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Hardware Start-ups in the Scale-up Process of Production – A Mapping of Challenges

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Abstract. The paper sets out to increase the understanding of how hardware start-ups scale-up their production, and elaborates further on the challenges they are facing in this phase, often called "the valley of death". The research design is based on a qualitative approach and data collection through deep-interviews of 14 hardware start-ups and 7 production experts with extensive experience of production scale-up. A theoretical review adds to the understanding of the relatively immature field and supports the data analysis. The study presented in the paper is part of an innovation project called "*Production Angels*" which is a new concept developed for the purpose of supporting Swedish hardware scale-ups to overcome the valley of death, and to produce their new product in Sweden instead of outside the country which is often the case. Many hardware start-ups do not survive this phase of the innovation process, ending up in selling the product idea or even company. The results of the data collection elaborates on a number of challenges the start-ups meet in the production scale-up phase, here categorized into seven areas; financing, market analysis & feasibility study, production competence & team building, prototype development & manufacturing, production process understanding, suppliers & manufacturers, and support from the innovation system.

Keywords. Hardware start-ups, scale-up, production, manufacturing, valley-of-death.

Introduction

The combination of the recent century's globalization together with the development of new technology has thrown the global market of manufacturing into a new competitive situation [1]. Manufacturing companies face constant challenges in improving their competitiveness, e.g. by launching new products. Using innovative technologies is another way [2]. This new industrial landscape also opens up for new business opportunities. Despite the competitive situation, Sweden has experienced a remarkable increase of newly registered firms during the recent years [3]. The increase of new innovative firms contributes to strengthen the country as an innovative and entrepreneurial nation [4].

In order to not only become a competitive nation in innovation and entrepreneurship, but also to strengthen our position as a future option on the global market for manufacturing, Sweden has yet challenges to address; 23% of the newly registered firms, further on denominated as start-ups, whom registered in 2012 filed for bankruptcy within three years [5]. These challenges of managing the scale-up process is often referred to as

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crossing "the valley of death" [6]. The notion refers to the significant amount of start-ups that meet difficulties in the ramp-up or scale-up process when managing the journey from conception to volume production. A frequently used strategy to pass this "valley of death" for hardware start-ups is to search for a contract manufacturer whom will operate the company´s production, partially or completely [7]. Since these contract manufacturers often operate on international markets, the settlements can lead to fatal consequences for the start-up as well as for Sweden in form of lost production opportunities. An international contract manufacturer increases the distance between research & development (R&D) and production [4]. The longer distance between start-up and manufacturer may also create additional challenges in the long run.

This paper is based on findings from two of the author's bachelor thesis from KTH Royal Institute of Technology as part of the innovation project "*Production Angels*". The aim of the explorative paper is to increase the understanding of the often neglected production scale-up phase, and to discuss the issues and challenges hardware start-ups perceive when starting production. The goal is to understand the start-ups' conditions to avoid the risk that they locate the production abroad or not even enter the scale-up phase at all but instead sells the product or company – often abroad. The paper elaborates on the current situation at the Swedish start-up scene of hardware products, and sets out to present some early findings demonstrating examples of challenges the studied start-up companies are facing in the early production phase and what they do to handle these challenges.

1. Theoretical framework

1.1. Upscaling of production

In the literature research process, a large literature gap has been found within the area of hardware start-ups in the scale-up process. There exist, however, some literature on the field of software development in start-ups and why these companies often fail [8, 9]. Despite a comprehensive research process including fields such manufacturing, entrepreneurship, innovation and management, the hardware scale-up literature is conspicuous by its absence.

It is critical for a hardware start-up to reach the desired production volume in a cost and time efficient way. The following are stated as differences between upscaling and a stable production [10]:

- Interruption - the scaleup production needs to pause to make corrections
- Uncertainty – difficult to plan during scaleup due to uncertain parameters
- Defects – something wrong with the product or production process
- Learning – new information for improvements are revealed
- Increased growth – the demand might increase during product launch
- Price reduction – the production cost per unit is decreased during scaleup
- Finite horizon – the upscale process is finite and followed by stable production

