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Hardware start-ups and manufacturing innovation

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ABSTRACT
This paper provides firstly an overview of the literature on hardware start-ups, which are also related to manufacturing innovation. It continues with a framework, based on an interview series with hardware start-ups and their respective stakeholders. It includes a discussion about the relevant challenges and success factors, along with a potential set of metrics that can be of help for the evaluation of start-ups.

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1. Introduction

Entrepreneurship is a crucial aspect of economic development, and its significance cannot be overstated. It drives innovation, creates jobs, and fosters economic growth in communities. Entrepreneurs are the driving force behind many of the world's most successful businesses, along with their ability to identify and seize opportunities that are essential to economic progress.

One of the most significant benefits of entrepreneurship is job creation. Entrepreneurs are responsible for starting new businesses, while these new ventures provide employment opportunities for people in the community. As these businesses grow, they create even more jobs, which help reduce unemployment rates and increase the standard of living for individuals and families.

Entrepreneurship also drives innovation. Entrepreneurs are often motivated by their desire to solve problems or meet unmet needs in the market. Through their innovations, they create new products and services that benefit consumers and other businesses. These new ideas and inventions often spark competition, leading to further innovation and improvement in the marketplace.

In addition to job creation and innovation, entrepreneurship also contributes to economic growth. New businesses generate revenue, which circulates in the economy, creating more wealth and opportunities. This growth can have a ripple effect, as other businesses in the community benefit from the increased demand for goods and services.

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Furthermore, entrepreneurship can help diversify the economy by reducing dependence on a single industry or sector. This diversity can provide stability at times of economic hardship and help create a resilient economy that can weather challenges and continue to grow.

Entrepreneurship is one of the key drivers of business creation and a central factor in fostering innovation and a prosperous economy. Moreover, it can significantly impact the national economic growth (van Stel et al., 2005). To secure a high level of entrepreneurial activities, the stakeholders from policy makers, academia to incumbent companies promote an environment, where entrepreneurship is strongly supported through a broad range of services and initiatives.

Startups play a crucial role in promoting innovation and entrepreneurship. These small businesses are the drivers of economic growth, as they bring new ideas and technologies to the market, by creating jobs and boosting the economic activity.

Startups are often founded by entrepreneurs who are passionate about solving problems and identifying opportunities in the market. They bring fresh perspectives and creative solutions to the table and are not afraid of taking risks in pursuit of their vision. This mindset fosters an environment of innovation, where new ideas are constantly developed and refined.

Through their innovative products and services, startups are able to disrupt established industries and challenge the status quo. This competition spurs incumbents to adapt and innovate, by creating a dynamic ecosystem that benefits consumers and the economy as a whole. Furthermore, startups are often able to move faster and more nimbly than larger, established companies do. They are able to pivot quickly in response to changing market conditions and can experiment with new ideas without being bogged down by bureaucracy and red tape. Startups are also major drivers of job creation. As they grow and expand, they hire new employees and create new opportunities for individuals anticipating to enter the workforce. This not only does it help reduce unemployment, but also stimulates the economic growth by increasing consumer spending and generating tax revenue.

Macroeconomically, the hardware innovation, especially in the high-tech sector, creates jobs, contributes to innovation and technology ecosystems that often serve as berths for further innovative projects, namely the service-creation. However, hardware development and manufacturing are usually cost-intensive and challenging when it comes to closing investment agreements. Furthermore, hardware delays scalability. Since the latter is one of the crucial evaluation criteria for start-ups, hardware start-ups take longer to break-even and thus put investments at risk.

Innovation is critical for the economic growth and development. It creates new markets, products and services, by generating job opportunities and driving the economic growth. Innovation enables companies to become more competitive, efficient and profitable, contributing to the overall economic growth. It encourages research and development, investment in new technology, along with the creation of new industries. Innovation also fosters social and environmental progress, which can improve the quality of life and create sustainable growth. Without innovation, economies stagnate, and businesses risk falling behind. Therefore, fostering innovation should be a top priority for governments, businesses, and individuals aiming at promoting economic growth and development.

As the macroeconomic and microeconomic goals of business objectives sometimes conflict with each other, special measures towards the specific support of hardware start-ups are of societal importance. They can serve as a competitive advantage for cities, regions and entire economic regions such as Europe.

There are several parameters that can affect the success potential of hardware start-ups, namely funding, technical expertise, market demand, manufacturing and supply chain, intellectual property, regulatory requirements, team and culture.

The research objectives of this paper are (a) to identify parameters, affecting the success potential of hardware start-ups by surveying the aspect of the specific practitioners and (b) to propose a model for its evaluation.

