents and movers in the international hardware start-up scene. For instance, the founder of the Makerspace Szoil[59] describes their concept and offerings as a place where people exhibit and even sell their products and can thus be a very good entry point for starting one's own business (Lindtner, Hertz and Dourish, 2014, pp. 146–147). Hence, Makerspaces also facilitate networking with potential cofounders and strategic partners. People can connect better while working and learning together, rather than when interacting in business conferences (Zwilling, 2014). Socialising platforms for funding, learning, and accessing tools are crucial for cutting development and production costs. In addition, finding access to a supplier and distribution network is more likely. Kalish(2014) stated that Makerspaces often receive grants and thereby have the ability to promote a variety of hardware start-ups, hence in such an environment, entrepreneurs have the chance to be more easily noticed by potential

[59] www.szoil.org (Accessed: 2 June 2019)

investors. In addition, venture capitalists and investors are eager to see the status of the product creations at first-hand. For example: UnternehmerTUM Makerspace is teaming up with companies such as BMW and with private investors to support hardware entrepreneurs (Becker, 2015b). Zwilling(2014) concluded therefore that Makerspaces tend to be a new kind of incubator or accelerator with the inclusion of support contacts, such as lawyers and marketing groups close at hand. Those statements show that the Maker Movement is not limited to access to tools and machines only. As a consequence of this findings, many players within the Maker Movement are included with respect to community building and learning.

Maycotte(2016) stress that Makerspaces and certain players within the Maker Movement have the potential to increase the likelihood of individuals becoming a successful entrepreneur, those time and costs can be saved by means that are available in the Maker Movement. Starting with access to technologies help to get ideas off the ground, then the support and the collaboration in such Makerspaces advances the development of the product idea and finally the Maker community can facilitate funding of projects and help to recruit talented employees (Maycotte, 2016).

Generally, in Makerspaces, personal support and methodical tools are offered which go far beyond basic idea creation activities. On the other hand, equipment such as 3D printers, laser cutters and milling machines provide the capability to create prototypes in a short period of time. This enables a faster visualisation and conception and therefore an improvement of the continuous development process of products (Walter-Herrmann, Büching and Corinne, 2013, pp. 124–125).

4.1.2 Fieldtrips to Makerspaces

The field research of this study has worldwide focus and was conducted in the USA, EU and China in 2016 and 2017. Makerspaces featuring all mentioned types, see 2.3.4, plus hardware start-up support centres, see 2.3.9, were investigated to identify as many players wirhin the Maker Movement as possible. The following have been visited:

- **Fab Lab:** Aalto FabLab[60] (Finland), FabLab London (United Kingdom), HappyLab Wien[61] (Austria), FabLab Graz (Austria), FabLab IAAC[62] (Spain), FabLab Shanghai[63] (China)
- **Hackerspace:** NYC Resistor[64] (USA)

[60] www.fablab.aalto.fi (Accessed: 2 June 2019)

[61] www.happylab.at/de_vie/ (Accessed: 2 June 2019)

[62] www.iaac.net/fab-labs/fab-labs-bcn/ (Accessed: 2 June 2019)

[63] www.fablabo.org (Accessed: 2 June 2019)

[64] www.nycresistor.com (Accessed: 2 June 2019)

- **Techshop/ alike models:** TechShop Arlington (USA), Artisan's Asylum[65] (USA), NextFab[66] (USA), Machine Room London[67] (United Kingdom), UnternehmerTUM Makerspace[68] (Germany)
- **Makerspaces at a library:** Techcentral Makerspace[69] (USA)
- **Academic Makerspace:** CEID[70] (USA), Columbia Makerspace[71] (USA), Miters[72] (USA), MakerWorks[73] (USA), MakerLodge[74] (USA), Design Factory Aalto[75] (Finland), ADD[76] (Finland), Design Factory Tongji[77] (China)
- **Makerspace at established company:** Autodesk Build Space[78] (USA)
- **Hardware start-up support centre:** BuildIt![79] (Estonia), WorldMaker Shenzhen[80] (China); HAX[81] (China), Troublemaker Shenzhen Maker Space[82] (China), MakerCollider[83] (China)

Every visit consisted of an upfront Internet search, a tour and an interview with the local staff. First, the Makerspace website was accessed to identify elements. During the tour through the space, the existence of specific players was checked. Finally, the local staff were questioned about what they have to offer, and new players were may discovered.

4.2 Analyse and synthesize of collected data on Maker Movement elements

The literature review, Internet search and field research resulted in a long list of players within the Maker Movement, as shown in Table 6. A syntax is defined for the development of the Maker Movement Element framework: subsystems are characterised as functions, described by a noun and a verb; elements are nouns, which include various players of the Maker Movement. In the

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[65] www.artisansasylum.com (Accessed: 2 June 2019)
[66] www.nextfab.com (Accessed: 2 June 2019)
[67] www.machinesroom.co.uk (Accessed: 2 June 2019)
[68] www.maker-space.de (Accessed: 2 June 2019)
[69] www.cpl.org/subjectscollections/techcentral/makerspace/ (Accessed: 2 June 2019)
[70] www.ceid.yale.edu (Accessed: 2 June 2019)
[71] www.make.columbia.edu (Accessed: 2 June 2019)
[72] www.miters.mit.edu (Accessed: 2 June 2019)
[73] www.makerworks.mit.edu (Accessed: 2 June 2019)
[74] www.makerlodge.mit.edu (Accessed: 2 June 2019)
[75] www.designfactory.aalto.fi (Accessed: 2 June 2019)
[76] www.addlab.aalto.fi (Accessed: 2 June 2019)
[77] www.sfc.tongji.edu.cn (Accessed: 2 June 2019)
[78] www.autodeskbuildspace.com (Accessed: 2 June 2019)
[79] www.buildit.lv (Accessed: 2 June 2019)
[80] www.szmaw.szoil.org (Accessed: 2 June 2019)
[81] www.hax.co (Accessed: 2 June 2019)
[82] www.troublemaker.site (Accessed: 2 June 2019)
[83] www.makercollider.com (Accessed: 2 June 2019)

field research, it was clearly evident that certain Makerspaces have a specific focus and therefore have special players/elements on offer.

Players within the Maker Movement have been combined to elements based on their similarity in order to develop a structured framework. The gathered elements were analysed again, checked for duplicates, and finally categorised. 112 players are identified based on the literature review and the Internet search. 27 visits to Makerspaces plus interviews are conducted, which lead to the identification of 53 additional players. In total, 165 players are documented, which are then synthesised and categorised in 33 Maker Movement elements and nine subsystems.

Identified player within the Maker Movement	**Synthesised to Maker Movement elements**
MakerFair, CES, Hackathon	Fair/ event
Maker's Row, The Maker Map, fablabs.io/labs, Makethingsdostuff, digitalsocial.eu	Maker related facility database
Meetup, Hardware Pioneers	Expert's roundtable
OSH Park	Community order platform
GrabCAD, Thingiverse, Github, 3dcontentcentral.com, YouMagine, Yeggi, Redpah, Sourceforge, Threeding, turbosquid.com, viewshape.com, openhardware.io, Bitbucket, GitLab	Open files repository (CAD files, norm parts, code)
forums.reprap.org, Quora	Discussion forum
Hackster.io, Instructables, Ravelry, Craftster, MakerShare, hackaday.io	Crowd based instruction
Formlabs Webinar, Workshops at Makerspaces/FabLab, fabacademy.org, online.stanford.edu, Courseara, udemy.com, lynda.com	Webinar/ workshop/ open online course
Fictiv Hardware Guide, Predictable Design, Open IDEO, Bolt Blog, Baldengineering, EEVBlog, Dragon Innovation, 3dhubs.com/knowledge-base/, Craftsy, build-electronic-circuits.com	Online collection of resources
Core77, Hackaday, Youtube, maker.blog	Online blog that inspire/ teach skills/ help to solve problems
Machinery's Handbook, MAKE magazine	Book/ printed magazine
Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker, tensorflow.org, r-project.org, osdn.net	Open-source software framework
Arduino, RaspberryPi, BeagleBone, Netduino, Intel Galileo, ESP8622	Open-source hardware
3D printer, laser cutter, 3D scanners	Digital prototyping machine
CNC router, saw, sander, etc. for wood	Wood shop
CNC router, welding, lathe, jet water cutter, etc. for metal	Metal shop
Circuit board production tools, LittleBits, Makerblocks, soldering iron, testing equipment, etc.	Electronics lab
Sewing machine, vinyl cutter, embroidery machine, etc.	Textiles area
Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA, etc.	Testing equipment (for electronics)
FirstBuild	Microfactory (for assembly)

IBM Bluemix, Amazon AWS, Google Cloud Platform, Microsoft Azure, thingspeak.com, create.arduino.cc, ifttt	Cloud computing platform
Inkscape	Free 2D design software
SketchUp, thinkerCAD, Makercase, Autodesk Fusion360, Vectary, Onshape, openjscad.org, shapeshifter.io, mattermachine.com, sharecad.org, blender.org, rs-online.com/designspark/, freecadweb.org	Free 3D design software
Simscale	Simulation software (CAE, CFD, FEA)
Upverter, DipTrace, KiCAD, Circuit Lab, resin.io, blynk.cc, circuito.io, TI Webench, CircuitMaker, codebender.cc, easyEDA, thingstud.io, Digi-Key scheme-it, Ltspice	Design software for electronics (IoT toolkit, PCB testing)
Protolabs, Fictiv, 3D Hubs, Ponko, Maketime, Protolabs, additively, quickparts.com, meltwerk.com, i.materialise.com, sculpteo.com	Platform for distributed manufacturing
Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net, Dragon Innovation, macrofab.com	Contract manufacturer for low volume
Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc	Online distributor of electronic components
Modulor	Raw materials in lowest volume/ material library
Kickstarter, Indigogo	Crowd funding
Companisto, Seedrs, fundedbyme.com	Crowd investment/ equity crowdfunding
Etsy, Quirky, Shapeway, Ebay, Amazon Lunchpad, Maker.me	Peer-to-peer e-commerce
Kaufhaus Kollektiv	Rent a physical retail space

Table 6: Overview of players within the Maker Movement and synthesised Maker Movement elements

4.3 Elements in the Maker Movement framework

The Maker Movement elements are categorised in nine subsystems: Connect with others (physical/live), connect with others (online/virtual), gather knowledge and skills, use of open-source, access to prototyping/ fabrication/ manufacturing facilities, use of CAx software, access to international shipping vendors, get seed capital funding, and get immediate customer feedback. Those subsystems and their relevance are described in detail in the following sections.

4.3.1 Connect with others (physical/live)

According to Inkpen and Tang(2005, p. 147), can networking provide organisations with access to knowledge, resources, markets, or technologies and the key argument to establishment a network is that through repeating as well as enduring exchange of relationships, a potential for knowledge acquisition and exchange is created. Within such networks, the transfer of knowledge manifests itself through changes in the knowledge or performance of the recipient, whereas knowledge, especially from outside, can be an important stimulus for change and organisational improvement (Inkpen and Tsang, 2005, p. 147). In the Maker Movement, networking is a crucial area that needs to be tackled during the establishment of each Makerspace (Hlubinka *et al.*, 2013, pp. 41–42).

A survey conducted in 2015 of 97 Makerspaces in the UK discovered that the most important reason for people to use the Makerspace was socialising (mentioned by 41% of responses) and not making (mentioned by 33% of responses), as might assumed (Sleigh, Stewart and Stokes, 2015, p. 7).

One Maker Movement element in this subsystem is *fairs/events* such as MakerFairs[84], CES[85] or Hackathons in general. This element is especially important in order on the one hand to meet potential customers, and on the other to gather inspiration for new product ideas. A different element within this category is the *maker-related facility database* itself. An online database or a map of these facilities, such as provided at Maker's Row[86] or fablabs.io[87], is helpful to increase the likelihood of collaboration occurring between Makers. Another element is the *expert roundtable* on a specific topic such as the Internet of Things (IoT) developments. Companies, like Meetup[88], promote expert roundtables.

4.3.2 Connect with others (online/virtual)

Technology and globalisation affect every aspect of our lives, and the development of the Internet in particular gives Makers the possibility to connect worldwide. On websites such as Instructables[89] or Hackster[90], the Maker community generates a large body of content themselves to provide a way to discover, access, and learn new skills and to exchange information on their latest product creations. This is summarised in the *crowd-based instructions* element. Permanent access to open and collaborative networks of educators and Makers worldwide who share ideas, insights, and best practices can generate a significant momentum in product development. This thought is also true for the element *discussion forum*, in which Makers get answers on their product development issues form a worldwide community.

The *open file repository* element, like GrabCAD[91] or Thingiverse[92], describes a related concept. Individuals share their designs with others mostly for free and everyone can download the files, develop them further and use them in their own product idea.

A different aspect of online communities can be found within the *community order platform* element. Companies like OSH Park[93] give Makers the possibility to upload their printed circuit

[84] www.makerfaire.com (Accessed: 2 June 2019)
[85] www.ces.tech (Accessed: 2 June 2019)
[86] www.makersrow.com (Accessed: 2 June 2019)
[87] www.fablabs.io/labs (Accessed: 2 June 2019)
[88] www.meetup.com (Accessed: 2 June 2019)
[89] www.instructables.com (Accessed: 2 June 2019)
[90] www.hackster.io (Accessed: 2 June 2019)
[91] www.grabcad.com (Accessed: 2 June 2019)
[92] www.thingiverse.com (Accessed: 2 June 2019)
[93] www.oshpark.com (Accessed: 2 June 2019)

board (PCB) files while other community members can agree to order the same PCB, and later a bigger batch of the PCB is ordered which leads to cost reduction for every community member.

4.3.3 Gather knowledge and skills

In most Makerspaces, a structure and culture that fosters and facilitates knowledge sharing is established. Learning, networking and obtaining support is already included in the subsystems described, but knowledge gathering can also be done in a one-to-many style, covered in the *online blog* element that inspires, teaches skills, and helps to solve problems, such as Hackaday[94]. The Fictiv Hardware Guide[95] or the Make: magazine[96] describe in various articles written by experts, design guidelines for specific projects, summarised in the *online collection of resources* element. The element *books/printed magazine* can also provide Makers with the possibility to learn new skills. The *webinar/workshop/open online course* element describes, for instance, detailed video tutorials for specific equipment or material offered sometimes also by companies such as Formlabs[97].

Learning has become the critical aspect for understanding and adapting to the ever-increasing speed of change. Organisations and individuals should find and develop ways of systematically integrating learning into all routines of organisational life, because organisations that learn faster will be able to adapt more quickly and thereby achieve significant strategic advantages in the global world of business (Marquardt, 2011, pp. 1–2). The Maker Movement has high potential to influence learning models by improving engagement through new models of hands-on and experiential learning. The practical experiences of tinkering, failing, and rapidly iterating allow learners to focus on the actual creation process as well as technology used in a Makerspace can provide a new perspective on usage of materials and can change the role from a consumer to a creator (Media Maker and Deloitte Center for the Edge, 2014, p. 5).

4.3.4 Use of open-source

The combination of open source software and hardware can boost product development, because a functional prototype can be realised in a much shorter timeframe. The integration of technology is made easy by pre-packed kits with a standardised set of tools, and advanced kits with expansion modules. The *open-source software framework* element describes various companies and organisations, which publish code snippets or software frameworks free. Products like Arduino[98] or RaspberryPi[99] are included in the *open-source hardware* element.

[94] www.hackaday.com (Accessed: 2 June 2019)
[95] www.fictiv.com/hwg/ (Accessed: 2 June 2019)
[96] www.makezine.com (Accessed: 2 June 2019)
[97] www.formlabs.com/resources/ (Accessed: 2 June 2019)
[98] www.arduino.cc (Accessed: 2 June 2019)
[99] www.raspberrypi.org (Accessed: 2 June 2019)

4.3.5 Access to prototyping/ fabrication/ manufacturing facilities

Access to tools for making is an integral part of the Maker Movement itself. Makers today have easy access to industrial standard production facilities provided by e.g. Techshops, Fab Labs or by Makerspaces in general, as described in section 2.3.4. The Maker Movement elements within this group are structured along the equipment on offer: *digital prototyping machine, wood shop, metal shop, electronics lab, textiles area,* and *testing equipment for electronics*. Affordable access to a *cloud computing platform* is gaining ever more importance in the product creation of hardware start-ups, in addition to the physical infrastructure mentioned. Another element in this subsystem is the possibility of renting a *microfactory* for small-batch size production, such as the facility at FirstBuild[100] in Louisville, Kentucky.

4.3.6 Use of CAx software

Computer-aided software for designing and simulating (CAx) is much more affordable today and Makers can use this on standard computers. Maker Movement elements such as free *3D design software* (e.g. SketchUp[101] or Fusion360[102], *2D design software* (e.g. Inkscape[103]), *simulation software* (e.g. SimScale[104]) and *design software for electronics* (e.g. Upverter[105], KiCAD[106] or Fritzing[107]) are included within this subsystem.

4.3.7 Access to international shipping vendors

Access to lower-cost, small-batch manufacturing, located particularly in hotspots such as Shenzhen (China) has increased, which makes small-batch production for hardware start-ups more economical and viable (Hagel, Brown and Kulasooriya, 2014, pp. 11–13).

The *contract manufacturer for low volume* element includes, for instance, Seeed Studio[108], a Shenzhen based company. Seeed Studio has specialised its offer to custom-made PCB and PCB assembly for low volume projects at an affordable price. This gives start-ups the possibility to test their product in a bigger customer group without the need for major financial backing.

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[100] www.firstbuild.com (Accessed: 2 June 2019)
[101] www.sketchup.com (Accessed: 2 June 2019)
[102] www.autodesk.com/products/fusion-360/ (Accessed: 2 June 2019)
[103] www.inkscape.org (Accessed: 2 June 2019)
[104] www.simscale.com (Accessed: 2 June 2019)
[105] www.upverter.com (Accessed: 2 June 2019)
[106] www.kicad-pcb.org (Accessed: 2 June 2019)
[107] www.fritzing.org (Accessed: 2 June 2019)
[108] www.seeedstudio.io/fusion.html (Accessed: 2 June 2019)

Another element is *platform for distributed manufacturing* such as Fictiv[109], 3D Hubs[110] or Protolabs[111]. On these platforms, start-ups instantly get on the one hand a quote for a specific part and on the other hand they can order the part made from any other desired material. These platforms typically do not own any production machinery themselves but have access to a diverse network of companies willing to produce parts even for a very small batch size. Thanks to these platforms, entrepreneurs can either start their production without taking a big financial risk or also move up to bigger batch sizes. This type of production can be scaled appropriately when involving more than one supplier.

Starting from a wide availability base for open-source hardware components, various suppliers for these parts plus extension modules or pre-assembled sensor modules, are now available. These suppliers, such as Sparkfun[112] or Adafruit[113], are summarised in the element *online distributor of electronic components*.

Obtaining the right raw material for products can be difficult for an individual because in some cases the correct raw material is unknown and most raw material suppliers ship only to other business partners or/and in big batch sizes. Therefore, players within the element *raw material in lowest volume/material library* are crucial for projects. For example, the German-based company Modulor[114] sells over 30,000 different articles in small batch sizes and also runs material libraries in Makerspaces.

4.3.8 Get seed capital funding

As stated in 2.1.2, hardware start-ups typically need more financial investments than software start-up, but nowadays new forms for getting the needed finical support for hardware start-up projects exist.

The Maker Movement element *crowd funding* describes platforms such as Kickstarter[115] or Indiegogo[116]. Kickstarter is a tool for entrepreneurs to obtain feedback on their ideas, and if they share them, they may be able to get financial support to produce them. In the past few years, over 15m people supported projects with total investment of over USD 4bn (Kickstarter, 2018). Through crowd funding start-ups get also feedback on whether there is any demand for the

[109] www.fictiv.com (Accessed: 2 June 2019)
[110] www.3dhubs.com (Accessed: 2 June 2019)
[111] www.protolabs.de (Accessed: 2 June 2019)
[112] www.sparkfun.com (Accessed: 2 June 2019)
[113] www.adafruit.com (Accessed: 2 June 2019)
[114] www.modulor.de (Accessed: 2 June 2019)
[115] www.kickstarter.com (Accessed: 2 June 2019)
[116] www.indiegogo.com (Accessed: 2 June 2019)

product they are making based on the amount of committed customers (Williams and Nadeau, 2014, p. 67).

Another element is *crowd investing*. In contrast to crowd funding, crowd investing focuses on equity. Investors provide investment capital for a business and receive ownership of a small piece of that business in return for their money. Companies such as Companisto[117], Crowdcube[118], and Seedrs[119], collect cash investment from the crowd for a project. When it is successful, supporters earn a return on their initial investment. Investors use crowd funding as a platform to spread their risks with others.

4.3.9 Get immediate customer feedback

The human-centred design processes, like Design Thinking, describes ongoing feedback, recommendations, and adaptions of product creations as essential for the success of a project (Brown, 2008, p. 86).

The *peer-to-peer e-commerce* element includes websites such as Etsy[120] or Shapeways[121]. An individual can start his/her own web shop on those websites within minutes. Then s/he receives customer feedback in terms of the quantity of articles sold and later in the form of customer reviews. These peer-to-peer e-commerce websites are also a very useful opportunity for Makers to sell their finished product to a bigger market, because of the internationality of website visitors. Furthermore, these firms handle the customers' payment process and the communication between customer and seller.

In various locations, the renting of a facility such as a shelf in an existing physical store to sell their own products is also popular among Makers. This is included in the element *rent a physical retail space.* Kaufhaus Kollective[122] in Munich is an example of this initiative.

4.4 Conclusion: Framing of the Maker Movement

This section aims to identify, describe and structure the Maker Movement ecosystem; therefore, the Maker Movement Elements framework is developed. The research conducted reveals 33 facets of the Maker Movement, so-called Maker Movement elements, in nine subsystems, as shown in Table 7. A Maker Movement Element is a collective term for facets or players that hold a role within the Maker Movement. The elements are detected based on a literature review, an

[117] www.companisto.com (Accessed: 2 June 2019)
[118] www.crowdcube.com (Accessed: 2 June 2019)
[119] www.seedrs.com (Accessed: 2 June 2019)
[120] www.etsy.com (Accessed: 2 June 2019)
[121] www.shapeways.com (Accessed: 2 June 2019)
[122] www.kaufhauskollektiv.de (Accessed: 20 December 2019)

Internet search, field trips, observations, and interviews with Makerspace operators. Many of the identified elements play multiple roles in the Maker Movement ecosystem.

Nevertheless, a clearly structured Maker Movement Element framework is a valuable asset to further assess specific offerings and services within the Maker Movement as also provides a good guideline for the further research study. In particular, researchers and Makerspace initiators will profit from the developed Maker Movement Element framework.

Subsystem	Maker Movement Element	Explanation
Connect with others (physical/live)	Fair/ event	Face-to-face networking can provide access to skills, knowledge, resources, costumers, and markets
	Maker related facility database	
	Expert's roundtable	
Connect with others (online/virtual)	Community order platform	Online access to open and collaborative networks worldwide to share ideas, insights, data, and best practices
	Open files repository (CAD files, norm parts, code)	
	Discussion forum	
	Crowd based instruction	
Gather knowledge and skills	Webinar/ workshop/ open online course	Help yourself and get knowledge and learn skills
	Online collection of resources	
	Online blog that inspire/ teach skills/ help to solve problems	
	Book/ printed magazine	
Use of open-source	Open-source software framework	Integration of open-source technology is made easy, standardized, and reliable
	Open-source hardware	
Access to prototyping/ fabrication/ manufacturing facilities	Digital prototyping machine	Get access to industrial manufacturing machinery, resources, and equipment
	Wood shop	
	Metal shop	
	Electronics lab	
	Textiles area	
	Testing equipment (for electronics)	
	Microfactory (for assembly)	
	Cloud computing platform	
Use of CAx software	Free 2D design software	Software for designing and simulating is much more affordable today, often online use is possible
	Free 3D design software	
	Simulation software (CAE, CFD, FEA)	
	Design software for electronics (IoT toolkit, PCB testing)	
Access to international shipping vendors	Platform for distributed manufacturing	Access to lower-cost, manufacturing worldwide makes small-batch production for hardware start-ups more economical and viable
	Contract manufacturer for low volume	
	Online distributor of electronic components	
	Raw materials in lowest volume/ material library	
Get seed capital funding	Crowd funding	Get financial support for projects
	Crowd investment/ equity crowdfunding	
Get immediate customer feedback	Peer-to-peer e-commerce	Get feedback to projects (e.g. by quantity of articles sold or customer reviews)
	Rent a physical retail space	

Table 7: Summary of the Maker Movement Element framework

5 Description of the study sample

Participants in this Mixed Methods study are hardware start-ups. These start-ups, for instance, can be found at Academic Makerspaces and universities in different locations within Europe. During sampling and in line with the scope of the research, constraints for selection of locations and start-ups are defined. First, availability and access to data due to personal contacts; second, proximity of the location resulting in a selection of locations within the DACH region; and third, existence of a Makerspaces which can be in proximity to a university as underlined in section 3.5.2.

Based on these constraints, three spots are selected: Graz University of Technology with FabLab Graz, Technical University Munich with UnternehmerTUM MakerSpace as well as Swiss Federal Institute of Technology in Zurich with ETH Student Project House. All three are well-known and established universities in the DACH region and fulfil all the given criteria. The locations are important because the hardware start-ups to be interviewed are selected on this basis. For each location, start-up databases are searched, and the operative staff of entrepreneurship centres and Makerspaces are questioned in regard to hardware start-ups. Then interviews are requested with entrepreneurs of the selected hardware start-ups.

The following section describes the chosen locations and gives an overview of to be investigated hardware start-ups. The location descriptions refer only to hardware start-ups specific offerings and do not have the intend to describe the whole start-up ecosystem at the chosen locations.

5.1 Examination of hardware start-up location

To gain a more complete picture of the ecosystem in which the hardware start-ups questioned work, the location itself and working entrepreneurs are assessed. This assessment checks for instance whether a Maker Movement Element is currently offered. Multiple data sources, such as observations, historical data, Makerspace websites and interviews with the Makerspace staff are used.

5.1.1 Location 1: Graz University of Technology

Austrian start-ups tend to group in or around the major Austrian cities. Vienna has evolved as Austria's main hub for start-ups, where more than 60% of Austrian start-ups are located, and other hubs are Linz, Graz, and Klagenfurt (Fassl and Dömötör, 2015). Start-ups located in Graz have the benefit of easy access to industrial companies and also have access to one of the three Austrian technical universities. The Graz University of Technology (TU Graz) is considered to be a good source of entrepreneurship. Numerous graduates and academic staff members have founded one or even several companies. Between 1950 and 2016, graduates, students or employees of TU Graz have founded 172 companies (TU Graz, 2017).

Science Park Graz[123] is the local business incubator in Graz, partly owned by TU Graz, and helps entrepreneurs to take the first step towards starting a company. Science Park Graz was founded 2002 and is part of AplusB[124], a publicly-funded Austrian incubator network that aims to bridge the gap between research areas and the economic success. All eight Austrian AplusB incubators aim to increase the success rate of start-ups and the development of innovative and technology-oriented spin-offs in the academic field. The Austrian ESA business incubation centre[125] (ESA BIC) has been run at the same location since 2016. The Europe-wide ESA's BIC network, initiated by ESA's Technology Transfer Programme Office, works to inspire entrepreneurs to turn space-related business ideas into commercial companies, and provide technical expertise and business-development support. In contrast to Science Park Graz, ESA BIC supports only space-related start-ups. Currently, 16 start-ups are incubated (ESA BIC Austria, 2018). Science Park Graz supports university graduates from all fields by providing professional counselling, coaching, infrastructure and financing during the pre-seed/seed start-up periods and incubates ten start-ups and has 85 alumni (Science Park Graz, 2017). A start-up is typically incubated for 18 months in Science Park Graz.

