Exploring Product Development of Cyber-Physical Systems in Startups: A Status Quo Study

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Abstract: In the interconnected world of today, we experience the evolution of mechatronic systems into cyber-physical systems (CPS) through their connection to the Internet of Things (IoT). Despite their vast potential for groundbreaking applications already present, e. g. autonomous cars or smart production systems, startups face significant hurdles in developing CPS, primarily due to limited knowledge and resources. Currently, only few scientific contributions cover how hardware-containing products are developed in startups and what possible challenges can be expected. This gap highlights a pressing need for research into the specific challenges and methodologies of CPS development within the startup ecosystem. The research goal of this paper is to set an explorative foundation for understanding the product development of CPS in startups to enable further research and suiting support for future founders. This paper offers a first attempt to give a qualitative description of the status quo of the development of CPS in startups. It begins by establishing an understanding of the four main problem fields discussed in the literature on CPS development, entrepreneurship, and hardware development in startups: The impetus of entrepreneurs in CPS-developing startups (1), the ideation of the CPS in development (2), the prototyping of CPS in startups (3) and processes, methods, and tools used in CPS development in startups (4). They are discussed by semi-structured interviews. Due to the limited number of possible participants, the interviews are conducted with a sample of eight founders and employees from CPS-developing startups in Southern Germany. Their answers are used to deduce recurring patterns and contradicting positions in their subjective experience with CPS development. The result of this paper are twelve proposed characteristic aspects of current CPS development practice in startups based on the deduced patterns. With this first qualitative description of the status quo of CPS development, this paper identifies potentially relevant topics that occupy CPS founders, delivers connecting points to current research in established research disciplines and reveals current missing research activities.

Keywords: Cyber-physical systems in startups, Product development methodology in startups, Entrepreneurship with cyber-physical systems, Problems of product development in CPS-startups, Product development characteristics of CPS-startups

1. Introduction

Although European industries are known for their ingenuity in developing high-tech products in hardware-intensive industry sectors (European Commission, 2021), startups tend to focus more on the development of software-related products: Only a fifth of German startups identify technology development and production as their business model, while 65% of them identify an exclusively digital business model in their startup (Kollmann et al., 2023). This tendency to focus on exclusively digital or software-related business models and products in startups is also represented in established literature: Kollmann describes digital ventures mostly in the meaning of ventures creating exclusively software-related products (Kollmann, 2022). Although his collected description applies to many hardware-related digital ventures, he only describes the development of software products in startups. Blank and Dorf relate to technology risk as a risk easily avoided by simulations (Blank and Dorf, 2017). That statement is debatable considering aspects that cannot be simulated with reasonable computation efford, i. e. because of not fully understood design-function-relations in physical domains. The established perception of startup products as software fails to reflect the reality of hardware-intensive product development activities in startups. This is also displayed in the German Startup Monitor 2022, where product development is identified as the second biggest challenge after sales since 2020 (Kollmann et al., 2022).

We have identified a lack of scientific understanding of hardware-intensive development activities in startups, especially when describing cyber-physical systems (CPS). CPS are integration of computation with physical processes (Lee, 2010) expanding mechatronic systems through the possibilities of the Internet of Things (Graessler and Hentze, 2020). A CPS-example is a “smart toothbrush” including mechanics, sensors, actors, intelligent control systems and an internet connection to related services like a monitoring app.

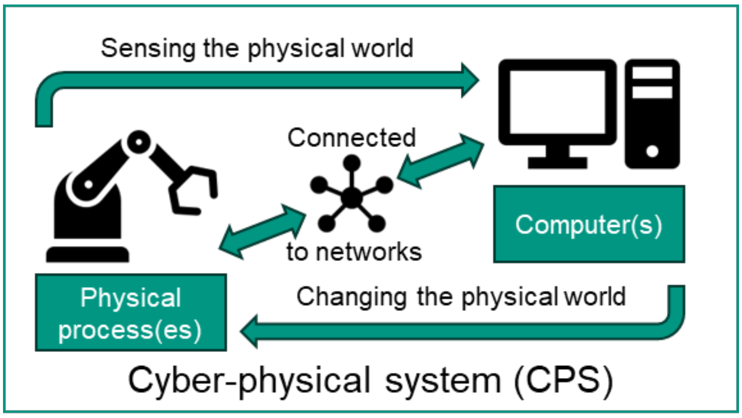

Figure 1: Definition of cyber-physical systems. Own illustration based on Lee, 2010