To serve the above objectives, after the examination of the notions of manufacturing innovation and hardware start- ups, the data acquired from a survey on selected hardware start-ups will be presented and will be analysed in conjunction to current literature by providing a qualitative examination of hardware start-up challenges. Finally, a framework of hardware start-ups success potential will be developed and proposed as a practical tool for the strategic planning of hardware start-ups.

2. Review of the notion of manufacturing innovation and hardware start-ups

Manufacturing, defined as the transformation of materials and information into goods for the satisfaction of human needs, is one of the primary wealth-generating activities for any nation and contributes significantly to employment (Chryssolouris, 2006). Manufacturing can be thought of as a system whose product design is the initial stage, whilst the delivery of finished products to the market is the final output. Since the field of manufacturing integrates many disciplines into engineering and management, it is useful to be divided in a way so as to facilitate the identification of innovation issues. Manufacturing can be subdivided into the following areas:

(1) **Manufacturing processes**, which alter the form, shape and/or physical properties of a given material
(2) **Manufacturing equipment**, used for the performance of manufacturing processes including automation devices and robotics
(3) **Manufacturing systems**, namely the combination of manufacturing equipment and humans, bound by a common material and information flow. Similarly addressing production planning and control. Whereby, the design and planning of a system is interwoven with its operation and control.

Manufacturing innovation may involve software and/or hardware approaches/dimensions with different gravity of relation (weak, medium or strong) as shown in Figure 1. In the case of hardware-related innovation, a large investment, extensive testing and in general, an overall significant effort is required to achieve potential success (Mamasioulas et al., 2020). In general, manufacturing start-ups have to cope with extensive challenges compared with other corresponding sectors (Snyder, 2019).

On the other hand, the term start-up refers to a company, in the early stages of its operations, founded by one or more entrepreneurs, who want to develop a product or

Manufacturing	System	XXX	X
	Equipment	XX	XXX
	Process	X	XX
		Software Related	Hardware Related
		Innovation	

Figure 1. Innovation and manufacturing areas (x weak, xx medium, xxx strong).

service for which they believe there is a demand. These companies generally start with high costs and limited revenue, so they seek capital from various sources, such as venture capitalists (Grant, 2022). Alternatively, a start-up can be viewed as a pool of entrepreneurial talent developing new innovations, in an identifiable and investable form, in progress to validate and capture the value of the innovation, being created with the ambition to grow rapidly with a scalable business model for maximum impact (startupcommons.org, 2021). According to literature (Blank, 2011) there is a number of different start-up types.

Businesses aimed at distributing a physical product, have come into greater focus in recent years, following the boom in software-based start-ups over the last decade. Although 'hardware is hard' (Goldberg, 2021) and there are important barriers for hardware start-ups, this sometimes turn into benefit (Grundy, 2020). The continuous reduction of barriers backs this up through the easy access to rapid prototyping technologies (Rayna & Striukova, 2021), direct manufacturing (Hannibal, 2020), as well as open source hardware (Li & Warren, 2019). Moreover, various online learning and video platforms and discussion forums offer an easy opportunity to acquire knowledge on technology and manufacturing processes (Tanenbaum et al., 2013) and democratise entrepreneurship by providing access to international market knowledge (Pergelova et al., 2018). In addition, the trend towards factory-free production is of great interest as a parameter for manufacturing innovation (Xing, 2021).

In the context of this study, the term hardware start-up is used for ventures, whose goal is to move a physical product into distribution. Regardless of the product's end use, this study covers start-ups developing traditional IT components and systems as well as pure physical products, without any data processing or sensing (DiResta et al., 2015).

However, developing hardware into a market-ready stage involves high risk. Especially in the so-called deep or manufacturing-oriented technology, the process is very challenging. Transferring a prototype into a product and the necessary testing skyrocket the time and cost compared with digital business models. The construction of hardware products

is very costly and requires external service providers or component manufacturers (Berg et al., 2020). The current theoretical study, mainly focuses on start-ups in general, covering a wide spectrum of challenges, ranging from organizational (Davila & Foster, 2007), gender (Gomes Neto et al., 2020), innovation and lean methods (Ries, 2011b; (Ghezzi, 2018), systematic risk (Hall & Woodward, 2010) to human resources management (Wise & Valliere, 2014). An assumption about unique challenges, faced by a company with a business model, based on technology and hardware, has been described in (Werwath, 2019). The contradiction between the agility of a start-up and the quality of product development is also addressed by a qualitative study (Berg et al., 2020). However, there is no framework in order for the challenges of hardware start-ups to be examined.

