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The Role of Makerspaces in Product Development of Hardware Start-Ups

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A case study in Europe's largest academic makerspace

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Abstract

Open access to design, prototype, manufacture and the opportunity to exchange knowledge enables individuals to invent and build hardware products themselves. This represents the core elements of the so-called Maker Movement and supports the creation of start-ups. Although the connection between makerspaces and start-ups already exists, the influence of the movement on product development and start-ups has not yet been scientifically investigated. This paper describes in detail a single makerspace. The outcomes may raise general awareness about supportive resources available at makerspaces and therefore may be fruitful for makerspace operators and hardware start-ups. Furthermore, best practice examples are examined in this paper.

Introduction & problem statement

The past decade has seen an immense increase in the number of makerspaces established either publicly in joint efforts by a group of individuals or for academic purposes that are hosted by schools or universities. In 2017, over 1,400 makerspaces were in existence worldwide. [1] The widespread access to capabilities for designing, manufacturing, and distributing in these locations enables individuals (so-called Makers) to easily invent and build hardware products themselves. As a result, it enables Makers to bring their ideas from zero to market maturity. [2]

Previous research by the authors has focused on analyzing and clarifying available players and functions in the Maker Movement ecosystem and introduced the term Maker Movement Element. A Maker Movement Element is a collective term for players that hold a supportive role within the Maker Movement ecosystem. In total 33 Maker Movement Elements and nine subsystems, such as access to prototyping/ fabrication/ manufacturing facilities, are described. [3] Based on this framework, a makerspace represents a physical location that offers a range and quantity of Maker Movement Elements to individuals.

Despite literature on supporting the enabling function of makerspaces in the development of start-ups [4], little knowledge is currently available about the demands of hardware start-ups in the Maker Movement ecosystem. [5] A hardware start-up is an individual or a group of individuals who recently started a business based on a physical product and aim to scale rapidly. This physical product may also

be combined with a software framework. For example, [Pebble smartwatch](#) combines both: an Internet of Things (IoT) based device with a smartphone application for setup and control. In general, a start-up is defined as a temporary organization searching for a repeatable and scalable business model.^[6] Start-ups are characterized by three elements: they are younger than 10 years; they feature innovative technologies and/ or business models; they have/ strive for significant employee and/or sales growth.^[7]

The term product development includes product concepts, technical designs, and necessary preparations, as well as the integration of the outcomes of those individual disciplines into a holistic solution. The result of product development is the description and documentation of the product itself, which includes detailed and obligatory designs of the product regarding technical functions, costs, quality, and time. It also represents the basis for evaluating the feasibility of the product in line with an economic and technological perspective.^[8]

This paper aims to clarify the connection and correlation between described Maker Movement Elements and their usage by hardware start-ups in product development based on a case study conducted at Europe's largest academic makerspace, the [UnternehmerTUM MakerSpace](#).

Methodology

The identification and classification of Maker Movement Elements is based on research previously carried out by the authors.^[3] Data was retrieved from various sources, including literature, Internet, and field observations, and was reviewed by makers. This paper is based on a single exploratory case study^[9] to illustrate connections and correlations between Maker Movement Elements and hardware start-up needs. The case focused on hardware start-ups connected with the UnternehmerTUM MakerSpace, which were studied to gather knowledge of their needs and usage of Maker Movement Elements. First, the start-ups are asked about current challenges and needs they face in product development and their experiences with makerspaces in general. In the second step, the Maker Movement Elements are narrowed down to those that are either known or have already been used by the hardware start-ups. Thirdly, they are asked to rank those elements based on their assumptions of how it will expedite product development, increase the quality of the product, and reduce its costs, as well as have outcomes for the hardware start-up's network/ community. An additional step analyzes what Maker Movement Elements are offered and how they are realized at the UnternehmerTUM MakerSpace location.

