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Characterizing Product Development Processes in Start-ups – an Empirical Study

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Abstract: The development of the first product generation of start-ups is under particularly high pressure to succeed. Start-ups are known for products with a high degree of novelty and therefore a high potential for innovation and high technological risk. Current approaches to support the development of the first product generation (G_1) with no direct predecessor rely on data from established companies. The product development of start-ups differs in many aspects, one is the lack of availability of internal empirical knowledge and references. The model of PGE – Product Generation Engineering offers the potential to identify, describe and support these characteristic influencing factors. Through literature review, an in-depth case study with a medical technology start-up and semi-structured interviews with three German start-ups, distinct characteristics of the G_1 product development of start-ups could be identified. Based on these findings, fields of action for methodical support were derived for prospective use in future research.

Keywords: Agile product development; Product Generation Engineering; Start-ups; Innovation management; Case study

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1 Introduction

The term "start-up" is often associated with a small team working on the next million-dollar idea in a garage. Former start-ups such as Amazon, PayPal or Facebook create the impression that the right idea at the right time is enough to be successful (Foo, 2012). But in reality, failure is more likely than success. As it is reported, over 90 % of start-ups fail (Söldner, 2019). The reasons for failure are diverse. They reach from "bad marketing" in the case of Segway to "was overtaken by competitors" in the case of StudiVZ (Triebel et al., 2018).

Start-ups are known for products with a high potential for innovation and a high degree of novelty, but they have to deal with limited financial resources and high technological risk (Bolumole et al., 2015). Additionally, the development of the first product of start-ups is under particularly high pressure to succeed because it is a critical factor for the survival of the new venture (Gartner, Starr and Bhat, 1999; Schoonhoven, Eisenhardt and Lyman, 1990).

One of the biggest challenges for start-ups is the product development itself (Kollmann et al., 2020). The objective of this work is to support the product development of the first product generation of start-ups to tackle the mentioned difficulties. But the product development processes within start-ups are often less structured and less formalized (Marion, Friar and Simpson, 2012), which makes empirical observation difficult.

With the model of PGE – Product Generation Engineering it is possible to achieve a comparable description for every product development process. Within this study, influencing factors are identified which characterize the product development process of the first product generation of start-ups. These findings are based on a literature review and a case study with a medical technology start-up. To validate and complement the identified factors, three interviews with start-up founders were performed. Finally, fields of action for methodical support are derived because the use of efficient methodology is essential for start-ups (Chacko and Suresh, 2021, p. 692).

2 State of the art

2.1 Type of enterprise "start-up"

The term "start-up" is defined by various authors. Hahn understands a start-up as a new venture during its founding process which seeks for capital (Hahn, 2018, p. 4). Vetter provides other constraints on the term, such as an uncertain future (Vetter, 2011, p. 63). The *German start-up Monitor* refers to start-ups as companies that are younger than 10 years, have planned employee and sales growth, and offer products with high innovation potential (Kollmann et al., 2020, p. 18). With this definition, it is possible to separate start-up founding from classic business ventures (Kollmann, 2019, pp. 3–4) which shall not be taken into consideration during this study. Other differentiating features of start-ups compared to traditional companies are the very limited possibilities and resources (Antolín-López et al., 2015, p. 26; Marion, Friar and Simpson, 2012, p. 651).

Failure is not the exception but the rule for start-ups. Only one in twelve new ventures is successful (Startup Genome LLC, 2019, p. 19). The reasons for failure are manifold, therefore only some of the most common shall be explained. Personal motives such as problems within the team could be identified as one of the most mentioned reasons why start-ups fail (Kulicke and Kripp, 2013, p. 10). Another reason is the development of a product which the market does not need (CB Insights, 2014, p. 4). Furthermore, scaling too much at the wrong time causes startups to fail (Startup Genome LLC, 2019, p. 20). The last reason to mention is the technological risk which is often too high to be managed (Kulicke and Kripp, 2013, p. 11). As it could be seen most of the reasons are caused within the venture itself. Product development is one of the areas that have the greatest impact on the reasons for failure mentioned above. Therefore, this study examines product development in a start-up environment.

