Developing Cyber-Physical Systems as Entrepreneurs: Agile Development in Startups and SMEs

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Abstract: As mechatronic systems evolve into cyber-physical systems (CPS) through IoT integration, start-ups face unique challenges in CPS development due to limited knowledge, resources, and time. Although they often adopt agile methods, this is typically done unconsciously. Prior research highlights four key problem areas: unclear entrepreneurial motivation, uncertainty in idea validation, resource-constrained prototyping, and low acceptance of tools and methods. Building on earlier exploratory studies, this paper presents a systematic literature review (SLR) of 1,929 papers to analyse CPS engineering practices across start-ups, SMEs, and large enterprises. We identify the types of CPS developed, compare engineering approaches, and propose a framework to classify CPS projects by organizational type and system level. The study outlines best practices and key requirements for successful CPS development and offers guidance to support tailored toolkits for diverse development contexts.

Keywords: Cyber-physical systems, Agile Development in Start-ups, 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 Comission, 2021), the focus of startups tens more on the development of products with a high share of software development: In 2023, 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) These numbers slightly vary for other years (Hirschfeld et al., 2024), but the overall trend is still represented in current data and publications in research of entrepreneurship, e.g. (Kollmann, 2022). Recent studies indicate that this is due to a discrepancy between idealized frameworks aimed at software projects (Völk et al., 2024). This becomes a problem when focussing on products that are not exclusively software such as CPS: they are integration of computation with physical processes (Lee, 2010) expanding mechatronic systems through the possibilities of the Internet of Things (Graessler & Hentze, 2020). According to Griffor et al., cyber-physical systems (CPS) can be categorized into three scopes: (1) Single CPS Devices, which refers to a basic CPS component or subsystem; (2) System CPS, which denotes an integrated system composed of multiple CPS components; and (3) System-of-Systems CPS (SoS CPS), which describes a higher-level assembly of multiple independent CPS systems.(Griffor et al., 2017) These classifications are also grounded in Ropohl's system theory.(Ropohl, 2009) In our study, we adopt a similar categorization and cluster CPS into three hierarchical levels, as illustrated in Figure 1: (1) Subsystem CPS, (2) System CPS, and (3) System-of-Systems (SoS) CPS.

We see that those systems have a high innovation potential but still are facing significant challenges in their deployment. Especially startups face significant challenges regarding the development of CPS, as regular approaches for startup engineering fail to address problem fields in the engineering of hardware-heavy or cyber-physical systems (CPS) (Völk et al., 2024).: Founders in CPS engineering are mostly technology-affine engineers looking for a challenge based on an initial idea mostly motivated from single domain viewpoints. They regularly lack an integrated innovation view of their product, while they have to mature the hardware systems early and fast, which results in development speed and resource usage as key parameters of the development.

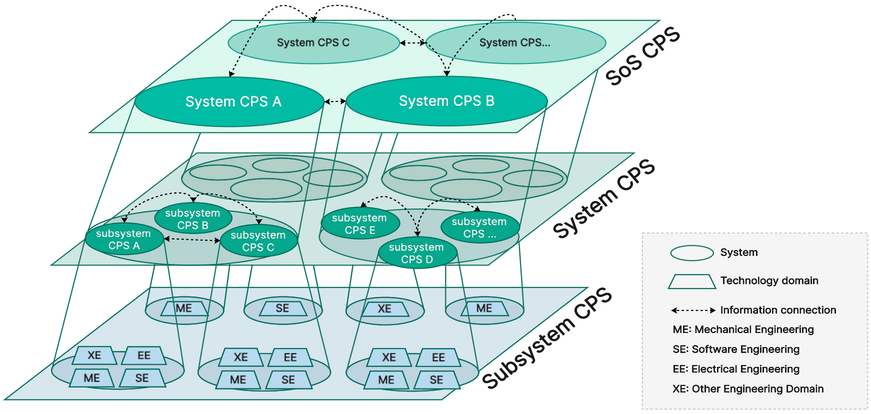

Figure 1: CPS levels. Own illustration

Especially the last characteristic logically results into adaption of agile practices in startups. Agility is the ability to rapidly and continuously adapt a development process in a situation- and demand-oriented way (Albers et al., 2021). Studies show that development in startups in general is implemented in an agile way (Pfaff et al., 2021). In the state of research, we do only have insights into specific CPS use-cases (Yeman & Malaiya, 2024) and still lack general insights into agile development practices in CPS engineering (Ahmad, 2020), especially for startups. To create meaningful support in designing processes and methods, we need an understanding of unique requirements, attributes or practices of agility in the engineering of CPS on different organizational levels.