Scope

The scope of the case is specifically the UnternehmerTUM MakerSpace. UnternehmerTUM MakerSpace is a 1,500 square meter facility on the campus of the Technical University of Munich

(TUM). It is open to the public, provides members with access to machines, tools, and software, and also supports community-building activities. It offers a place to realize ideas and innovative products in the form of prototypes and small- batch production volumes. The high-tech workshop provides various work areas such as metal and wood workshops together with textile and electronics facilities. In addition, 3D printers, laser cutters, and a water jet cutter make it possible to fabricate virtually any conceivable shape, even with industrial-grade machines. UnternehmerTUM MakerSpace is Europe's biggest academic makerspace and was opened in 2015 as part of UnternehmerTUM, the entrepreneurship center of TUM. UnternehmerTUM offers students, scientists, founders, and start-ups premium possibilities to develop ideas, fund prototypes, and start businesses.

On the other hand, the scope of the research is limited to hardware start-ups, which are already established and work at UnternehmerTUM MakerSpace, such as the start-up [Kewazo](#), which has already used various offerings and services of the makerspace and built a number of prototypes. Kewazo is creating a robotic system for autonomous scaffolding transportation and installation. All hardware start-ups interviewed for this paper are currently working on physical products and tend to be in the seed start-up phase. This indicates that a product concept exists, but no revenues have yet been created. In line with the research design, 13 hardware start-ups have been observed and interviewed in total.

Data gathering and structure

Each interview was separated into four sections: general questions on the start-up and on the entrepreneur concerned; detailed questions on his/ her current experiences with makerspace usage; knowledge and usage of Maker Movement Elements; and assessment of Maker Movement Elements based on costs, quality, time, and network/ community.

For the first section of the questionnaire, aspects were drawn from the European Startup Monitor survey. The European Startup Monitor is an annual study to promote transparency for the start-up environment in Europe and identify country-specific and common challenges of start-ups.[7] In line with personal-related queries like age, gender, and location of the hardware entrepreneur/ start-up, the following questions are used to describe the hardware start-up in detail:

- What is the current development stage of your start-up?
- How can your start-up product be categorized and best described?
- What customer and/or user does your start-up address?
- Through which customer does your start-up generate revenue?

- What types of organizations have you already cooperated with and why? What are the supporting factors of those organizations?
- What are the three biggest challenges your start-up is currently facing?
- What challenges do you face/did you face during product development in your start-up?

The second part of the interview asked about the entrepreneur's current experiences in a makerspace. The interviewees were specifically encouraged in this to think broadly and not only about UnternehmerTUM MakerSpace offerings or services. The following set of open questions was used to start a 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 realize your project in a makerspace?

The framework for the third section of the interview is grounded in the earlier introduced Maker Movement Element framework.^[3] In this section of the interview, each Maker Movement Element is introduced, discussed, and checked by the interviewed hardware start-up based on the criteria of knowledge, usage, and inclusiveness.

After clarifying the correct understanding of each element, the fourth part of the interview focuses on an assessment of the Maker Movement Element framework. The assessment for each element is

carried out in terms of cost and time reduction in product development, quality increase, and cost reduction of the product itself, as well as effects on the hardware start-up's network community. Each element is evaluated for each criterion based on a Likert scale (5... extremely likely, 4... likely, 3... neutral, 2... unlikely, to 1... extremely unlikely).[\[10\]](#)

Finally, the interviewed start-ups are observed during their work at the makerspace, and the location, UnternehmerTUM MakerSpace, itself is assessed on each Maker Movement Element. This location assessment checks if a Maker Movement Element is currently offered/ isn't currently offered. It is based mainly on a field study and interviews with the makerspace operators.

Data collection and results

Munich is an economic hub that offers entrepreneurs great resources, including access to top universities and companies. Many established, R&D-heavy corporations have their headquarters in Munich, including BMW and Siemens, which help with the incubation of start-ups through investments and other programs. UnternehmerTUM, the center for innovation and business creation at the TUM, is a key player in this ecosystem. Two thousand students a year attend UnternehmerTUM courses, and 50 scalable technology start-ups are established. UnternehmerTUM was founded in 2002. A new Entrepreneurship Center building, which hosts the UnternehmerTUM, the TUM Entrepreneurship Research Institute, the TUM Incubator, the UnternehmerTUM Venture Capital, and the UnternehmerTUM MakerSpace under one roof on the university campus in Garching (Munich) was completed in 2015.[\[11\]](#)

Out of this ecosystem, 13 hardware entrepreneurs were selected for interviews based on their product and relation to UnternehmerTUM MakerSpace. Each guided interview lasted approximately one hour and was recorded and transcribed to gather all the necessary information. Table 2 shows an overview of the interviewed hardware entrepreneurs and gives insight into the answers of the interview's section one, questions about the hardware start-up, and section two, questions about the experiences in makerspaces. In section three of the interviews, hardware start-ups are confronted with the Maker Movement Element framework for the first time. During this section, each element was discussed to establish a common understanding, and the interviewer notes whether a specific element is unknown/ known to the entrepreneurs or whether it is even used in their product development. The last section of the interview is based on an assessment of each Maker Movement Element concerning the following criteria: reduction of product cost, product development costs, and time in product development, as well as an increase in the start-up's product quality and network/ community.