2.2 PGE – Product Generation Engineering

The model of PGE – Product Generation Engineering according to Albers is based on the observation that products are not developed from scratch but are always based on references and previous generations. Two central hypotheses are the basis of the model of PGE. (Albers et al., 2020; Albers, Nikola Bursać and Eike Wintergerst, 2015; Albers and Rapp et al., 2019)

- Each product is developed based on a reference system R_n (see figure 1, left). Elements of the reference system (RSE) originate from existing or already planned socio-technical systems and the associated documentation and serve as a basis and starting point for the development of a new product generation G_n.
- The subsystems of a new product generation are developed based on reference system elements exclusively by three types of variation: During the carryover variation of a subsystem (CV), the corresponding reference system element is carried over and is, if necessary, only adjusted at the interfaces during the system integration. Variation of attributes (AV) is the new development of a subsystem while retaining the solution principle of the reference system element and changing function-determining attributes. In the new development by principle variation (PV), the function of the reference system element is fulfilled by an alternative solution principle.

The ratio of the number of subsystems developed by a particular variation type to the total number of subsystems of the new product generation gives the variation share of a variation type. The shares of subsystems developed with AV and PV can be understood as the new development share of a product generation. (Albers, Nikola Bursać and Eike Wintergerst, 2015)

Various case studies have shown that the characteristics of the RSE used and the type of variation, with which new subsystems are developed, are influencing factors on development targets such as cost, risk, innovation potential, and necessary development activities (e.g., Albers, Bursac & Rapp 2017). The impact of the origin of RSE and the share of AV and PV on the risk of the considered subsystem of the G_n can be visualized with the PGE risk portfolio (see Figure 1, right). Besides the type of variation and the origin of reference system elements, the complexity and the maturity level of RSE are further influencing factors (Pfaff, Rapp and Albers, 2021, in print).

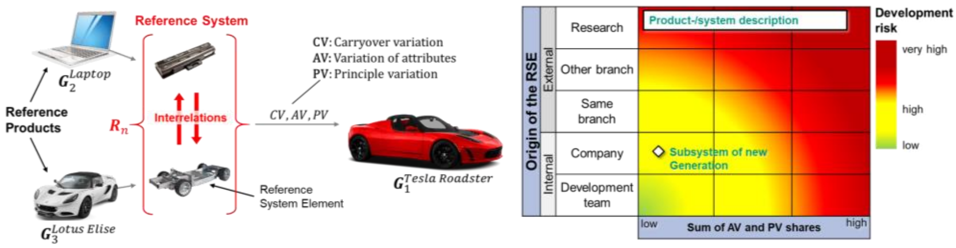

Figure 1 On the left: The reference system in the model of PGE (Albers and Rapp et al., 2019); On the right: PGE risk portfolio (Albers et al., 2017)

2.3 Product generation one (G_1) in the model of PGE

If the development of a new product generation is started in a company with no direct predecessor in its reference system, it can be characterized to be the product generation one (G_1) (Ebertz, Albers, and Bause 2019).

However, it is often not possible to make a definite statement as to whether a product generation is a G_1 or not. Instead, it should be considered how strong the G_1 character of a product generation is. The prospective characterization of the G_1 character of a product generation can be supported with the G_1 classification scheme. This uses seven criteria to assess whether the system under investigation can be understood rather as a G_1 or rather not. (see figure 2). (Albers et al., 2021)

