Information Systems Frontiers
https://doi.org/10.1007/s10796-022-10252-x

Cyber-Physical Systems in the Context of Industry 4.0: A Review, Categorization and Outlook

Sascha Julian Oks[1] · **Max Jalowski**[1] · **Michael Lechner**[2] · **Stefan Mirschberger**[3] · **Marion Merklein**[2] · **Birgit Vogel-Heuser**[4] · **Kathrin M. Möslein**[1]

Accepted: 8 January 2022

Abstract

Cyber-physical systems (CPS) offer great potential for the digital transformation of industrial value creation in the context of Industry 4.0. They unify and integrate several technological approaches, including big data analysis and artificial intelligence, enhancing real-time monitoring and control of manufacturing processes. An extensive knowledge base formed by various disciplines, including information systems, engineering, and computer science, already exists for CPS. However, this knowledge has not been holistically captured and structured to date. To address this research gap, this study conducts a large-scale literature review of 2365 papers representing the current state of the research and then develops a novel categorization on industrial CPS with 10 sections, 32 areas, and 246 fields. The categorization is presented in hierarchical graphical form and can also be utilized as a web tool. To conclude, a perspective on future research needs and potentials to enhance Industry 4.0 in both research and practice are offered.

Keywords Cyber-physical systems (CPS) · Industry 4.0 · State of research · Categorization

1 Introduction

Industrial value creation is undergoing significant changes as part of the digital transformation with Industry 4.0 as the guiding term (Lasi et al., 2014), which emerged from a German funding initiative in 2013 with a number of program equivalents worldwide (Li, 2018). Cyber-physical systems (CPS), in addition to other technologies and concepts, are of particular relevance for this process (Zhang et al., 2021). With their general concept of, "[…] integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa" (Lee, 2006, p. 1), CPS offer extensive application potentials within the industrial domain (Oks et al., 2017). In this, they contribute to the realization of use cases like the real-time monitoring and control of systems and processes, predictive maintenance, and the expansion of

---

✉ Sascha Julian Oks
sascha.oks@fau.de

Max Jalowski
max.jalowski@fau.de

Michael Lechner
michael.lechner@fau.de

Stefan Mirschberger
smirschberger@deloitte.de

Marion Merklein
marion.merklein@fau.de

Birgit Vogel-Heuser
vogel-heuser@tum.de

Kathrin M. Möslein
kathrin.moeslein@fau.de

[1] Chair of Information Systems, Innovation & Value Creation, Friedrich-Alexander-Universität Erlangen-Nürnberg, Lange Gasse 20, 90403 Nürnberg, Germany

[2] Institute of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Egerlandstraße 13, 91058 Erlangen, Germany

[3] Deloitte, Franklinstraße 46-48, 60486 Frankfurt am Main, Germany

[4] Institute of Automation and Information Systems, Technische Universität München, Boltzmannstraße 15, 85748 Garching bei München, Germany

human-machine collaboration, among others, and therefore drive the optimization of production, products, and services with increased effectiveness and efficiency (Colombo et al., 2017).

However, as CPS are utilized both in industry and many other application domains, they qualify as general purpose technology (Bresnahan, 2010). As is to be expected with a technology/a concept that is associated with vast potentials and a wide range of application possibilities, CPS attract research interest from a variety of scientific disciplines and are utilized by numerous communities of practitioners. CPS are therefore constantly being assessed from different perspectives, including the technological (hardware, software, architectures, information systems, etc.), the process-oriented (applications, procedures, operations, etc.), the organizational (value creation, cost-benefit considerations, business models, etc.), the socio-technical (human-computer interaction (HCI), work design, etc.) and others (Geisberger & Broy, 2015). As a result, an extensive knowledge base on the subject of CPS and their application in the industrial domain has already been established. However, this knowledge base is very diverse and wide-ranging and therefore complex and difficult to determine.