In order to better understand the situation for hardware start-ups a qualitative survey of stakeholders of the hardware start-up ecosystem in Austria and Germany has been conducted and there were identified proprietary challenges, which were condensed into a framework and are referred to as an approach for evaluating the innovation performance by using dedicated metrics. To consider the particularities of hardware start-ups, the scope of our research is limited to start-ups that handle higher operational complexity (beyond off-the shelf commodities) and rely on hardware or hardware-defined development as shown in Figure 2.

The start-ups phenomenon has been thoroughly studied in terms of its characteristics and has evolved into a special field of microeconomics and meso-economics by examining all aspects of the possibility of success (or failure) of such a company. Regarding the management models used, the so called 'Silicon Valley Model' has been coined to describe the abilities of successful companies to remain entrepreneurial and continuously innovate in an innovation economy (Steiber & Alange, 2016) although it has been criticized as not being applicable in all circumstances, since it is rather context dependent (Audretsch, 2019). Contrary to the 'classical' planning theory, the 'lean start-up' methodology that rejects long-term planning and embraces experimentation and iterative

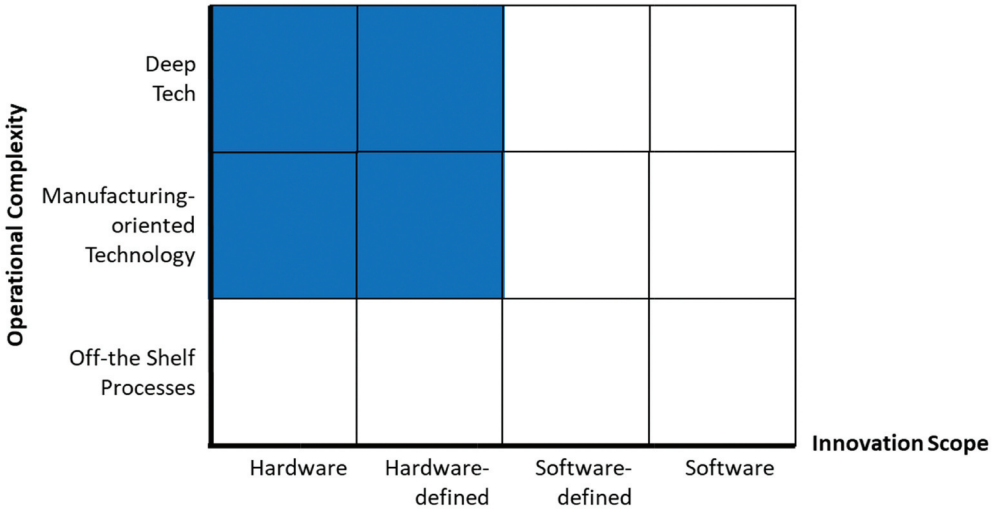

Figure 2. Operational complexity and innovation scope: the case of hardware start-ups.

learning, has received much attention from entrepreneurs, practitioners, and academics (Mansoori, 2017).

The current theoretical work mainly focuses on start-ups in general, covering a wide spectre of challenges ranging from organisational (Lee, 2022), gender (Gomes Neto et al., 2020), innovation and lean methods (Ries, 2011b; Ghezzi, 2018), systematic risk (Hall & Woodward, 2010) to human resources management (Wise & Valliere, 2014). On the other hand, several publications focus on specific challenges and failure causes of start-ups, whose business models are based on software (Giardino et al., 2014; Lopez-Munoz et al., 2023; Wang et al., 2016).

An assumption about unique challenges faced by a company with a business model, based on technology and hardware has already been described in (Werwath, 2019); the article focuses on the fact that the lean start-up methodology by (Ries, 2011a) is not entirely suitable for hard-science technologies. Werwath claims that there are more fundamental questions to be asked and answered in order for the right market fit to be found in the case of hardware start-ups than in typical software ventures. This is based on the fact that the technology developed can usually serve many different markets. Werwath introduced the assumption of 6 characteristics of hard science-based start-ups that differ from the soft science or IT-based ones that were considered for the design of the qualitative questionnaire (Werwath, 2019):

(1) Longer gestation periods with higher technical risk
(2) More intense Intellectual property considerations. IP becomes a foundational concern for this type of start-up
(3) Less available seed and investment capital for the start-up
(4) Often less competition, pursuing the same type of problem or solution, for a variety of reasons
(5) Much more non-dilutive capital is available for the student entrepreneur
(6) Corporations are often quite interested in this type of start-up; in many cases to gain access to business-based IP.

Currently, only the contradiction between the agility of a start-up and the quality of product development is being addressed by a qualitative study (Berg et al., 2020). However, there is no study for a holistic overview.