2. Research Aim, Research Questions, and Methodology

This study aims to better understand the dependency of the type of an organization to its deployment of agile practices in the context of the engineering of cyber-physical systems already present in established literature. To achieve this, we want to answer the following research questions (RQ):

- *RQ1: How do different types of organizations apply agile methodologies in their cyber-physical systems (CPS) engineering processes*
- *RQ2: What are the key similarities and differences in agile practices between established companies and startups in CPS development?*

3. Systematic Literature Review on Agile Product Development Practices in Engineering of Cyber-physical Systems in Different Organization Types

To address the research questions, a systematic literature review (SLR) is conducted to filter the relevant study in the first step. The review followed established guidelines recommended by (Heil, 2021) and the well-known guidelines of (Kitchenham et al., 2009). The adopted process is described in Figure 1.

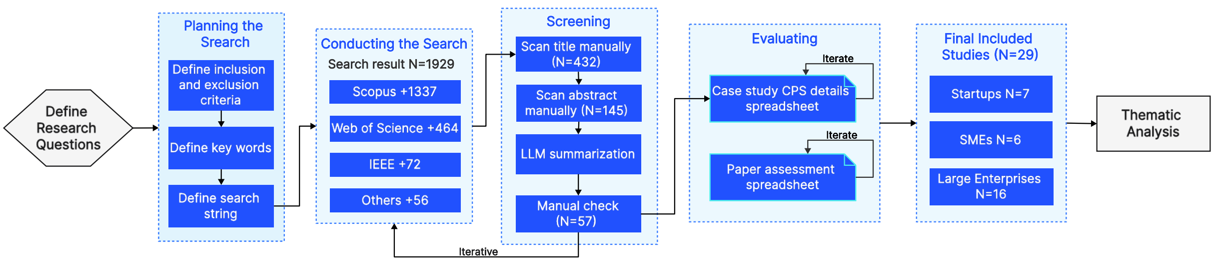

Figure 2: Systematic literature review adopted in this study. Own illustration

In the research planning phase, clear criteria were established to determine which studies would be included. Guided by the criteria, a set of keywords were identified from search topic. Boolean operators were used to construct search strings that combined these categories. This resulted into the following search string:

Search string: ST = [CPS] + [Product development] + [Agile] + [Organization type] + [Study type]

In more detail, the example search string could appears as follows:

"cyber-physical system" OR "CPS" OR "industrial automation" OR "IIoT") AND ("product development" OR "system engineering" OR"prototyp*") AND ("agile methodolog*" OR "scrum" OR "kanban") AND ("startup*" OR "early-stage compan*") AND ("case stud*" OR "empirical stud*" OR "industrial experience*" OR "practical application*" OR "failure analys*")*

The search was conducted across multiple academic databases, including Scopus, Web of Science, IEEE Xplore, ACM Digital Library, and others, covering literature published from 2014 to 2024. The application of the search string on these databases resulted in 1929 found papers.

To evaluate the papers fit to the research problem, we first scanned each research by title, then by the abstract. By the end of the abstract screening, there were 145 publications that appeared to match the defined inclusion criteria. To manage the amount of data, the Large Language Model Perplexity was used to summarize:

- Contextual Information of the given research including industry, project scale and organization type.
- CPS characteristics including-the hardware scope, connectivity technology and the CPS "level".
- The chosen development approach, in specific agile practices.
- Key findings as technical, process, and organizational insights

Each paper was uploaded individually into Perplexity to avoid information mixing and are reviewed manually. Each summary including the references to the actual paper was compared to the actual content of the paper, so no alteration based on mistakes the AI could do can alter the result of the analysis. After this quality insurance step, 57 out of the 145 papers were flagged as likely meeting all inclusion criteria. 6 Quality Assessment Criteria were set to evaluate 57 study candidates: (1) Is the scientific idea validated? (2) Is the case study validated as CPS engineering? (3) Does the publication focus on product development? (4) Is there any agile approach mentioned by the publication? (5) Does the publication include a personal opinion piece or viewpoint? (6) Has the publication been cited by other authors? Papers that do not meet QA1, QA2 and QA4 were excluded from further data analysis resulting in Figure 2 describes the results of the final included 29 studies in this SLR.

