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Challenges in the Development of Cyber-Physical Systems – Insights from Research and Industrial Practice

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Abstract

Despite the growing importance of Cyber-Physical Systems (CPS), there is still no consolidated overview in academic literature of the key challenges faced in their development. This study addresses this gap by combining a systematic literature review (2019–2024) with an exploratory survey of industry practitioners. The review identified 54 distinct challenges, with system complexity, interoperability, and modeling among the most frequently cited. The survey broadly confirmed the relevance of these challenges. However, the study also revealed additional, practice-driven challenges, including cybersecurity, tool fragmentation, and organizational frictions. The findings emphasize the necessity for integrated, model-based CPS development approaches that ensure consistency across domains and system generations, thereby establishing a foundational framework for subsequent research and method development.

Keywords: Cyber-Physical Systems; Development Challenges; Systematic Literature Review; Industry Survey

1. Introduction

The increasing digitization and connectivity of products are fundamentally transforming modern engineering. Once dominated by purely mechanical systems, today's product landscape is increasingly shaped by Cyber-Physical Systems (CPS) – integrated systems that combine mechanical components with electronics, software, and network connectivity [1]. CPS are now central to both industrial and consumer applications, from smart appliances and automated factories to smartphones and autonomous vehicles [2].

This shift in system architecture introduces far-reaching implications for development practices. CPS engineering demands tight collaboration across domains such as mechanical and electrical engineering and computer science, adding technical and organizational challenges beyond traditional product development [1].

Despite the growing importance of CPS, systematic insights into the specific challenges faced during their development remain limited. This paper addresses this gap by identifying and analyzing current challenges in CPS development through a systematic literature review (SLR) and an exploratory industry survey. The SLR identified 54 distinct challenges, including system complexity, heterogeneity, and inconsistencies in modeling. The survey confirms the practical relevance of most literature-based challenges while revealing additional, practice-oriented issues.

By combining findings from literature and industrial practice, this study provides a structured overview of critical development challenges in CPS engineering. The results contribute to a more nuanced understanding of the barriers that hinder effective CPS development, providing a foundation for future research on development methods, tools, and organizational structures tailored to the needs of CPS.

2. Research design

To systematically investigate the challenges of CPS development, this study employs a multi-method approach. By combining a systematic literature review with an exploratory industry survey, the study integrates academic and practical perspectives to develop a comprehensive understanding of development obstacles in CPS engineering.

2.1 Research Objective and Questions

The study aims to develop a structured understanding of the main challenges in CPS development by integrating insights from recent literature and industrial practice. It is guided by the following questions:

- RQ1: What challenges related to CPS development are discussed in recent scientific literature?
- RQ2: How does industrial practice validate and supplement these challenges identified in the literature?
- RQ3: What implications arise from the identified challenges for future CPS development approaches?

2.2 Systematic Literature Review

To address RQ1, a Systematic Literature Review (SLR) was conducted following established methodological guidelines [3,4]. The review aimed to identify challenges discussed in the CPS-related literature published between 2019 and 2024. A keyword matrix with four thematic blocks was used to iteratively refine the final search string [5].

Initially, the search encompassed literature published between 2015 and 2024 in the domains of computer science, engineering, mathematics, and medicine and was constrained to document types such as journal articles, conference papers, book chapters, and reviews. However, the initial search yielded 15,808 entries, many of which were irrelevant, resulting in low overall precision [4]. Consequently, the search string underwent refinement. Ambiguous or overly general terms, such as the abbreviation "CPS", were excluded. The temporal scope was narrowed to publications from 2019 to 2024, focusing on the most recent challenges in this dynamic field.

The final search string was performed in the Scopus database, which was selected for its broad disciplinary coverage [6]. The refined query yielded 978 results, which were filtered through a multi-stage screening process. The initial screening of these entries was conducted based on the title, resulting in the reduction of the sample to 318. A subsequent abstract review yielded 147 potentially relevant sources, which were then assessed in full text. A total of 36 publications were identified as being directly related to the research question [3,4].