FabLab Graz[126] was launched as the first Austrian university-based FabLab in 2014 on the TU Graz campus. The basic idea is to offer opportunities for every individual to invent and build hardware products themselves by having access to facilities for design, manufacture and gaining knowledge. FabLab Graz will be expanded in 2019 to 800 square metre. Starting in 2019, the new FabLab Graz will not only offer greater variety of production equipment for prototyping and small-batch production, but also infrastructure for co-working, product testing and demonstration. FabLab Graz is run by TU Graz itself. The FabLab Graz offers free access once a week (Thursdays between 14.00 and 18.00). On the other weekdays it is used for various university courses, but start-ups as well as partner institutes also have the possibility to rent the facility for their prototyping activities. Users are allowed to use all kind of machinery without an introduction course but under supervision of the FabLab Graz staff. On the free access day, users only pay for the material they consume. The current format of FabLab Graz offers ten FDM 3D printers in different sizes, two SLA 3D printers, one fibre-reinforced material 3D printer, two fully-equipped electronic workstations, a 3D scanner, two laser cutters, one small 4-axis CNC milling and various hand tools for woodworking. There are no dedicated facilities for metalworking and no possibility for PCB production at FabLab Graz, nor is there a water jet cutter or other industrial production machines (FabLab Graz, 2017).

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[123] www.sciencepark.at (Accessed: 2 June 2019)

[124] www.aplusb.biz (Accessed: 2 June 2019)

[125] www.esa-bic.at (Accessed: 2 June 2019)

[126] www.fablab.tugraz.at (Accessed: 2 June 2019)

In addition, two student-run Makerspace opened in 2017: ELab@TU Graz[127] is a student-run space, equipped with various tools and workspaces for electronics, such as electronic testing equipment, soldering iron, PCB mill, and reflow oven. Use of the lab is free for enrolled students at TU Graz. There is no dedicated opening time but the lab has a good availability during term time (E-Lab, 2017). HTU Makerspace[128], another student-run Makerspace, opened in May 2018. In contrast to FabLab Graz, HTU Makerspace is accessible at any time of day or night for enrolled students. HTU Makerspace is free of charge but restricted to enrolled students of TU Graz. Tools and machines, such as 3D printers, soldering stations, basic electronic equipment, bike repair equipment and a screen-printing machine, are offered (*HTU Makerspace*, 2018).

Idea Competition[129] is an annual contest that awards innovative business ideas with a high market potential that have arisen in the contest of academics. The best submissions will be rewarded with prize money for the total amount of EUR 12,000 (Idea Competition, 2018). The competition represents an ideal opportunity to get one's ideas evaluated and gain a place in the Science Park Graz. In addition, runs the Austrian Forschungsförderungsgesellschaft (FFG)[130] a spin-off fellowship program at universities, whereas a scientific staff member receives up to EUR 500,000 for a duration of 12 to 18 months to start based on results form a research project a start-up (FFG, 2018).

Various types of hackathon are run on a regular basis with TU Graz involvement. Green Tech Jam[131] is one example. In this 48-hour hackathon, students try to develop eco-friendly product concepts based on software and hardware prototypes. FabLab Graz also organised its first industrial funded 48-hour hackathon in spring 2018.

5.1.2 Location 2: Technical University Munich

Munich is an economic hub that offers entrepreneurs great infrastructure including access to universities, established giant German-based corporations, such as BMW and Siemens, as well as international companies, including Apple, IBM, Google and Microsoft. Based on Reddy *et al.*(2018), access to talent, the innovation environment, government support as well as the general quality of the Munich ecosystem stand out as major advantages for start-ups. Although there are not as many start-ups in Munich as there are in Berlin, the city has the largest median investment at USD 4.6m (Reddy *et al.*, 2018).

The Technical University Munich (TUM) wants to inspire its students, researchers and alumni to think and act entrepreneurially by systematically developing and supporting spin-offs. With its

[127] www.e-lab.at (Accessed: 2 June 2019)

[128] www.makerspace.htu.tugraz.at (Accessed: 2 June 2019)

[129] www.ideenwettbewerb.at (Accessed: 2 June 2019)

[130] www.ffg.at (Accessed: 2 June 2019)

[131] www.greentech.at/jam2019/ (Accessed: 2 June 2019)

vision "TUM. The entrepreneurial university", TUM has various elements in place for supporting and promoting start-ups. Hence, a major milestone was the founding in 2002 of the affiliated institute, UnternehmerTUM[132], which is the centre for innovation, business creation and entrepreneurship at TUM. UnternehmerTUM offers students, scientists, founders and start-up teams an exclusive opportunity to realise their ideas and projects. The 6,100 square meter Entrepreneurship Centre building has been in operation since May 2015 and hosts the UnternehmerTUM, the TUM Entrepreneurship Research Institute (ERI), TUM incubator, UnternehmerTUM Venture Capital (UVC) and the UnternehmerTUM MakerSpace under one roof on the university campus in Garching. More than 2,000 students visit UnternehmerTUM courses each year and 50 scalable technology start-ups are founded yearly (UnternehmerTUM, 2018). The start-up studies reported various times that TUM is ranked number one among the major German universities and More than 700 companies have been founded by TUM alumni since 1990 (Becker, 2015b).

The TUM incubator provides offices and workspaces as well as counselling free of charge to around 15-20 local start-ups per year (Becker, 2017). UnternehmerTUM itself offers individual support and systematic coaching in developing new products and services and building up a successful business. UnternehmerTUM is also one of 12 hubs of the Digital Hub Initiative[133] funded by the German government. The main aim of the Digital Hub Mobility is to promote partnerships among start-ups, established companies and research in order to foster the digital transformation as well as to actively encourage founding entrepreneurs, talents and investors to locate in the region (Digital Hub Mobility, 2018).

The Chancellor of Germany Angela Merkel said at her visit to UnternehmerTUM in 2015: *"This centre is a breeding ground – in the best sense of the word – for innovative start-ups. The entire knowledge of an outstanding technical university flows into this site. And the entire knowledge of a classic, flourishing industrial location like Munich also flows into this centre, as does the innovative power of young entrepreneurs"* (Becker, 2015a).

UnternehmerTUM MakerSpace[134] is a 1,500 square metre workshop that is open to the public and provides paid access to machines, tools, and software as well as a creative community. It offers a place to realise ideas and innovations in the form of prototypes and small-batch production. Various workshop areas are available, such as metal and woodworking shops as well as textile and electrical processing facilities. In addition, 3D printers, laser and water jet cutters make it possible to manufacture nearly every shape. MakerSpace offers training and consulting services as well as events for members with any level of knowledge, providing them with support and networking options (UnternehmerTUM MakerSpace, 2018). UnternehmerTUM MakerSpace is

[132] www.unternehmertum.de (Accessed: 2 June 2019)
[133] www.de-hub.de (Accessed: 2 June 2019)
[134] www.maker-space.de (Accessed: 2 June 2019)

one of Europe's biggest Makerspaces. UnternehmerTUM MakerSpace was opened in June 2015. Around 50 persons (part and full time) are employed. The biggest group of employees work as course instructors. The second largest group is the workshop staff and the third group deals with administrative tasks. Besides offering paid memberships to private persons and company representatives, MakerSpace provides students free access to the workshop. The space is open every day of the week: on Monday to Saturday 08.00 to 22.00 and Sundays from 11.00 to 19.00. In order to use the machines, mandatory fee-based introduction courses have to be taken by all members. A wide range of more than 50 courses is available to suit different skill levels and topics. The schedule and topics change weekly. The layout of the space is structured based on the type of the manufacturing process and the materials used: 3D printing (FDM, SLA, and SLS), laser cutting, metal shop, painting and finishing, welding, water jet cutting, wood shop, CAD work stations, textile, electronic workshop, plastics and project space. An event space and a coffee corner are also provided. Power tools, such as a drilling machine, jigsaw, etc. can be rented free of charge at the front desk.

TechFounders[135], one of the UnternehmerTUM start-up accelerator programmes, is a 20 week accelerator that prepares especially hardware start-ups for their first venture capital investments and helps establish strategic collaborations. In addition to initial funding of EUR 25,000 and free access to the MakerSpace, participants get support from industry experts, company founders, investors and scientists, who serve as mentors.

UnternehmerTUM Venture Capital[136] (UVC) invests in early stage DACH-based start-ups in the area of Industry 4.0, IoT, SaaS, Mobility and Smart Cities. The venture capital fund enrolled a first round with a volume of EUR 34m in January 2017 and has just finished the second round with EUR 80m. Ingo Potthof underlines that the *"unfair advantage"* of UVC is the proximity to UnternehmerTUM, Techfounders, and UnternehmerTUM MakerSpace (UnternehmerTUM Venture Capital Partners, 2018).

UnternehmerTUM hosts various events and meet-ups in line with entrepreneurship activities, such as Hack&Talk[137] and TechFest[138] to connect like-minded people. Techfest is a three-day hackathon with over 300 participants. The participants work on challenges in tracks, such as the IoT, AI, augmented reality or robotics, and gain access to the UnternehmerTUM MakerSpace as well as to a technology/hardware gadget library. This library includes gadgets like Microsoft HoloLens, HTC vives, Google Glasses, drones and also biosensors, Arduinos, and various other

[135] www.techfounders.com (Accessed: 2 June 2019)

[136] www.uvcpartners.com (Accessed: 2 June 2019)

[137] www.unternehmertum.de/hack-and-talk.xhtml (Accessed: 2 June 2019)

[138] www.techfestmunich.com (Accessed: 2 June 2019)

developer kits. The hardware gadget library is also accessible in entrepreneurship courses and to persons working in the UnternehmerTUM ecosystem.

Every entrepreneur in the ecosystem can also apply for Industrial Innovators Inniative prototyping grants[139] from EUR 2,000 up to EUR 10,000 (*UnternehmerTUM [x]*, 2018). The aim of the grants is to make prototyping more affordable for individuals with limited financial backing. Prototyping materials, hardware and software assets can be bought with the funds granted.

5.1.3 Location 3: Swiss Federal Institute of Technology in Zurich

Despite the fact that Switzerland is ranked the most innovative country in the world by the Global Innovation Index (Magnus-Sharpe, Badré and Shamoon, 2017), the country's start-up and tech scenes are often overshadowed by the more established and known European hubs. Many potential founders are put off by the comparatively high cost of living and the small local market. However, the ingredients for an active, engaged and rapidly growing start-up ecosystem can be found in Switzerland and has a level of secondary and university education that is ranked amongst the highest in the world (Gray, 2017).

The École Polytechnique Fédérale de Lausanne (EFPL) and the Swiss Federal Institute of Technology in Zurich (ETH) are a central force in driving forward the local start-up ecosystem and act as a launch pad for start-ups. The ETH has created 2,500 jobs with their spinoffs in recent years (Müller, 2017). Thanks to high average salaries, high standard of living, low tax rates and unemployment rates, the majority of young Swiss stay in the country once they complete their education and the high salaries are increasingly attracting foreign talent (Forsting, 2018). Entrepreneurial communities, like Impact Hub Zurich[140], are helping to bring the local start-up community closer together in many programmes and hackathons. ETH Zurich's core missions are teaching, research and the transfer of knowledge to business and society (ETH Zurich, 2017b). Modern and flexible infrastructure is a key factor and prerequisite for international excellence. In 2010, ETH Zurich founded the Pioneer Fellowships[141] and the Innovation & Entrepreneurship Lab[142] (ieLab) was established in 2012. The aim of these initiatives is to enhance the support of young entrepreneurs at ETH Zurich (ETH Zurich, 2018d).

The ieLab is a well-known player in the local ecosystem and promotes talented entrepreneurs and helps them along the development process from a product idea to market launch. The programmes and services offered by the ieLab are designed to make research results carried out at ETH available more quickly to the market and society (ETH Zurich, 2018b). The ieLab brings together entrepreneurs, experienced persons from the business world and alliance partners from

[139] www.industrialinnovators.eu/prototyping-grants/ (Accessed: 2 June 2019)

[140] www.zurich.impacthub.ch (Accessed: 2 June 2019)

[141] www.ethz.ch/en/industry-and-society/entrepreneurship/pioneer-fellowships.html (Accessed: 2 June 2019)

[142] www.ethz.ch/en/industry-and-society/entrepreneurship/ielab.html (Accessed: 2 June 2019)

industry. The Pioneer Fellowship programme is hosted in the ieLab and is awarded to individuals who have the intend to develop a highly innovative product or service to be exploited commercially and/or beneficially for society. Fellows receive CHF 150,000 (approx. EUR 130,000) over 12-18 months along with an extensive mentoring/ training programme, a work desks and access to a small workshop at the ieLab (Brenner, 2018).

The ETH Student Project House[143] (SPH) is a location where students can develop their own ideas outside of their curriculum. The aim of SPH is to improve students' ability to develop their own ideas and put them into reality in multidisciplinary project teams (ETH Zurich, 2017a). While the SPH provided the space, materials, and equipment for the project development process, students also received expert advice. These experts gave for instance an introduction into Design Thinking. The SPH at Hönggerberg has been in operation since 2017 and it is a pilot project. In a few years, the offering will also be available in a larger scale at the ETH location Zentrum.

The main infrastructural asset of SPH is a Makerspace. The Makerspace is open and free for all ETH students and ETH-affiliated persons. Machines such as FDM 3D printers, CNC milling machines, soldering equipment, laser cutters, power and hand tools are currently offered. Furthermore, an electronic components library and hardware library, including various kinds of screws and nuts, are provided (ETH Zurich, 2018c). In order to use advanced machines such as a laser cutter or CNC mill, a special introduction courses are needed. The space itself is run by a student team but supervised by ETH staff, hence working there should be a student-to-student learning experience. The SPH Makerspace is open Monday to Friday from 16:30 to 19.00. Various kinds of events such as 5-day design challenges in conjunction with industrial partners are hosted regularly at SPH.

ETH Bastli[144] is another completely student-run Makerspace focused on electronics. The lab offers free access and tools to implement and build one's own projects and ideas. During the fixed opening hours, Tuesday to Friday 12.00 to 13.00, persons can obtain required material directly from the internal component shop, ask questions or discuss problems, rent gadgets like a VR headset or an infrared camera, and can use the electronic shop (ETH Zurich, 2018a). If people want to continue working outside opening hours, they can request special access.

Technopark Zurich[145] brings together individuals, start-ups and companies from all fields of science, technology, and economics on its 47,000 square metre location outside of the ETH campus. 300 companies are based there and therefore it is one of the top locations for technology transfer in Switzerland with its key theme of connecting start-ups and established companies (*TECHNOPARK Zurich*, 2018). A large variety of rooms, offices, workshops and other spaces are available, all equipped with good infrastructure plus a range of counselling and coaching services.

143 www.sph.ethz.ch (Accessed: 2 June 2019)
144 www.bastli.ethz.ch (Accessed: 2 June 2019)
145 www.technopark.ch (Accessed: 2 June 2019)

5.2 Sample of hardware start-ups participants

As stated, the scope of the research is limited to hardware start-ups located in the selected DACH region. These hardware start-ups should have already established a company and worked at a Makerspace. All start-ups questioned are currently working on a physical product, which indicates that at least a product concept exists, but no revenues may have yet been created. In line with the research scope, 29 start-ups have been interviewed in total. Three conducted interviews needed to be filtered out as stated in the following.

	Graz									**Munich**			
	Start-up A	**Start-up B**	**Start-up C**	**Start-up D**	**Start-up E**	**Start-up F**	**Start-up G**	**Start-up H**	**Start-up I**	**Start-up J**	**Start-up K**	**Start-up L**	**Start-up M**
Currently in an accelerator										x			x
Alumni of an accelerator													
Currently in an incubator				x	x		x	x	x			x	x
Alumni of an incubator	x		x			x				x			x
Makerspace used	x	x	x	x	x	x	x	x	x	x	x	x	x
Supported by a university	x	x	x	x	x		x	x	x			x	x
Founded	2007	2017	2015	2016	2015	2016	2017	2016	2017	2017	2014	2016	2017
Number of founders	2	3	2	2	2	3	1	1	3	4	3	6	4
Who was interviewed	CEO	CEO	CEO	CEO	CEO	CEO	CEO	CEO	CEO	CEO	CEO	CTO	COO
Gender	m	m	f	m	m	m	m	m	m	m	m	m	m
Age	36-45	26-25	25-35	26-35	36-45	26-35	26-35	26-35	26-35	26-35	36-45	26-35	19-25
Short product debriefs	Cow sensor	CNC mill	Power producer	Auto-nomous charging	Drone safety	Med. Tech.	Power producer	Lab equip-ment	Energie & battery	Smart mirror	Laser cutter	Robotic	In-ventory tracking

	Munich									**Zurich**			
	Start-up N	**Start-up O**	**Start-up P**	**Start-up Q**	**Start-up R**	**Start-up S**	**Start-up T**	**Start-up U**	**Start-up V**	**Start-up W**	**Start-up X**	**Start-up Y**	**Start-up Z**
Currently in an accelerator													
Alumni of an accelerator	x				x								
Currently in an incubator	x	x	x							x			
Alumni of an incubator	x				x								
Makerspace used	x	x	x	x	x	x	x	x	x	x	x	x	x
Supported by a university	x	x	x		x	x	x			x	x	x	x
Founded	2015	2017	2017	2015	2017	2017	2016	2015	2018	2017	2018	2018	2017
Number of founders	3	3	2	2	2	3	2	1	2	2	4	9	2
Who was interviewed	CEO	CTO	CTO	CTO	ME	CEO	CEO	CEO	CEO	CEO	CTO	CEO	CTO
Gender	m	m	m	m	m	m	m	m	m	m	m	m	m
Age	19-25	26-35	26-35	26-35	26-35	26-35	26-35	26-35	26-35	19-25	19-25	25-35	25-35
Short product debriefs	Parking lot sensor	Auto-nomous driving	IoT juicer	Med. Tech.	Lab equip-ment	IoT self check-out	Re-usable stuff	Retrofit kits for cars	Cabin luggage	Wear-ables	Wear-ables	CFK printer	Cabel without core

Table 8: Overview of investigated hardware start-ups (anonymized)

Based on the current incubated and alumni database of Science Park Graz and on the user base of FabLab Graz, eleven hardware start-ups are selected and a person in charge of the desired start-up is interviewed. After conducting the interviews, two out of eleven interviews are filtered out for the analysis because they do not sufficiently match the scope of the research: one is filtered out because the start-up relocated early in the development to a different city and the other reached a very mature development stage and therefore cannot be longer treated as start-up.

Thirteen hardware start-ups from the UnternehmerTUM ecosystem were interviewed. All thirteen interviews fit the research scope described and can be used in the further analysis stage.

Based on the ETH SPH and ieLab user databases, twelve hardware entrepreneurs were selected for interview. However, only five replied to the request. After conducting the interviews, one interview out of the five is filtered out of the analysis because the entrepreneur has no intent to develop his idea and achieved results further to find a start-up.

In total, 26 out of 29 interviews are used for the further research steps. Table 8 shows an overview of the hardware start-ups interviewed and surveyed. Moreover, the table gives the first insights into the answers of interview section one, the questions about the hardware entrepreneur him/herself.

5.3 Conclusion: description of the study sample

The focus of this section is on the study sample and data collection. Participants in this research are hardware start-ups working at a Makerspace in locations within the DACH region. Constraints for selection are defined in line with the research scope described. First, availability and possibility to access data and hardware start-up due to personal contacts; second, the hardware start-up's location within the DACH region; and third, the existence of Makerspaces. Based on these constraints, three locations have been selected: TU Graz, TU Munich and ETH Zurich. All three are well-known and established universities in the DACH region and fulfil all the constraints. Participating hardware start-ups were selected based on the location.

In a first insight, Munich has positioned itself as a high-tech centre and the local network is fully utilised towards start-ups activities. UnternehmerTUM, which is TU Munich's entrepreneurship centre, is a breeding ground for start-ups. A part form that, UnternehmerTUM currently hosts one of the biggest European Makerspaces. Each location was assessed in detail through interviews with local Makerspace staff, observation in the Makerspaces, and internal as well as external accessible data.

All persons questioned are currently working on a physical product in a hardware start-up. Most interviewees come from the Munich area, this fact is based on the biggest and most matured hardware start-up ecosystem in this region. In line with the research design, 29 persons participate in total. Each qualitative interview with a person in charge of the selected hardware start-up was separated into three parts: first, general open-ended questions on the start-up of the entrepreneur concerned; second, detailed open-ended questions on his/her current experiences with Makerspace use; third, discussion of knowledge and usage of Maker Movement elements. After the qualitative interviews each interviewee is confronted with a quantitative survey to valuate numerically the developed Maker Movement Element framework based on costs, quality, time, and network.

6 Results and findings

The following paragraphs present the analysis and the results of the interviews, observations and survey conducted in order to clarify the ways in which the Maker Movement is currently supporting hardware start-ups in product development.

6.1 Qualitative data analysis

With the help of qualitative methods, a better understanding of a real-world phenomenon is created, and processes or structural features are highlighted. According to Rossman and Rallis(2017, pp. 3–6) qualitative research goes into the depth, not the breadth. Based on Creswell(2014, p. 183), qualitative methods differ in many aspects from quantitative methods. Although processes of qualitative research are in many steps similar. For structuring the transcribed interviews start-ups' characteristics, based on section 2.1, challenges and supporting factors in product development, see 2.2.2 and 2.2.3, as well as the Maker Movement Element framework, as stated in 4.3, are used. Hereinafter, qualitative themes are presented in figures represent the frequency of responses in order to easier compare the results (Flick, 2016, p. 47).

As already mentioned, the author interviewed a very homogeneous group of hardware start-ups. All have experience with a Makerspaces, mainly develop products for the Business to Business (B2B) market and develop hardware-focused products which may have a software aspect.

6.1.1 Hardware start-ups and their challenges

The interviewee is asked general questions on his/her start-up in the first phase to gain an understanding of the characteristics of the hardware start-ups interviewed. Then, based on literature and the EMS, see also section 2.1, as well as adapted to the research focus and on the given statements by the interviewees, the following characteristics of a start-up were formulated.

6.1.1.1 Type of start-up's product

The following groups were classified in order to provide an overview of the product on which the start-up is working: hardware-only product, which does not include any kind of electronics or software; hardware product with firmware, this product also includes electronics parts similar to a microcontroller and a programmed firmware to run the final product; hardware product with firmware and user software, this group includes the full range from a physical product to in most cases an applicable smartphone app for configuration and justification of the final product.

Subsequent interview questions are connected with the product itself, which the hardware entrepreneur is developing within his/her start-up. The researcher allows the interviewees to describe their product and clarify certain functions, and based on these statements, each start-up is assigned to one of the described themes of product types to be developed. The first theme is physical products only. An example of this theme is the Vendl[146] start-up. Vendl is developing an innovative packing solution for wheat beer. The second theme is physical product and firmware. Easelink[147] is an example of this theme. This company is developing an automated conductive charging robot; several lines of software code are included but no direct user interaction applications are provided. The third theme is physical product, firmware and user application. This theme is the most comprehensive hardware start-up. A physical product, a custom-made firmware, and a software application for the user to interact with the product needs to be developed. Rapitag[148] is an example of this theme. This company is developing security tags that can be opened automatically by using a smart phone. As shown in Figure 19, 13 (50%) of the hardware start-ups questioned come under this theme.

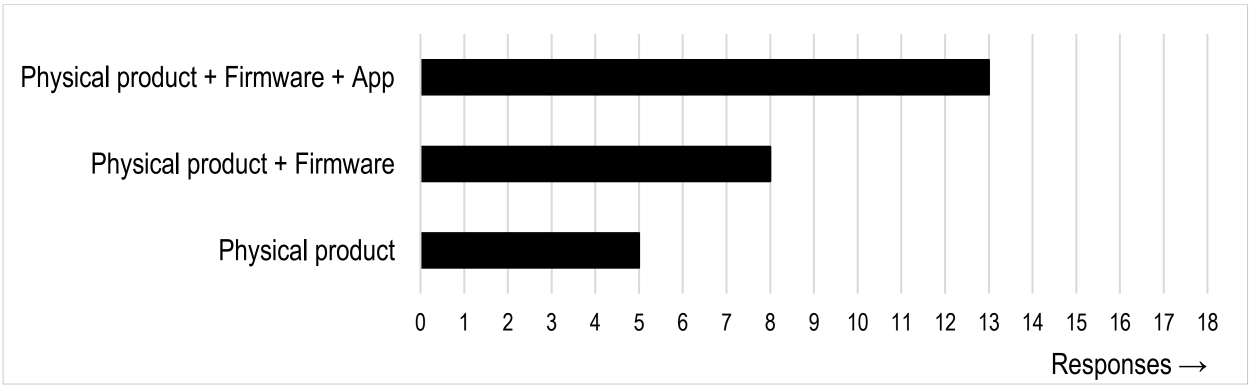

Figure 19: Themes of products to be developed of hardware start-ups questioned, n=26

6.1.1.2 Start-up stage

Another important aspect is the current start-up stage in which the hardware entrepreneurs see their venture. This characteristic matches the start-up with its corresponding developmental stage based on a self-assessment by the entrepreneur. After discussing the current development stage, the author defined the following groups based on the EMS: Seed stage (concept development, no revenues yet): Start-up stage (completion of a marketable/minimum viable product (MVP) with initial revenue and/or users); Growth stage (strong sales growth and/or user growth); Later stage (established market player/trade-sale or initial public offering (IPO) is planned or imminent); and Steady stage (the start-up does not have, intentionally or unintentionally, any substantial growth). As displayed in Figure 20 none of the start-ups interviewed fall into either the later or the steady stage, which is in line with the research scope. Most of the start-ups (69%) see themselves in the seed stage.

146 www.vendl.de (Accessed: 2 June 2019)
147 www.easelink.com (Accessed: 2 June 2019)
148 www.rapitag.com (Accessed: 2 June 2019)

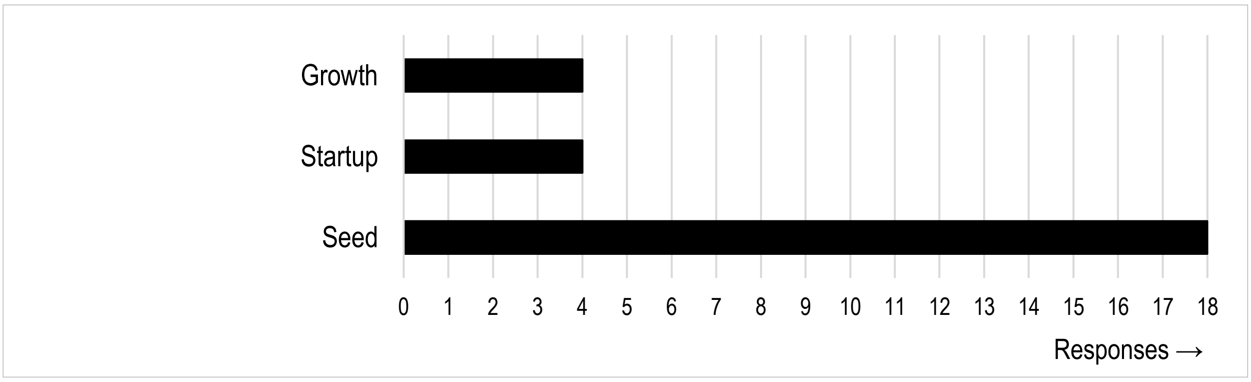

Figure 20: Start-ups' current stage of development, n=26

6.1.1.3 Products to be produced and sold

Another important aspect in characterisation of a hardware start-up is the expected amount of products to be produced per year. Naturally, the answers can only be seen as an estimate made by hardware entrepreneurs, but most of them have already created their business plans, and the volume of products to be sold is an essential component of the business plan. The responses are broken down into three groups: below 1,000 items per year; between 1,001 and 50,000 items per year; and more than 50,000 items per year. As shown in Figure 21, the smallest group (2, 8%) is 10,000 to 50,000 items per year whereas the biggest group is 50,000 and above per year (17, 65%).