It is therefore the motivation of this research, in order to exploit the full potential of CPS for the further establishment of Industry 4.0 (Vogel-Heuser & Hess, 2016), to disclose and examine the current state of knowledge on CPS and to categorize all CPS related and relevant topics within the industrial application domain, which is highly relevant and of great value to both the research and practice-oriented communities. This paper addresses the aforementioned research demand with the following two objectives: (I) Describe and analyze the state of research on CPS. (II) Develop and graphically present a categorization of CPS related and relevant topics in the context of Industry 4.0. This includes all subjects, technologies, concepts, and procedures that are related or relevant to industrial value creation. Both objectives are addressed in a comprehensive manner, based on a large-scale literature review. Concerning the first objective, the state of research is not thematically restricted to allow the derivation of analogies from other disciplines. This takes into account that CPS are studied and elaborated by a large number of disciplines, particularly in the area of basic research, of which the resulting knowledge cannot be strictly divided according to application domains. An exclusive focus on the area of manufacturing would therefore leave out relevant knowledge. Upon the second objective, the categorization is exclusively focused on CPS related and relevant topics in the context of Industry 4.0. This focus is feasible since for this objective it is no longer a matter of knowledge collection but of the subsequent step of arranging it in a structured, hierarchical, and comprehensive manner. The system of a categorization is therefore suitable, as it allows to present a vast amount of topics in a well-arranged form while also showing their interrelationships.

Thus, this paper provides an overview of research on CPS with pertinence for the Industry 4.0 domain and a categorization of all relevant topics for industrial CPS. It differs from a research survey paper in that it identifies and categorizes the topics but does not describe and analyze them in full depth, as this is done through narrowly defined concept-specific reviews as presented in related work chapter in Section 2.2.

The paper is structured as follows: After the introduction, the theoretical foundations of CPS in the industrial context are laid and related work is presented in Section 2. The third Section presents the methodological approach for the literature review and the subsequent analysis and development steps. The resulting state of research and categorization are presented in Section 4 in particular in graphical form. In Section 5 the paper closes with conclusions and an outlook regarding further consolidation and research needs in the field of industrial CPS.

2 Cyber-Physical Systems as an Enabler for Industry 4.0

This Section lays the groundwork for this research; the theoretical foundations of CPS are presented in 2.1 and additional related work is introduced that also seeks to structure industrial CPS in 2.2.

2.1 Foundations of Cyber-Physical Systems

The term CPS was introduced by E. A. Lee in 2006; since then, the topic has been further analyzed and developed in several scientific and practical disciplines (Geisberger & Broy, 2015). In essence, CPS are embedded systems that have both a cyber and a physical sphere between which there is a continuous and iterative information exchange (Alur, 2015). In the physical sphere, sensors are used to record environmental conditions, which are then evaluated in the cyber sphere using local computing power. The information obtained from the data stream can be either exchanged with other entities via communication interfaces or used in the physical sphere to affect the environment according to predefined rules of behavior via actuators (Lu et al., 2016). CPS can therefore be used for monitoring as well as controlling digital, physical, and especially hybrid processes (Jiang et al., 2018). The continuing miniaturization of computer hardware to the point of smart dust, coupled with the ongoing reduction of component costs, enables CPS to be used extensively in a wide range of contexts and conditions (Rajkumar et al., 2010). They can also be operated either