As a very first step of the scale-up process, the design and manufacturing of the prototype is crucial. Prototypes have different purposes, where the demo prototype is often

the first one that is made and used during internal discussions or presentations for investors. The most mature prototype is sometimes called a series prototype, which is developed to be manufactured in an industrial environment and in a larger quantity. Prototypes are useful during the development of hardware products, but expensive to develop. The cost could be as high as thirty percent of the total product development cost because of the material and competence demanding processes [11]. According to Elverum and Welo, (2016) prototypes can be used to validate and verify different construction and functional aspects during the development of new products [12]. Prototypes can add value during the product development phase by simplifying the communication of the product to customers and investors and increase the understanding of its components [11]. Prototypes can also be used as a communication tool between product design and production design and support the product development being made in parallel with the development of the production system [13]. The prototype visualizes the ideas of the product design and helps putting attention also on the manufacturability of the product. Furthermore, the use of prototypes for testing can increase the knowledge of the process, thus ease the production scale-up. Involving the production function early in the product development phase is important in general [13]. This is true for the effectiveness of the industrialization of products in manufacturing companies with already established production structures. For start-ups without any existing production competence, assets or capabilities, the prototype becomes a fundamental tool for communication.

Using external companies for production activities previously made internally is called outsourcing [14]. Outsourcing entails that the company needs to make decisions regarding which competitive factors to be prioritised, e.g. make or buy decisions. Five factors of competition that are considered for such decisions are listed below [7,15]

1. Lower cost – reached by manufacturing in low-wage countries, high volumes and by using the same platform to multiple customers or an innovative design
2. Quality – the manufacturing companies are experts in their respective areas, leading to the manufacturing of high quality products
3. Speed– specialised manufacturers may offer shorter lead times by investing in process technology, thus ensuring a high flexibility towards customers.
4. Flexibility – by using external manufacturers there is greater flexibility to follow rapid technical developments and reduce time to market.
5. Innovation – the purchaser can benefit from the supplier´s higher ability of innovation to improve product quality. Utilising the investments and innovations of the supplier can be more effective than trying to recreate them.

These factors for competition are contrary to each other, thus the companies are forced to trade-offs in their buy or make decisions [15]. Although outsourcing refers to existing manufacturing being transferred and not the start-up of new production, it could be interesting to learn from the outsourcing experience over the last two decades. A company´s production capability is often connected to a global network of suppliers and factories, which makes the company dependent on the range of these factories. The customer must adapt their products to the suppliers and the competitiveness is consequently affected by the capacity and capabilities of the supplier. Hence, there is a connection between product design and manufacturing and even the products that are developed internally must be integrated in the production system of the supplier [16].

1.2. Supporting the production scale-up

Entrepreneurs starting new companies is a recognised driving force to growth in regional economies. There are investments by both international and national actors to support and stimulate all types of entrepreneurship, for example financially through incubators or accelerators [17]. Accelerators is a structure or a concept that could be seen as a development of the incubator concept, and where the new company is offered both office space, support to build prototypes and access to a large network of investors and suppliers [17]. Sweden has a large quantity of incubators that strengthens the competitiveness of the country´s start-ups. In 2017, 217 start-ups where connected to incubators [18]. The development of accelerator programs for start-ups in hardware production has been successful in e.g. Shenzhen, China. In Shenzhen, often called the Asian Silicon Valley, there is a large ecosystem of digital technology with an extensive network of accessible production tools and open hardware [19]. This enables collaboration between different actors in the process of innovation, which makes it easier for production scale-up and the developments of prototypes. This environment is beneficial to companies that wish to scale their production, and has enabled a large quantity of active start-ups and accelerators. Some of the accelerators offer storage, prototype workshops and assembly lines, thanks to local resources. This open hardware in Shenzhen enables start-ups to produce in small quantities [19]. However, the fast development and growth of new hardware entrepreneurs in the China Shenzhen (e.g. supported by the HAX hardware accelerator) will most likely result in more research in the area, as presented in e.g. Lindtner et al. (2015), talking about "the maker movement", and stating further that many hardware face difficulties in transitioning from hobby to professional making and manufacturing [20].