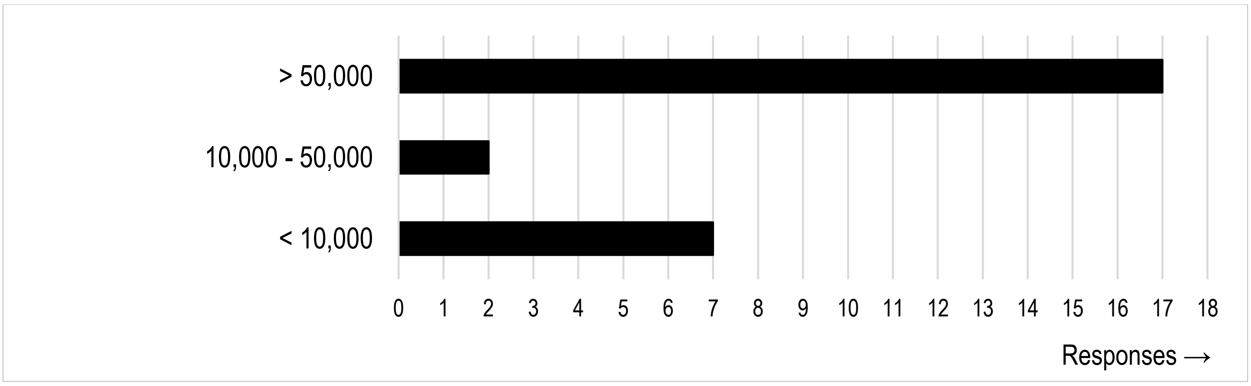

Figure 21: Expected volume of products to be produced/sold per year, n=26

6.1.1.4 Customers/users and market

This section distinguishes between customers through whom revenue is generated, and users who use the product/service. Possible groups are Business to Business (B2B) or Business to Consumer (B2C). Mixed groups of B2B customers and B2C users are included as well but those types are not very common. Figure 22 shows the number of start-ups assigned to each group on the basis of statements by participant start-ups.

Business-to-Consumer (B2C) stands for transactions, communication and business relationships between a company/start-up and individuals/consumers/customers. In contrast, Business-to-Business (B2B) refers to a situation where the start-up makes a commercial transaction with another business partner, which must not be the actual end customer. 70% of the start-ups interviewed were targeting B2B only, 15% B2C and 15% both B2B and B2C.

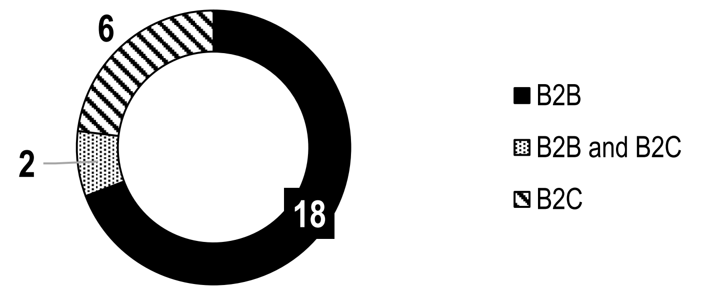

Figure 22: Targeted customers and/or users by hardware start-ups interviewed

6.1.1.5 Start-up foundation type

Moreover, it is important to note where a specific product idea has originated. Based on the statements, three groups are defined. The first group is product ideas that are independent and not directly connected to the hardware entrepreneurs' former job, in Figure 12 so-called independent ventures. The second group is product concepts that are based on a research activity, e.g. a PhD research study, at a university or a private research institute, so-called spin-offs from a university/research institute. The third group is spin-offs from a company, which means that the hardware entrepreneur has discovered a problem during his/her former career as an employee at a company which he/she is now tackling in his/her own start-up. As shown in Figure 23, 18 (69%) entrepreneurs mentioned that their start-up's product idea came from an independent venture and only two (8%) stated that they discovered and developed their idea while working for a company.

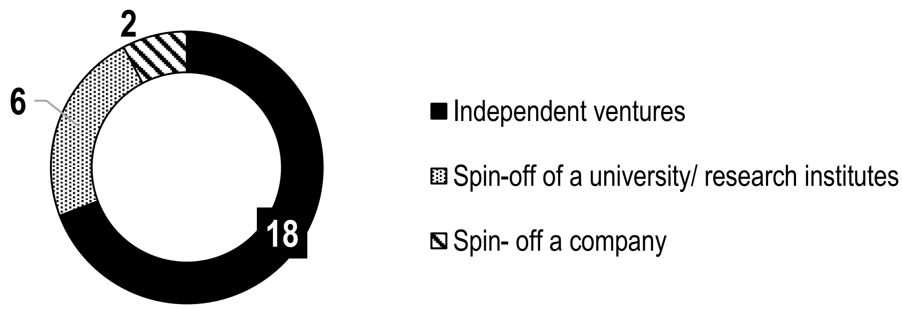

Figure 23: Sources of origin of product ideas, n=26

6.1.1.6 Biggest challenges being faced

The aim of this characteristic is to bring insight into the challenges that start-ups are facing. Various open-ended interview questions are used to investigate the three biggest challenges the hardware entrepreneur is currently facing within his/her start-up. Some interviewees mention less than three challenges in the statements collected by the interviewer.

The statements can be structured into five themes. Figure 24 shows the themes and the number of responses for each theme. By far the biggest challenge faced by the entrepreneurs interviewed at the present time is product development and this was specifically cited as challenge number one by 16 out of 26 respondents (61%). In terms of their current start-up stage, this seems to match the general pattern that is emerging, since all start-ups in the seed stage see product development as their main challenge. The second biggest challenges mentioned by hardware entrepreneurs is growth/ sales increase with 12 responses. In line with growth/sales increase, cash flow and raising more capital is seen as the third most important challenge faced by hardware entrepreneurs interviewed. Start-ups in a later stage, like the growth and start-up stages, may also view industrialisation of the product, including design-for-manufacturing (DFM), as a major challenge and this challenge received 4 responses. Hardware entrepreneurs in Graz, Munich and Zurich tend to have the same challenges.

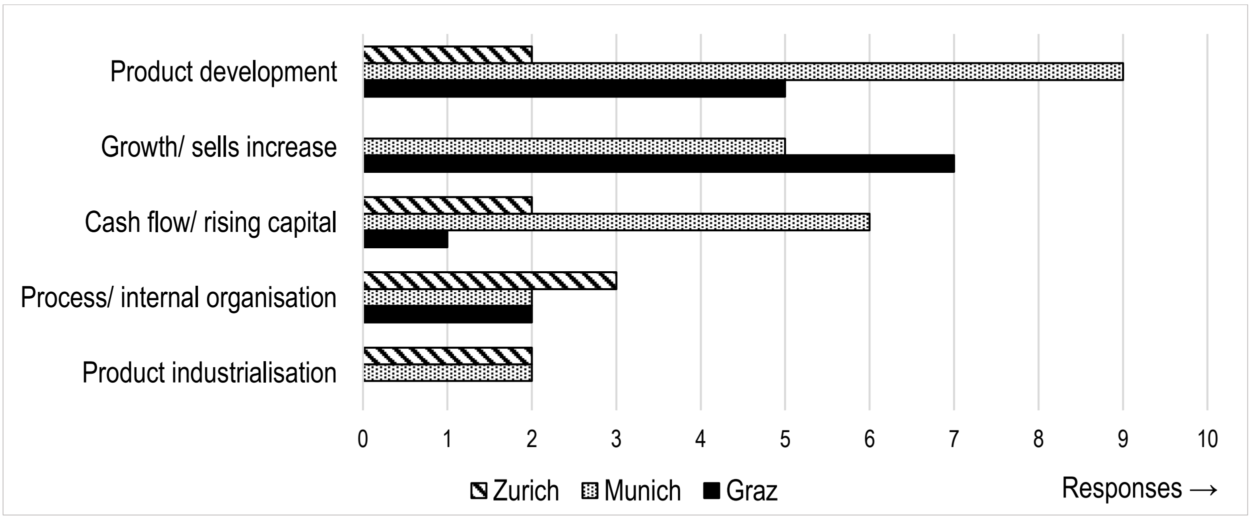

Figure 24: Themes for the biggest challenges of hardware start-ups questioned, multiple themes/responses per start-up possible, n=26.

6.1.1.7 Biggest challenges in product development

In line with the previous characteristic, this factor deals with specific challenges in the product development process of each start-up interviewed. The interviewer digs deep and wants to understand more details in line with the challenges in product development. Therefore, more open-ended questions follow on that aspect. Some hardware entrepreneurs mentioned only one reason, while others mentioned several. Again, all statements are collected, and structured into certain specific themes as shown in Figure 25. Statements responded in line with technical problem-solving score highest, followed by access to adequate prototyping/production infrastructure which was mentioned by nine (35%) interviewees. Participants from Graz and Zurich focus only on the three top-ranked themes, whereas participants from Munich also view budget, completing in time and gaining a competitive edge as a challenge in product development.

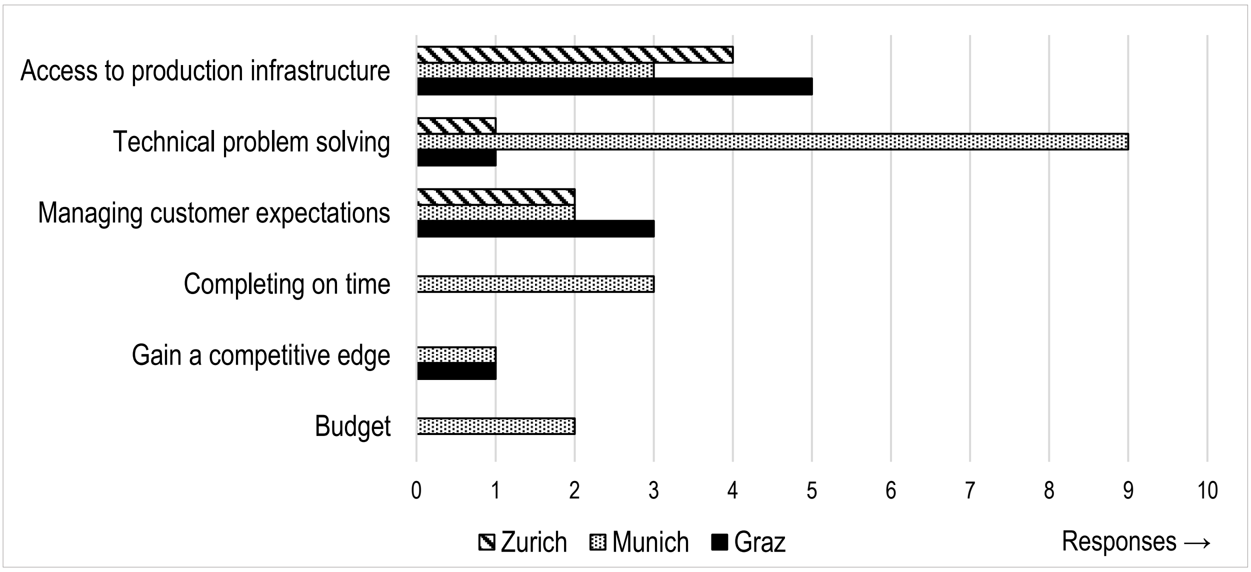

Figure 25: Themes for top challenges faced during product development of hardware start-ups, multiple themes/responses per start-up possible, n=26.

The above-mentioned themes fit to current knowledge in literature, as stated in section 2.1.7.1. Other characteristics, such as economic situation of the start-up, educational background of the entrepreneur, hierarchical structure of the start-up, or number of employees in the start-up, are not considered in this research.

6.1.2 The hardware start-up's experiences in a Makerspace

This section focuses on the current experience of hardware entrepreneurs in facilities similar to the concept of a Makerspace, and on the way in which start-ups realise their prototypes/product developments. Open-ended questions are used to gather a deep understanding of the themes. In line with the research scope, all hardware entrepreneurs interviewed are familiar with the concept of a Makerspace. Some visit a Makerspace daily to build their latest porotypes.

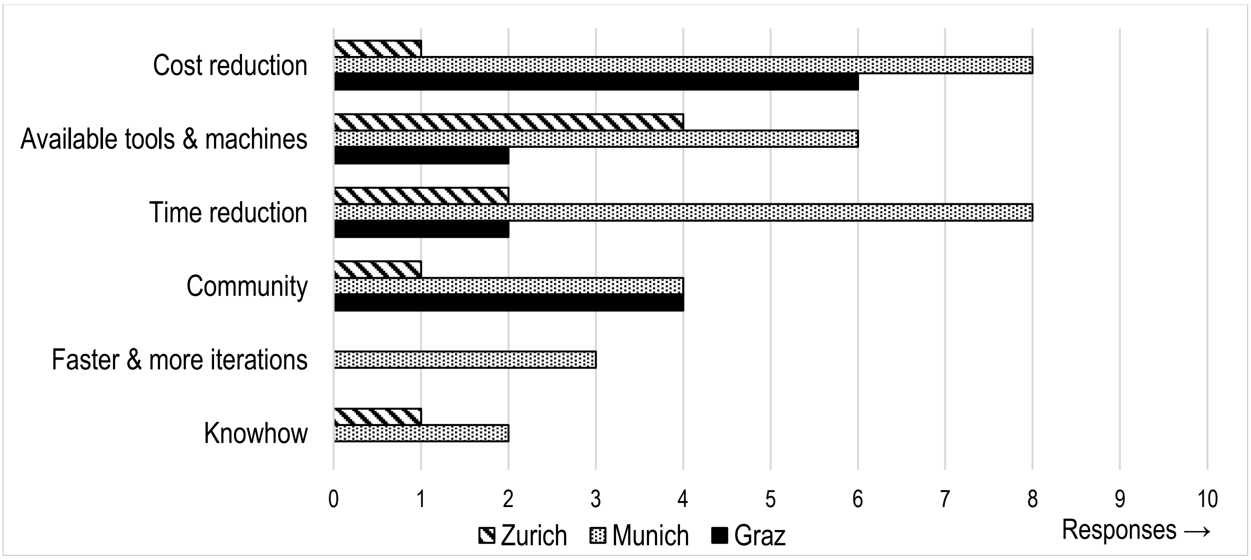

Figure 26: Themes giving main reasons for hardware start-ups to use a Makerspace, multiple themes/responses per start-up possible, n=26.

Entrepreneurs perceive Makerspaces in a generally positive light. The author clusters the given statements in themes. Six themes with the highest responses are shown in Figure 26. Many entrepreneurs concurred in the view that the main beneficial aspect is easy and cheap access to a wide variety of machines and tools.

"We would need to be in a Makerspace for around 50 years in order to pay back the investment we would need for a machine like a laser cutter... well, while that might just be possible, it's a dauntingly huge hardware investment for a start-up..."[149]

Another entrepreneur states this positive affect of a Makerspace in a similar manner:

"No, we do not have the budget to buy any equipment and here, with the Makerspace, it is awesome. You can actually use all the equipment you need daily from 08.00 to 22.00. This is unique. What it means for us is that we are not faced with any restrictions."[150]

Ranked third as main reasons why hardware start-ups choose to realise their prototypes/product in a Makerspace is the availability of specific tools and machines, which is connected with the reason cost reduction scored number one in Figure 26. Community received 9 out of 26 responses and ranked fourth. The possibility to carry out faster and more prototype iterations as a result of a Makerspace infrastructure is mentioned three times at the Munich location. This is also connected to time reduction which received twelve responses and ranked second.

In the observation of start-up teams working in the Makerspace it was clear to see that persons with access and good knowhow of possibilities in the Makerspace stick more to a so-called rapid prototyping mindset. This means that such persons immediately start to build something tangible, test it and iterate based on the learnings gathered when a technical issue arose. This phenomenon was especially observed in the UnternehmerTUM MakerSpace.

The following statement from a hardware entrepreneur gives clarification and emphasises faster iteration and time reduction in the product development process:

"I have to be honest, in a hardware start-up, a lot of software is included, but the hardware itself is needed so that the product eventually works. Therefore, it is almost impossible to be fast if you cannot build hardware yourself. [...] What is critical about product development in the hardware area is having access to machines. It's incredible! You contact an external contract manufacturer and even if you have a good business-relationship, it takes two weeks to obtain a CNC-milled part. Two weeks! Most likely you would love to get new parts in a two-day rhythm because than you can iterate fast, try if the new part works, and manufacture it again. [...] If you do not have the opportunity to do stuff yourself, you will lose."[151]

[149] Statement by an entrepreneur in Munich, translated by the author from German to English
[150] Statement by an entrepreneur in Munich, translated by the author from German to English
[151] Statement by an entrepreneur in Zurich, translated by the author from German to English

As shown in Figure 27, participants mention various different kinds of tools and machines that are used in their product development project for prototyping, testing and iterating. 3D printing, CNC milling and laser cutting play an important role as does the wood shop and the electronics area in particular. Vinyl cutters are only used for marketing purpose by the start-ups. Access to waterjet cutters, SLS 3D printers, or injection moulding would be interesting for many hardware start-ups, but these machines are not available at some investigated locations.

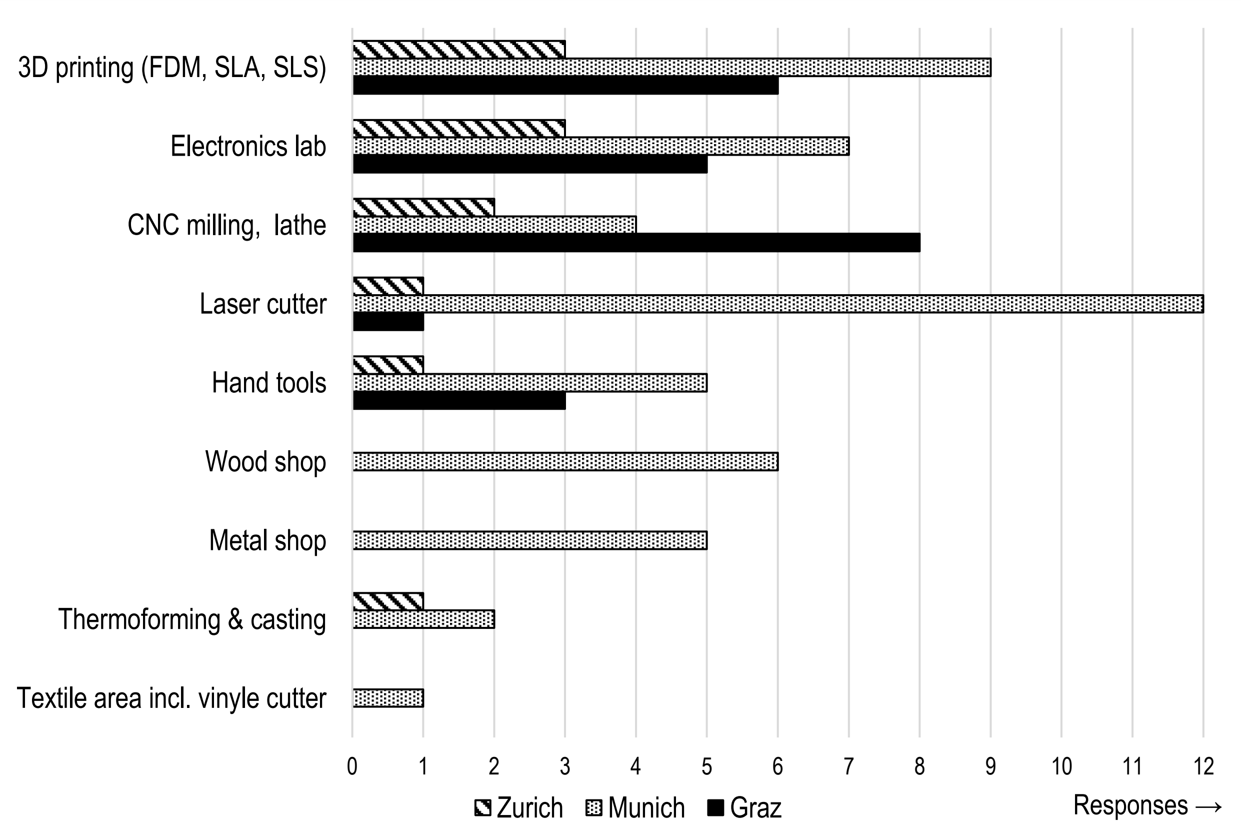

Figure 27: Tools and machines used by hardware start-ups in a Makerspace, multiple responses possible, n=26.

Some entrepreneurs also mentioned aspects that are currently missing in the ecosystem. For example, they have the need to hire an industrial expert on an hourly rate at the Makerspace. This service is demanded in particular for consulting on production processes such as injection moulding. Lots of time and costs are wasted in obtaining the correct moulds and material properties. Others also wish to have a Maker-project-showcase library, with the possibility of learning how others deal successfully with a specific function, as well as the opportunity for easily getting to know like-minded people.

One hardware entrepreneur, his start-up is currently almost in the growth phase, stated when looking back on his first iterations that especially such a network of expert and contact to likeminded peers is valuable feature:

"Well, in my opinion the access to experts is the most important thing and of course the gratefulness of access to experts and fellow sufferers ... Often you do not want to discuss what you made with others - since you prefer to try many times yourself before you ask someone in your nearby environment for help. But there is the opportunity to gain information from experts

and to meet fellow sufferers and this was extremely important in retrospect [...] Often you spend hours on various internet forums looking for help. But you do not discuss things in person with others." [152]

However, when interviewing the hardware start-ups, many restrictions they faced when working in a Makerspace arose. These statements were sometimes vague and generally applicable, but some were only location specific. The perceived statements are again structured in themes, as shown in Figure 28.

Surprisingly, entrepreneurs jointly state that the main restriction in using the UnternehmerTUM MakerSpace is compulsory participation in an introduction course before using any machine. This is evident in Figure 28, with seven responses only from the Munich location. In UnternehmerTUM MakerSpace, this regulation is obligatory because of the local safety procedures, and every user must attend an introductory course before he/she is allowed to use specific equipment items on their own. Courses are held frequently, but situations have arisen where entrepreneurs have had to wait one or two weeks for a place on a course. As observed, this restricts the amount of different fabrication technology used by entrepreneurs, may lead to inefficient manufacturing technique being used, and can result in wasted time in their product development process.

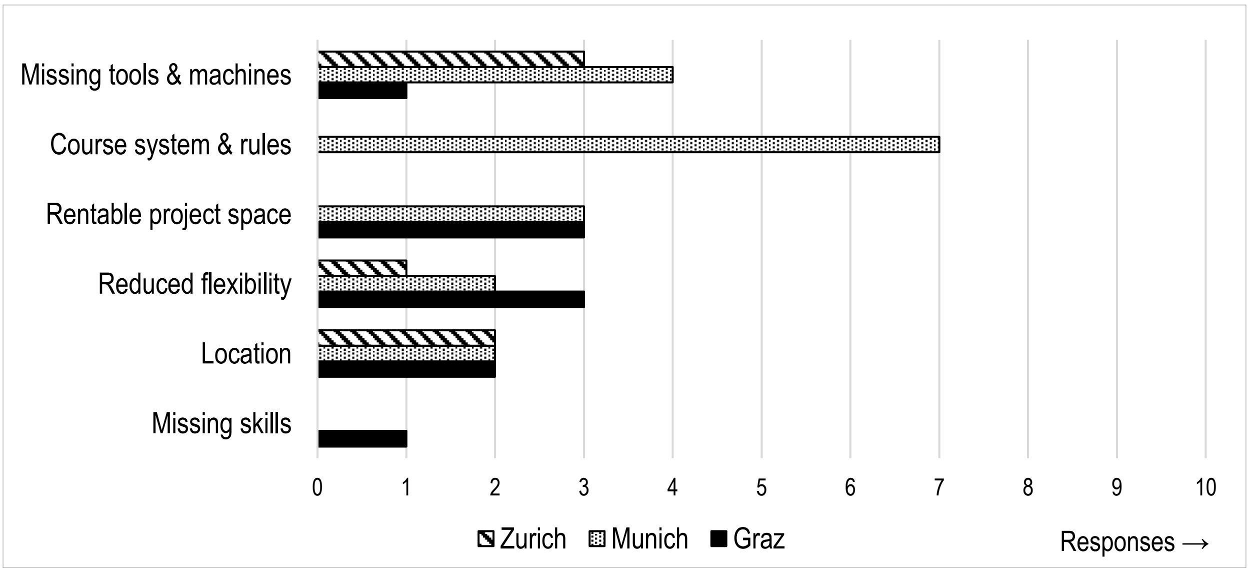

Figure 28: Themes for the main restriction when working as a hardware start-up at a Makerspace, multiple themes/responses per start-up possible, n=26.

Although, as stated in the previous section, UnternehmerTUM MakerSpace has a very comprehensive offering, seven responses were received from entrepreneurs stating that some machines or facilities were lacking. In this connection, most interviewees at UnternehmerTUM MakerSpace mention the lack of access to an injection moulding machine. Ranked equal third, all with six responses, are: rentable project space within the Makerspace where entrepreneurs

[152] Statement by an entrepreneur in Graz, translated by the author from German to English

can store their semi-finished prototypes; location of the Makerspace within the city; and flexibility. Flexibility is understood in terms of immediate access to a specific machine when required. This can be an issue at some Makerspaces due to the opening hours, an insufficient number of machines and overcrowding/over-booked machines. The quality of Makerspace machines is not seen as a restriction.

The participants were also questioned on how, ideally, a facility like a Makerspace can or should support their product development projects. Some added that a Makerspace should have experts available for each manufacturing technology offered who can be consulted when difficulties arise, others emphasised the establishment of a supplier network. Such a supplier database can include, for example, typical lead time of know suppliers and feedbacks orders. Another group of hardware start-ups interviewed see the requirement of having better support in production ramp-up/industrialisation in a Makerspace. In their view, this could be either as a consulting service or in the form of final product testing equipment, such as a climate chamber or material testing equipment. Along with these features, a material library or shop, with different types of raw materials that can immediately be used and tested, and a network of potential beta testers, are also seen as useful. Surprisingly, more specific, industrial, or specific manufacturing machines are not seen to be important.

6.1.3 Knowledge and usage of Maker Movement elements

In the following section, the participating entrepreneurs are confronted for the first time with content of the Maker Movement Element framework. In general, the interviews show that most Maker Movement elements and example companies for those are known and/or used by the hardware start-ups questioned although the actual term Maker Movement or the name of the element is sometimes unclear.

While the interviewer asked several detailed questions on the listed elements in order to record specific-use cases, unknown elements were also explained to the entrepreneurs in order to create a common understanding of all elements.

It is clear in this context that access to tools and machines in a facility like a Makerspace is most widely known and used by entrepreneurs. However, other elements such as the concept of renting a microfactory for the assembly of a first batch are still hardly known.

The interviewees' perception of community order platforms is very broad and differentiated. On the one hand, cost can be reduced but on the other hand, the timeframe for obtaining the ordered part is extended. A number of interviewees see no explicit use case scenario in those platforms.

Open-source electronic hardware is also well-known and widely used. Nearly every entrepreneur interviewed mentioned using an open-source hardware in their prototype or final product. Free CAx software, particularly for product design, is also widely used even though most interviewees stated that they do not use the free software offered in the long term because of the limited set of functions these software types provide. Due to the strong connection to a university, some hardware start-ups in the seed stage are still using an educational license for professional software. Free and easy-to-setup simulation software is hardly known and not used by the entrepreneurs interviewed. Surprisingly, fairs such as Maker Fairs are also little used in their work life and databases to find other Maker's facilities are mostly not known. This may be due to the fact that this resources still do not have many entries in Europe. Not used but known are funding platforms for seed capital and peer-to-peer e-commerce websites.

In addition, the interviews reveal that most players of the Maker Movement are covered within the developed elements framework as each entrepreneur interviewed was asked whether any commonly-used element was missing, but no new elements emerged directly as a result.

To obtain a more complete picture of the hardware start-up's environment, the Makerspaces at each location were also analysed by the author. Table 9 gives the impression at first glance of a very complete environment for each location in which some Maker Movement elements are still not offered, such as a microfactory for assembly.