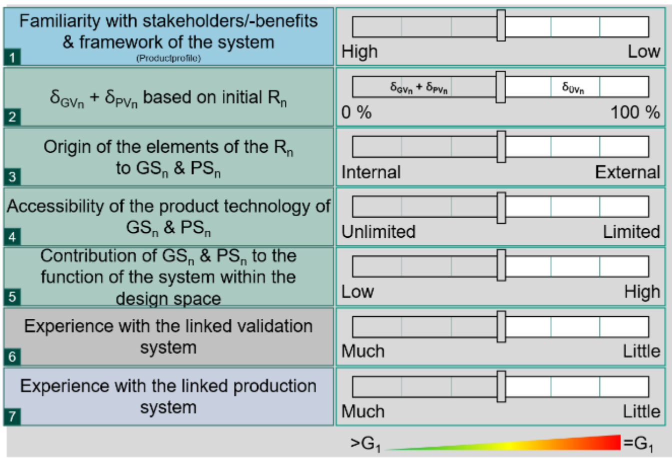

Figure 2 G_1 classification scheme (Albers et al., 2021)

Several potential implications follow from the classification of a product generation with a high G_1 - character. For instance, these developments often have to deal with a high development risk, a high amount of variations during late development stages and high validation efforts due to lack of empirical knowledge. (Albers et al., 2021)

2.4 Development processes – agile vs. plan-driven approaches

Product development can be modelled as the continuous interaction of the operation system, the system of objectives and the system of objects. The system of objectives includes all objectives, requirements and constraints of a product to be developed and their rationales and dependencies. The system of objects contains all documents and artefacts that represent solutions corresponding to the system of objectives. These are market-ready products as well as all intermediate and partial solutions such as drawings, models and prototypes. The operation system is a socio-technical system consisting of structured activities, methods, processes and the resources required for realization. The operation system creates the system of objectives and the system of objects and links the two together. (Albers and Lohmeyer, 2012)

Agile approaches originate from software development and are based on the agile manifesto (Fowler M, 2001). Through a systematic literature review, Albers, Heimicke at al. summarize the current understanding of agility in product development: Agility can be defined by the ability of an operation system to react to changing circumstantial conditions and to make changes in the sequence of synthesis and analysis activities in the project plan to achieve the greatest possible value for users, customers, and providers through the product. (Albers, Heimicke, Müller and Spadinger, 2019)

This is in contrast to plan-driven approaches to product development, which demand a definition of product requirements at the beginning of a project and planning for long time horizons (Petersen and Wohlin, 2010).

A core principle to support development teams in the development of mechatronic products in agile, plan-driven and hybrid projects is that each product is developed based on references (Albers, Heimicke and Spadinger et al., 2019).

3 Research questions and research methodology

The overall aim of this research work is to support start-ups in the product development of G_1. Current approaches to support the development of G_1 (Albers et al., 2021) rely on data from established companies but the product development of start-ups differs in many aspects. For successful methodical support of the development of G_1 within start-ups, it is necessary to identify characteristic influencing factors for the G_1 development process of start-ups. The model of PGE offers the potential to identify and describe these factors systematically. The following research questions have to be answered:

- Which influencing factors are characteristic for the development of G_1 in start-ups?
- What are fields of action in which start-ups should be supported in the development of G_1?

To answer these questions, this contribution uses data and insights from four start-ups located in Germany (one case study and three interviews). These develop and produce mechatronic products both for consumers (three start-ups) and for industry (one start-up). The companies are operating in different branches: Medical technology, sports equipment, microtechnology, and image detection using artificial intelligence. The G_1 classification scheme (section 2.3) and the PGE risk portfolio (section 2.2) are used retrospectively to compare and interpret the investigated product development processes.

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Thus, the evaluability and comparability with data of previous studies (e.g. Albers et al., 2017; Albers et al., 2021; Albers and Rapp et al., 2019) are granted.

At first, characteristic influencing factors for the development process of start-ups are identified through a literature review (section 4.1). The resulting factor model is validated and complemented through a case study in a medical technology start-up of which one of the authors is an employee (section 4.2). The case study is based on data gathered in different ways such as a workshop, participant observation in development projects and the analysis of internal documents. The results from the literature review and the case study are combined into an initial factor model and used to design semi-structured interviews with founders of start-ups (section 5). Three expert interviews have been performed with founders of operating start-ups. In the semi-structured interviews, the previously identified influencing factors are validated, complemented and their influence on the development of G_1 in a start-up environment is discussed. All interviews were recorded and subsequently transcribed. Based on the resulting factor model, fields of action for methodical support for G_1 development processes of start-ups are derived for prospective use in future research (section 6).