3. Hardware start-ups, framework and challenges

Sampling for the qualitative research phase was carried out by applying a snowball sampling strategy (Goodman, 1961). Relevant stakeholders and company representatives from the hardware ecosystem, were contacted and followed up on their recommendations for other potential interview partners. The requirements for the interviewed companies were the active operation in the Austrian, German, or both ecosystems and a business model, based on a hardware product. In addition, the objective was that a diverse representation of hardware entrepreneurship be ensured by covering a wide range of industries, encompassing various forms of hardware start-ups. This approach allowed us to capture a more comprehensive understanding of the challenges faced by

Table 1. Survey participants - start-ups.

Company	Team Size	Industry	Role	Professional Background
Start-up 1	7	Music	CEO; Co-Founder	Engineering
Start-up 2	5	Media Automation	CEO; Co-Founder	Engineering, Management
Start-up 3	23	Electronics & Health	CEO; Co-Founder	Engineering, Management
Start-up 4	6	Materials	CEO; Founder	Physicists
Start-up 5	16	Health	CEO	Management
Start-up 6	28	Automation	CTO; Co-Founder	Engineering
Start-up 7	3	Laboratory equipment	Founder	Chemistry

Table 2. Survey participants - stakeholders.

Stakeholder	Investments	Type	Role	Professional Background
Stakeholder 1	10	Venture Capital	Investment Manager	Physician, Entrepreneur
Stakeholder 2	28	Business Angel	Business Angel	Software Executive

hardware entrepreneurs across different sectors and provide insights that can be applied to the broader hardware industry.

Tables 1 and 2, show basic information about the interviewed start-up representatives and their start-ups, as well as stakeholders that are relevant players in the ecosystems. The sampling has targeted start-ups that had already reached a certain maturity. Except for two of the interviewed start-ups in the prototype's refinement phase, all the others had already sold their products to customers.

A semi-structured interview was conducted to get new insights into the real-life context of the phenomena of hardware start-up challenges (Robson, 2002). The structure of the questionnaire was divided into three sections: Introduction, Main Part and Closing. A funnel approach (Roller & Lavrakas, 2015) was used for the questionnaire design to gradually guide participants from general to more specific questions. This approach has led to new unanticipated insights into hardware entrepreneurship and more detailed information about certain known challenges. The duration of the interviews was one hour. The interviews were conducted online, recorded, transcribed and analysed using the inductive category development approach (Mayring, 2008).

The analysis has led to the formulation of 17 challenges, clustered into three main categories, represented in Table 3. The Ecosystem challenges represent external influences, depending on the start-up's ecosystem, whilst the team's influence on these challenges is minimal. Business-related challenges represent problems, which are connected to managerial domains, namely strategic management, human resources, finance,

Table 3. Identified challenges for hardware start-ups.

Identified Challenges - Categories		
Technology related	Business related	Ecosystem-related
T1: Product Development	B1: Strategy	E1: Quality of Support
T2: Certification	B2: Team and Human Resources	E2: Feedback Culture
T3: Intellectual Property	B3: Partner Collaboration	
T4: Production	B4: Time-to-Market	
T5: Sourcing	B5: Marketing & Sales	
T6: Scaling	B6: Market fit	
T7: Design	B7: Financing	
	B8: Grants	

and sales. Technology related challenges comprise tasks, related to prototyping, physical product development and manufacturing.

The development time and subsequently the time-to-market, has been identified as a significant issue in hardware start-ups; these findings can be well incorporated into the existing literature, examining the agility in production (Nguyen-Duc et al., 2018) and the contradiction between agility and quality in product development, in hardware start-ups (Berg et al., 2020). Furthermore, the observation of the influence of development time on time-to-market, has led to developing a framework that combines the start-up development and the product development phases (Reisdorfer Leite et al., 2020).

This part of the paper reveals a new perspective on this known problem. This perspective focuses on the underlying challenges and links them to an overly interdisciplinary comprehension.

3.1. Technology-related challenges

The study has revealed a lack of practical know-how in product development, in the existing supporting programs, offered by accelerators, incubators and supporting organizations and has shown that the development of a prototype is a less significant problem than the actual development of a product is. The prototypes are commonly designed and produced either in research laboratories, private workshops, or maker spaces that have the necessary infrastructure. The path between a prototype and a scalable production-ready product is more challenging than that of the initial phase. From the technical perspective, the development of products comprises various fields of expertise, including but not limited to sensors, programming, product design, material, process theory, manufacturing, sourcing and kinematics. This overwhelming variety of challenges brings a very diverse need for the expertise of the entrepreneurs. Moreover, the high complexity makes the pivoting of the business model or the product arduous and time-consuming. The product development of hardware products has to be realized with special emphasis on quality management and the fulfilment of product-specific standards. Certification, according to the standards requires the development and integration of a complex process, which is highly challenging, as well as time and cost-consuming for newly established companies. In the context of the ecosystem, the uncertainty and time duration of product development in hardware start-ups, the upper limit up to which a company is perceived as a start-up by the supporting institutions, should be questioned.