UnternehmerTUM MakerSpace is the only space analysed at the TUM location but compared to the others it offers the most advanced facility and services. In Graz, three Makerspaces are studied but neither a wood shop nor a metal shop is offered at any of them. The same is true for the Zurich location, where two Makerspaces are analysed. The ETH's spaces have two outstanding aspects; on the one hand, sph Makerspace presented a detailed description on its website of other Maker-related facilities outside of the ETH ecosystem in order that other Makerspaces also become known by their users. On the other hand, ETH bastli offers a paid PCB milling service and also acts as a contract manufacturer for small-batch sizes. All analysed spaces have a comprehensive software offering which is not only based on free or open-source software packages, but also on professional CAD or PCB design software. Offering these kinds of software is only possible because of the strong connection to educational aspects and therefore they are mainly free for Makerspace operators. UnternehmerTUM MakerSpace is also acting as a raw material retailer, where users can buy a limited amount of raw material directly in the space. The ETH spaces sell a variety of electronic components to their users. Crowdfunding, crowd investing, and peer-to-peer commerce do not have a role in any of the spaces analysed. UnternehmerTUM MakerSpace and FabLab Graz are using the Slack platform to connect their users with each other. Slack is also used in these locations as a discussion forum. UnternehmerTUM MakerSpace has a superior off-line course offering, including professional trainers and handouts, whereas elab@TUGraz, sph Makerspace and ETH bastli offer only the most essential machine introduction course. No Makerspace currently offers online courses. Open-source software frameworks and access to cloud computing solutions are not offered in the Makerspaces. However, cooperation exists in Munich with Google, SAP and Facebook and FabLab Graz has a partnership with IBM Bluemix.

✓	Yes
✗	No

Maker Movement elements	Zurich	Munich	Graz	UnternehmerTUM MakerSpace	FabLab Graz	elab @ TU Graz	HTU Makerspace@ TU Graz	ETH sph	ETH bastil
Fair/ event	✓	✓	✗	✓	✗	✗	✗	✓	✓
Maker related facility database	✓	✗	✗	✗	✗	✗	✗	✓	✗
Expert's roundtable	✗	✗	✓	✗	✗	✓	✗	✗	✗
Community order platform	✓	✗	✗	✗	✗	✗	✗	✗	✓
Open files repository (CAD files, norm parts, code)	✗	✗	✗	✗	✗	✗	✗	✗	✗
Discussion forum	✗	✓	✓	✓	✓	✗	✓	✗	✗
Crowd based instruction	✗	✗	✗	✗	✗	✗	✗	✗	✗
Webinar/ Workshop/ Open online course	✓	✓	✓	✓	✗	✓	✗	✓	✓
Online collection of resources	✓	✗	✗	✗	✗	✗	✗	✓	✗
Online blog that inspire/ teach skills/ help to solve problems	✓	✗	✓	✗	✗	✓	✗	✗	✓
Book/ printed magazine	✗	✓	✓	✓	✓	✗	✗	✗	✗
Open-source software framework	✗	✗	✗	✗	✗	✗	✗	✗	✗
Open-source hardware	✓	✓	✓	✓	✓	✓	✗	✓	✗
Digital prototyping machine	✓	✓	✓	✓	✓	✗	✓	✓	✓
Wood shop	✓	✓	✓	✓	✓	✗	✗	✗	✓
Metal shop	✗	✓	✗	✓	✗	✗	✗	✗	✗
Electronics lab	✓	✓	✓	✓	✓	✓	✓	✓	✗
Textiles area	✓	✓	✓	✓	✗	✗	✓	✗	✓
Testing equipment (for electronics)	✓	✓	✓	✓	✓	✓	✗	✗	✓
Microfactory (for assembly)	✗	✗	✗	✗	✗	✗	✗	✗	✗
Cloud computing platform	✗	✗	✗	✗	✗	✗	✗	✗	✗
Free 2D design software	✓	✓	✓	✓	✓	✓	✓	✓	✓
Free 3D design software	✓	✓	✓	✓	✓	✓	✓	✓	✓
Simulation software (CAE, CFD, FEA)	✓	✗	✓	✗	✓	✓	✓	✓	✓
Design software for electronics (IoT toolkit, PCB testing)	✓	✓	✓	✓	✗	✓	✗	✗	✓
Platform for distributed manufacturing	✗	✗	✗	✗	✗	✗	✗	✗	✗
Contract manufacturer for low volume	✓	✗	✗	✗	✗	✗	✗	✗	✓
Online distributor of electronic components	✓	✓	✗	✓	✗	✗	✗	✓	✓
Raw materials in lowest volume/ material library	✗	✓	✗	✓	✗	✗	✗	✗	✗
Crowd funding	✗	✗	✗	✗	✗	✗	✗	✗	✗
Crowd investment/ equity crowdfunding	✗	✗	✗	✗	✗	✗	✗	✗	✗
Peer-to-peer e-commerce	✗	✗	✗	✗	✗	✗	✗	✗	✗
Rent a physical retail space	✗	✗	✗	✗	✗	✗	✗	✗	✗

Table 9: Results of location assessment based on observation and internal/external data

6.2 Quantitative data analysis

In this section, firstly, the quantitative data of the knowledge and use of the Maker Movement Elements framework is presented, and secondly the assessment based on reduction of product costs and product development costs, time, increasing product quality and network effects is discussed. The data is explained with the help of descriptive statistics. Taylor(2005, p. 139) stresses that in contrast to inferential statistics, descriptive statistics describe, aggregate, and present how outstanding characteristics are distributed among the group of participants. Hence, descriptive statistics are often used to summarise findings of a research study and averages are widely used (Taylor, 2005, pp. 139–140).

6.2.1 Unknown, known or used Maker Movement elements

The first question of the survey is to tick for each Maker Movement element if it is unknown, known or used. The responses a gathered, analysed and presented in Table 10 and Table 11. Table 10 shows an aggregation of the derived data based on the in section 4.3 described Maker Movement elements subsystems. Elements within the subsystem use of open-source, gather knowledge & skills, and access to prototyping/ fabrication/ manufacturing facilities are overall most used. Most known but not used are elements within the subsystem get seed capital funding.

		Overall		n=26	Graz		n=9	Munich		n=13	Zurich		n=4
	Maker Movement elements subsystems	Unknown	Known	Used	Unknown	Known	Used	Unknown	Known	Used	Unknown	Known	Used
1	Connect with others (physical/live)	9,0	8,3	8,7	2,7	3,7	2,7	4,0	3,7	5,3	2,3	1,0	0,7
2	Connect with others (online/virtual)	7,5	4,3	12,5	2,3	1,5	5,3	3,8	2,0	5,5	1,5	0,8	1,8
3	Gather knowledge & skills	4,8	4,8	16,0	1,5	2,8	4,3	2,0	2,0	9,0	1,3	0,0	2,8
4	Use of open-source	3,5	5,0	17,5	1,5	2,5	5,0	1,5	2,5	9,0	0,5	0,0	3,5
5	Access to prototyping/ fabrication/ manufacturing facilities	4,3	6,5	14,4	1,9	1,9	5,0	1,8	3,5	7,4	0,6	1,1	2,0
6	Use of CAx software	5,3	7,8	12,8	0,5	2,5	5,8	3,3	4,3	5,5	1,5	1,0	1,5
7	Access to international shipping vendors	5,5	8,0	11,8	2,3	2,3	4,0	2,5	5,0	5,3	0,8	0,8	2,5
8	Get seed capital funding	2,5	20,0	2,5	0,0	7,5	1,5	2,0	9,5	0,5	0,5	3,0	0,5
9	Get immediate customers feedback	8,0	13,0	4,5	1,5	6,0	1,5	5,0	5,0	2,5	1,5	2,0	0,5

Table 10: Responses on knowledge of Maker Movement elements summarised in subsystems: unknown, known or used, numbers are amount of responses divide by amount of elements per subsystem

Results of the quantitative survey shows that most Maker Movement elements are known and used by the entrepreneurs questioned. As shown in Table 11, the data demonstrates that 33 out of 33 Maker Movement elements are known in total and that 32 are used in hardware start-ups routines. A similar overall picture can be seen when comparing the results of each location with each other. These statistics give an indication that the defined Maker Movement Element framework matches the work and needs of hardware start-ups.

The most extensively used elements are online blogs that inspire, teach skills and help to solve a problem (24 out of 26 responses for used), and also digital prototyping machines (21 responses), and metal shop (21 responses). Microfactory for assembly is a mostly unknown concept.

Other little-known elements are maker-related facility databases, community order platform, simulation software, and rent a physical retail space. Known but not used are elements such as crowd funding, crowd investment and peer-to-peer e-commerce.

Electronics are essential for all hardware entrepreneurs interviewed, and various elements are used intensively in this respect. These include open-source electronics hardware (19 responses), electronic workshop (19 responses), testing equipment for electronics (16 responses), design software for electronics (12 responses), and online distributor for electronic components (18 responses).

		Overall		n=26	Graz		n=9	Munich		n=13	Zurich		n=4
	Maker Movement elements	Unknown	Known	Used	Unknown	Known	Used	Unknown	Known	Used	Unknown	Known	Used
	Fair/ event	2	12	12	0	6	3	1	5	7	1	1	2
1	Maker related facility database	16	4	6	3	2	4	9	2	2	4	0	0
	Expert's roundtable	9	9	8	5	3	1	2	4	7	2	2	0
	Community order platform	18	4	4	5	2	2	10	1	2	3	1	0
2	Open files repository (CAD files, norm parts, code)	1	5	20	0	0	9	1	4	8	0	1	3
	Discussion forum	2	2	15	0	1	8	1	1	4	1	0	3
	Crowd based instruction	9	6	11	4	3	2	3	2	8	2	1	1
	Webinar/ Workshop/ Open online course	2	7	16	0	5	3	0	2	11	2	0	2
3	Online collection of resources	9	5	12	4	3	2	4	2	7	1	0	3
	Online blog that inspire/ teach skills/ help to solve problems	1	1	24	0	1	8	0	0	13	1	0	3
	Book/ printed magazine	7	6	12	2	2	4	4	4	5	1	0	3
4	Open-source software framework	6	4	16	3	2	4	2	2	9	1	0	3
	Open-source hardware	1	6	19	0	3	6	1	3	9	0	0	4
	Digital prototyping machine	0	4	21	0	2	7	0	2	11	0	0	3
	Wood shop	0	8	17	0	2	6	0	4	9	0	2	2
	Metal shop	0	4	21	0	1	7	0	2	11	0	1	3
5	Electronics lab	2	3	19	2	0	7	0	3	9	0	0	3
	Textiles area	6	10	9	4	3	2	1	5	6	1	2	1
	Testing equipment (for electronics)	4	6	16	1	1	7	2	4	7	1	1	2
	Microfactory (for assembly)	20	6	0	7	2	0	10	3	0	3	1	0
	Cloud computing platform	2	11	12	1	4	4	1	5	6	0	2	2
	Free 2D design software	1	13	12	0	3	6	0	9	4	1	1	2
6	Free 3D design software	1	5	19	0	1	7	1	3	9	0	1	3
	Simulation software (CAE, CFD, FEA)	13	5	8	1	3	5	10	1	2	2	1	1
	Design software for electronics (IoT toolkit, PCB testing)	6	8	12	1	3	5	2	4	7	3	1	0
	Platform for distributed manufacturing	7	11	7	3	3	2	3	6	4	1	2	1
7	Contract manufacturer for low volume	6	8	11	2	3	4	3	5	4	1	0	3
	Online distributor of electronic components	3	5	18	1	2	6	2	3	8	0	0	4
	Raw materials in lowest volume/ material library	6	8	11	3	1	4	2	6	5	1	1	2
8	Crowd funding	0	21	4	0	7	2	0	11	1	0	3	1
	Crowd investment/ equity crowdfunding	5	19	1	0	8	1	4	8	0	1	3	0
9	Peer-to-peer e-commerce	2	17	6	1	7	1	0	8	4	1	2	1
	Rent a physical retail space	14	9	3	2	5	2	10	2	1	2	2	0

Table 11: Responses on knowledge of Maker Movement elements: unknown, known or used, numbers are amount of responses

6.2.2 Assessment of Maker Movement elements

The second part of the survey is based on an assessment of each Maker Movement Element for each creation based on 5-point Likert scale, in which five is extremely likely and one is extremely unlikely. Meaning that every participating hardware start-up responded 165 answers. Table 12 shows aggregate results by means and standard deviations for every element and criterion. These results provide two perspectives: first, elements that are most helpful in a specific criterion, such as reduction of product costs, product development costs, or time, are displayed; and second, Maker Movement elements can be described with the biggest impact overall on all criteria.

It was striking that the hardware start-ups had no problem assessing the Maker Movement elements against the criteria. Only some stated, when handing in the completed survey, that in contrast to the other criteria network increase due to Maker Movement might not play a role at all and that product costs was more difficult to assess due to a lack of in-depth experience.

It is clear to see that in the reduction of product development cost and time criterion, the access to digital prototyping machines, such as 3D printers, laser cutters, etc., plays an important role - on average the reduction of product development costs was given a grade of 4.8 and time 4.8, where 5 is the maximum. Besides access to digital prototyping machines, Maker Movement elements that are needed for electronic prototyping were given very good grades: access to an electronic workshop was awarded 4.6 in reduction of product development costs, and testing equipment, especially for electronics, scored well (4.0) in the criterion boosting product quality. In the aspect of cost reduction for the final product, hardware start-ups agreed in placing the concept of a microfactory, open-source software frameworks, and electronic parts supplier (all 3.9) in the leading position. Fairs/events and expert roundtables, such as meet-ups, emerged with the best scores in the criterion network increase.

Another fascinating aspect is that across all Maker Movement elements the potential impact on the reduction of product development costs and time criterion is highest (122 and 124) and the impact on the network increase criterion is lowest (84). These values are calculated by the vertical sum of all Maker Movement elements per criterion. This correlation appears to be especially significant and interesting when compared to the initial statements by the interviewees on the network, that in contrast to other criteria, the Maker Movement element framework might not play a role at all.

The last column of Table 12 shows the so-called impact factor. The impact factor is calculated based on a horizontal sum of each element's means per criteria and shows which element is the most important overall criteria. Access to testing equipment, especially for electronics, digital prototyping equipment and also access to an electronic workshop, were given the highest values across all five criteria. These three elements, which are directly related to the infrastructure of a Makerspace, are followed by expert roundtables, electronic parts suppliers and open-source software frameworks. In contrast, the elements crowd funding, crowd investment, peer-to-peer e-ecommerce and rent a physical space did not play an important role for the hardware start-ups surveyed.

○	Means between 1,0 and 2,3
◑	Means between 2,4 and 3,6
●	Means between 3,7 and 5,0
◆	Impact factor between 5,0 and 11,6
▮	Impact factor between 11,7 and 18,3
▲	Impact factor between 18,3 and 25,0

	Maker Movement elements	Product costs *		Product development costs *		Time in product development *		Product quality *		Network *		Impact factor
		$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\bar{X}$	σ	$\sum\bar{X}$
1	Fair/ event	2,8	+/-1,3	2,8	+/-1,2	2,8	+/-1,0	3,2	+/-1,3	4,7	+/-0,6	16,1
	Maker related facility database	2,8	+/-1,3	3,0	+/-1,1	3,5	+/-1,2	2,8	+/-1,3	3,9	+/-1,3	16,0
	Expert's roundtable	3,3	+/-1,4	3,5	+/-1,3	3,6	+/-1,1	3,8	+/-1,0	4,5	+/-0,6	18,8
2	Community order platform	3,1	+/-1,4	3,9	+/-0,9	3,6	+/-0,9	2,2	+/-1,3	2,4	+/-1,2	15,2
	Open files repository (CAD files, norm parts, code)	2,8	+/-1,3	3,9	+/-1,1	3,8	+/-1,1	2,6	+/-1,1	2,1	+/-1,1	15,3
	Discussion forum	2,5	+/-1,4	3,4	+/-0,9	3,8	+/-0,9	3,1	+/-1,3	2,9	+/-1,2	15,8
	Crowd based instruction	2,5	+/-1,1	3,3	+/-1,1	3,5	+/-1,1	2,5	+/-1,2	2,3	+/-1,3	14,1
3	Webinar/ Workshop/ Open online course	3,1	+/-1,5	3,4	+/-1,2	3,3	+/-1,2	3,7	+/-1,0	2,7	+/-1,2	16,2
	Online collection of resources	2,9	+/-1,5	3,8	+/-1,1	4,1	+/-0,9	3,6	+/-1,2	2,3	+/-1,2	16,7
	Online blog that inspire/ teach skills/ help to solve problems	2,8	+/-1,5	3,7	+/-1,0	3,7	+/-1,1	3,4	+/-1,3	2,5	+/-1,4	16,0
	Book/ printed magazine	2,8	+/-1,5	3,0	+/-1,1	3,0	+/-1,2	3,7	+/-1,3	2,0	+/-1,0	14,5
4	Open-source software framework	4,0	+/-0,9	4,4	+/-0,6	4,4	+/-0,7	3,4	+/-1,1	1,9	+/-1,1	18,1
	Open-source hardware	3,5	+/-1,4	4,5	+/-0,7	4,5	+/-1,0	3,1	+/-1,1	1,8	+/-1,2	17,5
5	Digital prototyping machine	3,2	+/-1,2	4,8	+/-0,5	4,8	+/-0,5	3,7	+/-1,2	2,6	+/-1,5	18,9
	Wood shop	2,7	+/-1,1	4,3	+/-1,1	4,2	+/-1,0	3,1	+/-1,4	2,5	+/-1,5	16,8
	Metal shop	3,0	+/-1,1	4,4	+/-1,0	4,5	+/-0,8	3,5	+/-1,3	2,6	+/-1,5	17,9
	Electronics lab	3,3	+/-0,9	4,6	+/-0,7	4,7	+/-0,5	3,8	+/-1,3	2,6	+/-1,5	19,0
	Textiles area	2,6	+/-1,3	4,0	+/-1,2	3,5	+/-1,5	3,1	+/-1,3	2,5	+/-1,6	15,7
	Testing equipment (for electronics)	3,8	+/-1,0	4,6	+/-0,9	4,7	+/-0,6	4,1	+/-1,1	2,5	+/-1,5	19,6
	Microfactory (for assembly)	3,7	+/-1,2	3,6	+/-1,1	3,6	+/-1,2	3,4	+/-1,3	2,3	+/-1,3	16,6
	Cloud computing platform	3,6	+/-1,3	4,1	+/-0,8	4,2	+/-1,1	3,3	+/-1,4	1,5	+/-0,8	16,6
6	Free 2D design software	2,9	+/-1,4	4,2	+/-1,1	3,7	+/-1,4	2,6	+/-1,1	1,5	+/-0,8	14,9
	Free 3D design software	3,6	+/-1,2	4,4	+/-0,9	4,1	+/-1,3	3,2	+/-1,3	1,5	+/-0,9	16,8
	Simulation software (CAE, CFD, FEA)	3,7	+/-1,2	4,2	+/-1,1	3,7	+/-1,4	3,4	+/-1,3	1,5	+/-0,9	16,5
	Design software for electronics (IoT toolkit, PCB testing)	3,4	+/-1,4	4,4	+/-1,0	4,2	+/-1,0	3,4	+/-1,4	1,6	+/-1,0	16,8
7	Platform for distributed manufacturing	3,4	+/-1,4	3,7	+/-0,8	3,7	+/-0,9	3,1	+/-1,3	2,8	+/-1,2	16,6
	Contract manufacturer for low volume	3,9	+/-1,1	3,8	+/-0,8	4,0	+/-0,8	3,8	+/-1,2	2,4	+/-1,1	17,7
	Online distributor of electronic components	3,7	+/-1,3	4,1	+/-0,7	4,4	+/-0,7	3,6	+/-1,1	2,3	+/-1,4	18,1
	Raw materials in lowest volume/ material library	3,3	+/-1,4	4,1	+/-0,5	3,9	+/-1,0	2,8	+/-1,3	1,8	+/-0,9	15,9
8	Crowd funding	2,0	+/-1,3	1,6	+/-1,1	2,7	+/-1,3	2,0	+/-1,2	3,6	+/-1,4	12,0
	Crowd investment/ equity crowdfunding	2,0	+/-1,3	1,8	+/-0,9	2,6	+/-1,2	1,9	+/-1,1	3,6	+/-1,2	11,9
9	Peer-to-peer e-commerce	2,2	+/-1,3	2,2	+/-1,1	2,5	+/-1,3	2,3	+/-1,4	3,0	+/-1,4	12,2
	Rent a physical retail space	2,0	+/-1,3	2,2	+/-1,0	2,3	+/-1,2	2,6	+/-1,6	3,5	+/-1,4	12,6

Table 12: Results based on an assessment of the Maker Movement Element framework (* results of 26 surveyed hardware start-ups, σ ... standard deviation, $\bar{X}$ ... mean, $\sum\bar{X}$ ... horizontal sum means per criteria)

In addition, the standard deviation (SD or σ) is also shown for each criterion and element. The standard deviation is a measure of how far the individual numbers are distributed and indicates how far the individual measurements are on average away from the expected mean value (Bland

and Altman, 1996, p. 744). As a consequence of the calculated standard deviation it is shown that the hardware start-ups surveyed have a very common understanding of access to digital prototyping machines (σ = 0.5 , in some criteria) and the most diverse answers are given for rent a physical retail space (σ = 1.6, in product quality).

6.3 Validation: comparison to a different location within Europe

The gathered results may be true for the selected regions within Europe, but to see if this result and the chosen research approach can be transformed to other regions, the author looked for similar ecosystems within Europe in order to compare the defined approach and to test the findings. An equivalent ecosystem can be found at Aalto University in Helsinki.

A total of six interviews have been conducted in the Helsinki location, as shown in Table 13. The chosen hardware start-ups are selected on the basis of the same procedure as laid out in section 3.5.2, and qualitative and quantitative data is collected based on observations, the same semi-structured interview and on the survey as described in section 5.

	Helsinki					
	Start-up α	Start-up β	Start-up γ	Start-up δ	Start-up ε	Start-up ζ
Currently in an accelerator	x	x		x		
Alumni of an accelerator			x			
Currently in an incubator						
Alumni of an incubator						
Makerspace used	x	x	x	x	x	x
Supported by a university	x	x	x	x	x	x
Founded	2017	2016	2014	2017	2012	2012
Number of founders	2	3	4	5		4
Who was interviewed	CTO	CEO	Prod. Dev.	CEO	CEO	CEO
Gender	m	m	f	m	m	m
Age	26-35	19-25	26-35	19-25	26-35	26-35
Short product debriefs	Wear-able	3D printer	Smart lamp	IoT sensor	Through-able micro-phone	Dust collector

Table 13: Overview of hardware start-ups investigated in the Helsinki location (anonymized)

6.3.1 Examination of location: Aalto University in Helsinki

Helsinki has a rich entrepreneurial legacy. Nokia, based in a suburb of Helsinki, grew into a multinational company and a telecommunications pioneer as well as Linux was first developed at the University of Helsinki and today, the area hosts a leading technology events and is home to some of the leading gaming companies in the world, like Rovio and Supercell (Gibson, Robinson and Cain, 2015). This leads to the conclusion, that Helsinki's start-up ecosystem is well-positioned, has a strong base of talent and start-up experience, and several recent success stories to show.

Aalto University, the newly-formed primary university in Helsinki, is a multidisciplinary community where science, art, technology and business meet and has six schools with nearly

12,000 students (Aalto University, 2018g). A-Grid[153] is part of Aalto's ecosystem for entrepreneurs, rated by MIT among the top five rising stars globally and consists of student-led and university-run entrepreneurial activities with a variety of partners, researchers and established companies in one location(Aalto University, 2018a). A strong network to support start-up growth, including Aalto Design Factory[154], Aalto Start-Up Center[155], Start-up Sauna[156] and Slush[157] is provided to ongoing entrepreneurs at Aalto University. Hence has significant research infrastructure open for everyone, such as for micro- and nanotechnology, neuroimaging, bioscience, computational research, radio astronomy and space research. In addition, Aalto Studios facilitates film and TV, games and animation, VR/AR, product- and user experience testing, sensor data-analysis and fast prototyping(Aalto University, 2018a). In addition, Aalto Innovation Services[158] is responsible for the management of inventions, intellectual property and technology transfer, with the main focus on facilitating the translation of research into societal impact through commercialisation (Aalto University, 2018d). Furthermore, Aalto Start-Up Center[159] is a business accelerator on campus. Students who have an innovative business idea in the fields of information-technologies or creative industries and have a strong will to succeed are supported there (Aalto University, 2018e).

Aalto Design Factory (ADF) can be viewed as the primary Makerspace at Aalto University offering operational support, a vivid community and also various facilities for building physical prototypes, such as 3D printing, wood shop, metal shop and facilities for textiles. It was founded from a research project focused on creating an ideal physical as well as intellectual working environment for product developers and researchers, resulting in a leading facility which encourages and enables a fruitful interaction between students, researchers, and professionals (Björklund *et al.*, 2017, pp. 9–11). The roots of ADF arise from the interdisciplinary Product Development Project[160] (PDP) university course. The community working in ADF consists of researchers, students and staff from different schools of Aalto University, entrepreneurs and company representatives. The multi-purpose nature of the ADF makes it possible to maintain a high rate of use and keep things flexible and the staff empower people to take initiatives, share their passion and aim high (Aalto University, 2018b).

Another Makerspace on campus is the Aalto FabLab[161]. The Aalto FabLab can be used on Monday, Tuesdays, Thursdays and Fridays free of charge. It provides tools and machines typically

[153] www.agrid.fi (Accessed: 2 June 2019)
[154] www.designfactory.aalto.fi (Accessed: 2 June 2019)
[155] www.startupcenter.aalto.fi (Accessed: 2 June 2019)
[156] www.startupsauna.com (Accessed: 2 June 2019)
[157] www.slush.org (Accessed: 2 June 2019)
[158] www.innovation.aalto.fi (Accessed: 2 June 2019)
[159] www.startupcenter.aalto.fi (Accessed: 2 June 2019)
[160] www.pdp.fi (Accessed: 2 June 2019)
[161] www.fablab.aalto.fi (Accessed: 2 June 2019)

to other Fab Labs like laser cutter, 3D printers, CNC machines as well as a small material supply and introduction courses(Aalto University, 2018c).

1,500 square metre industry hall Start-up Sauna is co-working space on the campus of Aalto University, is a focal meeting point for entrepreneurs and investors, is open to everyone, and is an event space for founder talks, pitching competitions, hackathons and barbecues(Aalto University, 2018h). In total, over 100 events are hosted yearly. In addition, a seven-week seed stage start-up accelerator is held there. This location is also the birthplace of Aaltoes[162], Junction[163], and Slush.

Aaltoes is a student community who are fascinated about entrepreneurship. Their main goal is to shape the next generation of entrepreneurs and they are doing this by organising various events targeting students and those who are already running their own start-up (Aalto University, 2018f). Such events are Junction or Slush. In 2016, Junction provided the biggest one-day hackathon experience in Europe by bringing together hackers, designers, industrial partners, and hardware for one weekend and encouraging the development of ideas into actual projects together with like-minded people(Junction, 2018). It is a non-profit organisation run by volunteering students. In contrast, Slush brings together the leading actors of the global tech scene. Slush is also a student-driven, non-profit movement originally founded to change attitudes toward entrepreneurship (Slush, 2018).

6.3.2 Analyse of qualitative data from Helsinki

Table 13 shows an overview of the hardware start-ups interviewed. Overall, similar themes to Graz, Munich and Zurich can also be observed from the transcripts. Compared to the qualitative results of section 6.1, the group of hardware start-ups interviewed at the Helsinki location is comparable overall in regard to characteristics such as start-up stage, start-up age, product types, etc. and challenges. The analyse of the local environment and Makerspace reveals also a comparable picture as the location in the DACH regions. Both known Makerspaces, Alto Design Factory and Aalto FabLab, offer a good combination of access to prototyping facilities and a vivid community. However, both focus more on educational aspects than entrepreneurship, hence industrial-graded manufacturing facilities are missing.

Regarding the developed themes for major challenges start-ups are currently facing, product development is also ranked first. Five out of six responded that product development is among their current main challenges, as shown in Figure 29. Looking more closely at the product development theme, interviewees mentioned various reasons which can be classified in the same themes as described before. As shown in Figure 29, manging customer expectations, technical problem-solving, and access to production infrastructure are the top three themes.