4 Identifying influencing factors on the G_1 development process of start-ups

4.1 Literature review

Through literature review, seven influencing factors characteristic for the first product generation of start-ups could be identified (see figure 3).

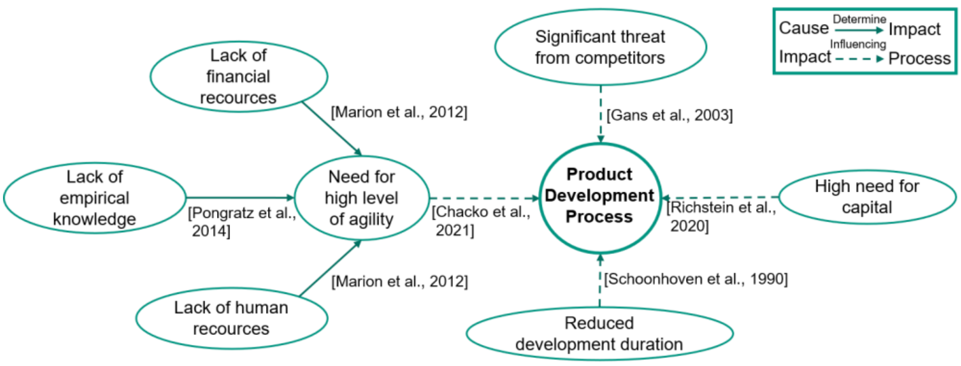

Figure 3 Initial influencing factor model with factors from literature

For instance, Marion et al. state that product development processes within start-ups cannot be compared with established companies. The main differences are a *lack of resources* (financial and personnel) and the need to *reduce the development duration* to achieve financial independence. This results in a less formalized development process. (Marion, Friar, and Simpson 2012; Schoonhoven, Eisenhardt, and Lyman 1990). The resulting *need for a high level of agility* (as defined in section 3.4) could be identified within two separate case studies from the literature. Chacko and Suresh use a multi-criteria performance index to assess the agility of start-ups and classify the product development process of the start-ups investigated as agile (Chacko and Suresh, 2021).

Hoffmann detects agility in start-ups through the occurrence of the reactions to changes caused by unplanned events (Hoffmann, 2020). Start-ups have a *lack of empirical knowledge*, especially in the planning phase, because they have no practical experience to refer to (Pongratz, Bernhard and Abbenhardt, 2014, p. 399). *Significant threat from established competitors* comes with the dilemma that those companies that would be potential partners are also the ones most likely to imitate the product (Gans and Stern, 2003, p. 334). The *high need for capital* is stated typical for products based on new technologies. (Richstein and Schierstedt, 2020, p. 56)

4.2 Validation and completion of the influencing factors through an in-depth case study

The subject of this in-depth case study was the development of a device for treating insect bites with locally applied heat, called *heat_it* (see figure 4). This device has been developed by the medical technology start-up Kamedi located in Karlsruhe, Germany.

Figure 4 *heat_it* connected to a smartphone displaying the user interface

The *heat_it* was the first product generation launched by Kamedi. It started as an idea for a student competition. Insect-bite-healers already existing in the market were bulky and not ready for use at all time. Therefore, the product claim was, that "we need a product, which treats insect bites effectively, is handy to use and always available." It was decided early that the device should be designed as a smartphone add-on. The battery of the smartphone provides the necessary energy. This made it possible to carry over (CV) the active principle but at the same time miniaturize the device (AV). To adjust the treatment parameters "duration" and "temperature", a smartphone app was developed.
The subsystems were categorized into the PGE risk portfolio (see figure 4). The AV and PV shares add up to 50 % at the system level under observation. The high AV and PV share and the high amount of external references resulted in high development risk.