To mitigate the limitations of keyword-based searches, a forward and backward citation analysis was conducted, identifying 14 additional relevant sources. In total, 50 publications were included in the final analysis [3,4]. The selected literature was analyzed through qualitative content analysis to extract and categorize the reported challenges. These findings formed the basis for the challenge list used in the subsequent survey.

2.3 *Explorative Industrial Survey*

To validate and expand upon the literature findings (RQ2), an exploratory online survey was conducted with professionals actively involved in CPS development. The study aimed to assess the practical relevance of literature-based challenges and to capture additional practitioner perspectives.

Based on the guidelines by Porst [7], the questionnaire included both closed and open items. Respondents rated the frequency of 15 literature-derived challenges using a four-point ordinal scale ("never" to "always") and were invited to describe any additional challenges or coping strategies [7]. The study concluded with demographic questions, following best practice guidelines [8].

The survey was conducted using an exploratory approach, meaning it was not designed to be statistically representative. The objective of the study was to obtain a qualitative and quantitative overview of the practical challenges encountered in the development of CPS [8]. Invitations were distributed via electronic communication exclusively to individuals actively engaged in CPS development, targeting professionals from CPS-relevant sectors, including automotive, aerospace, energy, medical technology, and robotics. The survey was implemented using LimeSurvey, allowing for standardized and device-independent participation.

Despite the exploratory nature of the survey, which entails certain limitations in terms of generalizability, it provides valuable insights into real-world development contexts and practical challenges faced by practitioners.

3. Results

This chapter presents the results of the SLR and the exploratory industrial survey conducted in this study. Together, these results address the first two research questions from both an academic and a practical perspective.

3.1 *Identified Challenges in CPS Development (Literature Analysis)*

As part of a systematic literature review (SLR), 50 relevant sources were identified. The analysis included both theoretical publications and empirical studies with industry involvement. A detailed content analysis extracted 54 distinct challenges in CPS development. A frequency analysis (see Figure 1) revealed that complexity is by far the most frequently cited challenge, followed by interoperability, heterogeneity, and modeling. Other commonly mentioned challenges include tooling limitations, increased development effort, costs, and multidisciplinarity.

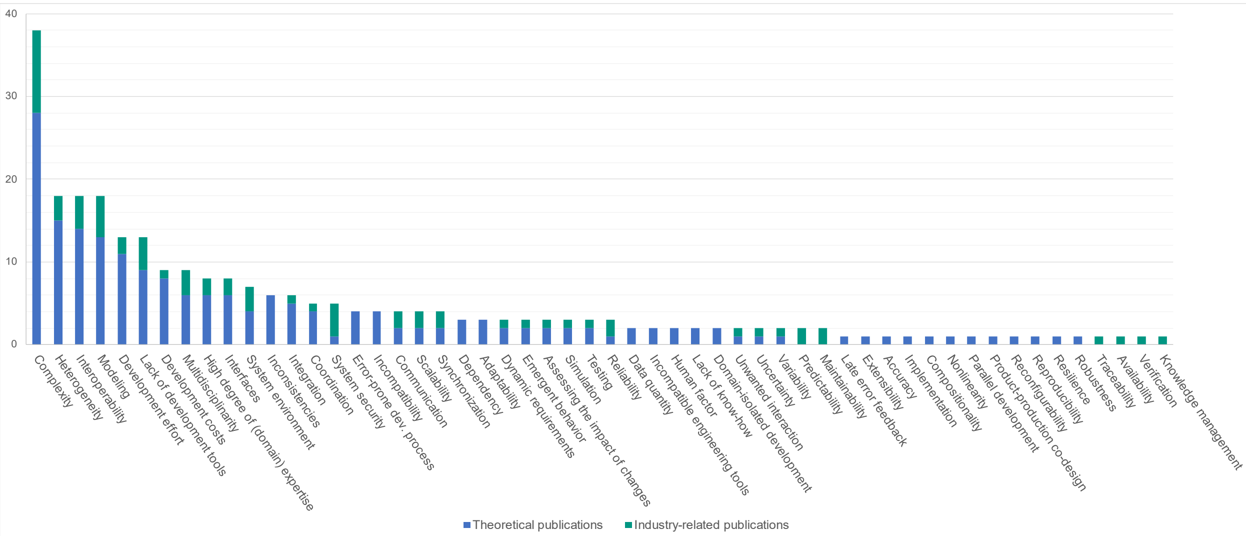

Figure 1: Frequency distribution of the CPS development challenges identified in the literature.