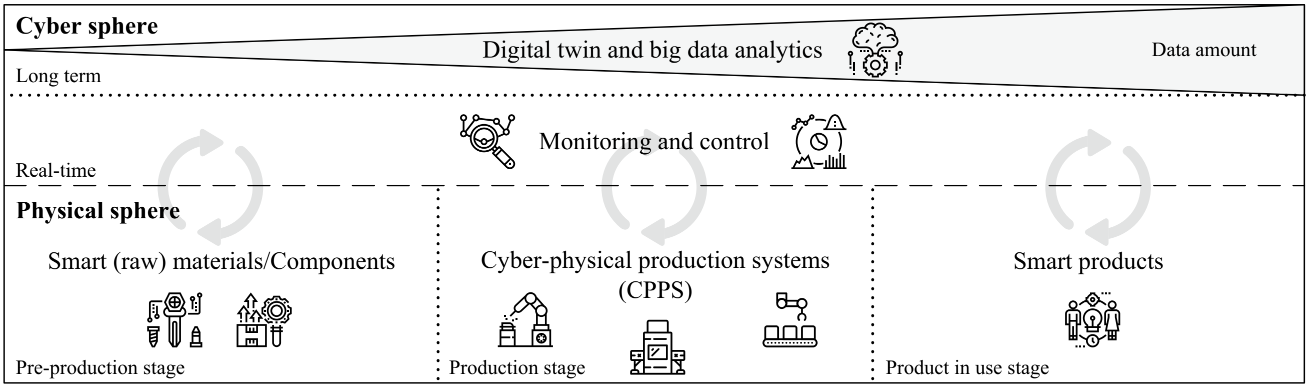


Fig. 1 Schematic functioning of industrial CPS

completely autonomously or in collaboration and interaction with humans (Gil et al., 2019).

Three dimensions are to be taken into account in the design, development, and operation of CPS, the technical, the human/social, and the organizational (Oks et al., 2017). In the technical dimension, application-specific and requirement-meeting hardware and software have to be orchestrated with an appropriate architecture. Furthermore, the CPS has to be integrated into existing physical and digital infrastructures, and desired interoperability with other systems (Gürdür et al., 2016) should be ensured by means of norms and standards (Hehenberger et al., 2016). The human/social dimension comprises the integration of humans into or the interaction of humans with a CPS. In this dimension, HCI, safety in use, and the consideration of ethical issues in system design are of major importance (Calinescu et al., 2019). The organizational dimension is determined by the insertion of the CPS into the application purpose and context within various institutional structures and frameworks (Oks et al., 2018).

In addition, CPS can be divided into three levels that categorize their application in terms of system size and reach. At the micro level, CPS are used in a personal or small-group individual context, usually limited to a local area. At the meso level, CPS applications are organization-wide and can have interregional system dimensions. At the macro level, CPS are deployed, often as volatile systems of systems (Trunzer et al., 2020), in application scenarios that encompass entire national economies or are even more far-reaching, and are designed transregionally or globally (Oks et al., 2017). Within these levels, CPS are used in various domains in the context of the digital transformation. These include urban development (*Smart City*), healthcare (*Smart Health*), mobility (*Smart Mobility*), building management (*Smart Home*) and, most prevalently, industrial value creation (*Smart Manufacturing*) (Geisberger & Broy, 2015). As previous stated, CPS qualify as a general purpose technology because of this wide range of applications across levels and domains (Bresnahan, 2010). The distinctive characteristic of technologies of this kind is that they can be used widely and cross-functionally with a high level of utility. Like previous general purpose technologies, such as the steam engine, assembly lines, or computers, CPS, in combination with other technologies of the digital age, are attributed the potential to unleash a surge in productivity that is qualifying to induce an industrial revolution (Liao et al., 2016; Rosenberg & Trajtenberg, 2009). For this reason, the digital transformation of industrial value creation through CPS is discussed under the guiding term *Industry 4.0* (Lu, 2017), which anticipates these far-reaching changes. Among other things, the establishment of CPS is considered to have the potential to address market megatrends, such as increasing individualization, dematerialization, and servitization, as well as increase sustainability by both optimizing existing processes and outputs and innovating new ones (Geisberger & Broy, 2015).