Following the approach outlined by Braun and Clarke, the analysis proceeded through the following steps: (1) familiarization with the data in the spreadsheets; (2) generation of initial codes by extracting relevant quotes from the studies; (3) identification of themes related to agile practice drivers, agile approaches, challenges, and CPS system levels; and (4) review and refinement of themes by clustering sub-themes into broader categories. The resulting set of literature is shown in Table 1.

Table 1: Overview of CPS agile development approach in this SLR

Source	ID	Approaches and Main Ideas
(Völk et al., 2024)	[1]	CPS Development Challenges – Startups face typical CPS challenges; use rapid prototyping instead of formal Agile.
(Julianasari et al., 2022)	[2]	Scrum Fail Analysis – TOPSIS reveals Scrum failed in CPS startup; better Agile planning advised.
(Vecchio et al., 2021)	[3]	Open-Source IoT – Modular open-source IoT platform enables fast, low-cost CPS prototyping.
(Berg et al., 2020)	[4]	Hardware Agile Practices – 5 CPS startups use tailored Agile; quality focus needed for long-term agility.
(Nguyen Duc et al., 2019)	[5]	MVP in IoT – Six CPS startups use MVPs and Agile, adapted for hardware constraints.
(Chiang & Lee, 2017)	[6]	Lean via Internet of Makers (IoM) – Small CPS firms cut development costs using IoM; share design files to speed up smart manufacturing.
(Nguyen Duc et al., 2018)	[7]	Hardware Agile Practices – Study shows tailored Agile in hardware startups; 3D printing, sprints, and vendor collaboration enable speed.
(Fritzsch et al., 2023)	[8]	DevOps & Microservices in CPS – Microservices and DevOps used in CPS, but need hardware adaptation
(Michalides et al., 2023)	[9]	Challenges in Scaled Agile – Challenges in Scaled Agile – Scaling Agile in hardware teams faces sync and resource issues.
(Tapio Schrey et al., 2022)	[10]	KONE's Agile Transformation – KONE uses Agile to shorten cycles and align with digital services.

Source	ID	Approaches and Main Ideas
(Kasauli et al., 2020)	[11]	Agile-Waterfall – Agile teams struggle with requirements in a waterfall-driven EV company.
(Cooper & Sommer, 2018)	[12]	Agile–Stage-Gate (ASG) – Agile sprints embedded in Stage-Gate boost speed and flexibility in manufacturing. (General Electric Company, Danfoss, Honeywell, Chamberlain)
(Salvato, 2018)	[13]	Agile–Stage-Gate-Management (ASGM) – ASGM integrates Agile practices (e.g., Scrum) into Stage-Gate for hardware
(Schmidt et al., 2018)	[14]	Hardware Agile Practices – Scrum/Kanban help manage rapid hardware changes, though not fully iterative.
(Sommer et al., 2015)	[15]	Agile–Stage-Gate – Combines Scrum at team level with Stage-Gate oversight for better product performance.
(Chai et al., 2018)	[16]	INDICS Smart Platform – INDICS combines IoT, AI, and lean to support smart factories, with SME use cases
(Fuchs & Hess, 2017)	[17]	Scrum for Industrial IoT **(IIoT) – Customized Scrum with coordination cycles fits complex IIoT projects.**
(Marlene Sharkey, 2023)	[18]	Honeywell's Agile Transformation – Agile pilot (Scrum/Kanban) speeds hardware delivery and boosts engagement
(Robin Yeman, 2025)	[19]	Success Patterns in Building CPS with Agile – Agile/DevOps practices enable large, safety-critical CPS development.
(Vodyaho et al., 2022)	[20]	Agile CPS Architecture **– Agile architecture for CPS uses knowledge graphs and automated modelling.**
(Erdin & Olcay, 2024)	[21]	Agile–Stage-Gate – Tailored hybrid ASG segments projects by complexity/TRL; SME battery case.
(Jusoh et al., 2019)	[22]	Agile Use in IoT SMEs – Malaysian SMEs mainly use Scrum for IoT/CPS development.
(Schuh et al., 2019)	**[23]**	Finding the Right Development process for CPS – Method for selecting best CPS development process by project conditions
(J. Hernández-Reveles et al., 2016)	**[24]**	Scrum + Agile Architecture – Scrum and specific architecture practices (runway, enabler stories, docs) for MVP.
(Khan et al., 2024)	[25]	Enhanced Agile V-Model: Hybrid V-model combines traditional V-model with Agile for regulated medical devices.
(Cederbladh et al., 2024)	[26]	CPS Collaboration Challenges - Key hurdles (data, modelling, automation) in agile CPS collaboration from EU project.
(D. Roy et al., 2018)	[27]	Multi-domain Agile CPS - Coupling domains and automation enables safe, agile automotive CPS.
(Luedeke et al., 2018)	[28]	CPM/PDD Agile Integration - Combines design thinking and Agile with CPM/PDD modelling for CPS.
(Yeman & Malaiya, 2024)	[29]	Agile adoption in CPS grows but faces regulatory and complexity challenges.