Another measure that can improve the likelihood of obtaining investments and financing the production of a product and the development of a business model, is to secure intellectual property with patents that allow the company's investor exclusive rights to the invention. This would prevent competitors from copying the technology. According to (Conti et al., 2013), some of the interviewees have perceived the patents as essential signals for external parties. The problems, associated with patents, have been weighted very differently among entrepreneurs. The different perceptions of the patenting challenge have arisen from the different founding structures and origins of the start-up. The interviews have shown that companies from the academic sector had access to services that allowed patent applications or had the know-how from previous activities. On the other hand, non-academics saw the challenge as significant, but surprisingly, not because of the costs, but more because of the time-consuming application process. The

fact that the costs are not considered a major issue is most probably due to the availability of grants that support patent applications.

Another aspect of a hardware start-up is setting up the product's production. This is the next challenge that influences both dimensions, financial and technical. As the production needs are highly dependent on the product, the types of challenge differ among various start-ups. The decision for outsourcing has turned out to be mainly dependent on the area of expertise of the venture and their product. The product is often innovative so that new production processes and machines have to be created in order either for a close cooperation with a manufacturing company or a company that develops production machines to be necessary. On the contrary, even if entrepreneurs have a product that can be outsourced, they are often confronted with the challenge of finding a contract manufacturer willing to cooperate with a start-up. The interviewees have repeatedly reported that willingness to cooperate with a new venture is very limited and that they are not taken seriously by the providers, which makes it extremely difficult to procure services and components.

Moreover, companies providing services or parts are used to collaborating with customers that order high volumes and the start-ups are not perceived as attractive customers. Although, an exception has been identified as stakeholders reported that issues started to arise when they had to scale up their production of a high-volume product for a B2C market. The European contract manufacturers were inundated with orders, whilst the interviews revealed that European suppliers and manufacturers could operate within a particular volume range and face problems if the order was outside that span. Hence, scaling up production in high volume markets is perceived as problematic by the entrepreneurs, since the situation in other geographical areas is more suitable and welcoming for start-ups than it is in Europe. Respectively, scaling the business is very difficult since on top of the marketing demand the need for physical production facilities is an additional hurdle compared with that of software ventures.

Another difficulty that has emerged from the interviews is the design of the products. A lot of products are developed from a purely technological point of view, without any focus on functional design or even attractive design. This seems to be a cultural phenomenon in the examined area. The product is designed from the perspective of minimum technological requirements, whilst the appearance or user experience is often neglected. This has been perceived by the interviewees as being contrary to other regions. Regarding the statements, the Anglo-Saxon entrepreneurs emphasize much more intensively on the design than Austrians and Germans do.

3.2. Business-related challenges

The interviewed stakeholders consistently agreed that developing physical products for the market is highly time-consuming, compared to software development. This fact is associated with the long iteration cycles, the multidisciplinary and the dependence on external factors in hardware development. It results in a long time-to-market period in which the product generates costs without generating any revenues and ends with the products' market-readiness. Accordingly, the surveyed stakeholders have stated that financing a hardware venture is very problematic, since most investors are reluctant to invest in hardware start-ups, due to the lack of acceptance for a long development cycle

and the high capital intensity, both of which are associated with the issue of product development. However, the cooperation with investors reveals tension on both sides. Investors are undeniably more interested in more easily scalable business models, such as software as a service, while hardware entrepreneurs typically have very naive ideas about the means of financing their start-ups. On the one hand, entrepreneurs often expect an investment in order to finance their entire production and development work. On the other hand, investors expect a clear strategy in which their investment is only one part. It is up to the entrepreneurs to present a combination of bank loans, advance payments from customers, investments and a clear business plan. The challenges for the hardware companies are therefore extremely high, especially when it comes to customers only wanting to pay in advance, when there is a product or when they have a specific guarantee. Not having a resilient order guarantee is usually a case for start-ups, since they do not have any production-ready products, or the production capability is in the phase between completed prototyping and production, when financing is essential. Simultaneously, the pre-production phase of a company is unique if it is compared with companies that do not have physical products as part of their business model. According to the interviews conducted, these aspects are often neglected in the existing accelerator programs. The difficulty in finding investors leads to a strong dependency on public grants. All interviewed start-ups have received grants, whilst those that already have succeeded in entering the market, have stated that it would not have been possible without public subsidies. However, several shortages have been identified by the interviewed start-up stakeholders, regarding the subsidy system of the EU and, more specifically, in their region. The interviewees stated that subsidy volumes for start-ups are not intended for radical innovations, and that young companies cannot receive high-tech development grants because they are focused on established companies and research institutions.