It was striking that the hardware start-ups had no problem assessing the product development cost, time, and quality criteria. But a difficulty arose when assessing the reduction of product costs due to the lack of experience gathered so far. In addition, while assessing their network/ community increase

due to Maker Movement Elements, some stated that in contrast to other criteria, the Maker Movement Elements themselves might not play a role at all.

Furthermore, UnternehmerTUM MakerSpace was assessed through discussions with the staff, visits to the space, provided historical data, and the company's website.

UnternehmerTUM MakerSpace was opened in June 2015. Around 50 persons (part and full time) are employed. Most of its employees work as instructors for courses. The second biggest group is the workshop staff and the third deals with administrative tasks. Besides offering paid memberships to private persons and company representatives, MakerSpace provides students free admission to the space. The makerspace is open every day of the week: from Monday to Friday from 8 a.m. to 10 p.m. and on Saturdays and Sundays from 11 a.m. to 10 p.m. To use any machine, all members are required to take fee-based introduction courses. A wide range of 59 courses for different skill levels and topics are available. The schedule and topics change weekly. The layout of the space is structured based on the type of fabrication process and materials used: 3D printing (FDM, SLA, and SLS), laser cutting, metal shop, painting and finishing, welding, water jet cutting, woodshop, CAD work stations, textile, electronic workshop, plastic, and project space. Moreover, event space and a coffee corner are provided. Mobile electronic equipment, like drilling machines, jigsaws, etc., can be rented for free at the front desk.

Table 1 gives an overview of the combined results of the interviews and also shows the offered Maker Movement Elements at the UnternehmerTUM MakerSpace.

Maker Movement Elements	Know by interviewed start-ups *	Product costs *	Product development costs *	Time in product development *	Product quality *	Network *	UnternehmerTUM MakerSpace **	Impact factor ***	Community based	Infrastructure based
	Y/N	1..5	1..5	1..5	1..5	1..5	Y/N	0..25	Y/N	Y/N
Fair / event		2,8	2,8	2,7	3,3	4,6		16,3		
Maker related facility (database)		3,3	3,0	3,5	3,3	4,1		17,1		
Expert's table		3,5	3,3	3,5	3,8	4,6		18,7		
Community order platform		3,0	4,1	3,8	2,5	2,5		15,9		
Open files repository (CAD, norm parts, code)		3,1	3,7	3,7	2,5	2,5		15,4		
Discussion forum		3,5	3,5	4,0	3,0	2,8		16,8		
Crowd based instructions		2,9	3,7	3,6	2,7	2,6		15,5		
Webinar / Workshop / Massive Open Online Courses (MOOCs)		3,5	3,7	3,7	4,1	3,2		18,2		
Online collection of resources		3,3	3,7	4,0	4,1	2,9		18,0		
Online blogs that inspire, teach skills, help to solve a problem		3,5	4,0	4,4	4,2	3,1		19,1		
Books / printed magazine		3,0	3,1	3,0	4,0	2,2		15,3		
Open-source software framework		4,3	4,5	4,5	3,6	2,3		19,2		
Open source (electronic) hardware		3,9	4,7	4,7	3,1	2,1		18,5		
Digital prototyping machine		3,4	4,9	4,8	3,8	2,6		19,6		
Wood shop		2,8	4,6	4,3	3,0	2,5		17,3		
Metal shop		3,3	4,6	4,5	3,7	2,6		18,7		
Electronics workshop		3,5	5,0	4,6	4,0	2,7		19,8		
Craft machine		2,3	4,1	3,2	3,0	2,9		15,6		
Testing equipment (especially for electronics)		4,1	4,8	4,7	4,1	2,6		20,3		
Microfactory (for assembly)		4,6	4,2	3,2	4,0	1,8		17,8		
Cloud computing platform		4,4	4,2	4,3	3,8	1,4		18,1		
Free 2D design software		3,0	4,0	4,7	2,5	1,3		15,4		
Free 3D design software		4,0	4,7	4,7	3,5	1,5		18,4		
Free simulation software		3,0	4,3	4,5	3,0	1,0		15,8		
Developer tools for electronics (IoT toolkit, PCB testing, ...)		4,0	4,6	4,5	3,4	1,7		18,2		
Platform for distributed manufacturing		3,2	3,4	3,4	3,7	3,1		16,9		
Contract manufacturer for low volume		3,9	3,5	4,1	4,2	2,7		18,3		
Electronic parts supplier		3,9	4,1	4,5	4,0	3,0		19,5		
Raw material in lowest volume (material library)		3,0	4,3	4,7	3,5	1,7		17,2		
Crowd funding		1,9	1,9	3,1	1,6	3,4		11,8		
Crowd investment (equity crowdfunding)		2,0	2,3	2,8	1,3	3,3		11,7		
Peer-to-peer (P2P) e-commerce		2,3	2,1	2,7	1,8	2,5		11,4		
Rent a physical space		2,0	2,5	2,8	2,8	3,4		13,4		