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[162] www.aaltoes.com (Accessed: 2 June 2019)

[163] www.hackjunction.com (Accessed: 2 June 2019)

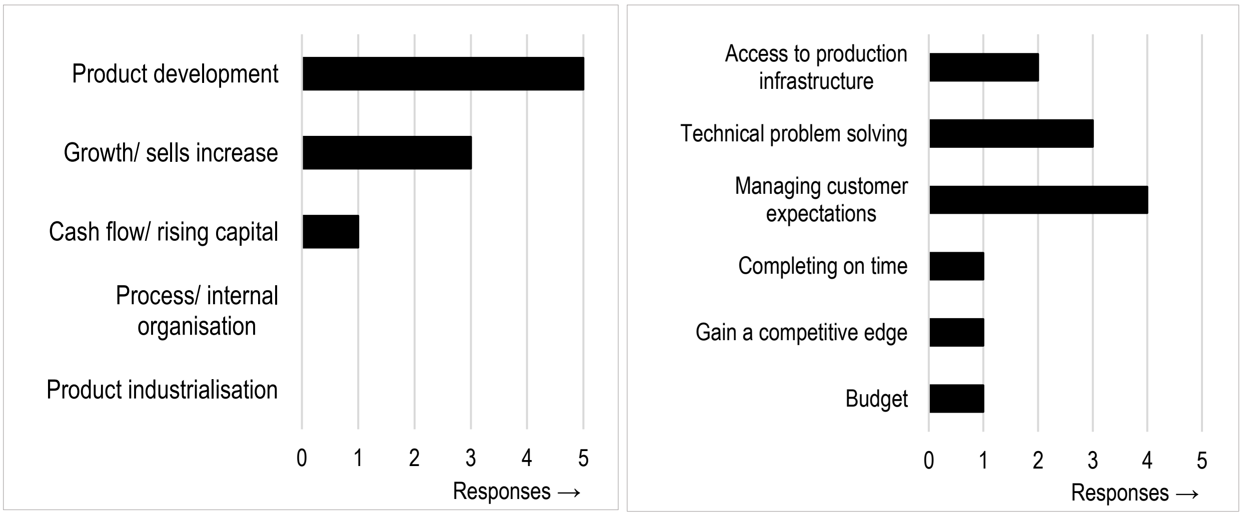

Figure 29: Left: responses on challenges currently faced, right: responses of biggest issues in product development projects, multiple themes/responses possible, n=6.

The following statements by the interviewees are based on their perceived opinion on the concept and use of a Makerspace. Figure 30 shows the results of the themes mentioned; the diagram on the left shows the themes of the main benefits of Makerspaces and the main restrictions can be seen in the right-hand diagram.

One entrepreneur interviewed stated the following when discussing the those benefits:

"When entering an official event as a start-up with a product in the hand, gives you a significant advantage because people are more interested - they come, they look, they try, they can touch it. That is the main point - people can touch the product you are working on…" [164]

Reflecting on that, this entrepreneur really believes that building a first prototype fast is very important, because than his concept can be tested by potential customers and he iterates based on the learnings gathered.

Another statement goes into available tools and machines theme: *"We bought our own sewing machine once, but it is not typical. But no, there's nothing else we have to buy when using the space."* [165]

In comparison, the cost reduction theme scores first as the biggest benefit of a Makerspace. As the main restrictions, the missing facilities and machines theme together with flexibility received the most responses. Both may be explained due the constraints of the ADF. ADF's main purpose is to educate product designers and therefore the access for start-ups to the machines and tools provided can be limited for certain timeframes. They have a students-first policy, which means that if an academic course or project work is taking place and students need the machines or tools, then start-ups do not have the right to access the facility in the same timeframe. In line with this policy, the ADF owns only a limited number of machines; no water jet cutter, pick&

[164] Statement by an entrepreneur in Helsinki

[165] Statement by an entrepreneur in Helsinki

place machine, injection moulding machine or similar industrial manufacturing machines are offered.

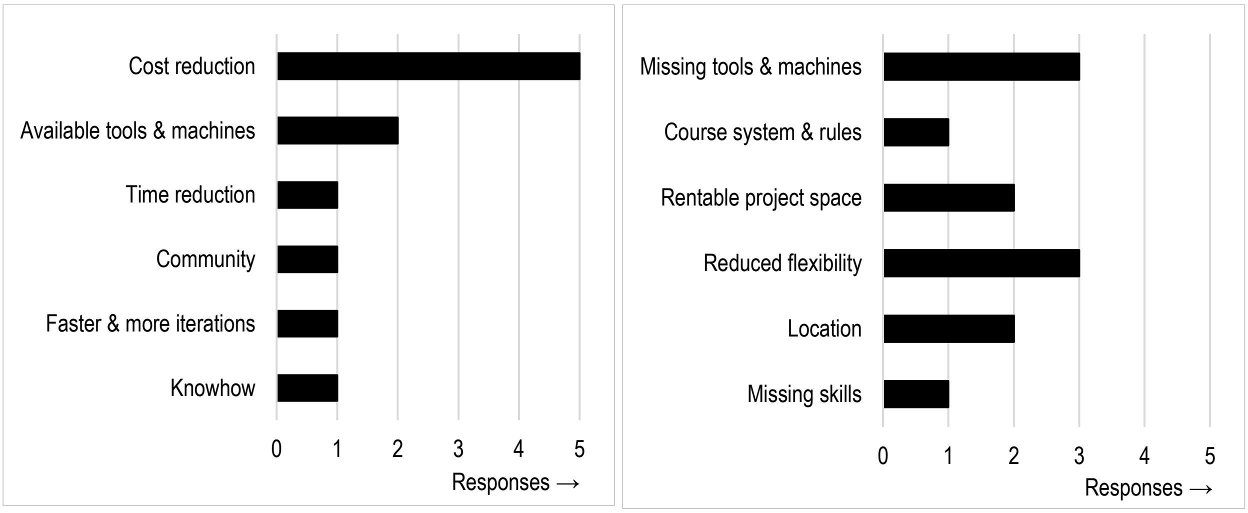

Figure 30: Left: themes why questioned hardware start-ups use Makerspace-like facilities, right: themes mentioned for the main restriction when using Makerspace-like facilities, multiple themes/responses possible, n=6.

All in all, the gathered themes are comparable to the themes developed in the DACH region. In particular, the challenges of hardware start-ups and issues in product development as well as perceived benefits of a Makerspace are very similar and comparable. However, themes for restrictions of a Makerspace in product development seem to be very location specific. In this regard, the interviewed entrepreneurs tend to mention only locally specific problems with their Makerspace such as the restriction at ADF or the mentioned limitations of UnternehmerTUM MakerSpace.

6.3.3 Analyse of quantitative data from Helsinki

The quantitative data collected from the conducted survey is analysed in a similar way to the procedure described in section 3.5 and 6.2.

Due to the low number of participants (n=6) in this, it is not possible to make in-depth assumptions exclusively on the quantitative data. The responses for the elements discussion forum, free 2D design software, free simulation software, raw material library and crowd investment were too low to be able to calculate statistical relevant figures, which is why no numbers are shown in Table 15.

However, Table 14 shows the knowledge and use of Maker Movement elements grouped in subsystems. Overall it is indicated as comparable to the results from the DACH region. Use of open-source, gather knowledge & skills, and access to prototyping/ fabrication/ manufacturing facilities are the main used and elements within the subsystem get seed capital funding are mainly known but not used.

	Maker Movement elements subsystems	Helsinki Unknown	Known	n=6 Used
1	Connect with others (physical/live)	1,0	3,0	2,0
2	Connect with others (online/virtual)	1,3	1,5	1,8
3	Gather knowledge & skills	0,0	1,0	5,0
4	Use of open-source	0,5	0,5	5,0
5	Access to prototyping/ fabrication/ manufacturing facilities	0,9	1,6	3,5
6	Use of CAx software	2,3	1,0	2,8
7	Access to international shipping vendors	2,3	0,3	3,5
8	Get seed capital funding	0,0	5,0	1,0
9	Get immediate customers feedback	2,5	2,5	1,0

Table 14: Responses in the Helsinki location on knowledge of Maker Movement elements summarised in subsystems: unknown, known or used, numbers are amount of responses divide by amount of elements per subsystem

As shown in Table 15, the top five elements overall are access to an electronic shop, expert roundtables, contract manufacturer for low volume, access to digital prototyping machines, and at number five with the same score are open-source software frameworks and access to a microfactory. Compared with the DACH location, the results of all the top five elements mentioned here are also at least in the top ten of the DACH location results. Access to digital manufacturing machines or an electronic shop are ranked second and third there.

Surprisingly, entrepreneurs questioned in Helsinki ranked contract manufacturer for low volume and access to a microfactory higher than their peers did in the DACH region. This higher ranking may be based on the development stages of the hardware start-ups interviewed. Three out of six of the start-ups interviewed are in the growth stage and one is in the start-up stage, which also leads to the assumption that these specific elements are more relevant for start-ups in those stages.

The lowest ranked factors are rent a physical retail space, peer-to-peer e-commerce, open file repositories, crowd funding and design software for electronics. The low ranking for physical retail space, peer-to-peer e-commerce and crowd funding is not a surprise when compared to the results of the DACH region.

○	Means between 1,0 and 2,3	◆	Impact factor between 5,0 and 11,6
◑	Means between 2,4 and 3,6	▮	Impact factor between 11,7 and 18,3
●	Means between 3,7 and 5,0	▲	Impact factor between 18,3 and 25,0

	Maker Movement elements	Product costs *		Product development costs *		Time in product development *		Product quality *		Network *		Impact factor
		X̄	σ	X̄	σ	X̄	σ	X̄	σ	X̄	σ	∑ X̄
	Fair/ event	◑3,3	+/-0,9	◑3,2	+/-0,7	◑2,8	+/-0,4	◑3,7	+/-0,9	●4,7	+/-0,7	▮17,6
1	Maker related facility database	◑2,8	+/-1,3	◑2,8	+/-1,0	◑3,0	+/-0,0	◑2,4	+/-1,0	◑2,8	+/-1,3	▮13,8
	Expert's roundtable	●3,9	+/-1,0	◑3,3	+/-0,5	●4,0	+/-0,8	●4,0	+/-1,1	●4,8	+/-0,4	▲20,0
	Community order platform	◑3,0	+/-1,4	◑2,8	+/-1,5	●4,0	+/-1,0	◑2,4	+/-1,5	◑3,0	+/-1,4	▮15,2
2	Open files repository (CAD files, norm parts, code)	○2,2	+/-0,9	◑3,2	+/-0,7	◑2,8	+/-0,8	○2,1	+/-1,1	○1,8	+/-0,9	▮12,1
	Discussion forum											
	Crowd based instruction	○2,3	+/-1,0	◑3,1	+/-1,1	◑3,6	+/-0,5	◑2,7	+/-1,0	○2,2	+/-0,9	▮13,9
	Webinar/ Workshop/ Open online course	◑2,9	+/-0,8	◑3,1	+/-0,8	●4,0	+/-0,6	◑3,3	+/-1,2	◑3,2	+/-0,7	▮16,5
3	Online collection of resources	◑3,3	+/-0,7	◑3,1	+/-1,2	●3,7	+/-0,9	◑3,4	+/-1,2	○2,0	+/-0,8	▮15,6
	Online blog that inspire/ teach skills/ help to solve problems	●3,7	+/-0,7	●3,7	+/-1,5	●4,4	+/-0,7	●3,9	+/-0,6	◑2,7	+/-1,1	▲18,4
	Book/ printed magazine	◑3,1	+/-1,2	◑2,7	+/-1,2	●4,0	+/-0,8	◑3,6	+/-0,9	○1,8	+/-1,2	▮15,3
4	Open-source software framework	●4,0	+/-1,1	●4,8	+/-0,4	●4,7	+/-0,5	●4,2	+/-0,4	○1,7	+/-0,9	▲19,3
	Open-source hardware	◑3,3	+/-1,4	●4,7	+/-0,5	●4,7	+/-0,5	●4,0	+/-0,8	○1,7	+/-0,9	▲18,4
	Digital prototyping machine	◑2,4	+/-1,5	●5,0	+/-0,0	●4,7	+/-0,5	●4,3	+/-0,9	◑3,0	+/-1,7	▲19,4
	Wood shop	◑2,4	+/-1,2	●3,8	+/-1,5	◑3,7	+/-1,5	●3,8	+/-1,6	◑3,2	+/-1,8	▮16,9
	Metal shop	◑2,6	+/-1,6	●4,1	+/-1,1	●4,2	+/-1,2	●3,9	+/-1,4	◑2,8	+/-1,9	▮17,6
5	Electronics lab	◑3,5	+/-1,5	●5,0	+/-0,0	●5,0	+/-0,0	●4,5	+/-0,8	◑3,2	+/-1,8	▲21,2
	Textiles area	◑2,7	+/-0,9	●4,3	+/-0,7	●4,2	+/-0,9	●4,0	+/-1,0	◑3,0	+/-1,8	▮18,2
	Testing equipment (for electronics)	◑3,0	+/-1,6	●4,4	+/-0,7	●4,2	+/-0,9	●4,4	+/-0,7	◑2,5	+/-1,8	▲18,5
	Microfactory (for assembly)	●3,8	+/-1,6	●4,0	+/-1,2	●4,5	+/-0,5	●4,0	+/-1,7	◑3,0	+/-1,6	▲19,3
	Cloud computing platform	◑3,3	+/-1,8	◑3,7	+/-1,6	◑3,7	+/-1,4	●3,8	+/-1,5	○1,6	+/-0,8	▮16,1
	Free 2D design software											
6	Free 3D design software	○2,2	+/-1,2	◑3,3	+/-1,5	◑3,0	+/-1,4	◑3,2	+/-1,1	○1,6	+/-0,8	▮13,3
	Simulation software (CAE, CFD, FEA)											
	Design software for electronics (IoT toolkit, PCB testing)	○2,0	+/-1,3	◑2,7	+/-1,7	◑3,0	+/-1,4	◑3,3	+/-0,9	○1,8	+/-0,8	▮12,8
	Platform for distributed manufacturing	●4,0	+/-1,0	●4,0	+/-0,8	●4,0	+/-0,7	●4,0	+/-0,7	◑2,5	+/-0,5	▲18,5
7	Contract manufacturer for low volume	●4,3	+/-1,1	◑3,7	+/-1,2	●4,2	+/-0,9	●4,3	+/-0,7	◑3,0	+/-1,4	▲19,5
	Online distributor of electronic components	●4,1	+/-1,0	●3,7	+/-1,2	●4,4	+/-0,7	◑3,6	+/-1,3	◑2,7	+/-1,4	▲18,5
	Raw materials in lowest volume/ material library											
8	Crowd funding	◑2,8	+/-1,6	○2,0	+/-1,5	◑2,4	+/-1,7	○2,2	+/-1,2	◑2,8	+/-1,5	▮12,2
	Crowd investment/ equity crowdfunding											
9	Peer-to-peer e-commerce	◑2,5	+/-1,1	◑2,8	+/-1,3	○2,0	+/-0,8	○2,0	+/-1,0	◑2,7	+/-1,2	▮11,9
	Rent a physical retail space	○2,0	+/-1,0	○1,8	+/-1,0	○2,0	+/-1,0	○2,2	+/-1,0	○2,3	+/-0,8	◆10,3

Table 15: Quantitative assessment results of the Helsinki location (* results of 6 interviewed hardware start-ups, σ... standard deviation, X̄ ... mean, Σ X̄ ... horizontal sum means per criteria)

The impact factors calculated based on the horizontal sum of each element also display similar results to the DACH region. Crowd funding, crowd investment, peer-to-peer e-commerce and rent a physical retail space are ranked lowest yet again and highest is electronics workshop. Comparing the results for each element for each criterion of Table 15 to the results calculated for the DACH region, product quality and network effects have the best match while time in product development and product cost have the weakest match. These findings lead to the assumption that the chosen research approach and the result drawn from the DACH region can be transferred to different region with Europe.

6.4 Conclusion: results and findings

In this section the qualitative and quantitative data is analysed separately, results are named and compared to a fourth location to see if the chosen approach can be transferred to other locations as well as to detect whether hardware start-ups from other regions than the selected DACH region see similar benefits and restrictions from the Maker Movement and the Makerspace concept in product development.

In the qualitative interviews, the author interviewed a very homogeneous group of hardware start-ups. All have experience with a Makerspace, they are currently mainly in the middle of the product development process, they are primarily developing products for the business-to-business market and focus on hardware-based products which may have a software aspect. The author has defined themes on the basis of the interview transcripts.

The following themes can be mentioned in regard to challenges in product development: managing and not meeting customers' expectations; gaining a competitive edge in relation to competitors; staying within the project budget; completing within a given time frame; gaining access to prototyping/production infrastructure and solving a technical problem. Themes for technical problem-solving and access to prototyping/production infrastructure received the most responses. Later in the interviews, hardware start-ups were confronted with the content of the developed Maker Movement Element framework. Overall, it has been revealed that the majority of Maker Movement elements are known to the interviewees and many are used in product development. Each entrepreneur interviewed was questioned as to whether any commonly used element is missing, but no new elements emerged directly as a result. However, some hardware start-ups also mentioned aspects currently missing in their local ecosystem. For example, they have a need to hire an industrial expert on an hourly rate at Makerspaces. Based on their statements, most of the time and money is lost in product development projects because expert knowledge is missing. Others also wish to have a Maker-project-showcase library, with the opportunity of learning how others deal successfully with a specific function or issue. This can be also an opportunity to get to know to like-minded people easily.

To gain a more complete picture of the interviewed hardware start-up's ecosystem, the locations are analysed by the author. The local ecosystems show a very complete image at first glance, in which some Maker Movement elements are not offered, such as a microfactory for assembly. The Makerspace at the Munich location has the most outstanding offering, especially in regard to the subsystem access to prototyping/ fabrication/ manufacturing facilities.

The quantitative survey and derived data are twofold: first, data is analysed for the knowledge and use of Maker Movement elements; and second, each element is assessed based on a numerical item score. The most extensively-used elements are online blogs that inspire, teach skills and help to solve a problem, as well as digital prototyping machines, metal shop, and open-source hardware. Rent a physical retail space is a mostly unknown concept. It is clear to see for the assessment part that the element access to a digital prototyping machine plays an important role in the reduction of product development cost and time criterion - on average the reduction of product development costs was given a grade of 4.8 and time was given 4.8, where 5 is the maximum. This statement is also in line with comments of the qualitative interviews that concern the main benefit of a Makerspace, which is detailly described a later in section 7.

Another fascinating aspect is that across all Maker Movement elements the potential impact of these on the reduction of product development costs criterion and the time criterion is highest and the impact on network increase criterion is lowest. This connection appears particularly significant and interesting when compared to the initial statements by the interviewees on the network that in contrast to other criteria the Maker Movement Element framework might not play a role at all. Furthermore, so-called impact factors are calculated based on a horizontal sum of each element's mean. These indicate which elements are the most important over all criteria. Access to testing equipment especially for electronics, digital prototyping machines, as well as access to an electronic workshop got the highest values across all five criteria. These three elements, which are related to the infrastructural offerings of a Makerspace, are followed by expert roundtables, electronic parts suppliers and open-source software frameworks. In contrast, the elements crowd funding, crowd investment, peer-to-peer e-ecommerce and rent a physical space got a very low ranking and therefore might not play an important role for the hardware start-ups questioned.

Finally, the data gathered in the DACH region is analysed and compared to the data collected in Helsinki in order on the one hand, to visualise, whether the chosen approach is transferable in principle to other locations/regions, and on the other hand to test if the hardware start-up needs and prerequisites on the Maker Movement Element framework is similar or not. It can be seen that these needs vary primarily on the basis of the current stage of development of a hardware start-up. Furthermore, the restrictions of working in a Makerspace also tend to relate to the local offerings and constraints, whereas the perceived benefits of the Makerspace concept have a tendency to be generalised. All in all, the results from Aalto University in Helsinki tend to be comparable with the results from the DACH region.

7 Interpretation and discussion

This section aims to interpret and discuss the knowledge, use and role of the Maker Movement elements in the product development of start-ups based on the generated data. Makerspaces are observed, and 26 hardware start-ups are investigated. Although only a limited number of interviews at three location are conducted, the results, as displayed in section 6.3, and in particular the research approach used, can be transferred effortlessly to other locations.

Based on the Mixed Methods design, the quantitative results will be underlined with the qualitative themes in the following paragraphs.

In short, the conducted study shows that various Maker Movement elements play a role in the product development by hardware start-ups. A clear knowledge of the Maker Movement Element framework for each hardware start-up or Makerspace operator thus represents a valuable asset as discussed in the following.

7.1 Mixed Methods research study data comparison

The focus of Mixed Methods is to collect, analyse, and mix both qualitative and quantitative data in a single study with the premise that the use of qualitative and quantitative approaches in combination provide a clearer and better understanding of the research problem than either one approach alone (Creswell and Clark, 2011, pp. 12–13). The previous section laid out a collection and an analysis of qualitative and quantitative data separately. The aim of this section is to combine this generated information and to further explain why the Maker Movement tends to support product development based on cost and time reduction in development, quality increase and cost reduction of the product itself, as well as has hardware start-ups' network effects.

Table 16 mixes, visualises and summarises the data and results from both qualitative and quantitative sources in a side-by-side comparison. A side-by-side comparison presents quantitative results and qualitative findings in a table so that both sources of data help to understand and provide side-by side evidence in a certain aspect (Creswell and Clark, 2011, pp. 223–226). The top row in the table names qualitative themes and the columns present qualitative and quantitative data based on those themes. The data is subdivided in the described criteria for product development: product cost, product development cost, time in product development, product quality and network. Per criterion and theme the weight total, which is the vertical sum of all Maker Movement elements results for this criterion and theme, the quantitively lowest ranked and highest ranked Maker Movement element for this criterion and theme as well as qualitative finds for this aspect are described.

Top themes of challenges faced by hardware start-ups? →
Criteria in product development? ↓

			Product development	Technical problem solving	Access to production infrastructure	Managing customer expectations	Product industrialisation	Cash flow/ rising capital
	Sample size		n=16	n=11	n=12	n=7	n=4	n=9
Product costs	Weight total (QUAN)	33..165	101,8	128,1	122,1	119,1	92,3	97,4
	Min (QUAN)	1..5	1,3 Crowd investment/ equity crowdfunding	2,6 Rent a physical retail space	2,2 Fair/ event	1,5 Rent a physical retail space	1,3 Crowd funding	1,8 Crowd funding
	Max (QUAN)	1..5	4,2 Microfactory (especially for assembly)	4,8 Testing equipment, Digital prototyping machines and Metal shop	4,8 Electronics workshop	5,0 Electronics workshop and Open-source software framework	4,3 Contract manufacturer for low volume	3,9 Contract manufacturer for low volume
	Analysis (QUAL)		The mainly not known Microfactory element is seen as highly valuable.	Many wish to have a service for hiring an industrial expert on an hourly basis to overcome technical problems.	Open-source software frameworks are often overlooked but can reduce product cost significant as well as good design and tested electronic components.		Contract manufacturer for electronics from China can significantly reduce product costs.	Crowdfunding or crowd investment is not seen as an option for rising capital.
Product development costs	Weight total (QUAN)	33..165	122,1	127,7	111,8	122,4	119,8	118,3
	Min (QUAN)	1..5	1,7 Crowd funding	2,1 Crowd funding	1,4 Crowd funding	1,2 Crowd funding	1,5 Crowd funding	2,0 Rent a physical retail space
	Max (QUAN)	1..5	4,8 Digital prototyping machines	5,0 Electronics workshop	4,6 Digital prototyping machines	4,8 Digital prototyping machines and Testing equipment	4,7 Metal shop	4,6 Digital prototyping machines
	Analysis (QUAL)		Product development cost can be reduced due to a Makerspace. Makerspaces are seen especially important when the equipment costs involved is high, like metal shop. Digital prototyping machines, like 3D printers or laser cutter, help to build cheap first prototypes.					
Time in product development	Weight total (QUAN)	33..165	125,3	110,4	85,9	92,9	117,7	125,5
	Min (QUAN)	1..5	2,6 Crowd investment/ equity crowdfunding	2,3 Crowd funding	1,6 Rent a physical retail space	1,2 Crowd funding	1,7 Rent a physical retail space	2,5 Fair/ event
	Max (QUAN)	1..5	4,8 Digital prototyping machines	4,5 Microfactory (especially for assembly)	3,6 Open-source software framework and Simulation software	4,4 Simulation software and Testing equipment	5,0 Electronics workshop	4,9 Electronics workshop
	Analysis (QUAL)		There is the need to build a functional prototype quickly in order to convince investors, customers or backers as early as	Try something new, build something, test it, learn and iterate are essential aspects in the start-up mindset. A Makerspace supports this behaviour, because the offered infrastructure is dedicated to rapid prototyping and fast iteration.			Missing infrastructure for product industrialisation is seen as a limitation. Start-up wish to have access to e.g. an injection moulding machines or polymer labs, which also results in cost reduced and speeds up development.	
Product quality	Weight total (QUAN)	33..165	101,0	114,8	94,2	95,7	101,8	99,9
	Min (QUAN)	1..5	1,6 Crowd investment/ equity crowdfunding	2,1 Crowd funding	1,7 Community order platform	1,2 Crowd funding and Rent a physical retail space	1,0 Community order platform	1,7 Community order platform
	Max (QUAN)	1..5	4,1 Testing equipment (especially for electronics)	4,5 Book/ printed magazine	4,0 Testing equipment (especially for electronics)	4,4 Simulation software and Contract manufacturer for low volume	4,5 Testing equipment (especially for electronics)	3,9 Book/ printed magazine
	Analysis (QUAL)		Many see a significant need for testing equipment, like material, optical, climate and electronics testing.	When technical problems occur questioned hardware start-ups, rely on their theoretical knowledge.	Typical digital prototyping machines are limited in terms of quality and therefore won't help start-ups.	Besides simulation software many stated that a library for materials and manufactured items is important to assume a reachable quality.	When scaling up a production testing is stated as a key feature.	Even though a community order platform might safes cost it is not used/ seen useful.
Network	Weight total (QUAN)	33..165	79,6	94,5	74,4	83,0	63,3	74,2
	Min (QUAN)	1..5	1,2 Design software for electronics (IoT toolkit, PCB testing)	1,0 Simulation software (CAE, CFD, FEA)	1,1 Raw materials in lowest volume/ material library	1,0 Cloud computing platform and Open-source software framework	1,0 Various elements	1,0 Free 2D design software
	Max (QUAN)	1..5	4,7 Expert's table	4,9 Fair/ event	4,7 Fair/ event	4,8 Fair/ event	4,7 Expert's table	4,6 Fair/ event
	Analysis (QUAL)		A typically Makerspace is not seen by questioned hardware start-ups as a resource for networking. However, a platform for industrial experts and talents should be established.					

Table 16: Side-by-side comparison of qualitative (QUAL) and quantitative (QUAN) data

7.1.1 Maker Movement elements help to reduce product costs

The quantitative survey shows that the concepts of a microfactory, electronic parts suppliers and open-source software frameworks are most important in this criterion. Taking a closer look at the microfactory, it can certainly be helpful for the hardware product development of start-ups. Considering that lots of problems and errors in a physical product are only detected in the product ramp-up phase, a microfactory for assembly can be of great importance for scaling start-ups. Even though the concept is very well-known and intensively used in large scale industrial production companies, the concept was hardly known to the hardware start-ups interviewed. When discussing in the interviews the pros and cons of such a microfactory, several stated they would use such a facility if it were accessible and affordable, especially because it would help them to get their products industrialised.

Surprisingly none of the investigated Makerspaces offer such a facility. In general, Maker Movement elements that are not offered tend to correlate with what is not known by the entrepreneurs interviewed. Microfactory for assembly, Maker-related facility database, community order platform or simulation software are examples of these unknowns.