In addition to the explained know-how areas, the entrepreneurs should display expertise in the area of marketing, regardless of the focus on either B2B, B2C or both markets. The composition of the interviewee sample was disadvantageous in terms of the marketing challenge. Due to the fact that the authors have focused on the CEOs of hardware ventures, most of the respondents had only a limited marketing knowledge. Furthermore, it is difficult to properly structure marketing challenges since they vary greatly, depending on the product and the target market. As described above, the main challenge of B2B ventures is to acquire the first customer for co-development, whereas B2C start-ups usually search for either direct marketing or a cooperation with a retail or distribution company. Both interviewed stakeholders from investing organizations, have expressed an estimate about the product-market fit being the most significant reason for the failure of a venture.

The described situation prompts entrepreneurs to collaborate with incumbent companies in partner collaborations. Operating in a similar field, they usually have a better understanding of the benefits and the technological innovation and can be supported through expertise in different fields. In the last years, these corporations have led to different models for the connection of corporates and start-ups being available in the ecosystem. However, it puts the entrepreneurs in a difficult position so as to weigh up the pros and cons of such a collaboration. The representatives' interviews have raised concerns about the corporate's goal in such a collaboration to

quickly purchase complementary technology or capabilities to solve their problems and enter new markets. This start-up scouting behaviour corresponds with the existing literature (Lerner, 2013; Weiblen & Chesbrough, 2015). However, the fear of being swallowed by a large company is often outweighed by the benefits of such a collaboration, especially the challenge of finding a pilot customer ready to co-finance the development.

Moreover, the interviews have shown the need for high interdisciplinarity in the team. Considering the above challenges, a team with expertise from the described areas, is essential that it should bring the clients the usual technology led development in a meaningful way and develop a suitable financing strategy. Stakeholders have stated that the funding expertise required is extremely high and approaches the know-how requirements of a fintech start-up.

This interdisciplinarity in start-ups has already been described in the literature. The most critical issues, which cause the failure of start-ups have been identified in areas that are usually outside of the know-how of a typical technology-driven entrepreneur (marketing, strategic management, finance management, project management and leadership) (Zbierowski, 2016). Regarding the literature, referring to the considered hardware start-us ecosystem, the interdisciplinarity in technical development focuses on the interaction between engineers and designers (Blanco et al., 2015).

New aspects of multidisciplinary alignment have evolved, especially the tension between having the necessary expertise within the team and obtaining it from external sources that was omnipresent in the interviews. In other words, a make or buy decision should be made. The entrepreneurs tend to outsource technical development to companies, which are specialized in that field, especially during the challenging phase of transforming a prototype into a production-ready product. However, the business strategy and funding alignment of particular interest in the investing parties, are often done on the side by entrepreneurs, who lack the necessary skill set, leading to problems and mismatched expectations between investors and entrepreneurs. Some of the entrepreneurs have admitted that they encounter problems in having hired business developers since their colleagues prefer to work with technicians or scientists and want to hire more of these professionals as they consider them more valuable to their business. The author has interpreted this phenomenon as a representation of 'a behavioural state, where a person operates in an anxiety-neutral position' (Bardwick, 1995), working in a familiar environment and in a homogenous group of people, often leading to a weaker team performance.

Examining this phenomenon from a psychological group dynamic perspective, a heterogenous group is difficult to be managed (MacLeod, 2018). This typical environment in a venture epitomizes the need for professional human resource management of that business, especially having considered the challenge of attracting employees to a start-up and the potential for rapid growth after reaching a certain level of maturity.

3.3. Ecosystem-related challenges

Entrepreneurs have pointed out that the support measures available are usually very theoretical. In addition, most entrepreneurship programs are not designed to develop physical products thus, companies lack networking opportunities with this thematic

focus. The interviewees' understanding is that the existing programs are much more software and fintech oriented. The entrepreneurs' greatest challenge is to handle the multidisciplinary nature of developing hardware products and finding practical support in the ecosystem.