To provide a structured overview, these 54 challenges were subsequently organized into six thematic clusters: (C1) System Properties, (C2) System Requirements and Qualities, (C3) Process and Organizational Challenges, (C4) Modeling, Verification, and Validation, (C5) Tooling and Technical Integration, and (C6) Human Factors and Knowledge Management (see Figure 2).

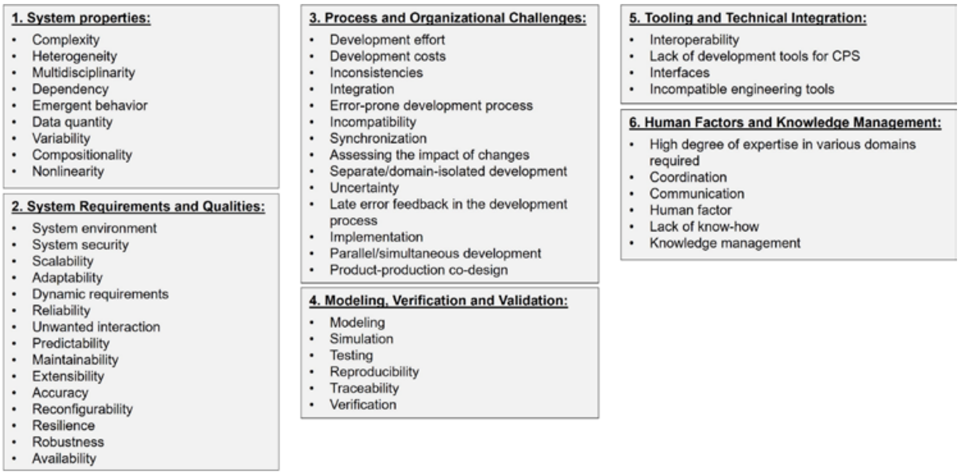

Figure 2: Classification of the 54 identified CPS development challenges into six thematic clusters (based on a literature review).

While these clusters facilitate thematic discussion, their boundaries are not always sharp. Certain issues inherently span multiple dimensions of CPS development. For instance, *heterogeneity* can be interpreted as both a fundamental system property (C1) and a root cause of interoperability issues in tooling (C5). Similarly, multidisciplinarity is not only a system property (C1), but also reflects challenges in process coordination (C3). These overlaps demonstrate the interconnected nature of CPS development, where technical, organizational, and human aspects are closely related. Against this background, the following sections discuss the challenges in each cluster in detail, starting with the fundamental system properties.

System Properties

This cluster addresses fundamental characteristics of CPS that complicate their development. The most frequently cited challenge is *complexity*, arising from the tight integration of mechanical, electrical, and software components [9]. These tightly coupled elements create large design spaces with many interdependencies, complicating modeling, simulation, and coordination among domain experts. Complexity is often described as a barrier to effective decision-making, driven by factors such as emergent behavior, nonlinearity, and dynamic temporal interactions [9,10].

The *heterogeneity* of CPS – referring to the integration of diverse components and modeling approaches across technical domains – is one of the most frequently cited challenges in the literature [11]. For example, mechanical models often utilize continuous variables, whereas software models are based on discrete states, complicating simulation and analysis. This challenge also has clear implications for tool interoperability (see C5), as heterogeneous systems require hybrid modeling approaches and demand alignment of semantics and timing constraints [10].

Closely related to heterogeneity, *multidisciplinarity* is another key challenge in CPS development. It refers to the need to bridge disciplinary boundaries between domains such as mechanical engineering, electrical engineering, physics, and computer science [12,13]. These disciplines often follow distinct methodologies, modeling languages, and toolchains, which makes integration difficult and hinders consistent system development [13,14]. While this phenomenon presents challenges related to human and organizational factors, such as intensive cross-domain collaboration, coordinated workflows, and suitable digital tools [9,15], the underlying cause is attributed to the system properties of the CPS.