The character of CPS as enabling technology brings innovation potential for future applications and business models. However, the development of CPS has many potential risks in the interdisciplinary development of technology (Mosterman and Zander, 2016) and in the understanding of business relations, business models, and the self-conception as producer and client in an interconnected business ecosystem (Schneider et al., 2023). Current research is focussing on understanding requirements for agile development of CPS, but still is unclear about the boundary conditions, requirements and problems of established development environments (Albers et al., 2024). For startups, the threshold for developing complex systems like CPS coming with this uncertainty could be even worse.

Only a few publications investigate the development challenges of startups addressing complex technical hardware-related systems such as CPS. Therefore, we want to establish a first understanding of potential challenges and characteristic aspects of the development of CPS in startups with this paper.

2. Research aim, Research Questions, and Methodology

This study aims to exploratively investigate the status quo of current development practices in startups developing CPS to give a first qualitative understanding of the current situation of CPS development in startups. To achieve this, we want to answer the following research questions (RQ):

RQ1:What challenges and problems do CPS-developing startups face?

RQ2:What is the current development practice in CPS-developing startups related to those challenges and problems?

The first research question is answered in section 3 through an explorative literature analysis on publications from entrepreneurship and product development covering topics related to CPS- or hardware development in startups. They are selected by analyzing different literature search engines like *Google Scholar* or Web *of Science* by combining the following search keywords, i. e. “CPS”, “startup”, “hardware”, “IoT”, “Industry 4.0”, “development”, “challenges”, and “problems”. Papers are included when contributing to the questions described in Section 3. The resulting understanding is refined into proposed problem fields of startups developing CPS.

The second research question is answered in section 4. Based on the literature-based proposed problem fields from section 3, semi-structured interviews are conducted. Semi-structured interviews are chosen to achieve a certain level of reliability in acquiring comparable data but also allow individualised feedback from different interview participants. This is needed due to the explorative approach resulting in unpredictable outcomes.

The structure is oriented on Renner and Jacob (2020), including a brief introduction to the topic, followed by easy and intuitively answered questions in a quick-time question segment, one open question per problem field and a short breakdown at the end. Each interview takes about 30 minutes. Each interview was conducted in German. The interview guideline can be accessed on the following link:

https://bwsyncandshare.kit.edu/s/tQs6rcANmGZpFYc

A shortened and anonymised transcript of each interview based on a consensual recording is checked by the interviewees. Quotes from the interviews are allowed to be shared in this publication.

The interviews are conducted with eight participants from different startups located in Southern Germany. The selection was based on the following criteria:

- The startup is working on a CPS-idea.
- The startup does not only work on software.
- The participants have an insight into engineering and decision making processes.

Four out of eigth of the participants are involved as founders; the other half are involved as employees in the startup. The individual experience in the corresponding startup ranges from a few months to 10 years with an average of around two and a half years. The startups are active in different industries, i. e. production technology, mobility, financial technology, intralogistics and consumer goods.

The quotes derived from the interviews are clustered into reoccurring patterns related to the proposed problem fields. Those patterns are presented as the proposed characteristics of the status quo of CPS development in startups (see section 4).

3. Result of the Explorative Literature Review

To understand the possible challenges of CPS development in startups, literature is analysed by their contribution to answering three describing questions: Who participates in the development of CPS in startups (1), what describes CPS development in startups(2), and how do startups organise their development activites (3)?

3.1 Who Participates in the Development of CPS in Startups?

The participants in CPS development are entrepreneurs, employees, investors, and external stakeholders. Their role in startups is described in many publications, one is of particular interest: Zaheer et al. (2022) analysed the impetus of founders involved in multiple startups. They discovered that the work of founders on their system, the flexibility in working on the system in development (SiD) and the decision to pivot in their entrepreneurial and product development journey are key motivators for entrepreneurs. They identify an "entrepreneurial journey"-framework shown in Figure 2.