Focusing on European Start-ups, the interviews have revealed a challenge that has to do with the feedback culture in the ecosystem. Having much experience, Stakeholder 1, described two dimensions of the problems. The first is that start-ups are often refused instantly by the potential investor and receive a generic answer. He expressed a wish to establish a culture of constructive feedback, so that the start-ups would improve, based on the inputs they received from investors. The interviewee has connected this problem to the fact that investors want to avoid situations of start-ups coming back to them repeatedly after having adapted small changes according to the feedback: Another Dimension of this problem is the fact that judges are often told not to be too direct and sceptical when giving feedback, so as to avoid discouraging the entrepreneurs. From the perspective of the start-up, this topic was mentioned in the context of investors being very positive, during the meeting with the start-up, without having actual interest. Regarding the representative of Start-up 2, this has to do with the fact that investors do not want to 'close their doors' in case the business model is to their interest in a later phase. However, for entrepreneurs, this may lead to time being wasted and resources with follow-up preparations.

4. Hardware startups success potential metrics

Start-ups are a major vehicle for implementing innovation also in the manufacturing world, hence and following the previous discussion, we try to address the potential of success, in general terms, of an innovation project.

One can possibly summarize the potential of an innovation project's success (Mamasioulas & Chryssolouris, 2023) through an Organization's Innovation Performance index (OIPi), which is in turn, can be considered as a function of five different business-related parameters:

$$\mathrm{OIPi} = \mathrm{f}(\mathrm{OC}, \mathrm{OM}, \mathrm{OF}, \mathrm{ODCORA}) \quad [1]$$

Where,

- OC is the Organization's commitment, describing the general attitude of the organization, mainly from its top management, towards innovation in general and the specific innovation project. It is rather a commitment-based human resource management issue that embodies the organization's ability to solve fuzzy and ill-structured problems (Jin Ko & Ma, 2019).
- OM is the Organization's maturity (experience, describing the level or plateau that the organization has reached in order to cope with innovation challenges (Nieminen, 2019).
- OF is the Organization's flexibility, describing the manner that the organization's potential, adapts to external challenges (Georgoulias et al., 2009) (Sopelana et al., 2012).

- ODC is the Organization's Dynamic Capability, namely the ability to detect opportunities; to learn how to develop structure, processes, projects and incentives; to take advantage of detected opportunities and continuously manage the alignment and realignment of its tangible and intangible assets, in pursuit of value generation (Teece, 2007).
- ORA is the Organization's Resources Allocation or Availability, as a rather quantitative dimension of the use of resources (Human, Financial, and/or Hardware) in relation to the Total investment in the innovation project.

The above metrics framework can be applied to a hardware start-up initial phase of development since it can be considered as a project. Based on the viewpoints of the surveyed companies, an initial evaluation of the framework's applicability/validation was performed:

4.1. Organization's commitment

The qualitative study reveals that start-ups tend to exhibit a high level of commitment, which is likely due to the small size of the venture team and the flat hierarchies that are common in these organizations. Both founders and employees strongly identify with the company's goals and see this commitment as a positive aspect of their work. However, the authors caution that measuring the level of commitment may prove challenging and that it may not be a useful indicator of innovation performance. Furthermore, the degree of commitment among start-ups is likely to be similar, so it may not provide meaningful differentiation among companies. One potential obstacle to maintaining this level of commitment, which can create significant financial pressure, particularly if the company is unable to secure investment, is the long time-to-market period that many start-ups face. This pressure may impact the organization's ability to continue developing the product and bring it to market.

4.2. Organization's maturity

The results of the study highlight the crucial role of the Organization's maturity dimension in the success of hardware start-ups. However, in contrast to the typical approach of evaluating an organization's existing processes and innovation history, in the case of start-ups, maturity needs to be assessed at the founder and team level. The maturity of the organization is closely linked to the experience and expertise of the team members. This finding aligns with the views of the interviewees, who have stated that the team's background is a critical factor in investment decisions. The study reveals that this dimension is particularly significant to the hardware entrepreneurship sector. The scarcity of skilled labour, along with the complex interdisciplinary requirements of developing a hardware product and business model, can have a significant impact on the organization's maturity in tackling the typical challenges of an innovation project.

4.3. Organization's flexibility

The lean start-up paradigm by (Ries, 2011a) postulates that the ability to respond quickly to customer demands and market changes is critical for the success of a start-up. However, in the hardware start-up sector, technology, which can limit the flexibility to change the entire business model or product, often takes precedence. Similar to established companies, hardware start-ups should have a structured product development and a stage gate process. However, start-ups should also leverage the organization's fundamental know-how to meet future customer needs. Organizational flexibility is a crucial factor for success in this context, and its absence can limit a start-up's ability to adapt to market changes. Long development cycles and dependence on external factors can reduce flexibility and make it difficult for hardware start-ups to pivot quickly. Additionally, securing financing and resilient order guarantees can be challenging, which can limit a start-up's ability to invest in new opportunities or respond to unexpected market changes.