2. Research methodology

The empirical base for answering the research questions consists of three phases: planning, data collection and data analysis, performed in sequential order which means that the analysis was made not in parallel, but after the collection of the data finished. The analysis aims to identify general connections, and analysing after collecting reduces the risk of unconscious influencing the interviewed respondents [21]. Based on the analysis of the empirical material, some early theoretical findings have been introduced [22]. The study is qualitative, creating an understanding of the phenomenon [21]. The focus of the study fulfils the *how*-question, motivating the case study methodology [23]. However, the research design used could not be described completely by the case study methodology due to a couple of reasons; the study has an exploratory approach and sets out to describe the phenomenon and the current status of hardware start-ups scaling up production. Therefore, a number of companies as well as experts have been in focus rather than one or a few cases. The data collection is based on a larger number of extensive deep-interviews, contributing to an understanding of the specific case and the phenomenon at large. The selected method has contributed to a contextual understanding, supporting an elaboration of the generic problem. One criticism against the qualitative method as research design is that it risks being to context specific and subjective [24]. Here, this is handled by selecting a larger number of interview cases in order to get an initial and broader picture of the phenomenon, rather than a thorough description of e.g.

one single case. The perception of the research areas lack of maturity has motivated the selection of research approach.

The starting point of the study was to formulate the aim and the guiding questions and to delimitate the problem, guiding the next step which was to work on the research design of the data collection and analysis. The interview was selected as a suitable technique for collecting the data, and the identification of sources for this data collection was one part of the planning procedure. The source of information was divided into two categories; 1) start-up companies and 2) experts with doucmented experience of start-ups and production scale-up. The reason for adding the second category for the interviews as part of the research design, was to include a more experience based and knowledge-oriented perspective of the area or phenomenon. The start-ups were selected based on a number of criteria: a) to be a fairly recently started hardware start-up company, i.e. a company with less than 7 years since corporate registration and operating in the industry of tangible products, with performed production scale-up or with the intention to scale-up towards volume prodution. The delimitation of 7 years was motivated by the possibility of the company performing a successful scale-up within the time frame; b) to include also companies failing the scale-up in the selection criteria; c) both national and international companies were included (the international companies had succeeded through the support of hardware accelerators and other facilitating organizations); d) companies from different market segment for hardware production were selected to get a general picture. For the selection of experts, production experts invited for the Production Angel panel in the pilot run at KTH Södertälje Science Park in 2018 were interviewed complemented with experts operating in research centers and accelerator programs. The sources, i.e. respondents in the study, were identified and selected though databases like Orbis, and by an ad hoc procedure based on recommendations from incubators, accelerators, research centras, researches network as well as own contacts. The response rate was 46% resulting in an inteview. In total, 14 hardware start-ups were interviewed, and 7 production experts.

The methodology for the data collection was the same for both focus groups, i.e. sources of information; A draft of the interview questions (formulated based on the aim and research questions) was prepared before every interview and sent to the respondent. The formulation of the interview protocol could be described as an iterative process since it developed gradually during the period of data collection, mainly by changing the order of the questions in the protocol to secure that the most important questions were prioritized if the time became an issue. The focus of the study evolved as the understanding and the knowledge of the area increased. The semi-structured interviews were organized around themes and areas of questions, rather than being solely specific and mandatory questions in accordance with Blomkvist and Hallin [22]. Central questions were formulated beforehand. The majority of the interviews were performed by the interviewers in pair, having different roles of being the interviewer or the one taking the notes. Both interviewers took part in the clarifying or follow-up part of each interview session. Half of the interviews were performed by skype or phone, and half by physical meetings. All interviews were taped and transcribed in three steps – first by transcription made by one of the interviewers, then the result was quality controlled by the other one, and finally corrections were made by the two interviewers together. The respondents were promised anonymity.

The data analysis was made through two phases: coding and interpretation of the data. The coding of the data was made through a categorization of the data, by searching for citations or terms in the documented interviews and based on the aim of the study. In

the next step, the terms were categorized to simplify the analysis. The categories were related to the as-is situation and the challenges of the production scale-up phase. Terms like production engineering and process knowledge etc. were also found relevant. The interpretation of the empirical material was made on the basis of the categories and their sub categories were put in relation to each other to visualize the connections and differences, and presented in the form of challenges.

The theoretical review was based mainly on peer reviewed papers, and books on e.g. research methodology. No earlier papers than 2000 was studied, and the search was made in Web of Science, Scopus and Science Direct. The main keywords were hardware, scale*up, start*up, production, manufacturing, make-buy, accelerator.

3. Results

This sections present findings of the challenges related to the scale-up process and how these are being handled in order to manage the process. These challenges are categorised as financing the scale-up of production, market analysis and feasibility study, production competence and team building, product prototype development and manufacturing, production processes understanding, suppliers and manufacturers, and support from the innovation system.