CPS used in the industrial domain are referred to as industrial CPS (Colombo et al., 2017). This term is used inclusively and covers not only CPS used in manufacturing, but also peripheral ones, such as in smart products, which provide relevant data for value creation (Oks et al., 2017). Industrial CPS are therefore broader in scope than cyber-physical production systems (CPPS) (Monostori, 2014). The schematic functioning of industrial CPS, which is shown in Fig. 1, can be described as follows: In the physical sphere, state data is collected throughout the production and product life cycle (Tao et al., 2020). This includes smart (raw) materials/components in the pre-production stage, CPPS in the production stage, and subsequently, smart products in the product in use stage. The recorded data is then used in the cyber sphere in two ways. First, in real-time for monitoring and control of statuses and processes. Threshold values and algorithms are used to detect (imminent) events to react in such a way that corresponding actuators are triggered in the physical sphere according to pre-defined system logic (Jiang et al., 2018). Second, the collected data is processed and aggregated in the form of a digital twin for production plants and (sub-)products in the long term (Biesinger et al., 2019). In addition, the vast, continuously growing data sets are analyzed using big data analytics (Marini & Bianchini, 2016). The insights gained in this way are then used to optimize the real-time methods of monitoring and control, thereby continuously enhancing the performance of the industrial CPS. Based on this scheme, industrial CPS constitute the basis for a large number of use cases in Industry 4.0, including predictive maintenance (Meesublak & Klinsukont, 2020), order and batch size planning (Huang et al., 2021), energy management (Ma et al., 2019), disaster prevention (Lei et al., 2020), and quality control (Colledani et al., 2018), among others.

2.2 Related Work

As is to be expected with a widely established general purpose technology, the literature base on CPS is already exceedingly comprehensive. Literature that is relevant for this research as related work in the form of reviews or systematizations on the topic of CPS can be divided into general, topic-specific, and industry-oriented perspectives.

As part of the general examination, Chen (2017b) reviewed and analyzed the theoretical foundations of CPS. In another general review on CPS, Liu et al. (2017) highlighted the system integration, architectures, and challenges associated with CPS. Using a less theoretical orientation, Hehenberger et al. (2016) introduced methods and applications for the design, modelling, simulation, and integration of CPS. Adjacent to these topics, there is a systematic review on interoperability and integration in the context of CPS by Gürdür and Asplund (2018). Besides the contributions mentioned above, which approach the subject of CPS from a broad viewpoint, there are also reviews, such as that by Muccini et al. (2016), on system self-adaptation, which examine CPS in general but exclusively with respect to one characteristic. In addition to reviews, there are also structuring works on CPS, such as that by Asare et al. (2012), who designed a CPS Concept Map with 51 items (e.g., applications, requirements, etc.) and their relations based on taxonomy developed during the 2012 NIST CPS Workshop.

Topic-specific research focuses on dedicated applications, technologies, or domains pertaining to CPS. A general overview of possible applications is given in a review by Chen (2017a). In this study, ten application areas are described and analyzed. The survey on CPS security by Humayed et al. (2017) is an example for reviews focusing on exclusively one application field. Other reviews, like those on blockchain-enabled CPS (Zhao et al., 2021) or CPS clouds (Chaâri et al., 2016), concentrate on technologies and their integrated operation with CPS. There are also dedicated reviews on CPS utilization in specific domains, such as the one by Haque et al. (2014) on healthcare.