Table 1: Interview results based on the Maker Movement Element framework and offered elements at UnternehmerTUM MakerSpace (* results of 13 interviewed hardware entrepreneurs on a Likert scale, ** based on observations in UnternehmerTUM MakerSpace, *** calculated based on a horizontal sum of each element's result)

Analyze evidence, synthesis, and findings

The following paragraphs provide an analysis and discussion of the ways in which makerspaces are now serving the needs of the hardware startup directly based on the described case and the data gathered. Furthermore, areas in which the needs and challenges of hardware start-ups are not currently being met by UnternehmerTUM MakerSpace are identified.

Hardware start-ups and their challenges

As already mentioned in the section *Data gathering and results*, the authors try to interview a very homogeneous group of hardware start-ups. All have experience with a makerspace, are in an early development stage with their start-ups, mainly develop products for the Business to Business (B2B) market, and develop hardware-focused high-tech products that can have a software aspect.

By far the biggest challenge faced by the interviewed hardware start-ups at present is product development and was specifically cited challenge number one by 9 out of 13 questioned. In terms of their current start-up stage, this seems to match the general pattern that is emerging since all start-ups in seed-stage see product development as their main challenge. Within the product development issue “technical problem solving” is the main driver. Start-ups in a later stage, also see the industrialization of the product and design for manufacturing as a major challenge.

The hardware start-up’s experiences in a makerspace

All interviewees perceive the makerspace in a generally positive light. Many of them 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 to pay back the investment cost for a machine like a laser cutter... well, while that might just be possible, it’s a dauntingly huge hardware investment for the start-up...”

Another entrepreneur states this positive effect of a makerspace similar:

“No, we do not have the budget to buy any equipment and here, with the makerspace, it is awesome. You can use all the equipment you need daily from 8 a.m. to 10 p.m. This is unique. What it means for us is that we are not faced with any restrictions.”

Some entrepreneurs also mentioned elements currently missing in the ecosystem. For example, they have the need to rent an industrial expert on an hourly rate at the makerspace. This service is especially demanded the consulting on production processes like injection molding. Lots of time and costs are wasted in getting the correct molds 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 issue, as also this might result in an opportunity to get to know to like-minded people.

Furthermore, some stated that the main restriction in using the UnternehmerTUM MakerSpace is the mandatory participation in introduction courses before using any machine. In the UnternehmerTUM MakerSpace, this is obligatory because of the local safety regulations. Resulting in that every user must attend a course before he/ she is allowed to use specific equipment on their own. Courses are held frequently, but situations arose where users had to wait one or two weeks for a place on a course. This restricts the amount of different fabrication technology used by hardware start-ups and can lead to wasted time within their product development process.

Surprisingly, the opening hours, the possible insufficient quality of makerspace' machines, or limit on the number of available machines are not seen as restrictions.