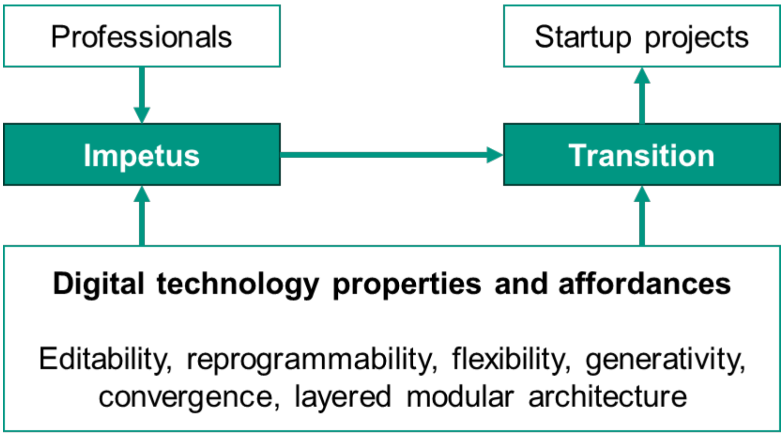

Figure 2: Digital Entrepreneurial journey framework. Own illustration based on Zaheer et al., 2022

Key enablers shown in Figure 2 are mainly found in software development environments. Complex constraints between engineering domains in CPS development are the strict opposite of these enabling factors, while generativity or layered modular architecture can be key aspects of CPS development activities. Thus, the motivation and impetus to get active in CPS-developing startups is questionable.

3.2 What Describes CPS Development in Startups?

The development of CPS in startups was not addressed in current literature. An answer has to be approached by the current understanding of related publications. This should include the driver of development (innovation), the development practice and related activities.

One of the main characteristics of startups is their *innovation orientation* (e. g. Kollmann et al. 2022, Kollmann et al. 2023, Steigertahl et al. 2018). Innovation can be described through many modeling approaches: Brown and Katz (2009) describe innovation as the overlap of the criteria "Feasibility", "Viability" and "Desirability", Albers et al. (2018) describe innovation as the combination of a demand situation (described in a product profile), an invention (through an idea and technical solution) and a successful market launch (displayed in market presence).

Recent research has shown that systems are not developed independently but rather *in generations* leading to the development of the SGE – System Generation Engineering (Albers and Rapp, 2021). They are based on a reference system containing all planned and already realized elements from internal or external sources interacting with each other. The reference system is steadily changing as new knowledge and references are gathered during the product development process (Albers et al., 2019). The reference system is transferred to a new system generation through three types of variation: carryover variation addressing only small changes in interfaces (1), an attribute variation changing the attributes of a known principle (2), or the principle variation implementing a new solution approach (3) (Albers et al., 2020).

Berg et al. (2020b) identify the need for activities preceding or succeeding the core activities in software engineering when working on hardware products in startups (*remark: they understand hardware as the combination of software and electronics to embedded systems, this does not include mechatronic aspects of hardware development*). This includes the *development of prototypes*, the *production*, and *logistics*. Especially prototyping is described as the main time-consuming activity in hardware development in startups (Looney et al., 2022). The time consumed by prototyping activities is heavily related to the usage of evolutionary development approaches, Hardware-Software-Decomposing, and the usage of agile development approaches. (Berg et al., 2020b). The speed of development in startups mainly is limited by resources available for development and the quality trade-offs and technical debt occurring during development (Berg et al., 2020a). Using approaches such as the SGE in startups usually results in the development of a first system generation based on high shares of principle and attribute variation of external reference system elements which contains a huge development risk (Pfaff et al., 2021).

The core activity in startups (and startup support) is *validation on different levels*: e. g. the early validation of the risky main business hypothesis with minimum viable products (MVPs) (Ries, 2012) or the validation of customer needs through iterative customer hypothesis validation (Blank and Dorf, 2017), but also the validation of the feasibility and the management of risk identified within the development project (Pfaff, 2021).

3.3 How do Startups Organise Their CPS Development?

As implied by Berg et al. (2020b) and Pfaff et al. (2021), agile development processes are needed to develop hardware systems in startups. As agile CPS development in companies isn't scientifically described in industrial practice (as startups) (Ahmad, 2020). To describe startups organisation of development activities, related publications are used.