Open-source software frameworks are often overlooked in the hardware-intensive offerings of a Makerspace also. However, based on the views of the interviewees, these frameworks are most likely to be well-designed and tested by hundreds of users and can therefore reduce the product cost significantly. None of the investigated locations highlight the existence of such frameworks.

7.1.2 Maker Movement elements help to save costs in product development

The Maker Movement elements on average received high scores in the quantitative survey based on the reduction of product development cost criterion. The access to prototyping/ manufacturing infrastructure elements got the highest scores. As described, these elements are also the inner core of the Makerspace concept. A Makerspace provides access to these machines mainly for free, which is mentioned as highly valuable by almost all interviewees. Furthermore, entrepreneurs mentioned that the support of a Makerspace is especially important when the equipment involves high investment costs, see also the data concerning the testing equipment element. One machine mentioned in the interviews as lacking in the analysed Makerspace is injection moulding. Injection moulding is an essential production technology when getting a product industrialised to scale. However, in principal, injection moulding has various downsides based on the entrepreneur’s statements: knowledge is limited, high quality suppliers are rare, lead times are long and costs for mould-making are also high.

Other requirements that are not being met by the Makerspaces include simulation software, a cloud computing platform and open-source software frameworks. Most of these elements are free to use and therefore these should be highlighted, and courses or workshops are needed in these fields in order to build awareness and teach the basic functions. This may support inexperienced hardware entrepreneurs in particular.

7.1.3 Maker Movement elements can be used to shorten product development time

As the quantitative data shows, access to machines in general is scored highest in this criterion as well. All elements, like the digital prototyping machines, wood shop, metal shop, and electronics lab, scored above 4.1 out of 5. Access to textiles area scored less. This lower score can be explained by the fact that only two entrepreneurs interviewed are developing products that require textiles and a sewing machine. This leads to the assumption that scores for specific infrastructure-focused elements depend on the product to be developed. Almost all participating start-ups are developing a product that requires electronics, so it is no surprise that electronics lab scores highest, along with digital prototyping machines. In general, the quantitative data matches the qualitative statements from the interviews here. Hardware start-ups need to build a first prototype quickly in order to try to convince investors, customers or other backers as early as possible in order to be able to learn and carry on development. A Makerspace provides start-ups great opportunities and possibilities in this fail forward/prototyping mindset, because most of the materials, tools and machines required for this are held at all locations and accessing these is possible without any delay. As stated by the entrepreneurs interviewed, fast iterations and short development cycles of two days or less are only possible due to extensive offerings at Makerspaces. One start-up stated that they did nearly 30 build-test-iterate cycles in the Makerspace until they achieved their final design.

However, some interviews revealed the weakness of the testing equipment in Makerspaces, which is mainly adequate for electronics. These entrepreneurs, who are mainly in later stage of development, mentioned a significant need for material and optical testing equipment such as a climate chamber. This equipment has high investment costs and therefore one solution could also be a partner network with established local companies, which offer their services to start-ups.

Also, often mentioned in the qualitative interviews was the access to a supplier network. Based on the entrepreneurs, such a network should only include well-known companies that can deliver good quality in a given lead time and, most importantly, are willing to work with start-ups. The necessity of such a supplier network can also be seen in the quantitative data. Such a supplier network would shorten the time in product development since the contract manufacturer for low volume element received very high scores.

7.1.4 Maker Movement elements increase product quality

Expert roundtables and meetups on certain technology aspects or generally on Maker-related projects scored second highest in the survey for the increase of product quality criterion. Although hardware start-ups are very familiar with these offerings, many mentioned time constraints as a reason for not participating in such events on a regular basis. They wished instead to have a service for hiring an industrial expert on an hourly basis to solve critical quality issues. In their view, such a service would have a high influence on product quality and could also speed up the product development process. Ideally, a Makerspace can act as a platform, host this service, connect the hardware entrepreneurs with the industrial experts and provide the location for the meeting.

Ranked low in the quantitative survey are open-source hardware and digital prototyping machines. In contrast to the previously-mentioned aspects, entrepreneurs mentioned in the interviews in regard to the quality aspect that such elements do not deliver a sufficient quality for the end product and they must therefore change to meet the industrial standards.

7.1.5 Maker Movement elements support enlargement of start-ups' networks

Enlarging the start-ups' networks as a result of Maker Movement elements seems to have the lowest score and therefore the weakest match. However, typical networking events such as fairs or hackathons are ranked number one.

This is also the only criterion in which the elements crowdfunding, crowd investment and rent a physical retail space received scores of more than 3 out of 5. Overall, the interviews show that these elements do not play any role for the selected start-ups, which is mainly due to the fact that most of these entrepreneurs questioned focus on B2B markets. Peer-to-peer e-commerce platforms or the possibility to rent a physical retail space are therefore elements more related to a craftsman who is trying to sell a specific amount of handcrafted products and may not be a matter of concern to a scalable technology start-up.

In general, a Makerspace can enlarge the network and community of a start-up, because other people run into each other and meet regularly at Makerspaces. As observed, discussions instantly start up about the manufacturing process used and the prototype itself. The same is true for the Maker-related facility database element, which scored third. This is especially helpful when a Makerspace does not offer enough capacity and knowledge or does not offer a sufficient number or range of machines and tools. As explained, entrepreneurs are engaged in developing many different products, from autonomous driving vehicles to small IoT devices, and it is therefore logical that they may need a large variety of different manufacturing technologies. A point also mentioned as potentially crucial by some entrepreneurs is the value of an extension of such a database to known suppliers who are willing to work with start-ups, as described before.

7.2 Makerspaces as product development facilities

As already mentioned in section 2.3.3, 2.3.4 and 2.3.5, community, operation as well infrastructure define Makerspaces and their success. Litts(2015, pp. 186–188) investigates Makerspaces as learning environments and notes rhetoric around Makerspaces is today primarily tool and machine focused, but more important are interdisciplinary learnings and the project-based engagements of Makers in Makerspaces. Baichtal(2011, pp. 14–15) or Britton(2012), for instance, conclude also that the community aspect seems to be the most important for the success of a Makerspace. Troxler and Schweikert(2010, pp. 4–7) named key aspects for operation, like openness, accessibility, interdisciplinary collaboration and exchange experiences. Hence, Böhm, Friessnig and Ramsauer(2015) and Karre(2015), give a clarification of typical Makerspace infrastructure. However, all of the three dimensions need to exist simultaneously, meaning for instance that a vivid community can only exist if an appropriate infrastructure and supportive operational staff is provided.

✓	**Yes**
○	**Mixed**
✗	**No**

Maker Movement elements	**Operations**	**Community**	**Infrastructure**
Fair/ event	✗	✓	✓
Maker related facility database	✓	✓	○
Expert's roundtable	✗	✓	✓
Community order platform	✗	✓	✗
Open files repository (CAD files, norm parts, code)	✗	✓	✗
Discussion forum	✗	✓	○
Crowd based instruction	✗	✓	○
Webinar/ Workshop/ Open online course	✓	✓	✓
Online collection of resources	○	✓	○
Online blog that inspire/ teach skills/ help to solve problems	○	✓	○
Book/ printed magazine	✗	✗	✓
Open-source software framework	○	✓	✗
Open-source hardware	✗	✓	✓
Digital prototyping machine	✓	✗	✓
Wood shop	✓	✗	✓
Metal shop	✓	✗	✓
Electronics lab	✓	✗	✓
Textiles area	✓	✗	✓
Testing equipment (for electronics)	✓	✗	✓
Microfactory (for assembly)	✓	✗	✓
Cloud computing platform	○	✗	○
Free 2D design software	✓	✓	✓
Free 3D design software	✓	✓	✓
Simulation software (CAE, CFD, FEA)	✓	✓	✓
Design software for electronics (IoT toolkit, PCB testing)	✓	✗	✓
Platform for distributed manufacturing	○	✓	✗
Contract manufacturer for low volume	○	✗	✗
Online distributor of electronic components	○	✗	✗
Raw materials in lowest volume/ material library	✓	✗	✓
Crowd funding	✗	✓	✗
Crowd investment/ equity crowdfunding	✗	✓	✗
Peer-to-peer e-commerce	✗	✓	✗
Rent a physical retail space	✓	✓	✓

Table 17: Match between Maker Movement elements and possible Makerspace offerings

Based on these thoughts and the here conducted study, infrastructure describes the physical assets of a space such as machines, tools or materials and software applications offered. Within operation, the local Makerspace staff and educational offerings can be seen. Community describes the actual Makerspace users and how those persons share their experiences. With a view to further clarifying the connections and implementation possibilities of the Maker Movement Element framework, Table 17 indicates for each element whether it can be viewed as infrastructure-based, operational facets, and community-driven.

7.2.1 Infrastructure

While analysing Makerspaces and elements it was clear to see that only 13 out of 33 Maker Movement elements are associated with a Makerspace infrastructure. This means that they are connected to an infrastructural investment, such as the purchase of 3D printers or laser cutters. 6 out of these 33 elements are marked as mixed. They are online but can be influenced by Makerspace infrastructure and operation. These elements, for instance, can be furnished with Makerspace own information and hosted on a Makerspace own infrastructure, but they are accessed via the Internet. Examples included Maker-related facility databases and online collections of resources.

The theme Available tools and machines is the number one reason for qualitative interviewed hardware start-ups to use a Makerspace. However, this research study demonstrates that typical Makerspace infrastructure, like 3D printers and laser cutters, is important but a more comprehensive offering is needed to boost the product development of hardware start-ups. Missing facilities is seen as a main restriction of Makerspaces and as stated previously, start-ups see a higher value in a Makerspace when it offers infrastructure with high investment costs. For instance, soldering irons are affordable for hardware start-ups right from the beginning of their venture but facilities such as an injection moulding machine or a large-scale CNC milling machine are out of reach. However, such expensive machines are essential for building a functional prototype. Thirteen respond the usage of CNC milling machines or lathes. Comparing the results of the quantitative survey, digital prototyping machines are more important than electronics, a metal shop or a wood shop. Least important of all is an area for textiles.

Seeing that access to expensive infrastructure is an enabler for hardware start-ups, Reif(2016) introduced as the president of the MIT a new platform in late 2016 to help local hardware start-ups to get off the ground. The so-called Engine[166] establishes a network of shared infrastructure surrounding the MIT campus, including offices, bio-labs, and Makerspaces. As is also concluded in this dissertation, his perception in introducing the Engine is comparable. The aim of Engine is to provide a pathway for breakthrough ideas and to help to shorten the time it takes to build physical prototypes so that start-ups become earlier investment ready.

7.2.2 Operations

Unmet hardware start-ups needs can be seen for the elements electronic part supplier, contract manufacturer for low volume, and platform for distributed manufacturing. These three elements are particularly essential when scaling a start-up. After finishing the first prototypes, hardware start-ups seek partners in order to get their products industrialised, but the analysed locations have very limited support offerings in this area. ETH Bastli, for example, runs a contract manufacturing service for PCB design and production, and UnternehmerTUM MakerSpace

[166] www.engine.xyz (Accessed: 2 June 2019)

provides contract manufacturing particularly for 3D printing, water jet cutting and CNC milling. Both services are not designed to support in industrialisation nor to produce hundreds or thousands of similar parts.

Compared to the other investigated Makerspaces, UnternehmerTUM MakerSpace invests significant efforts to enable Makerspace users to work independently. Courses are frequently offered for each type of tool and machine. However, these efforts are seen by the interviewees as the biggest negative aspect of the space because it slows down their process and leads to inappropriate machine use due to the courses not being available at the right time. Furthermore, unexperienced users on the one hand may become overloaded by the countless offerings in the beginning but on the other hand this system makes sure that everybody gets the basic knowledge to use a machine themselves. What is might missing is an overview course that teaches how product development can work more efficiently in a Makerspace.

On the other side, one often mentioned and developed theme for restrictions of hardware start-up working in a Makerspace is reduced flexibility, mainly due to opening hours of a Makerspace, operation rules or unavailable tools and machines. Therefore, many trade-off decisions must be made when setting up Makerspace operations between necessary restrictions and provided user flexibility.

7.2.3 Community

As shown in Table 17, 20 out of 33 Maker Movement elements have a connection with the community aspect, meaning that these elements in the main cannot be directly influenced by a Makerspace operations and thus cannot be infrastructure wise implemented. However, not surprisingly, these community-based elements also have a great influence on the product development of hardware start-ups. Open-source software frameworks or hardware, and file repositories are good case of this.

Many interviewed hardware start-ups stated also that community is a main reason to use a Makerspace. The most important aspect in regard to community is sharing and a prototyping mind-set within a Makerspace's community. As observed and discussed in the interview, people working in a Makerspace like to share their knowledge and experience with each other. The Maker Movement Elements framework lists certain facets, and in particular expert roundtables and collections of resources, which scored highest quantitatively, foster product development. Looking at qualitative themes, the collections of resources can also be a collection of showcases, like products, principals and functions, developed in a Makerspace. This collection may give others the possibility to learn how a problem can be solved through Makerspace capabilities.

Interviews conducted also show that some elements are currently not known to hardware start-ups but would most likely have a positive influence on the work in a Makerspace. One support factor might be to set up a knowledge platform. This platform can provide missing knowledge to the community, such as describes of unknown elements, it can highlight possibilities which are not connected to machines and tools, such as open-source software frameworks, and users can share best practice examples. Such a platform is also considered to be highly valuable by the interviewed entrepreneurs. Another important function that a knowledge platform can feature is described in the online blogs element. Content can inspire, teach skills and help to solve problems and this is seen as helpful among the hardware start-ups surveyed.

7.3 Maker Movement elements as supporting factors to hardware start-ups

This dissertation focuses on the problem of how the Maker Movement can support the product development projects of hardware start-ups in terms of cost and time reduction in product development, quality increase and cost reduction of the product itself, as well as the expansion of hardware start-ups' networks. Various best practice examples and statements derived from the data gathered are already given. Nevertheless, it is clear that the "one size fits all" strategy cannot be applied here, because the products to be developed are too diverse in the first place. Having now described the findings of the Mixed Methods research study and implications Makerspaces this section summarises and outlines a new version of the Maker Movement Element framework, which is dedicated to the product development of hardware start-ups. However, in a next step this framework should be solidify be another scientific research project and more data.

7.3.1 Matching of supportive elements to needs and challenges of hardware start-ups

Based on generated themes, observation and quantitative data, certain Maker Movement elements can be matched to needs and challenges by hardware start-up in product development. Hardware start-ups in general need various aspects in order to mast their physical product development project and certain elements within the Maker Movement can be considered to support those. The match is structured along the three dimensions, which are important for running a Makerspace successfully: infrastructure, operations and community, the earlier introduced Maker Movement element framework and Mixed Methods research study data.

Table 18 shows the result of the adapted framework, which is derived from the developed qualitive themes and quantitative data. In particular themes for challenges of hardware start-ups and experiences as well as observation and discussion of the Maker Movement elements are taken in account. This qualitative data is mixed with quantitative results from the survey. In comparison to the original Maker Movement Element framework laid out in section 4.3, eight elements are renamed, four summarise comparable elements, eleven are deleted, and five are added. All in all, 27 Maker Movement elements are named in this adapted framework. The new framework gives, based on the gather and analysed data, a more detailed list of possible supporting factors in product development due to the Maker Movement. Needs and challenges in product development of hardware start-ups, like time pressure, flexibility, resources, skills, industrialisations can be encountered with those described Maker Movement elements.

✓	Yes
○	Mixed
✗	No

Maker Movement subsystems and elements		Operations	Community	Infrastructure	Explanation
Connect with others (physical/live)	Ask an industry expert platform	✓	✓	✗	This is a service where start-ups can hire industry expert on an hourly bases to solve technical problems faster or clear out problems line with product industrialisation.
	Prototypes/ showcase/ technology museum	✓	✓	✓	Individuals learn and connect with others through built prototypes or showcase and technologies shown in gallery.
	Expert's/ Maker's roundtable	✗	✓	✓	Possibility to connect and exchange knowledge with likeminded at weekly/monthly roundtables.
Connect with others (online/virtual)	Open files repository (CAD files, norm parts, code)	✗	✓	✗	Online platforms enable the possibilities to connect worldwide to likeminded as well as the exchange knowledge, files and expertise. No budget and involvement are needed.
	Discussion forum	✗	✓	○	
	Crowd based instruction	✗	✓	○	
Gather (hardware) knowledge & skills	Machine and tools courses and methodical workshops	✓	✓	✓	Seen valuable to reduce time in product development and the gather skills are machine courses and workshop.
	Knowledge platform	○	✓	○	A web-based knowledge platform is seen important and can combine three Maker Movement elements: Online collection of resources, Online blog and Books/magazines
Access to prototyping/ fabrication/ manufacturing facilities	Material/ (open-source) components/ norm parts sale	✓	✗	✓	Having the right materials at hand when prototyping is sentential to keep in the set timeline and budget therefore an in-house sale should include various raw materials, open-source electronic components and norm parts.
	Testing/ working/ project space	✗	✓	✓	Hardware start-up desire not only office space but also a workshop space to build up prototypes over a longer period of time.
	3D printer and laser cutter	✓	✗	✓	Digital prototyping machines is renamed to 3D printer (FDM, SLA) and laser cutter, which are the most used tools for building rapid prototypes.
	Wood shop	✓	✗	✓	Wood shop includes now a CNC router, sander, band saw, vertical saw and hand tools.
	Metal shop	✓	✗	✓	Metal shop includes now metal 3D printing (SLS) and large-sized CNC machines
	Electronics lab	✓	✗	✓	Electronics lab includes circuit board production tools and soldering iron but also electronic kits like Little Bits and Makerblocks to rapid prototype
	Textiles area	✓	✗	✓	Textile area includes sewing machines and embroidery machines.
	Microfactory (for assembly)	✓	✗	✓	Hardware start-up need also space for testing mass manufacturing of their product and a microfactory can help.
	Industrial grade manufacturing technologies	✓	✗	✓	Industrialisation is a big challenge for almost all hardware start-up, therefore facilities with similar manufacturing technologies, like water jet cutting, vacuum deep drawing, or injection modelling are needed to build and test.
	Product testing lab (electronics, mechanics, optical, ...)	✓	✗	✓	Build, test and iterate is the development cycle of many hardware start-up, hence equipment is needed to test prototypes.
Software and components	Cloud computing platform	○	✗	✗	Scaling is easier when selecting the appropriate cloud computing platform. Operations can help.
	Open-source software framework	○	✓	✗	Well developed and tested open-source software frameworks have the potential to reduce cost and time significantly, hence guidelines should be given.
	Professional CAD software	○	✗	✓	Educational software licences are not designed to be used by start-ups as result commercial software licences are necessary.
	Simulation software (CAE, CFD, FEA)	✓	✓	✓	Simulations can help to manage customer expectations and solve technical problems.
	Design software for electronics (IoT toolkit, PCB testing)	✓	✗	✓	Well-designed electronics can help to ease out industrialisation. A first step is an electronic design.
Supply chain	Platform for distributed manufacturing	○	✓	✗	Distributed manufacturing platforms are currently not intensively used by the questioned hardware start-up because of high cost, but they play a role when time is limited.
	Supplier platform for components and contract manufacturing	✓	✓	✗	A supplier platform combines the element of Contract manufactures, Maker releated databse and Online distributors. Yet again hardware start-ups have limited knowledge of available supplier and therefore a database gives access and shorten time.
Get customers feedback and funding	Crowd funding	✗	✓	✗	Even though crowd funding is popular among hardware start-up, it is not seen valuable.
	Physical retail space and peer-to-peer e-commerce	✓	✓	✓	A physical retail space and peer-to-peer e-commerce is seen as time-consuming and not helpful.

Table 18: Maker Movement Element framework dedicated to hardware start-ups

The Maker Movement Element framework dedicated to hardware start-ups product development can especially be important for start-up support programmes and Makerspace operations. Resources are limited and a good match between specific elements and start-up's needs is essential for promoting the creation of new scalable start-ups more powerfully. Furthermore, it can support initiators in setting up a new Makerspace. After defining boundary conditions (e.g. size of a Makerspace, budget etc.), initiators are given a recommendation for Maker Movement elements of case specific relevance for them that can be implemented.

7.3.2 Importance of different elements due to different start-up characteristics

Characteristics of hardware start-up, like stage of development, founding, product type or market, are defined within this research, see section 2.1 and 6.1.1. These characteristics can function as a filter for the quantitative data. The aim of this model is to investigate if there exist start-up specifics needs based on those characteristics. Due to the fact that the data set is limited to 26 completed surveys, the authors selected only four characteristics to apply the filter and to test the assumptions: the start-up's product type, start-up stage, market, and current biggest challenges. The results are shown in the appendix.

Surprisingly, the results are not as diverse as expected. The lowest five elements have almost similar elements: rent a physical retail space, peer-to-peer e-commerce, crowd funding, and crowd investment. In comparison with the overall results from Table 12, these elements are also the lowest ranked there and therefore play no role at all in product development projects for the hardware start-ups questioned. A similar picture can be seen for the highest ranked elements. Access to testing equipment, digital prototyping machines and expert roundtables are three elements that are ranked in the top five in almost every group. For the product type groups, hardware and hardware plus firmware, access to a metal shop, wood shop and craft machines were all ranked in the top five, which is linked to the fact that software components and electronics play a minor role for those start-up groups. The product type of hardware, firmware plus application, sees a higher demand in the element contract manufacturer for low volume ranked number five and electronics.

A slightly more diverse picture of the highest and lowest ranked Maker Movement elements can be seen when filtering the results to the current biggest challenges start-ups are facing. Expert roundtables scores high again while crowd investment and crowd funding score low. However, simulation and 3D design software seem to be more important for those entrepreneurs who stated that they currently face challenges in growth and increasing sales.

Building on that, the ultimate goal would be that start-up characteristics can be used to define hardware start-up architypes and selected aspects of those architypes combined with the generated data can give a specific benchmark for other start-ups, which also fall within the defined architypes. Knowing these best-practice examples, important elements and applying them in a hardware start-up may result in higher success rates, reduced product costs, shortened product development time, increased product quality and an enlarged network. Figure 31 shows the steps required in this model. Nevertheless, far more quantitative data is needed in order to create a reliable selection and hypothesis.

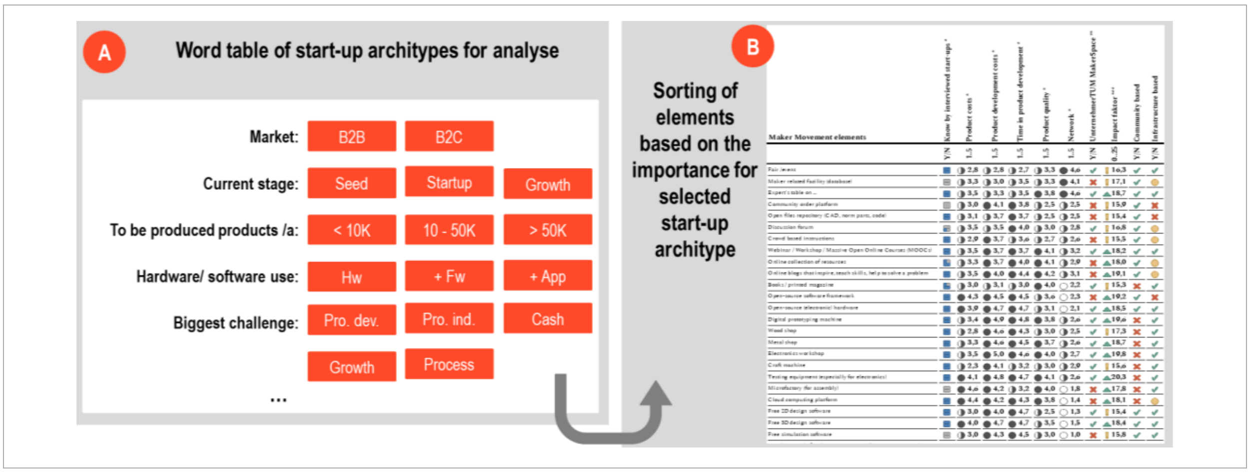

Figure 31: Match word table of start-ups characteristics to define architypes and to obtain different Maker Movement elements

The models above and statements by the hardware entrepreneurs show that the Maker Movement Elements framework in general gives a good overview and toolset for fostering product development for hardware start-ups. Makerspaces are the host of many elements and product development projects are supported extraordinarily well in those locations.

7.4 Limitations of the research study

Within this research study, two limitations are striking; one relates to the limited size of the quantitative data sample and the other is connected with the limited scope of the research regions.

This is due to the fact that in this research the Convergent Parallel Mixed Methods design is applied, and the research has the same sample size for qualitative and quantified data. The sample size is therefore for the quantitative analysis alone very limited and assumptions based only on the quantitative data might not be valid. But these assumptions can in most cases be supported with qualitative data from the interviews which support the validity but in other cases, as mentioned in 7.3.2, more quantitative data is needed to make profound statements.

The scope of this research is limited to the selected locations within the European DACH region due to reachability, accessibility of in-depth information and availability of hardware start-up. Considering that this region includes Europe's leading technical universities, the responses may be influenced by the large and diverse offering already provided. However, section 6.3 shows that the gathered results are comparable to other regions within Europe in principle.

7.5 Conclusion: interpretation and discussion

The focus of Convergent Parallel Mixed Methods is to collect and analyse the two datasets separately and then combine both to provide a clearer and better understanding of the research problem than either one approach alone can generate. Mixing, interpretation and discussion of the collected and analysed data is described in this section. The section helps to further explain why the Maker Movement tends to support product development based on cost and time reduction in product creation, quality increase and cost reduction of the product itself, as well as entrepreneurs' network effects. Based on the research design, the quantitative results will be underlined with the qualitative themes.

According to the quantitative findings, the microfactory element in particular can help to save product costs. This element scores high even though it is rarely known/used by hardware entrepreneurs, nor offered by any of the investigated locations. Qualitative statements underpin the importance of having such a facility for instance just to fulfil customer orders with higher quantities of products in the start-up phase. A minority of participating start-ups that face this situation build up a rough microfactory in their own offices themselves.

However, Maker Movement elements that are not offered tend to correlate with what is not known by interviewed entrepreneurs. A microfactory for assembly, maker-related facility databases, community order platform or free simulation software are examples of these unknown elements.

The open-source software frameworks element and software-focused elements in general are often overlooked in the hardware-intensive offerings of Makerspaces. However, based on the views of the interviewees, these frameworks are most likely well-designed and tested by hundreds of users and therefore they can reduce the product cost. Again, none of the Makerspaces visited highlight their existence. Another need that is not being met by the Makerspaces investigated can be seen in simulation software and cloud computing platform. Most of these elements are free to use and therefore a Makerspace should highlight these offerings and should organise courses or workshops in these fields to build awareness, which is particularly valuable for inexperienced entrepreneurs.

The Maker Movement elements asset for the reduction of product development cost criterion compared to others received on average the highest scores in the quantitative survey. The subsystem access to prototyping/ fabrication/ manufacturing facilities received the highest scores in total, which is substantial for a Makerspace and this can be directly influenced through Makerspace operations. A Makerspace provides access to such machines largely for free, and this is mentioned in the interviews as highly valuable by almost all interviewees. Furthermore, entrepreneurs mentioned that the support of a Makerspace is especially important when the equipment has high investment costs. It is viable for interviewed entrepreneurs to buy for example a soldering iron themselves, but not a laser cutter.

As the quantitative data shows, access to craft machines scored lower than access to other machine elements. This lower score can be explained by the fact that only two interviewed entrepreneurs are developing products that incorporate textiles. This leads to the assumption that scores for infrastructure-focused elements depend on the product to be developed. Nearly all participating start-ups are developing a product that needs electronics, which explains why electronic workshop scores highest along with digital prototyping machines. On the whole, the quantitative data matches the qualitative statements from the interviews. Hardware start-ups need to build a first prototype quickly in order test their assumptions and to convince investors, customers or other backers as early as possible in order to be able to iterate and carry on development. A Makerspace provides great flexibility and possibilities in this process. For example, most of the prototyping machines are held at a single location so that accessing those machines is possible without any delay. As stated by the entrepreneurs interviewed, fast iterations and short development cycles of two days or less are only possible due to the Makerspace concept. One start-up stated that it had the possibility to develop around 30 different prototypes in the Makerspace until it achieved its final design. Each prototype gave them the possibility to learn something and test the semi-finished product with customers.