Additional challenges in this cluster include implicit *dependencies* between components and environments, unpredictable *emergent behavior*, and *nonlinearity* [9,16,17]. CPS also generate large *quantities of heterogeneous data* and must support *variability* and *compositionality* across evolving configurations [11,17–19].

System Requirements and Qualities

This cluster covers the demanding requirements and quality attributes that CPS must meet to ensure reliable and safe operation. These challenges stem largely from the complex and dynamic *system environments* in which CPS are embedded. Unlike traditional "closed-world" assumptions, CPS operate in heterogeneous, open environments where contextual information is continuously sensed and affected. This complicates the prediction, simulation, and verification of system behavior [20,21]. Ensuring correct operation under unforeseen conditions whilst taking into account the variability of the environment remains a key challenge [9].

In the context of increasing interconnectedness and the critical applications of CPS, assuring *security* is paramount. This includes functional safety, access control, data privacy, and protection against cyberattacks [12,22,23]. These security requirements are closely related to system robustness and resilience, which also influence process-level risk management (see C3).

Scalability is another core requirement, as CPS must maintain performance across increasing system size and workload. The issue of scalability in CPS is particularly important given the considerable number of components involved [24,25]. In this context, *adaptability* is equally critical, enabling CPS to dynamically reconfigure their behavior and internal states in response to changing environments or system goals [11,12]. CPS must handle dynamic and often conflicting requirements that evolve during their lifecycle [17].

In addition, several Quality of Service (QoS) attributes impose specific requirements. *Reliability* ensures continuous, fault-free operation, which is vital in highly automated or safety-critical contexts [26]. *Maintainability* refers to the ability to repair systems efficiently and with minimal effort, while *availability* and *extensibility* relate to system uptime and future-proofing [18].

Predictability, defined as the capacity to reliably predict the behavior of a system, is of particular importance. However, this capacity is challenged by large state spaces and complex *(unwanted) interactions* within the system [9,18]. Similarly, the importance of *accuracy* in sensor and actuator technology cannot be overstated when considering the potential consequences of failure in sensitive applications [18].

In addition, *reconfigurability*, *resilience*, and *robustness* are cited as challenges. Reconfigurability enables CPS to autonomously adjust their configurations in response to faults or changing requirements. Closely related to this, resilience and robustness describe the system's ability to sustain service quality under stress or partial failure without fundamental loss of function [18].

Process and Organizational Challenges

This cluster addresses the process and organizational challenges that impede efficient CPS development. High *development efforts* and *costs* often result from the integration of heterogeneous technologies, extensive simulation requirements, and frequent iterations between engineers and domain experts [10,27–29]. *Integration* and *implementation* are often error-prone due to *incompatible tools* and *domain-isolated development* [30–33] (see C5).

Managing *inconsistencies* is a recurring problem, especially in *synchronizing* physical and cyber components given their asynchronous development cycles [12,17]. This issue is not purely procedural but also linked to knowledge management and communication (see C6). The high interdependency of system components complicates *assessing the impact of* (design) *changes*, necessitating improved traceability and dynamic risk management [34,35]. Moreover, *uncertainty* in design, stemming from incomplete knowledge and variability in system components, exacerbates these challenges [17,25]. Additionally, *late feedback on errors* due to late-stage testing increases both development time and risk [32].

Parallel development efforts, such as *co-design of product and production systems*, remain underutilized due to unclear interfaces and integration difficulties, limiting potential time-to-market reductions [36,37]. Overall, CPS development is a highly *error-prone process* that requires improved coordination, integration, and process synchronization mechanisms to address these process and organizational challenges [29].

Modeling, Verification and Validation

This cluster focuses on the methodological and technical challenges of modeling and validating CPS. *Modeling* CPS is challenging due to the need to represent both physical and cyber components across multiple engineering domains. Key difficulties include integrating continuous physical dynamics with discrete computational behaviors, managing heterogeneous models with different time scales, and ensuring interoperability across tools and domains [10,38,39]. These modeling challenges often originate from system properties such as heterogeneity (see C1) and lead directly to tool integration issues (see C5). The lack of unified modeling standards and the complexity of combining domain-specific modeling languages further complicate this task [14,40].