Agility is a challenge to hardware development in general, i. e. in the common understanding or view of agile development in physical products, in time restrictions in manufacturing processes, in physical restrictions or appropriate incrementation of the product (Atzberger et al., 2020). In startups, customized iterative practices, sufficient competence in teams, and collaborative decision-making are enablers for agility and quality (Berg et al., 2020b). Reference processes for hybrid approaches between planned and agile product development are proposed (e. g. Stock and Seliger, 2016), but not documented in practice.

Product development in the early stage of startups is characterized by the finding, the definition, and the realisation of the startup idea (Kollmann, 2022). In most cases, the idea for startups is already established. Many founders use accelarator or incubator programs to structure and develop their startup. Besides the structured environment, programs mainly contribute to enabling financing, help to validate the product idea and collaboratively work on the individual learning experiences (Crișan et al., 2021).

3.4 Proposed Problem Fields of CPS Development in Startups

Analysing the literature given above, four main problem fields of the development of CPS in startups arise:

Table 1: Proposed problem fields

Problem field	Explanation
I	*The unclear impetus for entrepreneurs and their ideas*: We cannot be sure how exactly ideas for CPS-developing startups come up and what motivates founders to work on CPS. Present literature mostly covers software-developing startups, the risks for developing CPS seem to be higher than for software-developing startups.

Problem field	Explanation
II	*Uncertainty in idea generation for and validation of CPS in startups*: Validation was identified as one of the main activities of startups in product development. This especially includes not only feasibility but more the viability and desirability of the startup idea. Typical methods of product engineering and entrepreneurship tend to not fully suit CPS-developing startups. The methods heavily rely on established knowledge (e. g. from SMEs' previous customer interactions) not present in startups or on boundary conditions not suiting hardware development (because of complications with potential intellectual property, i. e. Ries, 2012).
III	*CPS-Prototyping with limited resources*: Startups developing CPS rely on a fast product development process, cost-sensitive resource usage decisions and qualitative adequate results they can sell. Literature generally identifies prototyping as a key influencing factor on those objectives but does not propose sufficient support to deal with the challenges of technical debt, knowledge generation, and management, or development risk management.
IV	*Uncertainty in the acceptance and usability of processes, methods, and tools (PMTs) provided*: In a more general way, literature reported that neither established agile approaches nor classical project management methods fully satisfy the high demand for customized iterative approaches in CPS-developing startups.

4. Characteristics of the Status Quo of CPS Development in Startups

The following section will propose twelve characteristics of the status quo of CPS development in startups based on the results of the conducted interviews described in Section 2 and respective quotes underlining them. Each quote contains an identifier (letters A-H) and the actual quote in italics. They individually contribute to the initial clarification of the conducted problem fields.

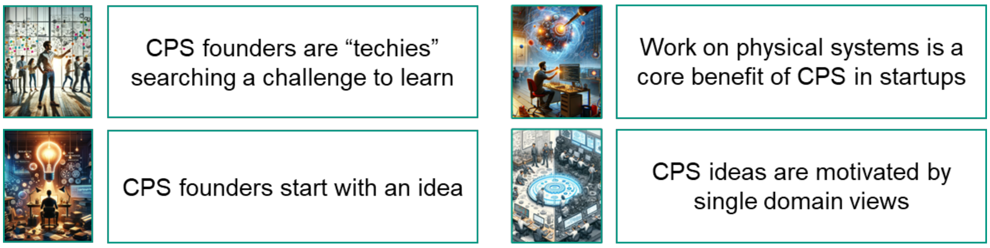

Figure 3: Characteristic aspects regarding problem field I. Own illustration

Problem field I: the unclear impetus for entrepreneurs and their ideas

- *CPS founders are "Techies" searching for a challenge to learn:* Most of the participants describe themselves as technology-oriented rather than business-oriented with three of them identifying as "Techies" and three of them between both categories. They are driven by a will to learn (e.g. A: *"We wanted to manage something complex"*; D: *"After my studies I wanted to work in an environment I could learn the most"*). Also, CPS founders want to achieve the qualities of "generalists" working on many topics rather than expertise in one single field of action (D: *"I wanted to position myself broadly and act as a generalist rather than choosing the narrowness of a specialist."*; G: *"I realise that I lack experience in certain tasks, especially in the execution of things and the various manufacturing techniques."*, also H).
- *CPS founders regularly start with an idea:* Out of seven clear answers on the source of the vision or idea of the startups, six stated that the original idea was present way before the founder team for the startup came together. Only one participant stated that the team came together before the startup idea was found. This was due to the constellation as part of an innovation project in a student lab where students were joined together to openly search for an innovation idea. The most common source of ideas were personal needs rather than validated demand situations (e.g. B: "the co-founder had the given problem and has found no suitable solution on the market") and existing technology from research (C based on the EXIST research transfer) or industry projects (E as an industry spin-off). Most of the ideas are technology-driven (rather than demand-driven) and are searching for a suitable business model.