3.1. Financing the scale-up of production

A category that all experts as well as start-ups identified as a main challenge in the scale-up process was the financing. A majority of the Swedish start-ups had searched for external funds from business incubators, venture capital firms or banks. Most of them agreed that an initial fundraising is relatively available at the start-up scene. However, some polarization exists linked to the start-up's geographical location – Stockholm based start-ups mean that the competition with the high number of software companies in the region complicates the fundraising, both in terms of finding investors but also in terms of motivating a higher need of capital due to the differences in operations. The view on the difficulties in foreseeing expenses and the fact that hardware production often ends up being more capital consuming than expected, was shared by experts and start-ups.

The interviewed companies state that the initial capital is relatively available in Sweden. The problem is to extend the capital longer in the process, for example to get investors to invest before having a demo-prototype avaliable for demonstration. The manufacturing of the demo-prototype requires capital and without capital the start-up risks facing a dead-end, never even being able to initiate the real production scale-up process. The majority of the companies, however, state that capital is often enough to be able to manufacture the first prototype. The next phase of creating a factory prototype/serial prototype is a capital intense activity requiring more resources than often expected. Overall, getting funding from incubators and banks could be problematic in this critical phase before results are demonstrated. This view was also shared by the experts interviewed. The problem is summerized by an expert as the following:

"*Sometimes one can get capital but then it is not enough to be completely finished. However, one is on not ready enough to go for another round either".*

This step of the scale-up process is difficult to handle for the hardware start-ups. Those companies managing the situation mentioned the fact that they found the "right" investor as a winning factor. By that is meant an investor who without guarantees takes

the risk of making a larger capital assignment despite a decision foundation based merely only on skethes. However, it could also take several years of investments rounds. The companies in the study that had decided to finish the process and sell their idea mentioned this "return alley" as the main reason for doing so.

3.2. Market analysis and feasibility study

A smaller, but still relevant part of the respondents highlighted the market analysis and the feasibility study as a major challenge in relation to the scale-up process. This was in focus mainly among those start-ups not having performed them carefully. One of the experts identified these activities as the largest challenge, motivated by the prototype that was needed to be adapted and developed outgoing from the validated market area with its related requirements and regulations. If not being done, the development of the prototype will be more difficult and the risk of recasting the prototype several times increases. One company coming relatively far in the process with an established volume production in Sweden had, due to lacking a good feasibility study, put the price on the product too high resulting in a limited sales volume when the product was put on the market. Although the price could be motivated by a high cost of the production process, the market was not willing to pay the set price. Several experts highlighted the issue connected to the example above and stated that a common problem is to design too much, forgetting what functions that are important to the customer, resulting in a higher end-price. Also, a common challenge according to the experts is that the product is not designed for production which results in a product that becomes complex to manufacture and, therefore, requires more resources.

Another concrete situation exemplified by a start-up illustrated problems due to shortages of the feasibility study; this specific product was designed to be made in plastic and was initially produced in this material. However, as the product was put on the market there was a high interest from the customers – but they required the product to be in a metal-looking material. To meet this demand, larger adaptations were necessary in the production process, for example related to machining and control. Consequently, it required a completely new production process with new machines and the change resulted in a demand for increased capital. The company meant that this could have been avoided if the pre-study had been made in a good way, identifying the real customer needs and that the lack of this investigation costed several million SEK.

3.3. Production competence and team building

The majority of the interviewed start-up companies and experts said that the lack of production competence is a challenge in the scale-up process. The experts stated that this is a general shortage, adding that start-ups in particular lack the necessary competence to build a competitive production. This view was shared by the companies, both regarding availability of internal and external production competence. This situation in Sweden affects their strategy for the production scale-up. All interviewed start-ups having internal access to more extensive production experience had chosen to build their own production line for their production. The availability of production competence was identified as a success factor among those companies that has succeeded with their production scale-up. One start-up mentioned that it was not until a production resource was recruited that the work on prototypes and production development started. Here, it was a production student from a local university that worked only for some hours per

week with the initial production tasks. One of the experts with a background at a technology centre for innovation of hardware describes this centre where university students are recruited for the purpose of supporting production development for those start-ups that have contacted the centre. An additional consequence was that the new companies got a base for their recruitment.