Knowledge and usage of Maker Movement Elements

Table 1 shows that most Maker Movement Elements are known and/or used by the questioned hardware start-ups. The entrepreneurs state that 33 out of 33 Maker Movement Elements are known and 30 are used in their daily routines. These statistics indicate that the defined Maker Movement Element matches the work and needs of the hardware start-ups. The most extensively used elements are *online blogs that inspire, teach skills and help to solve a problem, as also digital prototyping machines, and open-source hardware*. *Rent a physical space* is a mostly unknown concept, which can be used to sell a final product directly to end customers and to obtain immediate feedback. This element might not be essential since the questioned hardware start-ups mainly focus on the B2B market. Other very little-known elements are *maker-related facility database, community order platform, micro-factory for assembly, free simulation software*.

However, considering those elements might be helpful for the hardware start-ups. Taking into account that lots of problems and errors on a physical product are only detected in the production ramp-up phase, a *micro-factory for assembly* can be especially useful for scaling start-ups. Similar assumptions can be made for simulation software. A *maker-related facility database* can be especially helpful when a makerspace does not offer enough capacity or does not offer a sufficient number and range of machines and tools. As explained, hardware start-ups are engaged in developing many different products, from autonomous driving vehicles to small IoT sensors, and it is, therefore, logical that they may need a large variety of different fabrication technologies. A point also mentioned as potentially crucial by some interviewees is the value of an extension of such a makerspace database to suppliers, like locksmith's shops or foundries willing to work with start-ups. The perception by interviewees of the *Community order platform*, like OSH Park for electronics, is very broad and differentiated. On the one hand, the cost can be reduced, but on the other hand, the timespan for obtaining the ordered part is extended.

Assessment of Maker Movement Elements

The results, as shown in Table 1, of the Maker Movement Element assessment can be interpreted in two perspectives: First, characterization of elements which are most helpful in a specific criterion, like reduction of product- or product development costs, time. Second, the description of Maker Movement Elements with the biggest impact on all criteria. The results of both perspectives can be seen in Table 1 and are analyzed here.

It is clear that for both criteria, reduction of product development cost and time the *Access to digital prototyping machine*, like 3D printers, laser cutters, etc., play the most important role: on average the reduction of product development costs was given a grade of 4.9 and time 4.8, where 5 is the maximum. This is also in line with the initial qualitative statements concerning the main benefit of a makerspace, as described in the section above. Besides *Access to digital prototyping machines*, Maker Movement Elements which are needed for electronic product development were given very good grades: *Access to electronic workshop* was awarded a maximum 5.0 in the reduction of product development costs and *testing equipment especially for electronics* scored well (4.1) in the criterion boosting product quality. In the issue of cost reduction for the final product, hardware start-ups interviewed agreed in clearly placing the concept of a micro-factory in the number one leading position. *Fairs/ events* and *expert roundtables*, such as meet-ups, emerged with the best scores in the criterion network/ community increase.

Another fascinating aspect is that across all Maker Movement Elements, the potential impact on the criteria reduction of product development costs (126) and time (129) is highest but the impact on network (87) increase is lowest. These values are calculated by the vertical sum of all Maker Movement Elements per criterion. This correlation appears especially vibrant 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.

Testing equipment especially for electronics as well as *access to an electronic workshop* got the highest values through all five criteria, followed by *access to digital prototyping machines*. Those three elements, which are directly related to investments in equipment, are followed by *electronic parts suppliers*, *open-source software frameworks*, *metal shop*, and *expert tables*. In contrast, the element of *crowdfunding*, *crowd investment*, *peer-to-peer e-commerce* and *rent a physical space* did not have an important role for the questioned hardware start-ups. The figures that emerged are certainly influenced by the types of products to be developed by the start-ups, but the perception that the electronic area in a makerspace is gaining ever more importance is proven positive.

Assessment of the location

Table 1 at first glance gives the impression of a very comprehensive environment for hardware start-ups, in which only a few elements are not offered, such a *micro-factory for assembly*. Maker Movement Elements that are not offered tend to correlate with what is not known by interviewed hardware start-ups. *Micro-factory for assembly*, *maker related facility database*, *community order platform*, or *free simulation software* are examples of these unknowns.