- *For CPS founders, work on physical systems is a core benefit of CPS rather than software-only-systems:* The aspect of motivation in working on and shaping of software systems stated by Zaheer et al. (2022) could not only be confirmed but can be extended to the motivation of creation of physical and therefore touchable artifacts (H: *"My first internship was in a startup creating administrative software. That didn't work out. (…) For me, it's important to have something tangible, something I can touch. I am naturally talented with my hands and love building things."*). Contrary to our initial assumptions, this perceived benefit is not diminished by hardware-specific challenges such as hardware costs.
- *CPS ideas are motivated by single-domain views:* In the first section of the interviews conducted, one specific question addresses the self-understanding of the company and the product developed. Similar to the questions before and after, they could choose between two extreme statements: One the one hand software-driven development (Remark: *"the iPhone on wheels" if their company would develop a car rather than their actual product*) or a hardware-driven development (Remark: "the best *possible car with cool software features" if their company would develop a car rather than their actual product*). While in the other questions, many participants had problems deciding on one of the two extremes, this question has only extreme answers. Five out of eight participants identify software as the driving domain of their company. This leads to the hypothesis that current CPS development is mostly based on the view of one single technical domain as a dominant view rather than an integrated understanding of the interdisciplinarity of the system.

Figure 4: Characteristic aspects regarding problem field II. Own illustration

Problem field II: Uncertainty in idea generation for and validation of CPS in startups

- *Validating the CPS idea is the main challenge in CPS-developing startups:* Validation in general is already described as one key activity in startups by established literature. This is confirmed by the participants of the interview study (B: *"Finding the* right *idea is extremely difficult. (…) You have to try, test and watch things and have to evaluate if they work or not"*). Although difficult, only real customer contact is seen as the last instance of validation (D: *"Only the validation through concrete sales KPIs can give you an indication, if we are looking in the right direction"*).
- *An integrated view on feasibility, viability, and desirability is hard to find in CPS startup founders and workers:* CPS development needs interdisciplinary cooperation between technology domains, but its engineering in startups also needs an integration of technological and entrepreneurial thinking. Some of the most technologically trained founders do see the feasibility aspect as the most relevant for business. (C: *"There is no* minimal version *of hardware products"*, E: *"Answering the question of how the product can be monetized or how the business model fits into the overall image can be done later on."*). Business-oriented development aids, i. e. the Business Model Canvas (BMC), achieve mixed reviews by technology-oriented founders (A: *"Its usage was exhausting and annoying, but (…) many decisions [in hardware and software] do rely on this, especially what we are focusing on in our validation in prototyping activities"*, but also in D: *"I think there is no realistically filled BMC"*).

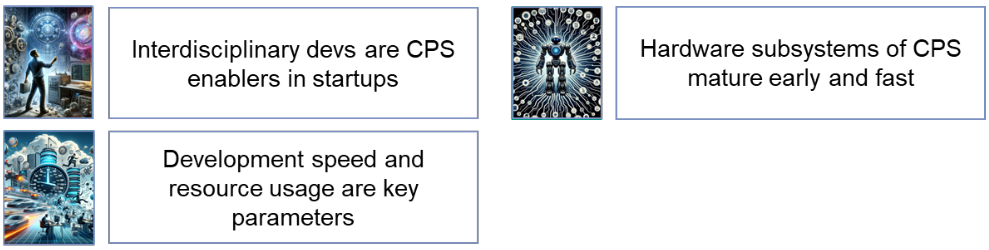

Figure 5: Characteristic aspects regarding problem field III. Own illustration

Problem field III: CPS-Prototyping with limited resources

- *Interdisciplinary developers are enablers for CPS development:* Developers who not only understand themselves as generalists in their respective domains but also look at different domains, are key resources for development activities and efficient prototyping in startups. (D: *"After my studies, I* *wanted to learn as much as possible. (…) I wanted to have a broader knowledge and become a generalist rather then a specialisit, [so I decided for a startup to work in].”*, F: *“I have to few experiences in certain domains”*). Their ability to easily overcome communication burdens and inefficiencies is a major benefit for startup development activities (E: “*Our Electronics engineer has a very good understanding of software, (…) the resulting smooth communication was very helpful*.”