In regard to the product quality criterion in the quantitative survey, open-source hardware and digital prototyping machines are ranked low compared with others. In this respect, entrepreneurs mentioned the quality aspect that these elements do not deliver a sufficient quality for end products and therefore they must change to meet industrial standards.

Enlarging hardware start-ups' networks as a result of Maker Movement elements seems to have the lowest score and therefore the weakest match with their needs. However, typical community events such as fairs are ranked number one and expert roundtables came second. Entrepreneurs confirmed that expert roundtables are a very important factor for meeting like-minded people, solving problems or receiving advice.

Based on these views and with a view to the further clarification of correlations and implementation possibilities of the Maker Movement Element framework, the authors indicated for each element whether it is community-driven, infrastructure-based, influences operations or supports product development.

Furthermore, certain models/ use cases for the Maker Movement Element framework in product development are described. For example, the quantitative data is split up in groups according to the qualitative classification of a start-up. Surprisingly, the results for each group in this model are not as diverse as expected. The lowest five elements for each group are almost always the same elements: rent a physical retail space, peer-to-peer e-commerce, crowd funding, and crowd investment scored low almost always. A similar picture can be seen for the highest ranked elements. Access to testing equipment, digital prototyping machines and expert roundtables are three elements that are almost always ranked in the top five. For the hardware only and hardware plus software firmware product type groups, access to a metal shop, wood shop and textiles area received a ranking in the top five, which is linked to the fact that software components and electronics play a minor role for those start-ups. The hardware, firmware plus user app product type group sees a higher demand in the contract manufacturer element for low volume, which is ranked number five. The ultimate goal would be that the characteristics can be used to define start-up architypes and that selected items for these architypes combined with the generated data can give specific best practices. Awareness of these elements and applying them in the hardware start-up may result in higher success rates. Nevertheless, far more quantitative data is needed to create a reliable choice and hypothesis in this model.

8 Conclusion, contribution, and outlook

This research study shows that the Maker Movement enables the creative and fruitful creation of new ideas, prototypes, products and start-ups. Zwilling(2014) emphasises that *"the Maker Movement and start-ups were made for each other"*, which is underlined by the present dissertation.

In the following paragraphs, the overall conclusion of the research study is presented, which focuses on the answers to the research question. Moreover, the contribution to theory is stated and implications on the industry are discussed and specified. Lastly, suggestions for further research are given.

8.1 Implication: research questions

This study investigates the Maker Movement's role in hardware start-ups' product development projects. The cross influence of the Maker Movement and product development projects, especially in hardware start-ups, is investigated and a proper set of Maker Movement elements may help to solve critical challenges in product development for hardware entrepreneurs. The research questions are answered in this dissertation and the main findings are summarised in the following:

1. What elements exist in the Maker Movement?

The ultimate goal of the Maker Movement is democratisation of the means of manufacturing in order that everyone is able to produce his/her own products. This has a big impact on various fields. In educational formats, for instance, people mostly do not stick to digital models and illustrations only but can rapidly build a physical model and prototype to communicate function and features more easily. The current rise of the Maker Movement is prompted by various factors but the introduction of new machines types, access to infrastructure, open-source hardware and software, easier sourcing of parts, as well as the possibility for direct distribution of physical products are among the most important ones. Makers, individuals who work in the ecosystem of this movement, are inspired by the work of others, share their own work, and learn to create their own innovative products. The Maker Movement is no longer just a hobbyist movement. New financing possibilities, such as crowd funding, and the existence of professional Makerspaces on a global scale with a rich offering of machines, tools and support along the product development process, further empowers this development.

Since literature gives no clear structure for the Maker Movement ecosystem, a framework is developed to uncover certain facets or players within the Maker Movement. Based on a literature review, field trips, observation and open-ended interviews with Makerspace operators and users, the so-called Maker Movement Elements framework is developed and presented.

Many of the identified elements can play multiple roles in product development and in the Maker Movement ecosystem. Nevertheless, a clearly structured Maker Movement Element framework is a valuable help as discussed in the following:

- Classification of Makerspaces: Makerspaces can be classified based on the amount and type of elements they offer, and then certain patterns can be identified.
- Based on the framework and patterns, it can support initiators in setting up a new Makerspace; firstly, the Maker Movement Element framework presents a holistic picture of facets in the Maker Movement, then after defining the purpose and focus of the space, a selection of specific Maker Movement elements can be made to match the targets and be implemented.
- Evaluation of the Makerspace: A Makerspace evaluation can be important because resources are mostly limited and a good match between specific elements and user needs is essential for promoting more powerful new product creations. Requests for specific elements can be clarified through interviews with Makerspace operators and users.
- A link between Makerspace user needs and element offers can be shown.

It was clear when analysing the Maker Movement Element framework and Makerspaces that only 13 out of 33 Maker Movement elements are directly associated with an infrastructure investment such as the purchase of 3D printers or laser cutters. 6 out of these 33 elements are marked as mixed types meaning that they can be online but are also influenceable by Makerspace operations. These elements can, for instance, be filled with a Makerspace's own information and hosted on a Makerspace infrastructure, but they are accessed via the Internet. 14 Maker Movement elements are only Internet-based and have no direct connection to infrastructure or the operation of a Makerspace.

2. **What influences viewed by hardware start-ups exist on product development at Makerspaces?**

In the context of this dissertation, a start-up is a business younger than ten years, selling a single service or product and having the ability to scale rapidly. Building on that, a hardware start-up characterises a group of start-ups that are developing physical products. These products can also include software aspects and connectivity features, like IoT devices. A hardware start-up sells its products in either a physical and/or a virtual market.

In general, hardware start-ups are gaining popularity. Graham(2012c), for instance, mentions that no single force is driving this trend, but he listed important aspects: first, the spread of smartphones and tablets makes it possible to build new products controlled by and even incorporating them; second, electric motors have improved; third, wireless connectivity of various types can be bought and implemented easily; fourth, getting products manufactured is easier and more straightforward as a result of Makerspaces, as well as open-source electronics, 3D prints, laser cutters, and CNC mill machines; sixth, selling products is less of a bottleneck because of online platforms.

Based on literature, earlier studies, and subsequently in the qualitative interviews conducted, the biggest challenge of hardware start-ups are seen in product development. Various sources state that it is harder to develop hardware products than software products. They need more time to reach the market and the development of a hardware product is more expensive because a bigger team needs to be involved, materials need to be bought, and prototypes need to be built. The testing of hardware products is also a big challenge too. Software can be tested by means of a demo server or beta access whereas before starting the testing of a hardware product, a functional prototype and appropriate testing equipment is needed, which in many cases can only be fulfilled when appropriate suppliers and producers are selected. However, testing is important because an incomplete product results in unfulfilled customer satisfaction and can crash the start-up before it has even started.

Two mainly USA based-empirical studies are cited in regard to the issues of Makers and entrepreneurs. Both name insufficient funding and resources as the biggest issue. Ranked second is access to manufacturing and third is access to knowhow. As described in this study, all three can be provided by a facility, such as a Makerspace.

Several factors are identified in the qualitative interviews for issues in the product development projects of hardware start-up whereas a Makerspace can have influences. These factors can be grouped in the following themes:

- **Technical problem:** Most of the hardware start-ups questioned are aiming to develop high-tech products and technical problems often arise on their journey. Many mentioned that prototyping, testing and iterating as well as meet-ups with like-minded people or industrial expert consultants are the key resources in order to overcome these issues.
- **Access to prototyping/production infrastructure:** In contrast to software start-ups, hardware start-ups have the need to build various physical prototypes in a short time interval. Many interviewees have a strong connection to their local university and received support in terms of accessing the university workshop when the local Makerspace does not have sufficient machines and tools available. Nearly all entrepreneurs mentioned that it would not be possible without this backing to progress so far in the product development process.
- **Managing customer expectations:** Building physical prototypes as early and as rapidly as possible tends to give start-ups a significant advantage because people and/or potential customers are more interested in the actual product itself. Furthermore, they can interact with the product early on and can actually get their hands on the product the start-up has been developing. This can help start-ups to meet and manage customer expectations.
- **Budget:** Keeping to a fixed budget is often mentioned as a problem. This issue is even more complex for hardware start-ups, because without available funds, no tangible prototype can be built. Start-up support centres are mentioned here as an essential source in providing initial prototyping grants without complex application processes.

- **Completing on time:** Finishing developments in a desired timeframe seems to be a greater challenge for hardware start-ups because various parts may need to be sourced externally. This can significantly increase the time it takes to finish a specific development stage. As mentioned by the interviewees, start-ups need to be fast. They like to develop new product features or prototypes in time intervals of less than two weeks. Access to the means of manufacturing has an essential role here.
- **Gaining a competitive edge:** Product ideas or concepts need to involve a competitive edge. Greater excellence can be achieved when customers, users and/or industry experts are included early in the product development process. Start-ups need to build up their own network of individuals who are willing to provide support.

Open-ended questions and observations are used to gain in-depth understanding on how interviewed hardware start-ups realise their product development projects. Influences on the concept of a Makerspace are described in line with the prototyping actions. Start-ups perceive Makerspaces in a generally positive light. Many start-ups agree with the view that the main beneficial aspect is easy and cheap access to a wide variety of machines and tools. They believe that this helps them to speed up their product development projects and also reduces costs. Some added that a suitable Makerspace for product development should have experts available for each manufacturing technology who can be consulted easily when difficulties arose while others emphasise the establishment of a supplier network. Another hardware start-ups interviewed see the requirement of obtaining support in the production ramp-up/industrialisation in a Makerspace as essential. In line with these statements, a material library/retail area that holds different types of bulky raw materials that can be used and tested immediately, is also seen as useful. Surprisingly, higher quality industry graded production machines and high specific manufacturing tools are not perceived as important.

Sourcing of parts and finding the appropriate manufacturing partner is seen as big challenges of the interviewed European based hardware start-ups. Anticipating this challenge, HAX[167], a popular hardware start-up accelerator, invites its participating start-ups to a three-months stay in Shenzhen. Shenzhen is world famous for electronic products and local suppliers provide components for just about anything start-ups can and want to produce. Participating start-up teams report that they can speed up tremendously due the local circumstances and to proximity to those suppliers, see for instance Vance(2019, 5:43f).

3. **How do the themes mentioned by hardware start-ups help to explain why the Maker Movement and product development matches?**

In this research, the qualitative interview data of hardware start-ups further explains why the Maker Movement, as measured quantitatively, tends to support product development based on cost and time reduction in product development, quality increase and cost reduction of the

[167] www.hax.co (Accessed: 2 June 2019)

product itself, as well as hardware start-ups' network effects. In general, the research supports a clarification of how the Maker Movement supports product development projects of hardware start-ups.

The following quantitative results can be highlighted by the qualitative themes mentioned:

- **Maker Movement elements help to reduce product costs:** The quantitative survey shows that especially the concepts of a microfactory, electronic parts suppliers and open-source software frameworks are important. Taking a closer look at the microfactory, it can be confirmed through the mentioned statements that this is an important asset in the product ramp-up/ industrialisation phase of a hardware start-up in particular. Nevertheless, it is currently not available at any investigated Makerspace.
- **Maker Movement elements help to save costs in product development:** Elements which are in line with access to machines and open-source electronics received the highest scores here. A Makerspace provides uncomplicated access to these machines, and this is mentioned as highly valuable by almost all interviewees.
- **Maker Movement elements can be used to shorten product development time:** As the quantitative data shows, access to machines in general scored highest. Short development cycles and reduced time to find for instance the proper sourcing partners to get prototypes manufactured fast are the qualitative statements given to underline the quantitative findings.
- **Maker Movement elements increase product quality:** Expert roundtables, testing equipment and electronic parts supplier scored highest here. Although expert roundtables are well known by hardware entrepreneurs, time constraint is the main mentioned reasons for not frequent participation. They wish instead to have a service where they can hire an industrial expert on an hourly base in order to solve critical quality issues precisely when a problem arises. In their view, such a service would have a high influence on product quality and can also speed up the product development process. Ideally, a Makerspace could act as the host of such a service.
- **Maker Movement elements support enlargement of start-ups' networks:** Items in this criterion have the lowest scores overall and therefore the match with start-ups' needs seems to be weak, which can also be seen in the interviews. However, typical community events such as fairs or hackathons are ranked number one.

Statements by hardware start-ups show that the Maker Movement Elements framework in general provides a good overview and toolset to foster the product development of hardware start-ups and Makerspaces host many elements. Product development projects receive extraordinary support within these locations.

Nearly all participating start-ups are developing a product that needs electronics and can be made with digital prototyping machines, and these scored highest. On the whole, the quantitative data matches the qualitative statements from the interviews. Hardware start-ups need to build a first prototype fast in order to test and iterate. A Makerspace provides great flexibility and possibilities in this process because various prototyping machines are held at a single location, so that access is immediately possible, and the use may also be free of charge. As confirmed by the entrepreneurs interviewed, fast iterations and short development cycles of two days or less are only possible due to the Makerspace concept. One start-up stated that it built around 30 different prototypes in the Makerspace in a short space of time until the final design was achieved. Each prototype gave the possibility to learn and test the product idea with customers.

This research study demonstrates that typical Makerspace infrastructure, such as 3D printers and laser cutters, is important, but a more comprehensive offering and services are needed to boost the product development of hardware start-ups. Start-ups see a higher value in a Makerspace when it offers infrastructure with high investment costs.

However, the hardware start-ups questioned also have unmet needs. Electronic part supplier, contract manufacturer for low volume and platform for distributed manufacturing are a few such examples. These elements are particularly important when scaling a start-up. After the first functional prototypes have been completed, hardware start-ups are on the lookout for partners in order to get their products industrialised, but the Makerspaces analysed have very limited support offerings in this field. Again, more offerings for product ramp-up, such as a microfactory, which received a very high numerical score, can be a valuable asset for entrepreneurs in this stage.

Based on the data generated in this study, time and cost in product development in particular can be saved with the use of specific Maker Movement elements. In addition, the quality of the final product can also be increased. In today's fast changing economy, it is vital to reduce costs and time to market for the development of new products and it is reasonable to assume that community-shared equipment, infrastructure, and mutual interests offer a breeding ground for upcoming ventures. Nevertheless, a sufficient offering of software programs, courses, and platforms to generate new skills, as well as experts willing to help, play an essential role for hardware start-ups' product development. Based on these premises, the subjects reviewed here provide insights into assessing the effects on cost, time and quality, and the influence these have on product development as a result of Maker Movement elements.

The chance to further promote the creation of hardware start-ups is given when the right set of elements is provided within the local ecosystem.

8.2 Implication: industry view and managerial suggestion

In recent years, the concept of the Makerspace has gained international renown and various new locations at universities, schools and established companies are currently in the planning, construction or launch phase. This study can have a high value in particular for the initiators of a Makerspace. Currently, initiators only have access to a limited number of publications, especially on setting up an appropriate operational model and basic infrastructure for a Makerspace. Therefore, only assumptions can be made on the use, appropriate selection of infrastructure and the operational services of a newly-opened Makerspace. Makerspace concepts in line with the support of hardware start-ups are covered in this dissertation. This research is also of high value for people who currently operate a Makerspace because the current services and offerings can be compared and checked for completeness.

Makerspace users, such as entrepreneurs and start-up teams, can profit from this research as well. These persons can study the themes and best practice examples mentioned in order to generate new skills and knowledge of supportive facets based on the Maker Movement for their product development projects.

The third group that may see high value in this research is policy decision-makers and university management. The dissertation and the Maker Movement Element framework in particular, as well as the conclusions drawn, provide a tool for well-grounded decision making. The scientifically evaluated results show the benefits and disadvantages of the increasingly popular Maker Movement. In general, Makerspaces are perceived as very positive by the hardware start-ups interviewed. Due to the selected locations for this study, Graz University of Technology, Technical University of Munich and the Swiss Federal Institute of Technology in Zurich, especially university management/ staff can may draw direct connections. Furthermore, the approach employed can be transferred to other locations to assess local environments and match them with the locations described in this dissertation. These assessments can further help to detect shortcomings and new infrastructural or operational facets can be applied with the help of this study.

8.3 Implication: theoretical and research perspective

From an academic research perspective, this research supports a common understanding of facets within the Maker Movement and their role in product development. Researchers have often studied organisations in a single location and either qualitative or quantitative research methods have been applied. In this study, Mixed Methods research is carried out to create a deeper understanding of the sample of hardware entrepreneurs in multiple locations currently working in a Makerspace. This design and structure have not yet been applied to the selected group and therefore new high relevance is created for the scientific community.

Various researchers are currently working on publications that deal with the Maker Movement and educational aspects, but as stated in the beginning, the field of entrepreneurship in the Maker Movement setting is particularly scarce. Very few studies have been published with such a focus. However, the power provided by the Maker Movement to gain support is substantial.

Another research stream covered in this dissertation is on the characteristics, types and challenges of hardware start-ups and gives a first insight into their special circumstances. Even though the group of hardware start-ups is growing, the scientific literature is also very limited. The assumption created can also lead to changes in curricula for the emerging group of hardware start-ups support programs such as accelerators.

8.4 Final discussion, limitations and validity

This dissertation, "The role of the Maker Movement in product development – Identification of Maker Movement elements and their effects on hardware start-up's product development projects", has the intent to accomplish three overall goals: first, to explicitly identify the ways in which Makerspaces are currently directly serving the needs of hardware start-ups; second, to explicitly identify areas in which the needs and requirements of various hardware start-up in product development are not being met today; and third, simply adding to a body of research that aims to raise awareness among start-up of the resources available to support their ventures in the Maker Movement. Based on these goals, three research questions were formulated and elaborated on in this research work: "What elements exist in the Maker Movement?", "What influences viewed by hardware start-ups exist on product development at Makerspaces?" and "How do the themes mentioned by hardware start-ups help to explain why the Maker Movement and product development matches?". The first research question was answered based on an empirical research study, which had a worldwide scope. The results are described in section 4. The seconded research question was discussed as part of a Mixed Methods research study and the findings are laid out in section 6.1. The in this dissertation carried out Mixed Methods research study had a focus on hardware start-ups situated in the European DACH region. Qualitative and quantitative data was gathered simultaneously, separately analysed and then mixed. The third research question, which was also the main research question for the Mixed Methods research study, is answered in section 6 and 7.

Due to the newness of the Maker Movement and unknown principles within the movement, a research design was chosen to encounter this. The Maker Movement Element framework was developed based on an empirical research study and gave the later carried out Mixed Methods research study a structure. A Mixed Methods approach was used because the described aspects can be better understood when strength of qualitative and quantitative research designs are combined. However, this approach limits the research in the amount of investigated locations and hardware start-ups. Validity and reliability threats are encountered with a variety of strategies in this dissertation, as shown in 3.5.6. Intermediate results of this dissertation were discussed with other researchers, presented to the scientific community at international conferences and publicised in articles. Furthermore, current knowledge in literature is detailly described which also enhances research reliability. Overall, it can be stated that the chosen design and approach was achievable, the mechanisms were compared to a different location as shown in section 6.3, as well as the goals of the research have been met and the research questions were able to be answered. The interpretation and discussion of the findings highlighted two applications important for hardware start-ups and Makerspace operators: first, operators learn which needs especially by hardware start-ups exist and how a Makerspace can serve these, see section 7.2; and second, hardware start-ups are promoted in their product development through the introduction of supportive factors based on the Maker Movement and a match of those elements to their challenges, see section 7.3.

8.5 Further research

Four continuing research directions appear to be most interesting based on the results and limitations derived from this research:

Firstly, a future project could compare a higher amount of and more diverse locations with each other. Locations, in which individuals do not have access to any Maker Movement infrastructure, should also be included. This cross-location synthesis can provide a more universal understanding of the effects on product development in a hardware start-up as a result of local Makerspaces and ecosystems.

Secondly, a larger quantitative survey with hardware start-ups from the whole of Europe can be conducted to generate more understanding on the needs of specific start-up architypes. When conducting this research, it may also be necessary to shorten the developed Maker Movement elements list to just the elements that are regularly used and already known by most entrepreneurs in order to obtain higher quality in regard to the answers given.

Thirdly, based on the gathered statements, challenges and needs of hardware start-ups a new study may link these results to curricula of higher education institutions. The likelihood is high that especially academic Makerspaces will have a profound impact on educational models. The developed Maker Movement Element framework and the given themes are a good starting point for this study.

Lastly, this research focuses on hardware start-ups' product development projects. Nevertheless, the present research approach can be transferred to other groups that deal with product development projects. One interesting group could include company representatives who may have different needs and demands on the Maker Movement ecosystem in general or on a Makerspace specifically.

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10 List of figures

11 List of tables

12 List of abbreviations

B2B Business-to-business

B2C Business-to-consumer

CAD Computer-aided design

CAM Computer-aided manufacturing

CAx Computer-aided technologies

CFD Computational fluid dynamics

CNC Computer numerical control

DACH Germany (D), Austria (A), Switzerland (CH)

DFM Design for manufacturing

ESM European start-up Monitor

ETH Swiss Federal Institute of Technology in Zurich

FDM Fused Deposition Modelling

FEA Finite element analysis

IDE Innovation driven enterprise

IPO Initial public offering

MIT Massachusetts Institute of Technology

MVP Minimum viable product

n Number of participants

PCB Printed circuit board

QUAL Qualitative

QUAN Quantitative

SD/ σ Standard deviation

SE/CE Simultaneous Engineering/ Concurrent engineering

SLA Stereolithography

SLS Selective laser sintering

SME Small and medium -sized enterprise

TUG Graz University of Technology

TUM Technical University of Munich

13 Appendix

A. Qualitative interview guideline (exemplary)

- In which country is your start-up located? In which city is your start-up located?
- When was your start-up founded?
- How was your start-up founded? How many people / who founded the start-up?
- Which role describes your position in the start-up?
- What is your gender?
- How old are you?
- How was the start-up founded?
- Which category best describes your start-up?
- What is the type of the to be developed product? Which function are included?
- What is your start-up's current stage of development?
- Which customers and/or users does your start-up address? Through which customers does your start-up generate revenue?
- With which type of organization have you already cooperated with and why?
- What are the three biggest challenges that your start-up is currently facing?
- What are top challenges do you may face during product development in your start-up?
- Expected number of products to be produced and sold?
- How often do you use a Makerspace?
- Could you briefly describe which experience you already have with Fab Labs/ Makerspaces/ Hackerspaces?
- Do you mainly experiment/ carry out feasibility analysis by using rapid prototyping or do you produce your final products in Fab Labs/ Makerspaces/ Hackerspaces?
- Which machines/ tools do you mainly use in your product development?
- Do the available 3D printers/ machines fulfil their requirements?
- Do you/ employees/ colleagues attended courses or workshops to learn about certain "new" topics?
- Do you think that the change of the settings/ working in a Makerspace changes the view on your project?
- What cloud be the main reason why you chose to realize your project in a Makerspace?
- What are the main restriction you face in a Makerspace? Do you face any restrictions when working on your product development projects / prototyping?
- What challenges of hardware start-ups can be solved through Maker Movement/ Makerspace offerings, which not?
- How should Makerspaces support in the product development?
- What is the ideal Makerspace for your product development project?

B. Quantitative survey

The survey was introduced to the participants by a clarification of important terms, like Maker Movement element, product development, cost, time and quality in product development and start-ups' network.

Which Maker Movement elements are unknown, known or already used in your start-up life? (please tick ✓)

KNOWN	USED	MAKER MOVEMENT ELEMENT	EXAMPLE
		Fair	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on …	Meetup, Hardware Pioneers
		Event	Hackathon, Hardware Club, Startup competition
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	Mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
		Webinar on … / Workshop on …	Formlabs Webinar, Workshops at Makerspaces/Fab Lab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander, … for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter, ... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment, …
		Access to craft machine	Sewing machine, …
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
		Free 2D design software	Inkscape, Sketch
		Free 3D design software	SketchUp, thinkerCAD, Makercase, Autodesk free edu
		Free simulation software	Simscale
		Developer tools for electronics (IoT toolkit, PCB testing, ...)	Upverter, DipTrace, KiCAD, Circuit Lab, resin.io, blynk.cc, circuito.io, TI Webench, LTspice, CircuitMaker
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (equity crowdfunding)	COMPANISTO, SOSV
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, 's Fachl

Which Maker Movement elements can be used to shorten product development time?

(please rate from **1… extremely likely, 2… likely, 3…neutral, 4… unlikely** to **5… extremely unlikely**)

	Connect with likeminded (physical/live)		
		Fairs	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on …	Meetup, Hardware Pioneers
		Events	Hackathon, Hardware Club, Startup competition
	Connect with likeminded (online/virtual)		
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
	Knowledge gathering & skills		
		Webinar on … / Workshop on …	Formlabs Webinar, Workshops at Makerspaces/FabLab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
	Use of open source		
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
	Accessible manufacturing hubs		
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander,... for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter,... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment,…
		Access to craft machine	Sewing machine,…
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
	Use of CAx software		
		Free 2D design software	Inkscape, Sketch, Qcad
		Free 3D design software	SketchUp, thinkerCAD, Makercase, Autodesk free edu
		Free simulation software	Simscale
		Developer tools for electronics (IoT toolkit, PCB testing, ...)	Upverter, DipTrace, KiCAD, Circuit Lab, resin.io, blynk.cc, circuito.io, TI Webench, LTspice, CircuitMaker
	Access to International shipping vendors		
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
	Funding for seed capital		
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (Equity crowdfunding)	COMPANISTO, SOSV
	Get immediate customers feedback		
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, 's Fachl

Which Maker Movement elements helps to save costs in product development?

(please rate from **1… extremely likely**, **2… likely**, **3…neutral**, **4… unlikely** to **5… extremely unlikely**)

	Connect with likeminded (physical/live)		
		Fairs	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on …	Meetup, Hardware Pioneers
		Events	Hackathon, Hardware Club, Startup competition
	Connect with likeminded (online/virtual)		
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
	Knowledge gathering & skills		
		Webinar on … / Workshop on …	Formlabs Webinar, Workshops at Makerspaces/FabLab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
	Use of open source		
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
	Accessible manufacturing hubs		
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander,... for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter,... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment,…
		Access to craft machine	Sewing machine,…
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
	Use of CAx software		
		Free 2D design software	Inkscape, Sketch, Qcad
		Free 3D design software	SketchUp, thinkerCAD, Makercase, Autodesk free edu
		Free simulation software	Simscale
		Developer tools for electronics (IoT toolkit, PCB testing, ...)	Upverter, DipTrace, KiCAD, Circuit Lab, resin.io, blynk.cc, circuito.io, TI Webench, LTspice, CircuitMaker
	Access to International shipping vendors		
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
	Funding for seed capital		
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (Equity crowdfunding)	COMPANISTO, SOSV
	Get immediate customers feedback		
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, ‘s Fachl

Which Maker Movement elements helps to reduce product costs (complexity, material, design, ...) ?

(please rate from **1... extremely likely, 2... likely, 3...neutral, 4... unlikely** to **5... extremely unlikely**)

	Connect with likeminded (physical/live)		
		Fairs	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on ...	Meetup, Hardware Pioneers
		Events	Hackathon, Hardware Club, Startup competition
	Connect with likeminded (online/virtual)		
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
	Knowledge gathering & skills		
		Webinar on ... / Workshop on ...	Formlabs Webinar, Workshops at Makerspaces/FabLab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
	Use of open source		
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
	Accessible manufacturing hubs		
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander,... for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter,... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment,...
		Access to craft machine	Sewing machine,...
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
	Use of CAx software		
		Free 2D design software	Inkscape, Sketch, Qcad
		Free 3D design software	SketchUp, thinkerCAD, Makercase, Autodesk free edu
		Free simulation software	Simscale
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	Access to International shipping vendors		
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
	Funding for seed capital		
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (Equity crowdfunding)	COMPANISTO, SOSV
	Get immediate customers feedback		
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, ‘s Fachl

Which Maker Movement elements increases product quality?