Even though the element *online blogs that inspire, teach skills, help to solve a problem* is popular and seen as helpful among questioned hardware start-ups (cross criteria factor 19.09), such an online platform is not offered by UnternehmerTUM MakerSpace. This element can for example effortlessly be implemented through a self-hosted Wiki or WordPress website. Other unmet hardware start-up needs can be seen for the *Electronic part supplier*, *Contract manufacturer for low volume*, and *Platform for distributed manufacturing*. Those three elements are especially essential when scaling a start-up. After finishing the first functional prototypes, hardware start-ups are on the lookout for partners to get their products industrialized, but UnternehmerTUM MakerSpace has very limited support offerings in this field. Some interviews show that the testing equipment offered, which is mainly for electronics, is not sufficient. Hardware start-ups mentioned a significant need for material and optical testing equipment, as well as a climate chamber. This equipment is expensive, so and a solution for makerspaces can be the creation of a network of established local companies, which offer fee-based services, but could partner with start-ups. Another unmet need can be seen in the fields of *Simulation software*, *Cloud computing platform*, and *Open-source software frameworks*. Most of these elements are free to use and therefore a makerspace should host courses or workshops in those fields to create awareness and teach the first steps, especially for hardware start-ups. But many free and educational software licenses do not allow commercial use and are therefore not designed to be used by start-ups. This results in that a makerspace needs professional licenses.

UnternehmerTUM MakerSpace invests significantly in enabling makerspace users to work independently. As described, obligatory 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, inexperienced users on the one hand, may become overloaded by 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 missing is an overview course that teaches how product development can work more efficiently in a makerspace.

Potential impact on operations, community, and infrastructure of a makerspace

Community, operation, as well as infrastructure, define makerspaces and their success. Litts 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 in makerspaces. [12] Baichtal or Britton, for instance, conclude also that the community aspect seems to be the most important for the success of a makerspace. [13] [14] Troxler and Schweikert named key aspects for operation, like openness, accessibility, interdisciplinary collaboration, and exchange experiences. [15] Hence, Böhm, Friessnig, and Ramsauer give a clarification of typical makerspace infrastructure. [16] However, all of the three dimensions need to exist simultaneously, meaning for instance that a thriving community can only exist if an appropriate infrastructure and supportive operational staff are provided. Based on these thoughts and with a view to the further clarifying of correlations and implementation possibilities of Maker Movement Element framework, the authors marked in the case of each element in Table 1 whether it is community-driven or infrastructure-based.

While analyzing the UnternehmerTUM MakerSpace it was clear that only 24 out of 33 Maker Movement Elements are associated with a makerspace infrastructure. This means that they are connected to an infrastructural investment, like the purchase of 3D printers or laser cutters. Six out of those 24 elements are marked as mixed. They are online but can be influenced by makerspace operators. These elements can, for instance, be fueled with a makerspace's own information and hosted on a makerspace infrastructure, but they are accessed via the Internet. Examples are *maker related facility database* and *online collection of resources*. 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.

Twenty out of 33 Maker Movement Elements are community-centered, which means that those elements are mainly not directly influenced by a makerspace operator and need not be physically implemented. But not surprisingly, those community-based elements also have a great influence on the product development of hardware entrepreneurs. *Open-source software frameworks* or *hardware, open file repositories* are good case examples of this. Many interviewed hardware start-ups stated that the community is the main reason to use a makerspace.

Conclusion and discussion

This paper aims to identify and describe the knowledge, usage, and role of the Maker Movement Elements in the product development of start-ups based on a case study with local hardware start-ups at UnternehmerTUM MakerSpace. Moreover, this case study was conducted in Europe's leading academic makerspaces and 13 hardware start-ups are interviewed. Although the case study includes

only a limited number of qualitative interviews and quantitative data at a single location, the results and especially the research approach used can translate to other locations.

The conducted interviews show 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 makerspace operator thus represents a valuable asset as discussed in the following:

First, the described procedure can be used for the assessments of makerspaces in general; also, requests for particular elements can be clarified through interviews with makerspace operators and users as shown in this paper. Furthermore, this paper allows visualization of the link between a hardware start-up's needs as well as the offerings and services of a makerspace. This is especially important for an academic makerspace, because typically resources are limited and a good match between specific elements and hardware start-ups is essential for promoting the creation of new scalable start-ups more powerfully.