- This is also seen in the according competences of a CPS startup founder identified by a serial entrepreneur, Interviewee B: “*A good CPS founder has a systems talent* (meaning a combination and coordination ability) *and a development talent* (meaning a good problem understanding and a bond to software and hardware)”.
- *Hardware subsystems of the CPS have to mature early and fast:* Hardware in startup is a big factor for risk assessment. Therefore the hardware has to mature a lot earlier than software features (C: *“After 10 years in the market we have released the second generation of our product.”*, G: *“There are fewer adjustments in the hardware. We make continuous improvements, but there will be no radical redesign of the concept.”*). The early validation of the overall feasibility is the most relevant task in the early stages (A: *“This was our proof-of-concept: Our idea is possible, the rest is a question of money invested”*). Besides that, the desirability has to be validated through mock-ups centered on customers and investors (G: *“We first worked on the aspects customers and users would get in touch with, the technical details came later.”*, D: *“We first checked if the customer matches with the vision of the product.”*). An interesting observation was made in the description of Interviewee H: They are developing CPS for in-house solutions selling a product produced on their own CPS. Without their contact with customers, H describes that hardware and software changes can be implemented much faster and easier which would not be possible if they used their CPS directly with customers.
- *Speed and resource usage are the most important development parameters in Prototyping:* The relation of prototyping speed, resources, and achieved quality for hardware startups focused on embedded systems can be confirmed for CPS. Hardware availability and resource consumption is important for prototyping (A: *“Our [student] projects budget was 500€ while needed sensors cost about 100€. (…) The development focus has to slim down!”*). The focus on achieved quality in prototyping highly differs through the interview sample (B: *“If a too high-quality focus is set, the development becomes too slow. The optimum has to be readjusted over time!”*, E: *“Quality of prototypes is not important. Functionality is the centre of attention.”*, G: *“Quality is no problem for us, it's more the available resources and the achievable speed”*, but also D: *“In our industry, quality has to be fulfilled. It must be externally validated and approved, especially due to product liability.”*). Technical debt is a relevant factor but results in inefficient usage of resources (A: *“You mess around a lot, which you later regret. We could not reuse any of our prototypes.”*). That collides with the stated positive effect of evolutionary approaches in hardware design stated by Berg et al. (2020a).

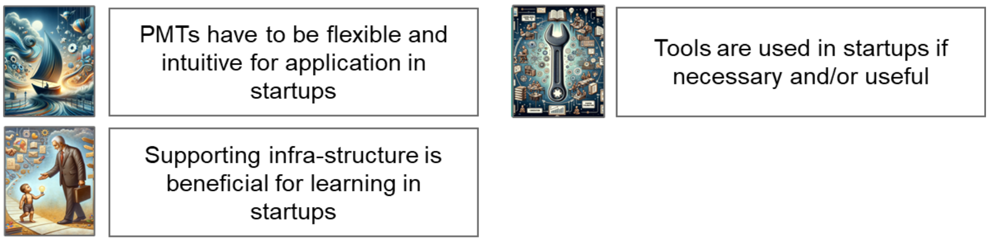

Figure 6: Characteristic aspects regarding problem field IV. Own illustration

Problem field IV: Uncertainty in the acceptance and usability of PMTs provided

- *PMTs have to be flexible and intuitive:* Seven out of eight s describe their development processes as very agile. Most of the participants are aware of the usage of methods and processes but describe a strong individualised (and sometimes repurposed) way of using them. (B: “*I would never use the method I developed as an expert in its entirety in a startup. In the thinking process of course, but in its entirety, we do simply not have the resources for that.*”, H: *“I do not use the methods learned in university in my everyday business in the startup, but I take a methodical approach based on them”.*) Most of the s describe their PMT usage as mostly intuitive, not as rigid following. (G: “*Our approach is so agile and free, we do not use an agile framework for our processes.*”, “*There are rough targets we are working on, but we do not formalize everything or structure it in a process”,* D: *“We are using kind-of SCRUM, but do not rigidly. (…) It is suited to our needs”*).