4. Results of the Systematic Literature Review

Organizations across various sectors have adopted agile methodologies in cyber-physical systems (CPS) engineering, with adoption patterns differing significantly based on organizational size, domain, and culture. A total of 53 case studies were identified from the selected publications. Figure 3 presents the distribution of these case studies by industry domain. The majority are from large-scale industrial automation and Industrial Internet of Things (IIoT) projects, followed by a substantial number in the medical devices and systems sector. Startups are primarily represented in the consumer electronics and medical device domains, while small and medium-sized enterprises (SMEs) are predominantly involved in industrial automation and IIoT.

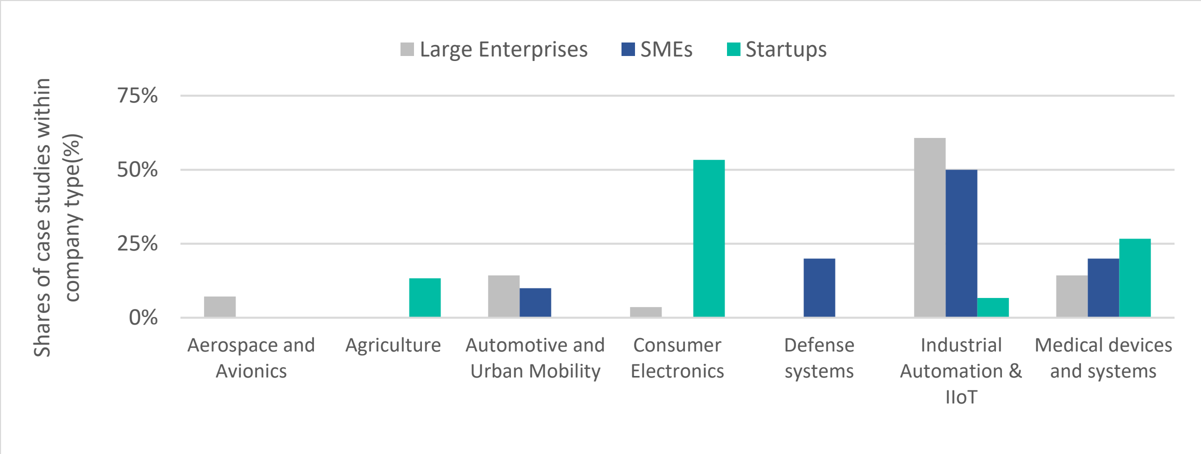

Figure 3: Number of case study in the included paper by industry domain

4.1 CPS Level Corresponding to the Organizational Maturity

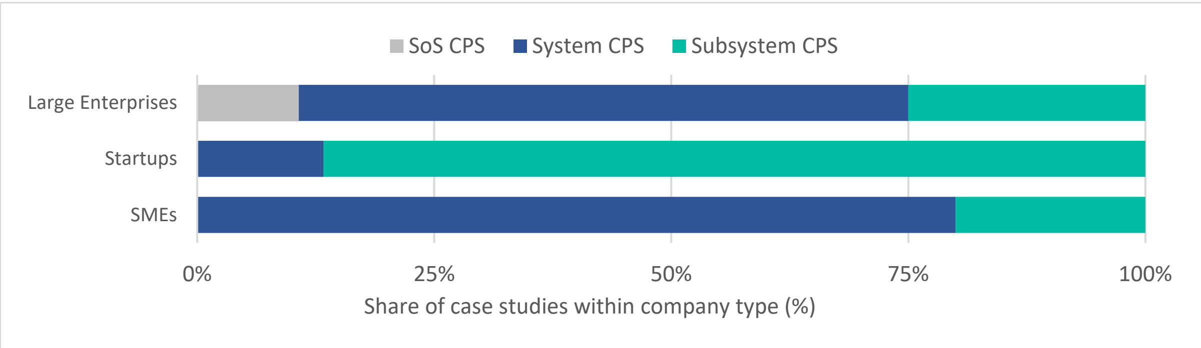

Figure 4: Organizational Case Studies by CPS Level

The data observed from the 53 case studies suggest that system complexity tends to increase with organizational maturity as shown in Figure 4. Startups primarily focus on **Subsystem CPS (**e.g. [5, 6]), small and medium-sized enterprises (SMEs) are mainly involved at the **System CPS** level (e.g. [3, 22, 23]), and large firms predominantly engage with **System CPS** as well. Additionally, there are three documented cases involving **System-of-Systems (SoS) CPS (e.g. [8])**, which are typically associated with the most mature and complex organizational settings. This seems clear: The threshold entering a sub-system (or component) level of a complex system is not as big as for a big SoS solution, so big companies have no advantage in competing with startups with no previous knowledge. Still, this should not be seen as an absolute allocation, but rather an indication of the current state in research. Yet, to get a fully functional CPS, all different layers have to be represented, implying that a successful integration of a subsystem CPS made by a startup needs a bigger framework crated by an SME or large company where the solution can get adapted into.

4.2 Drivers of Implementing Agile Practices

Adaptability is the primary reason organizations adopt agile practices. Startups, operating under high uncertainty, need flexible methods to handle evolving requirements [5][7]. Agile approaches emphasize responsiveness to change in dynamic settings [1][4][7], which is equally vital for SMEs facing shifting market demands [21]. The ability of agility to integrate new requirements, insights, and customer feedback throughout development is a key advantage [23].

For startups, speed is the second major driver, essential for meeting time-to-market demands [2][4][5][6][7]. As one study notes, "the competitive environment of hardware startups makes speed inevitable" [4]. In contrast, SMEs prioritize customer-driven development slightly above speed. For instance, in a medical device case study, agile was combined with the V-model to incorporate feedback from patients and doctors [25]. In Make-to-Order (MTO) settings, SMEs rely on agile methods like Scrum sprints to respond quickly to client needs and integrate changes efficiently [17][22][24]. Tools like user stories help Product Owners align requirements with buyer expectations [24].