Second, this case study can be vital for hardware start-ups in general, because the interviews conducted show that some elements are currently not known to hardware start-ups but would most likely have a positive influence on their product development process. For a makerspace operator, one simple solution, according to the interviews, would be to set up their knowledge platform for their users. Best practice examples can also be described on a platform of this kind.

Third, it can support initiators in setting up a new makerspace. After defining boundary conditions (e.g. size of a makerspace, budget, etc.) and focus (e.g. time, quality, cost, network), initiators are given a recommendation for a Maker Movement Element of case-specific relevance for them that can be implemented.

The case study shows that UnternehmerTUM MakerSpace offers a fruitful environment for the creation of new ideas, prototypes, products, and start-ups. For instance, Zwilling emphasizes that “the Maker Movement and start-ups were made for each other” [\[17\]](#), which is underlined by the described case study. Based on the data generated and analyzed, especially time and cost in product development can be saved through the use of certain Maker Movement Elements. 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 tools, courses, a platform to generate new skills, as well as experts plays an essential role for hardware start-ups' product developments. Based on these premises, the issues reviewed here provide insights into assessing the effects on cost, time, and quality and the influence these have on product development resulting from Maker Movement Elements.

A continuing research project can compare several locations with each other. This cross-case synthesis can provide a more universal understanding of effects in product development from a hardware start-up due to makerspaces and Maker Movement Elements in general.

The chance to further prompt the creation of scalable hardware start-ups is given when the right set of elements is provided within the ecosystem.

Appendix

	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					x				
Alumni of an accelerator					x								
Currently in an incubator			x	x	x	x	x						
Alumni of an incubator	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		
Founded	2017	2014	2016	2017	2015	2017	2017	2015	2017	2017	2016	2015	2018
Number of founders	4	3	6	4	3	3	2	2	2	3	2	1	2
Who was interviewed	CEO	CEO	CTO	COO	CEO	CTO	CTO	CTO	ME	CEO	CEO	CEO	CEO
Gender	m	m	m	m	m	m	m	m	m	m	m	m	m
Age	26-35	36-45	26-35	19-25	19-25	26-35	26-35	26-35	26-35	26-35	26-35	26-35	26-35
Short product debriefs	Smart mirror	Laser cutter	Robotic	In-ventory tracking	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
Start-up stage													
Seed													
Startup	x		x	x	x	x	x		x	x	x		x
Growth		x						x				x	
Customer	B2B	B2B, B2C	B2B	B2B	B2B	B2B	B2B	B2B	B2B	B2B	B2B	B2C	B2C
Currently biggest challenges													
Product industrialisation										x	x		
Process/ internal organisation									x			x	
Cash flow/ rising capital					x			x	x	x	x		x
Growth/ sells increase	x	x									x	x	x
Product development	x	x	x	x		x	x	x	x				x
Biggest challenges in product development													
Budget				x						x			
Gain a competitive edge													x
Completing on time				x						x			x
Managing customer expectations					x						x		
Technical problem solving	x		x		x	x	x		x		x	x	x
Access to production infrastructure		x						x				x	
Makerspace experience and usage													
Textile area incl. vinyl cutter				x									
Thermoforming & casting								x					x
Metal shop		x	x			x	x		x				
Wood shop	x					x	x		x		x		x
Hand tools			x			x	x					x	x
Laser cutter	x	x	x	x		x	x	x	x	x	x	x	x
CNC milling, lathe					x				x	x	x		
Electronics lab	x	x		x	x			x		x		x	
3D printing (FDM, SLA, SLS)	x		x	x	x	x		x	x	x	x		
Main reason you choose to realize your project in a makerspace													
Knowhow				x	x								
Faster & more iterations	x					x	x						
Community									x	x	x		x
Time reduction	x		x	x	x	x	x		x			x	
Available tools & machines	x	x					x		x		x	x	
Cost reduction			x	x		x		x	x	x		x	x
Main restrictions you face in a makerspace													
Location										x		x	
Reduced flexibility			x						x				
Rentable project space						x			x		x		
Course system & rules		x	x	x			x			x	x		x
Missing tools & machines	x				x			x		x			
Missing certificates	x												

Table 2: Overview of interviewed hardware entrepreneurs at UnternehmerTUM MakerSpace

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