Building the team for the production scale-up was mentioned by many of the experts and companies as a central challenge. Here, it is about creating the right team with the right competence. One of the experts emphasized this challenge as the most important one to handle in order to succeed with the production scale-up. It was said that a team with the right competence gets the necessary support in taking the right risks and the knowledge on how to understand its processes. Also, the majority of the experts agreed that a competent team is a success factor to drive the scale-up process forward, as illustrated by the following citation of an expert:

"It is one thing to come up with a good business idea but then to succeed with the scale-up, production and other business questions like sales and marketing demands a great team".

At the same time as the majority of the experts highlighted this challenge to be turned into a success factor, the majority of the start-ups said that it was complicated to build a team with the right competence since it was difficult to identify what competence that was needed to support the process together with the issue to find the right competence. One company that was started by a person with previous experiences from production, chose to handle the scale-up process by building a factory. This respondent also mentioned that even as an entrepreneur with production competence, it was a challenge to find other people with the right competence. It was stated that it is a difference between being employed at a production unit, vs. developing production in one's own factory. The latter case puts higher demands on the founder who not only has the responsibility for developing the production but also for developing the company as a whole.

Most start-ups perceived a lack of production support from external actors. Incubators were said to offer good business support, but was lacking knowledge to advice in questions that falls under the production area. Some companies used students, others contacted consultants to secure the production competence. One company mentioned the issue to use consultants since it only solved the current issue, besides that it was expensive in the long run. Also, the use of consultants did not increase the internal production competence. Several companies chose to source their production to contract manufacturers as a consequence of the lack of production competence – and the sourcing was often made abroad. The following citation comes from a start-up who decided to put the whole production in China:

"It was both difficult and expensive to build own production so now we hope that they somehow solve it in their factories".

The start-ups that had sold their idea mentioned lack of production competence as one of the most important reasons for finishing their investment in own production.

3.4. Product prototype development and manufacturing

Many experts and start-ups in the study mentioned the prototype development as a central challenge in the scale-up process. Interviewed companies said that this was one of the more capital requiring challenges, however, there were differences related to the product type. Technology intense products or products with low tolerance intervals categorised this issue as crucial, while other start-ups categorized it as extensive. The

experts agreed that efficient prototype development is a precondition to a successful scale-up process. Also, most of the respondents shared the same picture, that it is relatively easy to develop a prototype serving the purpose of demonstration. It is often made in a material which is easy to manufacture, but it is often not the same as the final product. This is considered to be one of the reasons behind the challenges. One start-up had developed a prototype in plastic, and it was not until the development of the serial prototype in a more environmental friendly material that the company discovered that the material required new demands on both design and manufacturing. It resulted in the company having to go back to the drawing table again. All experts and start-ups agreed that there is a great difference between demo- and series prototype, since the serial- or factory prototype puts other demands on the production process and the development of it. Also, it is agreed by many of the respondents that it is problematic to find actors with space and resources that could be considered a "Prototype Lab".

The development of the prototype could get expensive, often more than expected. The interviewed international start-ups participated in accelerator programs where fast prototype development was a central point of the program. One start-up in Shenzhen made a serial prototype in 3 months, while previously working on it for two years without succeeding. The large network of suppliers and material was put forward as a success factor in the Shenzhen area, and important to the prototype phase. Also, the requirements on the connection between the prototype and the production process resulted in challenges, as in one example where the design of the demo prototype put too extensive requirements on the production process. To cite an expert:

"You have to test with production all the time. If a prototype costs 800 000 SEK to develop, you cannot rebuild it several times".

Or citing another expert:

"You have to build as much knowledge of your product as possible, otherwise you risk that the development of the prototype takes too long time and you run out of money".

3.5. Production process understanding

A smaller part of the start-ups and experts interviewed identified (production) process understanding as a central challenge. It relates both to production competence and prototype development meaning an understanding of what production processes that contribute to the creation of a finished product. One company in their production scale-up process mentioned that the lack of having access to a workshop hindered them to build knowledge about the product and an understanding of the production processes that it required. Another start-up had designed a small-scale production unit which contributed to the understanding of the production process in order to support the discussion with the contract manufacturer. This particular start-up had the ambition to get the product out on the market in a relative high speed and that was their reason for contacting the contract manufacturer instead of building own production, growing more organic and scaling up step by step. The challenge was here to find a manufacturer that could handle the process according to its initial design.