Simulation tools often fail to cover the full scope of CPS, especially real-time aspects and hardware-in-the-loop (HiL) integration, thereby impeding the efficacy of system testing [14,20,41]. *Testing* is further complicated by the oracle problem, which refers to the process of determining the correctness of system outputs. This challenge is compounded by the complexity of the system and the manual effort required during the integration of third-party software or the execution of hardware experiments [32,42].

Verification efforts are constrained by the inherently nonlinear and nondeterministic behavior of CPS, necessitating scalable approaches that handle uncertainties and incomplete models [25]. Moreover, *traceability* and *reproducibility* are critical, especially in safety-critical domains, but often require time-consuming documentation efforts [43].

Tooling and Technical Integration

This cluster addresses the technical and infrastructural foundations required for CPS development. One of the most frequently cited challenges is the *lack of interoperable tools* and consistent interfaces across engineering domains. The use of heterogeneous modeling languages, incompatible file formats, and fragmented, domain-specific toolchains impede seamless data exchange and system integration [19,44,45]. These *interoperability* issues arise both between engineering tools and across models, requiring alignment of semantics, syntax, and technical protocols – a task that is often technically complex and organizationally underprioritized [22,27,28]. While standards such as STEP exist to support such integration, their adoption remains limited, and integration efforts frequently compromise code quality and maintainability [17,27]. These technical integration challenges are often the practical manifestation of fundamental system heterogeneity (see C1) and process fragmentation (see C3).

The absence of unified modeling platforms and toolchains further exacerbates the problem. CPS development often lacks tool support for traceable workflows from requirements to implementation, as well as mechanisms for managing complex model structures [25,39]. Existing tools often address only (domain) isolated views, such as physical design, without providing a holistic CPS development perspective [9,41].

Interface management is a further critical issue. Poorly defined *interfaces* between components, models, and domains hinder collaborative development and increase the risk of costly integration errors [16,46].

Human Factors and Knowledge Management

This cluster emphasizes the human and organizational dimensions of CPS development. Developing CPS requires a *high level of expertise across various domains*. The literature repeatedly emphasizes the need for cross-domain knowledge among developers, encompassing both technical proficiencies and application-specific knowledge [14,38,47,48]. A closely related issue is the *lack of know-how*, often due to limited personnel resources or insufficient expertise in specific areas [20,24]. *Human factors* also pose a challenge in the development of CPS. Therefore, it is essential to design human-machine interfaces and consider humans as an integral part of the system [11,12].

Communication across domains is frequently hindered by a lack of mutual understanding [40,46]. Although basic information exchange may be similar in hardware and software development, domain-specific language and symbols complicate communication in CPS contexts [31]. Another challenge that is closely linked to communication is *knowledge management*. Engineers must frequently deal with implicit, undocumented knowledge that is difficult to formalize and maintain. This often forces engineers to rely on informal communication channels, complicating traceability and decision tracking [17].

Finally, *coordination* across teams and organizational units is another key challenge. Missing multidisciplinary coordination can create barriers between development phases [32]. Distributed teams, site-specific processes, and inconsistent resource allocation increase the effort needed for effective coordination [31].

3.2 Validation of challenges through an exploratory industrial survey

To assess the practical relevance of the CPS development challenges identified in the extant literature, an exploratory online survey was conducted among industrial practitioners. The primary objective of this study was to assess the extent to which these challenges are encountered in real-world CPS development and to identify additional, practice-based challenges not captured in the literature.

A total of 61 individuals participated in the survey, with 20 respondents completing the questionnaire in full, thus forming the basis for the analysis. The majority of participants reported over ten years of professional experience in engineering roles, and 95% indicated direct involvement in CPS development activities. This provides a solid basis for deriving industry-relevant insights.

In an open-ended question, participants were first asked to describe the main challenges they currently face in CPS development. The most frequently mentioned challenge was *security*, encompassing both cybersecurity concerns and issues related to product safety. Other recurring challenges included *incompatible tools* and *interfaces*, insufficient *interdisciplinary communication*, *compatibility* between existing products, and maintaining *updateability*. These statements align closely with the challenges identified in the literature, especially regarding complexity, heterogeneity, and multidisciplinarity.