The development has been characterized with the G_1 classification scheme (see figure 5), according to which the *heat_it* can be considered as a G_1. This is mainly due to the low level of in-house knowledge. The RSE of the *heat_it* development were completely outside the company. Additionally, there was no experience to rely on while developing a production and validation system. Another important factor was, that the subsystems which performed the main function, had to be developed using principal variation (PV) and variation of attributes (AV). All this resulted in a high G_1 character of the development. For established companies, this classification would be a reason to reevaluate the development project and consider a change or cancellation (Albers et al., 2021, p. 11).

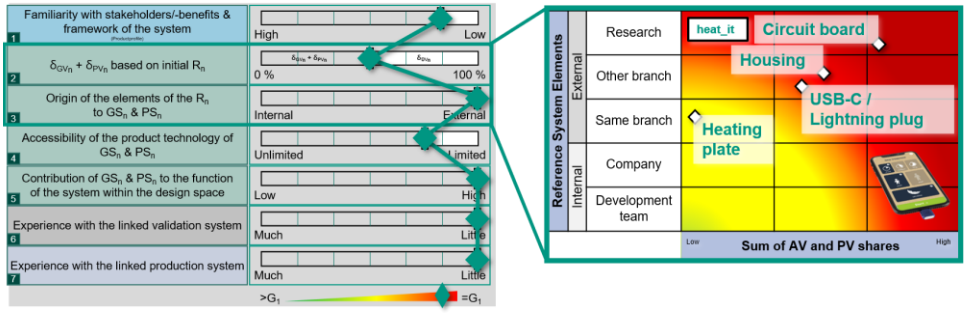

Figure 5 G_1-classification scheme of the *heat_it* including risk portfolio

Further observations were made during the development process. The start-up faced a *significant threat from a competitor* in the form of a legal confrontation during the market launch. This forced the start-up to adjust its external appearance and the app to avoid further legal steps from the competitor. A lack of experience may have been responsible for the occurrence of this incident. The *lack of empirical knowledge* led to uncertainties. Furthermore, the development was driven by the *lack of financial and human resources*. Flexible allocation of staff capacity to high-priority tasks was one measure to deal with this shortage. The start-up had to *react agilely* to deal with these uncertainties. The team had to come up with unconventional solutions, such as using a partially 3D-printed production system, to overcome financially limited resources. Additionally, the high self-motivation of the founders played an important role to overcome the challenges.

4.3 Synthesis of the findings in a factor model

As a result of the case study and the literature review, the initial influencing factor model is supplemented. Influencing factors added through the case study are optically highlighted within the figure below.

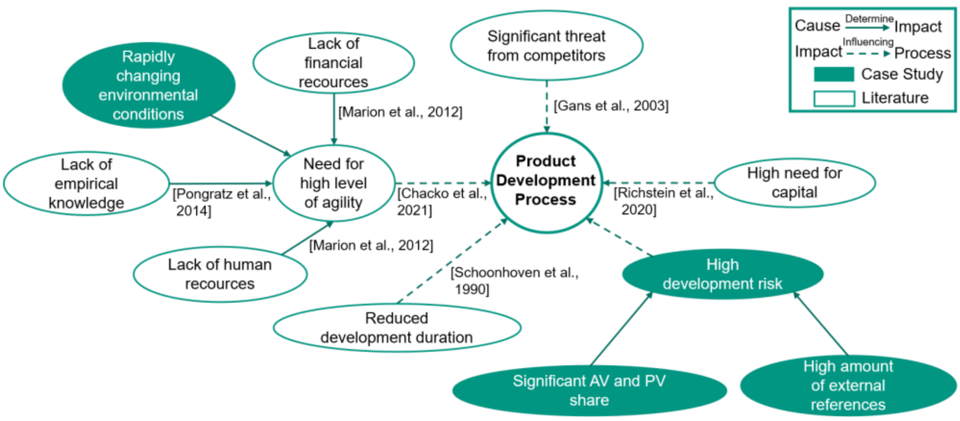

Figure 6 Influencing factor model with factors from literature and *heat_it* study

It is visible that some factors not only influence the product development process but are also influenced themselves. The high need for a high level of agility of start-ups arises from the need to cope with constantly changing environmental conditions, the lack of knowledge for planning robust processes and limited human and financial resources.