As mentioned, all start-ups in the study that started own production had production competence in the team. As put forward to describe the strategy:

"By understanding the process we can get everything in place and have a stable production tact. We will develop the production in-house until we have a functioning product and good volumes. In the long run we might outsource simpler parts of the

production but since the product is new/fresh it is good to have production close to the (note. product) development".

One start-up mentioned that the understanding of the product is essential in order to design the production process and that an understanding of the process cannot be reached until it delivers products according to specification. Although being a challenge, the understanding of the production process can be translated into own control of the specific processes. This view was shared by those experts identifying process understanding and knowledge as a challenge.

3.6. Suppliers and manufacturers

With only a few exceptions, all start-ups and experts considered it to be a main challenge to find manufacturers and suppliers. Here, they defined suppliers as actors supplying the company with components and material, while manufacturers refer to actors which partly or completely produce the product for the start-up company. Not having an existing network of manufacturing companies was one difficulty, not being prioritized as a small customer was another part of the challenge. As one start-up said:

"We have had repeatedly problems with finding good suppliers. We had initiated a collaboration with two different suppliers which both chose to finish our collaboration when they got larger orders. We have been approximately 1,5 years delayed due to the supplier problem".

Another start-up stated:

"*It is difficult to find suppliers. The challenge is to find a supplier with reasonable prices while also being flexible and having short lead times. When you have high volumes, this is not a problem but it is difficult in the scale-up phase when you still produce in small volumes"*.

According to several respondents, low volumes do not only result in lower prioritization but create also higher cost per part as a consequence of not having advantages of scale. It may force the start-ups to put higher prices on the products than the market is not willing to pay, i.e. the volumes do not come. One start-up had set a low price to become established on the market, which had put them into a critical situation where they will go bankruptcy if the volumes do not increase. To handle the situation, most start-ups in the study turned to the foreign market in order to cope with the financial calculations. Both suppliers and manufacturers of larger parts of the product were contracted internationally, the majority had contracts with actors in Asia and the Baltics. The few start-ups with products within the sustainability segment did, however, not consider contracts with actors far away as an option (like in Asia). Longer delivery times, and reduced transparency of the processes were negative consequences found of using international suppliers and manufacturers, but they did not find the Swedish market to be an alternative due to higher costs. The experts on the other side emphasized the advantages of having local actors for the production, especially in the initial phase when it was considered important to be close to the development to handle early problems. It was also added that the initial advantages of low-cost countries will be neutralized with the current increasing automation in production. Still, all experts pointed to the advantages of buying sub-components and to use suppliers for parts of the production which are not strategically important to the hardware start-up. This is preferably done locally though as illustrated by the following citation from an expert:

"If you can produce or buy geographically local you save a lot, especially in early phases when there are many issues. We are moving towards a society where just-in-time and delivery times becomes even more critical. It means that it might be worth paying another 20 % extra given the delivery of the parts within a day compared to three weeks. The quality control of the process is important and I believe the costs could be reduced this way compared to only think of cheap labour".

The international start-ups interviewed highlighted short delivery times and short distances to both suppliers and manufacturers as success factors in the scale-up process. In Shenzhen, it was even possible to take a look at the components and then have them delivered one hour later. That was one reason for many start-ups establishing their business in the Shenzhen area, along with the possibility of building own production capabilities there.

3.7. Support from the innovation system

A large part of the interviewed Swedish start-ups had participated in incubator programs, and they all emphasized that the support from the incubators were focused on business related aspects such as financing, market analysis, sales, marketing and leadership. Being part of a context and sharing knowledge with other start-ups was found positive. However, all agreed that production focus was missing in the incubators as put forward by one company:

"When we finally were going to produce, we had no idea of how you do. We had no longer a need for business support but a very big need for production support".

Most start-ups had not thought about production before it was to be developed. This was one of the reasons why they decided to go through with the scale-up process with help from a contract manufacturer. All start-ups participating in an incubator program stated that they would have wanted production as a part of the program, helping them to start thinking of production in an early phase. Also, a production oriented coach similar to the business coaches was needed to facilitate the process, according to the respondents. Having a sounding board, i.e. someone with long experience of production, combined with a service connecting them with different actors like suppliers and manufacturers, was proposed to be part of the incubator program. No start-up in the study had access to any production related lab. The interviewed international start-ups had participated in a business incubator program besides the hardware accelerator program, where the latter one focused more on starting up production which clearly reduced the time for scale-up.