To evaluate the literature-based findings, participants were asked to rate the practical relevance of 15 most relevant challenges from the literature review using a four-point Likert scale (from “never relevant” to “always relevant”). The results indicate a strong alignment between academic and industrial perspectives. No challenge was designated as “never relevant” by more than 15 % of respondents, and many received high confirmation ratings.

The most prominent challenges were complexity (95 % “often” or “always” relevant), multidisciplinarity (90 %), and a high degree of domain expertise (90 %). Other key challenges included safety and security requirements, high development costs, and lack of interoperability. Interestingly, modeling, which is frequently emphasized in the academic literature, received comparatively lower ratings. Although 45 % of participants still considered it as “often” or “always” relevant, it appears to be perceived as less urgent compared to more operationally tangible issues, even though it plays a foundational role in addressing system complexity.
Figure 4 provides a detailed overview of the assessments for each of the 15 selected challenges, illustrating the varying degrees of perceived relevance across the surveyed sample.

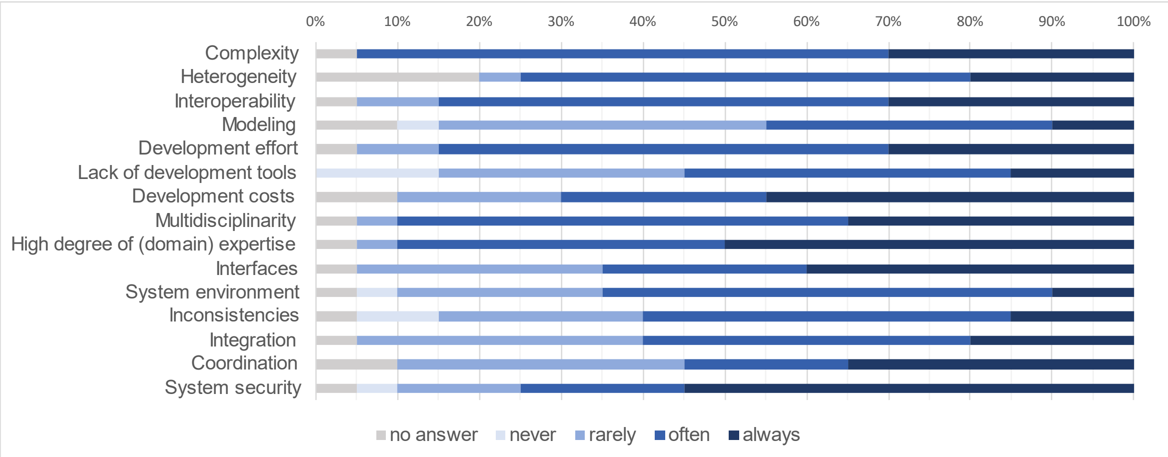

Figure 3: Industry practitioners’ relevance ratings of 15 literature-identified challenges in CPS development.

Participants also shared selected strategies they applied to address the challenges. For security, both technical solutions (e.g., firewalls, encryption, role-based access control) and organizational measures (e.g., integrated security processes, regular audits, dedicated IT-security teams) were reported. To deal with complexity and multidisciplinarity, companies rely on cross-functional development teams, structured onboarding and training programs, early-stage system modeling, and comprehensive system-level documentation. Digital twins and simulation tools were also mentioned as key enablers for analyzing system behavior and supporting integration. For challenges related to interoperability and interface management, respondents emphasized the need for standardized communication protocols, reference architectures, and early coordination with suppliers. Furthermore, regular stakeholder feedback and active customer involvement were described as effective means of maintaining clarity of objectives and ensuring alignment with market requirements.

4. Discussion

The results of the exploratory survey confirm the high practical relevance of many CPS development challenges reported in recent literature, particularly complexity, multidisciplinarity, and interoperability, each validated by more than 80 % of participants as often or always relevant. This alignment underlines the necessity of system thinking and integrated development approaches that span engineering domains, product life cycle phases, and system generations.