5 Validation of findings through expert interviews

To gain insights into the development processes of further start-ups during their G_1 development, interviews were performed. The interviews were planned as semi-structured interviews following a guideline (Renner and Jacob, 2020, pp. 16–17). This guideline is divided into five main topics with open and closed questions to validate the identified factors:

1. Starting situation for the development process
2. Product development process
3. Influencing factors
4. Methods and process models
5. Development risk

5.1 Structure of the interviews

Start-up founders from three different ventures (see table 1) were acquired to participate in this interview study. All founders have experience with the successful development and market launch of G_1. All products have been developed and launched during the last three years.

Table 1 Company information

Start-Up	*Branche*	*Business Relationship*
A	Sports equipment	B2C
B	Micro technology	B2B
C	Image detection using artificial intelligence	B2C

The interviews were conducted and recorded using software for video calling and lasted an average of 40 minutes. After transcription, respondents were allowed to check and approve the transcript.

5.2 Results of the interviews

The majority of influencing factors could be confirmed directly through the answers given in the interviews (see table 2). The given examples in the following table are translated due to the interview language, which was German. The source of the examples is given in brackets at the end.

Table 2 Summary of the interview responses which directly prove the relevance of the influencing factors

Influencing factor	*Examples*
High need for capital	"We then realized interim financing at the end of the EXIST scholarship and then also closed a financing round last year." (A)
High self-motivation of founders	"In the end, however, we simply worked a lot. Even on weekends and in the evenings." (A)
	"The product idea was born from a personal motivation" (C)
Significant threat from established competitors	"They try to work with a software-based solution and do not provide their own hardware. [...] This called our principle into question because we have a large development effort with our hardware product and our user interface." (C)
Lack of personal resources	"[...] there was definitely work for a lot more people and we could have done some things faster." (A)
	"We had limited or predetermined access to machines in addition to limited human resources." (B)
Lack of empirical knowledge	"With our current product, we have developed features that are "nice to have" in retrospect, but do not generate any basic value. Of course, this drags out the development process. I would change these […] points in retrospect." (A)
	"(laughs) Start-ups can't do anything." (B)
	"The second time we were able to do a lot of things better than the first time." (C)
Lack of financial resources	"Our product development just took a long time due to limited resources. The process was driven by available financial resources." (C)
	"From that point of view, I am sure that we would have been faster if the funding had not been uncertain at different times." (A)
Significant AV and PV share	"No, the material did not exist like that. It was only developed through research." (A)
	"Technically very new and with high knowledge deficits." (C)
High amount of external references	"The [...] issue that has required the most development effort and into which the most research has gone relates to the material of the band." (A)
	"The reference product is the Microgripper research […]" (B)
	"Yes, this is a very research-related topic. We partly work with models for which the scientific publications came out in the same year." (C)

Some other factors could be verified indirectly from context. The *need for a high level of agility*, which influences the product development process, was a result of the limited resources (personnel, finances, knowledge). The founders interviewed described incidents where they were forced to react agile on changing environmental conditions. One incident was an externally contracted development, which failed due to a lack of experience in the supervision of external developments (C). The start-up was forced to

react after the failure and started a new development within the company.
The *high development risk* is a result of the *high amount of external references* and the *significant AV and PV share*. The founders confirmed that subsystems with a high development risk required the highest development time.