4. Discussion and conclusion

The results paint a picture of some of the challenges hardware start-ups face when going from the early phase of having a business plan and some product drawings and sketches, to the preparation and scaling up of the production of the product. The 14 start-up companies and 7 experts interviewed in this study share, in most cases, the same picture. The overall situation could be summarized in Table 1:

Table 1. Challenges when hardware start-ups scale-up their production

Challenge category	Challenges - factors
Financing scale-up	• Requirements to show proven results • Need for enough capital to realize a functioning demo prototype and in the next step, a functioning serial (factory) prototype • Need for more capital than e.g. software products • Difficult to foresee production related costs, i.e. capital needed • Difficult to find the "right" investor (flexible, long-term strategy)
Market analysis & feasibility study	• The product needs to be designed for production from the outset • Risk of not meeting market demands due to lack of feasibility study, e.g. by wrong pricing strategy or wrong material
Production competence and team-building	• Lack of production competence within the internal team • Difficult to find external competence • Incubators lacking production competence
Prototype development & manufacturing	• Difficult to find available actors to create the prototype – need for "prototype labs" • The development of the serial prototype is capital intensive • Extensive product knowledge is needed to create a good prototype • Big difference between (simple) demo prototype and serial prototype (requiring extensive focus on the production process) • Prototypes can become very expensive (more than calculated)
Production process understanding	• Need for production competence • An understanding of how production processes contribute to the realization of a finished product needs to be created • Lacking a "shop floor" lab to build product knowledge and understanding of corresponding production processes
Suppliers & manufacturers	• Difficult to find suppliers of components and manufacturers for larger parts of the product • A small start-up is less prioritized by the suppliers • No economy of scale advantages due to low volumes resulting in higher costs affecting pricing strategy, and risking volume growth • Long-distance suppliers prolong delivery times and reduce transparency and control
Support from the innovation system	• No production support in the incubator programs • Incubator programs not preparing start-ups to think about production in an early phase, resulting in the use of contract manufacturers • Need for an experienced production coach, similar to business coach

The results point at a number of challenges as summarized in Table 1. There are many different challenges a hardware start-up meets when initiating the production scale-up phase. A central challenge is evidently the lack of production competence, both within the internal corporate team and to find right external production competence, as well as within the support functions in the innovation system (like incubators). Some companies had solved the problem by involving production engineering students just to get started. The need for support from experienced production experts was expressed by all respondents. Besides the lack of competence, the lack of financial capital was a challenge, from finding the "right" investor to getting enough money to create the prototype and to get started. As always, the preparation phase determines much of the final result. It was stated that the feasibility study was very important to be able to prepare the right product for the market, and also to design the product for production. A category of challenges was related to production process understanding; to understand production and how it could contribute to the product. The challenges with designing for production and understanding the process are in line with Kampker et al. (2017) as well as Javadi et al. (2016) [11, 13]. Production competence and production labs were mentioned as

challenges in achieving this necessary production understanding. The question of make or buy – and who should be responsible for components manufacturing or for manufacturing or assembling larger parts of the product – was obviously a big issue for all start-ups. They expressed the challenge of finding the suppliers, and the problem of being low prioritized compared to larger customers. The small-volume issue not only resulted in not being prioritized by the suppliers but also resulted in higher production cost which, in the end, had to be handled through a higher price to customer. The issue of supplying globally was also highlighted including the different problems related to it, like long lead times and lack of transparency and control.

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The study presented in this paper is an early work performed with the intention of increasing the understanding and knowledge of a field that is quite underestimated both as part of the innovation process and the innovation system as such, where e.g. the incubators supports the business part but not at all the production scale-up. Similarly, to the best of our knowledge there is not much research that supports the knowledge building of how to scale-up production if you are a new start-up with a hardware product idea you want to realize. While scaling up in a general sense could be highlighted, it still becomes an abstract idea which does not end up in concrete support on its operationalization, i.e. on how and what to do in practice to actually produce the product in a growing production volume – with the right functions, in the right time, and with a competitive price that the market is willing to pay for.

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