At the same time, the survey reveals a set of additional, practice-driven challenges that remain underrepresented in academia. These include compatibility with existing products or customer applications, maintaining updates and upgrades across large and heterogenous product portfolios, and increasingly complex cybersecurity requirements – not only for protecting data but also for ensuring safe operation under abnormal conditions. Human and organizational barriers, such as rigid development structures, siloed teams, insufficient cross-domain understanding, and resistance to change, further complicate CPS development. Security, in particular, emerged as the single most frequently mentioned challenge, likely reflecting recent European regulatory developments.

A comparison with the existing literature indicates that many technical problems – such as inconsistencies between interdependent models, delayed error identification, or limited tool interoperability – are closely linked to organizational and process factors. For instance, inadequate cross-functional coordination can exacerbate consistency management challenges, while the absence of formalized knowledge management processes can impair traceability and reproducibility across system generations. These observations suggest that technical solutions alone are insufficient; progress requires the collaborative development of methods, tools, and organizational structures.

From a Smart Manufacturing perspective, these challenges have direct implications for long-term, cross-generational CPS development. Ensuring consistency between heterogeneous, view-specific models used by different domain experts is becoming increasingly important as systems become more configurable and evolve over time. The absence of effective mechanisms for detecting and resolving inconsistencies can compromise both agility and reliability. Rising regulatory and safety requirements necessitate the incorporation of compliance and resilience into development workflows at the earliest stages. Addressing these challenges calls for integrated engineering environments, standardized toolchains, and methods that enable cross-domain collaboration and continuous updates and upgrades across product generations.

However, these results must be interpreted with regard to the boundary conditions of the study conveyed. While the survey includes 20 participants it is essential to keep in mind, that these participants are located in Germany, potentially introducing geographic or regulatory bias, particularly regarding security challenges. The exploratory study is to be regarded as a complement to the literature review, acknowledging its specific conditions potentially hindering generalizability. Also taking into consideration, that the literature review solely focused on English as well as German literature sources, neglecting gray literature, the combined findings may limit the breadth of captured challenges. Despite these limitations, the combined findings provide a robust initial picture of CPS development challenges in industrial practice, highlighting areas where further empirical investigation is needed.

Overall, the study underscores the need for holistic approaches for the development of CPS, integrating technical, organizational, and cross-generational aspects. Advancing model-based engineering methods with integrated consistency checking, automated impact analysis, and tool interoperability is crucial. Equally important is the promotion of interdisciplinary training, reevaluation of team structures, and enhanced cross-domain communication to facilitate seamless collaboration across system generations and lifecycle phases. The validation of these findings in various industrial and geographical contexts is imperative to ascertain their generalizability and adapt solutions to domain-specific requirements.

5. Conclusion

This study aimed to identify and analyze key challenges in the development of CPS by combining a systematic literature review with an exploratory survey among industry practitioners.

A structured review of publications from 2019 to 2024 identified 54 distinct challenges, grouped into six thematic clusters. Among the most frequently cited were issues related to system complexity, interoperability, heterogeneity, modeling, and the lack of sufficient development tools. The subsequent survey broadly confirmed the relevance of these literature-based challenges, particularly complexity, multidisciplinarity, and domain-specific expertise. It also revealed additional, practice-driven challenges underrepresented in academic discourse, including cybersecurity, cross-domain collaboration difficulties, insufficient compatibility, and maintaining updates and upgrades.

As an overview study, this work offers an initial, structured understanding of the breadth and interrelations of CPS development challenges. It synthesizes academic and industrial perspectives, highlighting not only the technical but also the organizational and process-related barriers that hinder cross-generational and cross-domain CPS engineering. This integrated perspective serves as a foundation for further, more targeted empirical investigations and for the prioritization of research and development efforts.

These findings highlight a growing need for holistic CPS development approaches. Cross-domain engineering environments, standardized toolchains, and semantically enriched model representations are essential to maintain consistency across disciplines and system generations. The increasing complexity and configurability of CPS, combined with the need for continuous evolution and updateability, emphasize the limitations of fragmented development practices.

In conclusion, this study synthesizes current CPS challenges and outlines directions for research and method development. Advancing model-based, consistency-preserving, and cross-generational engineering strategies will be critical to meeting the growing demands of CPS development in complex industrial settings. Pilot studies and industrial implementations will be key to validating these approaches and adapting them to diverse real-world contexts.

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