(please rate from **1… extremely likely, 2… likely, 3…neutral, 4… unlikely** to **5… extremely unlikely**)

	Connect with likeminded (physical/live)		
		Fairs	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on …	Meetup, Hardware Pioneers
		Events	Hackathon, Hardware Club, Startup competition
	Connect with likeminded (online/virtual)		
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
	Knowledge gathering & skills		
		Webinar on … / Workshop on …	Formlabs Webinar, Workshops at Makerspaces/FabLab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
	Use of open source		
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
	Accessible manufacturing hubs		
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander,... for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter,... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment,…
		Access to craft machine	Sewing machine,…
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
	Use of CAx software		
		Free 2D design software	Inkscape, Sketch, Qcad
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	Access to International shipping vendors		
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
	Funding for seed capital		
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (Equity crowdfunding)	COMPANISTO, SOSV
	Get immediate customers feedback		
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, ‘s Fachl

Which Maker Movement elements supports to enlarge your network?
(please rate from **1... extremely likely, 2... likely, 3...neutral, 4... unlikely** to **5... extremely unlikely**)

	Connect with likeminded (physical/live)		
		Fairs	MakerFair, CES, IMTS
		Database of Maker facilities (Makerspace)	Maker's Row, The Maker Map, fablabs.io/labs
		Experts' table on ...	Meetup, Hardware Pioneers
		Events	Hackathon, Hardware Club, Startup competition
	Connect with likeminded (online/virtual)		
		Community order platform	OSH Park
		Open files repository (CAD, norm parts, code)	GrabCAD, Thingiverse, github, traceparts
		Forum	mikrocontroller.net
		Crowd based building instructions	Hackster.io, instructables, Ravelry, Craftster, MakerShare
	Knowledge gathering & skills		
		Webinar on ... / Workshop on ...	Formlabs Webinar, Workshops at Makerspaces/FabLab, University courses
		Online collection of resources	Fictiv Hardware Guide, Fictive Hardware Blog, Predictable Desgin, Open IDEO, Bolt Blog, Stack Overflow, Quora, Baldengineering, EEVBlog
		Online blogs that inspire, teach skills, help to solve a problem	Core77, Hackaday, Youtube, maker.blog
		Books or printed magazine	Machinery's Handbook, MAKE magazine
	Use of open source		
		Open-source software framework	Bootstrap, AngularJS, Spring Boot, Apache Spark, Docker
		Open-source (electronic) hardware	Arduino, RaspberryPi
	Accessible manufacturing hubs		
		Access to digital prototyping machine	3D printer, laser cutter, 3D scanners little bits, Makerblock
		Access to wood shop	CNC router, saw, sander,... for wood
		Access to metal shop	CNC router, welding, lathe, jet water cutter,... for metal
		Access to electronics workshop	Circuit board production tools, Little Bits, Makerblocks, soldering iron, testing equipment,...
		Access to craft machine	Sewing machine,...
		Access to testing equipment (especially for electronics)	Lynx 3D Microscope, Spectrum Analyzer, Network Analyzer VNA
		Rent a micro factory	FirstBuild
		Access to cloud computing platform	IBM Bluemix, Amazon AWS, Google Cloud developer, Microsoft Azure
	Use of CAx software		
		Free 2D design software	Inkscape, Sketch, Qcad
		Free 3D design software	SketchUp, thinkerCAD, Makercase, Autodesk free edu
		Free simulation software	Simscale
		Developer tools for electronics (IoT toolkit, PCB testing, ...)	Upverter, DipTrace, KiCAD, Circuit Lab, resin.io, blynk.cc, circuito.io, TI Webench, LTspice, CircuitMaker
	Access to International shipping vendors		
		Platform for distributed manufacturing	Fictiv, 3D Hubs, Ponoko, Maketime, Protolabs, additively
		Contract manufacturer for low volume	Seed Studio Fusion, Circuithub, Sunstone, Screaming Circuits, aisler.net
		Electronic parts supplier	Sparkfun, Adafruit, Aliexpress, Digi-Key, itead.cc
		Raw material in lowest volume (Material library)	Modulor
	Funding for seed capital		
		Crowd funding website	Kickstarter, Indigogo
		Crowd investment (Equity crowdfunding)	COMPANISTO, SOSV
	Get immediate customers feedback		
		Peer-to-peer (P2P) e-commerce	Etsy, Quirky, Shapeway, ebay, Amazon Launchpad, Maker.me
		Rent a physical space	Kaufhaus Kollektiv, 's Fachl

C. Results for Maker Movement element assessment based on hardware start-up characteristic

a. Highest and lowest ranked elements per characteristic market, stage and product type

Market
B2B n=18

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Testing equipment (for electronics)	4,7	+/-0,6	4,5	+/-0,9	3,7	+/-1,0	3,9	+/-1,1	2,8	+/-1,5	19,6
2	Digital prototyping machine	4,7	+/-0,5	4,7	+/-0,6	3,7	+/-1,1	3,7	+/-1,3	2,9	+/-1,6	19,3
3	Electronics lab	4,7	+/-0,6	4,6	+/-0,7	3,4	+/-1,0	3,8	+/-1,3	2,9	+/-1,5	19,3
4	Online distributor of electronic components	4,4	+/-0,7	4,3	+/-0,7	3,7	+/-1,4	3,8	+/-1,2	2,4	+/-1,5	18,8
5	Expert's roundtable	3,5	+/-1,2	3,5	+/-1,4	3,0	+/-1,5	3,7	+/-1,0	4,4	+/-0,6	18,1
29	Book/ printed magazine	3,0	+/-1,3	2,9	+/-1,3	2,4	+/-1,6	3,6	+/-1,4	1,9	+/-1,0	13,8
30	Rent a physical retail space	2,1	+/-1,2	2,3	+/-1,2	2,0	+/-1,3	2,5	+/-1,5	3,4	+/-1,4	12,3
31	Peer-to-peer e-commerce	2,3	+/-1,2	1,9	+/-1,0	2,1	+/-1,3	2,2	+/-1,3	2,9	+/-1,5	11,5
32	Crowd investment/ equity crowdfunding	2,3	+/-1,0	1,9	+/-0,8	1,9	+/-1,4	1,7	+/-0,8	3,6	+/-1,4	11,3
33	Crowd funding	2,4	+/-1,2	1,5	+/-0,7	1,8	+/-1,2	1,7	+/-0,8	3,6	+/-1,5	10,8

Market
B2C n=8

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Testing equipment (for electronics)	4,6	+/-0,5	4,9	+/-0,7	3,8	+/-1,0	4,4	+/-1,0	2,0	+/-1,2	19,6
2	Expert's roundtable	3,9	+/-0,7	3,7	+/-0,9	3,4	+/-1,3	3,9	+/-0,9	4,6	+/-0,5	19,5
3	Simulation software (CAE, CFD, FEA)	4,8	+/-0,4	4,8	+/-0,4	4,4	+/-1,2	3,6	+/-1,5	1,6	+/-0,8	19,2
4	Electronics lab	4,8	+/-0,4	4,6	+/-0,7	3,0	+/-0,7	3,8	+/-1,5	2,1	+/-1,3	18,3
5	Digital prototyping machine	4,8	+/-0,4	4,8	+/-0,4	2,9	+/-1,4	3,7	+/-1,2	2,1	+/-1,1	18,2
29	Textiles area	3,1	+/-1,6	4,0	+/-1,4	2,3	+/-1,1	3,2	+/-1,2	2,0	+/-1,3	14,6
30	Peer-to-peer e-commerce	3,4	+/-0,9	2,6	+/-1,2	2,1	+/-1,3	2,4	+/-1,4	3,1	+/-1,3	13,6
31	Crowd based instruction	2,8	+/-1,0	2,8	+/-0,7	2,2	+/-0,7	2,6	+/-0,8	2,5	+/-1,1	12,9
32	Rent a physical retail space	2,6	+/-1,2	2,2	+/-0,7	2,0	+/-1,2	2,7	+/-1,7	3,3	+/-1,4	12,8
33	Crowd investment/ equity crowdfunding	3,1	+/-1,1	1,8	+/-0,9	2,1	+/-1,1	2,1	+/-1,2	3,6	+/-1,0	12,8

Stage
Seed n=18

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Testing equipment (for electronics)	4,7	+/-0,6	4,7	+/-0,8	3,6	+/-0,9	4,1	+/-0,7	2,5	+/-1,5	19,7
2	Expert's roundtable	3,9	+/-1,1	3,7	+/-1,2	3,6	+/-1,5	3,9	+/-0,9	4,6	+/-0,5	19,8
3	Electronics lab	4,9	+/-0,3	4,7	+/-0,6	3,1	+/-1,0	3,9	+/-1,4	2,7	+/-1,5	19,2
4	Digital prototyping machine	4,8	+/-0,5	4,8	+/-0,6	2,9	+/-1,0	3,5	+/-1,1	2,6	+/-1,6	18,6
5	Open-source software framework	4,5	+/-0,6	4,6	+/-0,5	3,8	+/-0,9	3,1	+/-1,2	2,0	+/-1,3	18,0
29	Rent a physical retail space	2,6	+/-1,1	2,4	+/-1,0	2,1	+/-1,1	2,9	+/-1,6	3,6	+/-1,4	13,7
30	Book/ printed magazine	2,8	+/-0,9	2,9	+/-1,0	2,5	+/-1,5	3,4	+/-1,3	1,8	+/-0,9	13,5
31	Peer-to-peer e-commerce	2,7	+/-1,3	2,4	+/-1,2	2,1	+/-1,2	2,4	+/-1,3	2,9	+/-1,4	12,5
32	Crowd funding	2,6	+/-1,3	1,8	+/-1,2	1,8	+/-0,9	2,1	+/-1,3	3,5	+/-1,4	11,8
33	Crowd investment/ equity crowdfunding	2,8	+/-1,3	2,0	+/-0,9	1,9	+/-1,2	2,1	+/-1,1	3,4	+/-1,2	12,2

Stage
Startup n=4

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Simulation software (CAE, CFD, FEA)	5,0	+/-0,0	4,5	+/-0,5	5,0	+/-0,0	5,0	+/-0,0	3,0	+/-0,0	22,5
2	Free 3D design software	5,0	+/-0,0	4,8	+/-0,4	4,5	+/-0,9	4,5	+/-0,9	2,3	+/-0,5	21,1
3	Online distributor of electronic components	4,8	+/-0,4	4,0	+/-0,7	4,5	+/-0,5	4,0	+/-0,7	3,7	+/-0,9	20,9
4	Testing equipment (for electronics)	4,8	+/-0,4	4,5	+/-0,9	4,5	+/-0,9	4,8	+/-0,4	2,0	+/-0,8	20,5
5	Digital prototyping machine	4,5	+/-0,5	5,0	+/-0,0	3,8	+/-1,6	4,8	+/-0,4	2,3	+/-0,5	20,3
29	Textiles area	2,7	+/-1,2	3,5	+/-1,5	3,0	+/-2,0	2,7	+/-0,9	2,0	+/-0,0	13,8
30	Crowd funding	3,7	+/-0,9	1,3	+/-0,5	2,8	+/-1,5	2,3	+/-1,3	3,7	+/-1,2	13,7
31	Peer-to-peer e-commerce	3,0	+/-0,0	1,7	+/-0,5	2,3	+/-1,2	2,0	+/-0,8	3,3	+/-0,9	12,3
32	Crowd investment/ equity crowdfunding	2,5	+/-0,5	1,5	+/-0,5	2,0	+/-1,0	1,0	+/-0,0	4,5	+/-0,5	11,5
33	Rent a physical retail space	1,0	+/-0,0	2,0	+/-1,0	1,0	+/-0,0	1,5	+/-0,5	2,0	+/-0,0	7,5

Product
Hardware n=5

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Testing equipment (for electronics)	4,7	+/-0,5	4,8	+/-1,1	3,3	+/-1,2	4,7	+/-0,5	2,3	+/-1,9	19,9
2	Electronics lab	5,0	+/-0,0	4,3	+/-0,9	3,3	+/-1,2	4,8	+/-0,8	2,3	+/-1,6	19,6
3	Metal shop	4,4	+/-0,8	4,8	+/-0,4	3,4	+/-1,0	4,0	+/-0,6	3,0	+/-1,8	19,5
4	Expert's roundtable	4,0	+/-1,2	4,0	+/-1,2	3,8	+/-1,6	4,0	+/-1,2	4,8	+/-0,4	19,8
5	Textiles area	4,3	+/-0,8	4,5	+/-0,9	3,3	+/-1,5	4,0	+/-0,7	2,5	+/-1,7	18,6
29	Crowd funding	2,4	+/-1,0	2,3	+/-1,6	2,2	+/-1,5	2,2	+/-0,7	4,2	+/-1,0	13,5
30	Open files repository (CAD files, norm parts, co	3,2	+/-1,3	3,4	+/-1,4	2,4	+/-1,5	2,6	+/-1,4	1,6	+/-0,8	13,3
31	Crowd investment/ equity crowdfunding	2,4	+/-1,0	2,3	+/-0,8	2,4	+/-1,7	2,4	+/-1,2	4,4	+/-0,8	14,1
32	Peer-to-peer e-commerce	2,2	+/-1,2	2,0	+/-0,7	2,6	+/-1,6	2,4	+/-1,5	3,6	+/-1,7	12,8
33	Rent a physical retail space	1,6	+/-0,5	1,5	+/-0,5	2,6	+/-1,6	2,2	+/-1,5	3,8	+/-1,5	9,1

Stage
Growth n=4

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Contract manufacturer for low volume	4,6	+/-0,5	4,2	+/-0,4	4,2	+/-1,2	3,5	+/-1,5	1,8	+/-0,7	17,8
2	Expert's roundtable	3,0	+/-1,3	3,6	+/-1,2	2,8	+/-1,2	3,7	+/-1,2	4,4	+/-0,8	18,2
3	Digital prototyping machine	4,8	+/-0,4	4,6	+/-0,5	3,3	+/-1,1	3,5	+/-1,5	2,6	+/-1,6	18,5
4	Testing equipment (for electronics)	4,4	+/-0,5	4,4	+/-1,2	3,7	+/-0,9	3,7	+/-1,6	2,6	+/-1,6	18,1
5	Online distributor of electronic components	4,6	+/-0,5	4,2	+/-0,7	3,7	+/-1,6	3,2	+/-1,3	1,6	+/-0,8	17,6
29	Crowd based instruction	3,2	+/-1,6	2,6	+/-1,4	2,3	+/-1,4	3,0	+/-1,5	2,6	+/-1,4	13,7
30	Crowd funding	2,4	+/-1,5	1,0	+/-0,0	2,0	+/-1,5	1,6	+/-0,8	4,0	+/-1,3	11,3
31	Peer-to-peer e-commerce	2,0	+/-1,3	1,0	+/-0,0	2,4	+/-1,5	2,0	+/-1,5	3,0	+/-1,7	10,3
32	Crowd investment/ equity crowdfunding	1,8	+/-0,8	1,0	+/-0,0	2,3	+/-1,6	1,8	+/-0,8	3,8	+/-1,3	10,7
33	Rent a physical retail space	1,5	+/-0,9	1,0	+/-0,0	2,3	+/-1,6	2,3	+/-1,6	4,0	+/-1,2	8,8

Product
Hardware + Firmware n=8

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Digital prototyping machine	4,9	+/-0,3	4,9	+/-0,3	3,1	+/-1,1	3,6	+/-1,2	2,9	+/-1,4	19,1
2	Testing equipment (for electronics)	4,4	+/-0,7	4,3	+/-1,2	3,4	+/-0,9	3,4	+/-1,2	2,7	+/-1,5	18,9
3	Metal shop	4,6	+/-0,5	4,3	+/-1,0	3,4	+/-0,7	3,6	+/-1,4	2,7	+/-1,5	18,7
4	Wood shop	4,6	+/-0,5	4,3	+/-1,0	3,0	+/-0,8	3,4	+/-1,3	2,7	+/-1,5	18,4
5	Online distributor of electronic components	4,0	+/-0,8	4,0	+/-0,8	3,6	+/-1,2	3,4	+/-0,7	2,1	+/-1,4	18,1
29	Simulation software (CAE, CFD, FEA)	3,5	+/-1,1	3,0	+/-1,6	2,8	+/-0,8	2,3	+/-0,5	1,0	+/-0,0	12,7
30	Crowd based instruction	3,3	+/-0,9	2,7	+/-1,0	2,1	+/-0,8	2,4	+/-1,0	1,7	+/-0,9	12,7
31	Peer-to-peer e-commerce	2,2	+/-1,2	1,5	+/-0,9	1,8	+/-0,8	1,3	+/-0,4	3,4	+/-1,0	10,6
32	Crowd investment/ equity crowdfunding	2,2	+/-1,1	2,2	+/-1,2	2,2	+/-1,0	2,4	+/-1,0	3,3	+/-1,1	12,4
33	Crowd funding	2,2	+/-1,1	1,5	+/-0,9	1,8	+/-0,8	1,3	+/-0,4	3,4	+/-1,2	10,1

Product
Hardware + Firmware + App n=13

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact factor 0..25
1	Testing equipment (for electronics)	4,8	+/-0,4	4,8	+/-0,6	4,0	+/-0,8	4,4	+/-0,9	2,3	+/-1,4	19,8
2	Expert's roundtable	3,6	+/-1,0	3,6	+/-1,2	3,1	+/-1,4	4,1	+/-0,6	4,6	+/-0,5	18,9
3	Open-source software framework	4,8	+/-0,4	4,6	+/-0,6	4,2	+/-0,7	3,5	+/-1,1	2,1	+/-1,2	18,7
4	Digital prototyping machine	4,9	+/-0,3	4,8	+/-0,4	3,0	+/-1,3	3,8	+/-1,3	2,3	+/-1,4	18,2
5	Contract manufacturer for low volume	4,0	+/-0,8	3,7	+/-0,6	3,9	+/-1,2	3,8	+/-1,3	2,3	+/-1,3	17,6
29	Community order platform	3,4	+/-1,0	3,7	+/-1,0	3,0	+/-1,2	1,9	+/-1,1	2,4	+/-1,0	14,5
30	Crowd funding	3,1	+/-1,4	1,4	+/-0,7	2,0	+/-1,3	2,2	+/-1,4	3,5	+/-1,5	12,1
31	Crowd investment/ equity crowdfunding	2,9	+/-1,3	1,8	+/-0,7	1,9	+/-1,1	1,9	+/-1,0	3,1	+/-1,4	11,8
32	Peer-to-peer e-commerce	2,9	+/-1,3	2,2	+/-1,2	2,1	+/-1,2	2,2	+/-1,4	2,5	+/-1,3	11,3
33	Rent a physical retail space	2,3	+/-1,3	2,3	+/-0,7	1,5	+/-0,7	2,6	+/-1,7	2,8	+/-1,2	10,0

b. Highest and lowest ranked elements per characteristic currently biggest challenges in once start-up

Biggest challenegs

Product development n=18

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact faktor * 0..25
1	Expert's roundtable	3,6	+/-1,3	3,8	+/-1,1	4,0	+/-0,8	3,9	+/-1,0	4,7	+/-0,4	20,0
2	Testing equipment (for electronics)	3,9	+/-0,9	4,5	+/-1,0	4,6	+/-0,6	4,1	+/-1,1	2,2	+/-1,3	19,2
3	Digital prototyping machine	3,3	+/-1,2	4,8	+/-0,4	4,8	+/-0,5	3,5	+/-1,3	2,4	+/-1,4	18,8
4	Electronics lab	3,2	+/-0,9	4,7	+/-0,7	4,6	+/-0,6	3,5	+/-1,5	2,4	+/-1,3	18,4
5	Online distributor of electronic components	3,9	+/-1,2	4,0	+/-0,6	4,3	+/-0,8	3,9	+/-0,9	2,3	+/-1,6	18,4
29	Book/ printed magazine	2,8	+/-1,4	2,8	+/-1,2	2,7	+/-1,0	3,6	+/-1,3	1,8	+/-1,1	13,6
30	Rent a physical retail space	1,6	+/-1,0	2,3	+/-1,2	2,8	+/-1,2	2,5	+/-1,7	3,5	+/-1,4	12,6
31	Crowd funding	1,7	+/-1,1	1,7	+/-1,2	2,9	+/-1,4	2,0	+/-1,4	3,3	+/-1,4	11,7
32	Peer-to-peer e-commerce	1,8	+/-1,1	2,2	+/-1,3	2,6	+/-1,3	2,0	+/-1,3	2,6	+/-1,3	11,3
33	Crowd investment/ equity crowdfunding	1,3	+/-0,7	2,0	+/-0,9	2,6	+/-1,3	1,6	+/-1,0	3,1	+/-1,1	10,6

Product industrialisation n=8

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact faktor * 0..25
1	Electronics lab	3,3	+/-0,8	4,3	+/-0,9	5,0	+/-0,0	4,3	+/-0,4	1,7	+/-0,9	18,5
2	Expert's roundtable	2,8	+/-1,8	3,7	+/-1,2	3,0	+/-1,6	3,5	+/-0,9	4,7	+/-0,5	17,6
3	Testing equipment (for electronics)	3,5	+/-1,1	4,3	+/-0,9	4,8	+/-0,4	4,5	+/-0,5	1,0	+/-0,0	18,1
4	Online distributor of electronic components	3,0	+/-1,4	3,7	+/-0,5	4,8	+/-0,4	2,5	+/-1,1	1,7	+/-0,9	15,6
5	Digital prototyping machine	2,8	+/-0,4	4,3	+/-0,9	4,8	+/-0,4	4,3	+/-0,4	1,0	+/-0,0	17,1
29	Book/ printed magazine	2,8	+/-1,8	3,0	+/-0,8	3,8	+/-1,1	4,3	+/-0,8	2,0	+/-0,8	15,8
30	Microfactory (for assembly)	1,5	+/-0,5	3,0	+/-0,0	2,0	+/-0,0	2,5	+/-0,5	2,0	+/-1,0	11,0
31	Crowd funding	1,3	+/-0,5	1,5	+/-0,5	1,8	+/-0,4	2,0	+/-0,8	3,7	+/-0,9	10,3
32	Rent a physical retail space	2,3	+/-1,2	2,0	+/-0,0	1,7	+/-0,5	1,7	+/-0,5	3,3	+/-1,2	11,0
33	Community order platform	2,5	+/-1,5	3,0	+/-0,0	3,5	+/-0,5	1,0	+/-0,0	1,0	+/-0,0	11,0

Cash Flow n=18

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact faktor * 0..25
1	Electronics lab	3,4	+/-0,7	4,5	+/-0,9	4,9	+/-0,3	3,8	+/-1,1	2,2	+/-1,4	18,7
2	Metal shop	3,3	+/-0,7	4,6	+/-1,0	4,6	+/-0,5	3,9	+/-1,1	2,1	+/-1,4	18,5
3	Digital prototyping machine	3,3	+/-0,7	4,6	+/-0,7	4,9	+/-0,3	3,7	+/-1,2	2,0	+/-1,4	18,4
4	Testing equipment (for electronics)	3,4	+/-0,9	4,4	+/-1,1	4,7	+/-0,5	3,8	+/-1,2	2,0	+/-1,5	18,2
5	Expert's roundtable	3,3	+/-1,4	3,3	+/-1,3	3,6	+/-1,4	3,3	+/-1,2	4,5	+/-0,7	18,1
29	Rent a physical retail space	2,2	+/-1,1	2,0	+/-1,0	2,8	+/-0,9	2,3	+/-1,4	3,9	+/-1,3	13,2
30	Book/ printed magazine	2,4	+/-1,7	2,9	+/-1,1	2,8	+/-1,2	3,9	+/-0,8	1,8	+/-0,8	13,7
31	Cloud computing platform	2,2	+/-1,1	2,5	+/-1,0	3,0	+/-1,2	2,2	+/-1,1	3,1	+/-1,4	13,0
32	Crowd based instruction	2,3	+/-1,1	3,0	+/-1,3	3,6	+/-1,0	2,3	+/-1,1	1,3	+/-0,7	12,6
33	Crowd investment/ equity crowdfunding	2,0	+/-1,2	2,2	+/-0,9	2,9	+/-1,4	2,5	+/-1,3	3,6	+/-0,9	13,1

Growth/ sells n=4

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact faktor * 0..25
1	Simulation software (CAE, CFD, FEA)	3,8	+/-1,1	4,8	+/-0,6	4,6	+/-0,5	4,4	+/-0,9	2,5	+/-1,4	20,1
2	Free 3D design software	3,4	+/-1,3	4,8	+/-0,4	4,7	+/-0,5	3,8	+/-1,1	2,5	+/-1,2	19,3
3	Online distributor of electronic components	3,5	+/-1,2	3,5	+/-1,3	3,9	+/-0,8	4,1	+/-0,9	4,5	+/-0,7	19,4
4	Testing equipment (for electronics)	3,4	+/-0,9	4,6	+/-0,6	4,6	+/-0,7	3,8	+/-0,8	2,5	+/-1,3	18,9
5	Digital prototyping machine	3,9	+/-1,1	4,3	+/-0,6	4,5	+/-0,7	3,5	+/-1,1	2,5	+/-1,2	18,7
29	Textiles area	2,7	+/-1,2	3,1	+/-1,0	3,1	+/-1,2	2,7	+/-1,2	2,7	+/-1,1	14,2
30	Crowd funding	2,5	+/-1,4	1,8	+/-1,3	3,3	+/-1,1	2,0	+/-1,0	4,0	+/-1,2	13,6
31	Peer-to-peer e-commerce	2,4	+/-1,4	1,8	+/-0,7	2,7	+/-0,8	2,5	+/-1,4	3,3	+/-1,4	12,6
32	Crowd investment/ equity crowdfunding	2,6	+/-1,5	1,7	+/-0,7	2,8	+/-0,8	1,9	+/-1,1	4,0	+/-1,2	12,9
33	Rent a physical retail space	2,3	+/-1,5	1,8	+/-0,7	1,7	+/-0,7	2,4	+/-1,4	3,3	+/-1,4	11,4

Process/ internal organisation n=4

#	Element	Time in product development 1..5	σ	Product development costs 1..5	σ	Product costs 1..5	σ	Product quality 1..5	σ	Network 1..5	σ	Impact faktor * 0..25
1	Expert's roundtable	3,0	+/-1,5	4,0	+/-1,1	4,0	+/-1,4	3,7	+/-0,9	4,4	+/-0,5	19,1
2	Testing equipment (for electronics)	3,7	+/-0,9	4,8	+/-0,4	4,8	+/-0,4	4,2	+/-0,9	1,8	+/-1,2	19,3
3	Electronics lab	3,5	+/-0,8	4,8	+/-0,4	5,0	+/-0,0	4,0	+/-0,8	1,8	+/-1,2	19,1
4	Metal shop	3,1	+/-0,8	4,7	+/-0,5	4,6	+/-0,7	3,7	+/-1,0	2,3	+/-1,6	18,4
5	Digital prototyping machine	2,6	+/-1,0	4,8	+/-0,4	4,6	+/-0,7	3,9	+/-0,8	2,5	+/-1,5	18,3
29	Platform for distributed manufacturing	3,0	+/-0,8	3,5	+/-0,5	4,0	+/-0,8	1,7	+/-0,9	2,0	+/-1,0	14,2
30	Crowd based instruction	2,2	+/-1,0	3,0	+/-0,7	4,0	+/-0,6	2,6	+/-1,6	2,4	+/-1,2	14,2
31	Peer-to-peer e-commerce	2,3	+/-1,0	2,3	+/-1,1	2,6	+/-1,2	2,3	+/-1,3	3,2	+/-1,3	12,6
32	Crowd investment/ equity crowdfunding	1,7	+/-0,9	2,0	+/-1,0	2,7	+/-1,4	1,6	+/-1,0	3,0	+/-1,3	11,0
33	Crowd funding	1,7	+/-0,9	1,7	+/-0,9	2,7	+/-1,4	1,6	+/-1,0	3,2	+/-1,3	10,8