4.3 Different Agile Practices Across Organizations

Agility is the ability to rapidly and continuously adapt to both expected and unexpected changes, ideally turning them into opportunities. This study identifies two main categories of agile practices.

- Process-Oriented Practices: These span from organizational-level models to team and individual execution frameworks. Gren emphasizes the importance of addressing agility at macro (organization), meso (team), and micro (individual) levels for coherent implementation [Gren, 2017].
- Technology-Oriented Approaches: These embed adaptability into system architecture and design, enabling long-term responsiveness in complex environments.

Startups typically operate at the subsystem CPS level [2][4][5][6], prioritizing speed and minimizing upfront planning and documentation [1][4]. They often accept technical debt to validate concepts quickly, using mock-ups or partial prototypes instead of full hardware–software integration [5]. Agile practices are informal and team-focused, including simplified Scrum, ad-hoc methods, and extended sprints [5]. However, partial adoption can reduce effectiveness—e.g., one Agri-tech startup using partial Scrum completed only 50% of tasks per iteration [2]. Technology-oriented practices include rapid prototyping (e.g., 3D printing, CAD) and open-source IoT platforms to cut costs and development time [5][7].

SMEs focus on system-level CPS development [21][22][23][24], aiming to boost efficiency, speed, and stakeholder satisfaction [16][21–25]. They often combine agile with plan-driven models [21][23][25], especially architecture-centric ones [24]. Scrum is the most common framework [4][17][22], with projects split by domain and executed in short sprints [23]. Hybrid models (e.g., Scrum with Stage-Gate or V-model) balance flexibility and structure [21][23][25]. Technology-oriented practices include reusable platforms and AI-enhanced decision-making. For example, the INDICS platform supports intelligent factories through data-driven efficiency and quality improvements [16].

Large enterprises are increasingly applying agile to physical product development, extending its use from software to mechatronic and CPS systems [9]. These firms often develop CPS at the system or SoS level, frequently in collaboration with universities [26–28]. Their goals include market responsiveness, safety, collaboration, and customer satisfaction [8][10–15][17][18][26][29]. Agile is typically used at the team level, while plan-driven models remain at the macro level for compliance [11–13][15][21][23][25]. Common methods include Scrum, Kanban, Design Thinking, and DevOps [8][13–15][17–19][26][28], often within hybrid models (e.g., Agile-Stage-Gate, Agile-V-Model) [11–13][15][21][23][25]. Safety frameworks like FMEA ensure regulatory compliance [29], while CPM/PDD links design to implementation [28]. Technology-oriented practices include Agile Architecture [20], Digital Twins [19][20][29], CI/CD [26], Microservices [8], MDE [8], AI/ML [26], and agile tools like Jira [11][18].