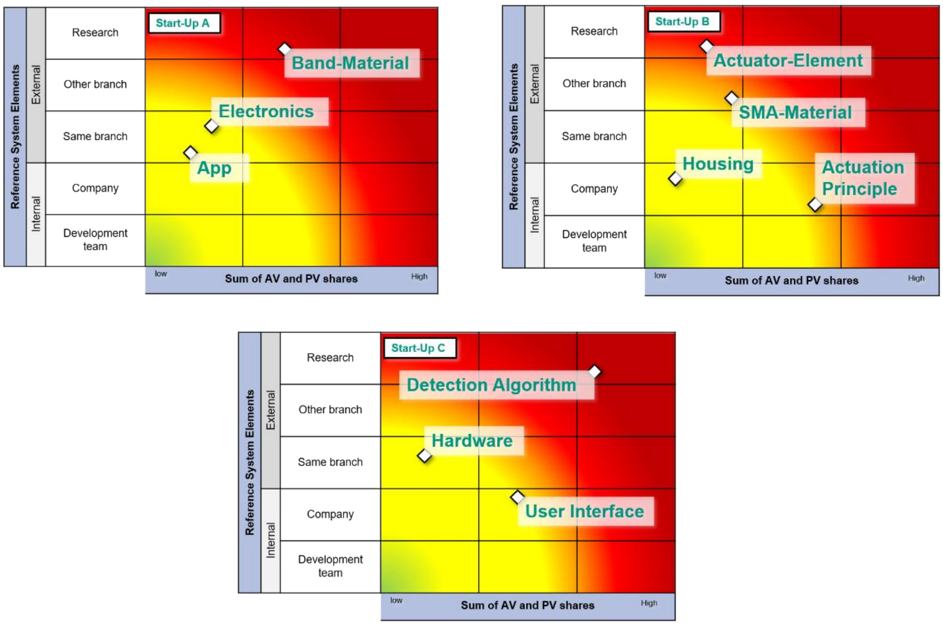

Figure 7 PGE risk portfolios from the investigated start-ups: Overall a high share of AV and PV and mainly external reference system elements

One factor could not be identified within the interviews. *Reduced development duration* seemed not to be a relevant factor. The development was driven by the financial resources available. The founders of start-up B even refused to establish a company for the first two years because they wanted to focus on research to prepare the technology for market entry. Therefore, this factor is not included in the final factor model.

The G_1 developments described were classified in the G_1 classification scheme. It became evident that these look similar to the scheme of the *heat_it* (figure 4). The AV and PV share is above 50 % for the system level under observation and the reference system elements are mainly external. Also, the subsystems with the highest development risk are the ones with the highest contribution to the main product functions. Low experience with the related production and validation system could also be observed.

5.3 Summary of the results in a final factor model

With the interview data, it was possible to verify all but one of the influencing factors. The interviews proofed that the identified factors are relevant for the development process of start-ups. This answers the first research question.

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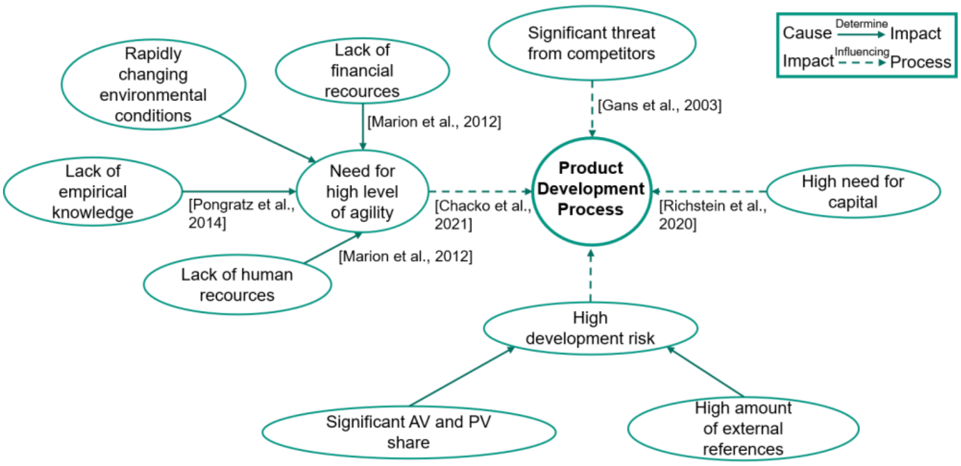

Figure 8 Reviewed influencing factors with a relevant impact on the product development process of start-ups

Two categories characterize the G_1 product development process of start-ups particularly. The first one is the *need for a high level of agility*. It is mentioned within the literature, the case study and during the interviews. Therefore, it can be suggested:

„G_1 development processes in start-ups require a high level of agility“.