- *Tools are used if necessary and/or useful:* Especially tools for development activities are the most relevant tools used in everyday business (G: *"Without such tools [as e. g. CAD systems] the amount of work would not be realisable and it would not be up-to-date."*). Besides that, tools are used for collaboration and knowledge management (D: *"We use Miro or OneNote to collect ideas [and communicate our thoughts]."*).
- *Supporting processes and environments are beneficial for organising and learning startups:* Especially inexperienced founders and startup employees tend to benefit from supporting processes and environments like incubators, accelerators, or student labs. Key aspects are the transfer of needed basic knowledge on entrepreneurship and product development not present as well as the given structure through deadlines or workshops (A: *"All of us are Techies, we look at the system with our nerdy view, not a business view. Because of that our participation in the lab was good."*, C: *"What has given us a big benefit was an accelerator program. Many of our foundations were build up there."*, E: *"Student startup competitions where a good structure we could orientate ourselves on."*).

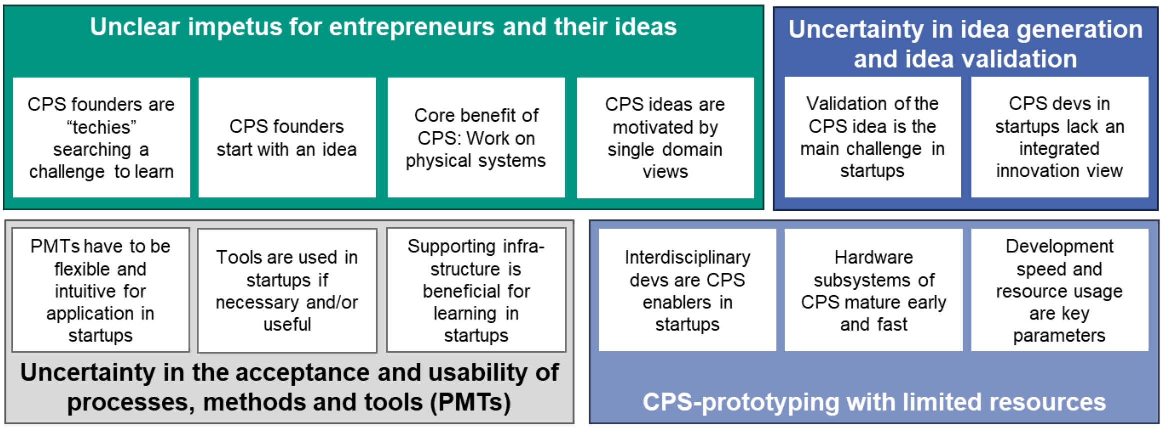

Figure 7: Twelve proposed characteristic aspects of CPS development in startups. Own illustration

5. Discussion

This paper is a step into describing and understanding the CPS development in startups. With the explorative approach of the study based on eight interviews, a qualitative overview of the perceived status quo of startups is proposed.

The validity of the results is influenced by many factors due to the explorative approach used. The broad, but not deep analysis of the respective literature in section 3 leads to the possibility for not included aspects and conceptions of hardware development in startups. Also, the number of interviewees and the diverging background of the participants leads to the possibility of a non-representative sample.

Because of these limitations, the proposed problem fields and characteristic aspects of CPS development in startups are first qualitative descriptions of the status quo of CPS development in startups and are open for discussion. Nevertheless, this study builds up an empirical dataset on CPS development in startups and a foundation for future research activities.

Future studies should verify the proposed problem fields with a systematic literature review and conduct more interviews in specific target groups (e. g. specific industries, in the same complexity levels of the SiD or with entrepreneurs with comparable backgrounds). In the long term, the development of suited support for CPS development in startups is needed. It should consider current research findings in product development as well as in entrepreneurship. A strong cooperation of both research disciplines is needed to generate a positive impact on the future entrepreneurship ecosystem for CPS startups.

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