4.4 Challenges of Implementing Agile Practices

The results identified agile practice challenges in 9 categories and compare them across different organizations as shown in Figure 5. Startups, SMEs, and large CPS organizations face several key challenges when adopting agile practices. Process and workflow issues arise due to the mismatch between agile methods and hardware development. Hardware constraints make rapid iterations costly and slow. Limited resources and expertise, especially in project management, hinder implementation. Cultural resistance and rigid hierarchies slow agile adoption. System complexity, including IoT integration, complicates coordination. Safety and compliance requirements conflict with agile's flexibility. Organizational restructuring is often needed but difficult. Teams face a steep learning curve, especially with partial agile use. Lastly, sharing development data can lead to intellectual property concerns as operations scale.

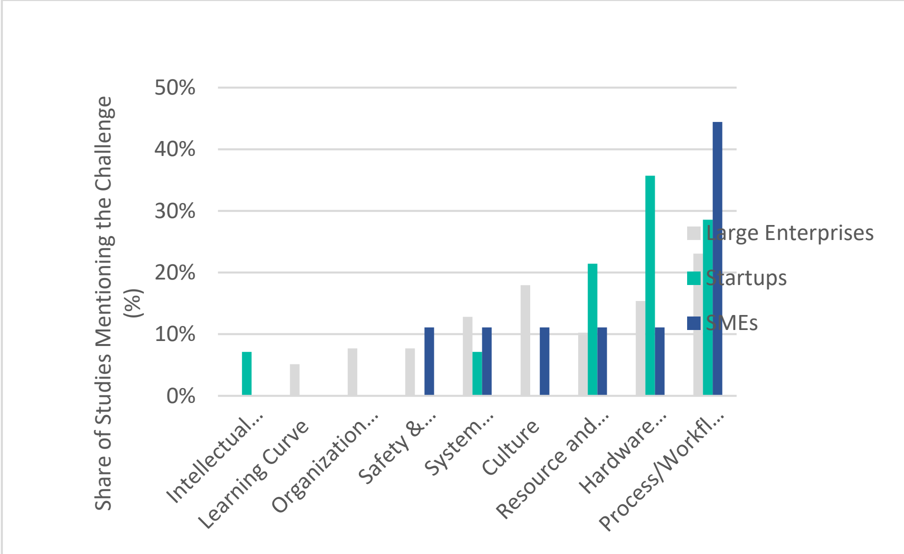

Figure 5: Agile practice challenges in CPS engineering across organizations

5. Summary and Outlook

This study presents a comprehensive review of the current state of research on the adoption of agile practices in the engineering of cyber-physical systems (CPS) across different types of organizations. From an initial pool of 1929 papers, 29 were systematically selected to analyse the prevailing challenges and practices among startups, small and medium-sized enterprises (SMEs), and large companies. Our findings suggest that the level of manageable complexity is connected to the organizational maturity: startups typically focus on developing individual CPS components, SMEs tend to integrate CPS, and large companies often connect CPS into broader Systems-of-Systems. This progression is also reflected in the application of agile practices. While all types of organization value adaptability, their motivations differ: startups generally lack prior knowledge and seek to acquire it rapidly, whereas SMEs and large companies possess substantial knowledge but struggle to apply it in a context-sensitive and needs-driven manner. These differences are also evident in the challenges reported: Case studies on startups often emphasize hardware constraints, while those on SMEs and large companies highlight issues related to complexity and process management. This results into two differing views on agility: Startups tend to organize their agile approaches unstructured facilitating them there needed, while established firms apply agility in a stricter and more structured way. Notably, findings are mainly limited to the current state of research. As startups tend to focus on their own progress and less on research collaborations, there might be a limitation to the findings shown based on the different motivation to participate in active research.

Nevertheless, the results lead to a critical implication for the design of tools and methods: researchers cannot assume that solutions tailored to one organizational type will be effective for others. Challenges of and reasons for the application of agility highly differ by the maturity of the organization wanting to apply them. While our results are only based on the assessment of agility, we state that this is transferable to the overall motivation for the usage of processes, methods and tools. Future research should therefore focus on identifying the core requirements of each organizational type. While SMEs and large companies have already received considerable attention, startups represent a promising and underexplored area in (agile) process development research.

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Ethics and Artificial Intelligence (AI) Declaration

No ethical clearance was required. AI was used as indicated in section 3 and for editorial changes.

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