4.4. Organization's dynamic capability

From the surveyed companies one could conclude that some of them lacked in ability to adapt their resources and develop the proper processes towards achieving their goals. Others though, understand that developing such properties from the early stage of their companies' life is of crucial importance. In conclusion, hardware-focused start-ups typically face challenges in successfully penetrating the market, due to high development costs and long timelines, which limit their ability to take advantage of identified opportunities and negatively impact their dynamic capability. It is therefore essential that start-ups prioritize the development of adaptive processes and agile resource management in order to enhance their ability to respond to changes in the market and capitalize on opportunities quickly. By doing so, they can increase their chances of success in the highly competitive hardware industry.

4.5. Organization's resources allocation

As described, investors tend to invest in easily scalable businesses, namely, software as a service; therefore, the dimension of Resource allocation and availability plays a vital role for hardware entrepreneurs, while they are seeking for capital. A strategic financing plan, combining bank loans, advance payments from customers, investments and a clear business plan is essential to a successful fundraising. Likewise, human capital plays a significant role in every start-up and strongly interferes with all other dimensions, since it is the core team that defines the entire organization. This makes ORA a vital dimension to measure its innovation performance. Additionally, the ability to protect IP and hold patents on a crucial technology should be considered an asset. The hardware resources are highly dependent on the nature of the product, intended to be produced while not being part of the quality durability.

A further survey should be conducted not only by researchers but also by financial experts and even by some stake holders. Related to that, the application of the proposed metrics will be also of interest.

As the survey was limited to successful start-ups, a corresponsive investigation could be performed also on failed start-ups, providing useful insight regarding the evaluation of the introduced success potential metrics structure.

5. Conclusions and outlook

Entrepreneurship is generally considered being an indispensable precondition for sustainable innovation and therefore, contributes to a competitive economy. Manifold evidence proves the importance of start-ups to the industrial ecosystem, in terms of innovation, employment and substantial growth. Against this background, hardware start-ups play an essential role as their macroeconomic benefit usually spans beyond the respective (hardware) product, towards a larger accompanying ecosystem and potential added-value services. In contrast, hardware start-ups often need higher investments over a longer period of time, until a scale-up for a successful business case is achieved. The resulting challenge is of importance for hardware start-up entrepreneurs, potential investors and public authorities, especially funding agencies.

The respective paper contributes to a better understanding of the current situation, ongoing challenges and relevant success factors of hardware start-ups, exemplified by empirical findings from the Austrian and German start-up ecosystem.

Our results show technology-related challenges, referring to the often-underestimated efforts spent on scaling up a production-ready product. Furthermore, this often comes with other hardware-specific processes, such as certification needs, which often cannot be parallelized but take additional time. Therefore, our interpretation of this evidence is to reconsider the maximum duration of funding and the maintenance of the eligibility criteria of the start -up for public support. Regarding business-related challenges, the application development further pressures the time-to-market period and often leads to unplanned prolongations. These findings are consistent with the importance of balanced and complementary management teams that are well-grounded in the start-up literature, which is not endemic for hardware start-ups, but is also considered being a major success factor in our survey. Due to the particularities of tangible artefacts at the core of a hardware start-up's idea, ecosystem-related challenges account for a further interesting field of action. The reported importance of 'feedback culture to the ecosystem' represents a difficult but complex challenge, whilst having the potential to be shaped into a success factor for a prosperous hardware start-up environment.

The presented metrics for assessing the success of hardware start-ups' provide an approach to develop the empirical findings towards an indicator set in support of decisions, based on the innovations' success potential. The metrics consider the respective particularities of hardware start-ups as they are based on qualitative criteria that expand the traditional set of financial KPI metrics and rather general recommendations of potential success in entrepreneurship.

At the present time, the findings are limited to a restricted data set for Germany and Austria. Furthermore, the concept for the metrics is still located at a conceptual level. Nevertheless, the results contribute to a better understanding of challenges for hardware start-ups and potential metrics for the evaluation of success factors.

For future research, elaboration of the presented results, towards three dimensions, has been planned. First, the empirical findings will be extended towards a broader geographical scope as well as to a larger dataset of hardware start-up activities. Second, the evaluation concept is planned to be tested and applied on existing ventures as well as towards forecasting support for new hardware start-ups. The latter (prescriptive) approach has the potential to enlighten the traditional blind-spot of biased scientific knowledge towards successful start-up narratives. Last but not least, relationships and iterations among empirical evidence, metrics and forecasts are planned to be examined in a pursuing research framework for the success factors of hardware start-ups.

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