Secondly, the classification of the product development processes in the model of PGE with the risk portfolio and the G_1 classification scheme showed similar results for all start-ups. In all start-ups investigated, the AV and PV share was over 50 % at the subsystem level under observation. The share of external references exceeded 80 % on average. Following this, it is suggested:

“G_1 development processes in start-ups have a high share of AV and PV and a majority of the reference system elements are of external origin.”

6 Fields of action for methodical support

Building on the possible measures in the case of strong G_1 character (Albers et al., 2021), the findings of this study are used to derive fields of action for methodical support for start-ups during their G_1 product development.
The first approach considered is *collaboration with external partners*. This is already mentioned in the literature as an important support for start-ups during product development (Friederici, 2020, p. 111; Grichnik and Gassmann, 2013, p. 133; Reh, 2020, p. 34). Based on the relevant factors, the respective goal of the collaboration can be defined more clearly. On the one hand, the lack of empirical knowledge of the founders is to be compensated. On the other hand, external partners can contribute to the reduction of the knowledge deficit, triggered by external reference system elements. Depending on these objectives, a selection of possible partners can be made.
The *implementation of a systematic knowledge management* approach should contribute to the successive reduction of uncertainty. In this context, the term "knowledge" refers in particular to experience. If the experiences from different situations are documented, they

can serve as a basis for future development generations and product generations. This could reduce uncertainty. Furthermore, the targeted use of RSE (both external and internal) to reduce uncertainty is also conceivable in this context. This could be investigated during the product development of the second product of Kamedi. It uses subsystems of the *heat_it* as central reference system elements. This resulted in a considerably lower development risk.

Finally, the *early assessment of the development risk* is an important field of action. This is based on the finding that the founders of the investigated start-ups underestimated the development risk (A, B, C). At the same time, knowledge of the level of risk at the beginning of the development was not considered beneficial (A). Putting the development risk into perspective could allow start-ups to realistically estimate the effort without taking away their openness in problem-solving. This could be implemented with measures derived from the PGE risk portfolio which are adapted to the specific start-up development environment. For example, external references are the rule rather than the exception for start-ups and therefore cannot be avoided, but the handling of them must be supported.

7 Conclusion and outlook

Through literature review, an in-depth case study and three interviews with German start-up founders, distinct characteristics of the product development of the first product generation (G_1) of start-ups could be build up using the model of PGE - Product Generation Engineering as an analysis framework. External factors such as rapidly changing environmental conditions and internal factors such as a lack of human and financial resources create an uncertain, volatile development environment in start-ups where a high level of agility is required. The use of PGE - Product Generation Engineering in the special development environment of start-ups has a lot of potentials. As G_1 development in start-ups is associated with high risks due to the high AV and PV share and mostly external reference system elements, systematic variation and use of reference system elements are key success factors.

These insights allowed the derivation of fields of action in which methodical support with high applicability and usefulness for start-ups can be developed. Collaboration with external partners can compensate for the lack of empirical knowledge and the knowledge deficit through external references. Systematic knowledge management can contribute to the successive reduction of uncertainty through development generations and product generations following the G_1. The early assessment of the development risk helps to realistically assess the development effort without limiting the solution space too much. Support in these fields of action enables start-ups to develop G_1 with a high AV and PV share and high innovation potential whilst managing risk and development effort to increase the chances of success.

The focus in this study has been on successful start-ups in Germany which have developed mechatronic products. The transferability of the results to start-ups from other industries and countries cannot be granted. The majority confirmation of the factors from the literature indicates a general validity of the results.

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