There is also a wide range of preliminary work in the Industry 4.0 domain. For example, Dafflon et al. (2021) dealt with the general challenges, approaches, and used techniques of CPS for manufacturing in their literature review. The relevance of CPS to complementary concepts and technologies, such as internet of things (IoT), big data, and cloud computing, in the context of digitalized industrial value creation has been analyzed (Kim, 2017). The question of interoperability standards to enable interconnectivity between these technologies and the devices employing them was addressed in the review of Burns et al. (2019). Furthermore, a systematic mapping study of architectures, technologies, and challenges for CPS in Industry 4.0 was conducted by Hofer (2018). Further articles focusing on CPS architectures for manufacturing were contributed by Lee et al. (2015) and Pivoto et al. (2021), whose reviews drew specific attention to applications involving the industrial internet of things. Other reviews investigated the characteristics of CPS in the context of smart factories (Napoleone et al., 2020) and smart manufacturing (Thoben et al., 2017). The topic of smart manufacturing, in particular the control of its processes, was also examined in a literature review by Rojas and Rauch (2019). The design process of CPS for manufacturing was analyzed in the course of a literature review by Lozano and Vijayan (2020); Hermann et al. (2016) contributed design principles for Industry 4.0 scenarios. A general state of the art on the topic of Industry 4.0 with an additional outlook on future trends was provided by (Xu et al., 2018). In addition to the analytical studies and reviews cited above, there is also research on industrial CPS that present concepts that structure thematic areas in different forms. Against this backdrop, Monostori et al. (2016) offered 23 keywords, roots, expectations towards research, case studies, and R&D challenges regarding the implementation of CPS in manufacturing. Additionally, an application map for industrial CPS was introduced by Oks et al. (2017), which indicates specific CPS application fields for both production and smart products. In addition, a taxonomy consisting of nine items for techniques for approaching big data-related issues in CPS by Xu and Duan (2019), a classification of CPPS applications provided by Cardin (2019) and a concept map of CPPS research topics by Wu et al. (2020) should be mentioned in this regard. Along with that, Berger et al. (2021) provided a terminology, taxonomy, and reference model for entities in CPPS from a self-organizing systems' perspective. Concluding, there was a trend map for cyber-physical systems research and education in 2030 introduced by Gürdür Broo et al. (2021), that provides 44 possible influencing factors in 7 categories regarding this topic.

Although the work outlined above is very extensive and contributions came from a wide variety of disciplines, there is yet no comprehensive approach to the topic of CPS in the form of a state of research nor a categorization of CPS related and relevant topics in the context of Industry 4.0 that are presented coherently in a suitable form. This work addresses this research gap through its two objectives.

3 Research Method

In order to address the two research objectives of this study, we chose the following research design: A comprehensive systematic literature review for data collection was conducted. The resulting data set was analyzed and transferred into a state of knowledge on CPS research and a categorization of CPS related and relevant topics in the context of Industry 4.0. Following the suggestions of vom Brocke et al. (2015) for conducting literature searches in information systems research, we defined the search scope as follows. We chose a sequential process, following the recommendations of Tranfield et al. (2003), which is described in more detail in subsequent paragraphs. Indexing services and databases were chosen as sources (cf. Fig. 2). As described in the motivation for this research, both the state of knowledge on CPS and the categorization of CPS related and relevant topics in the context of Industry 4.0 are intended to provide a comprehensive, general, and holistic overview of the subject area The coverage of our literature search, therefore, is comprehensive as well, in order to include as many relevant publications as possible (cf. vom Brocke et al., 2015). In terms of technique, we primarily applied a keyword search; the exact procedure is described below.

A systematic literature review was chosen for data collection and analysis because of its transparent, exhaustive, and heuristic qualities. In a systematic literature review, research contributions on a specific topic are localized, assessed, and interpreted. It differs from a traditional narrative review because of its methodological strategy and the detailed description of each individual process step. Furthermore, it aims at minimizing bias and increasing the reproducibility and transparency of the researchers' approaches, decisions, and conclusions (Tranfield et al., 2003). The concrete procedure follows the recommendations of Denyer and Tranfield (2009) and Tranfield et al. (2003); it consists of five steps with sub-steps. All of these were performed manually by the research consortium of this paper, with one exception where the Citavi 6 function to detect and sort out duplicates was used. There were no fewer than five researchers involved in any step of the workflow. Table 1 explains the five main steps of the systematic literature review.

In the first step (1), the two research objectives were defined according to the motivation for this research: The first objective is (I) to describe and analyze the state of research on CPS, and the second is (II) to develop and graphically present a categorization of CPS related and relevant topics in the context of Industry 4.0.

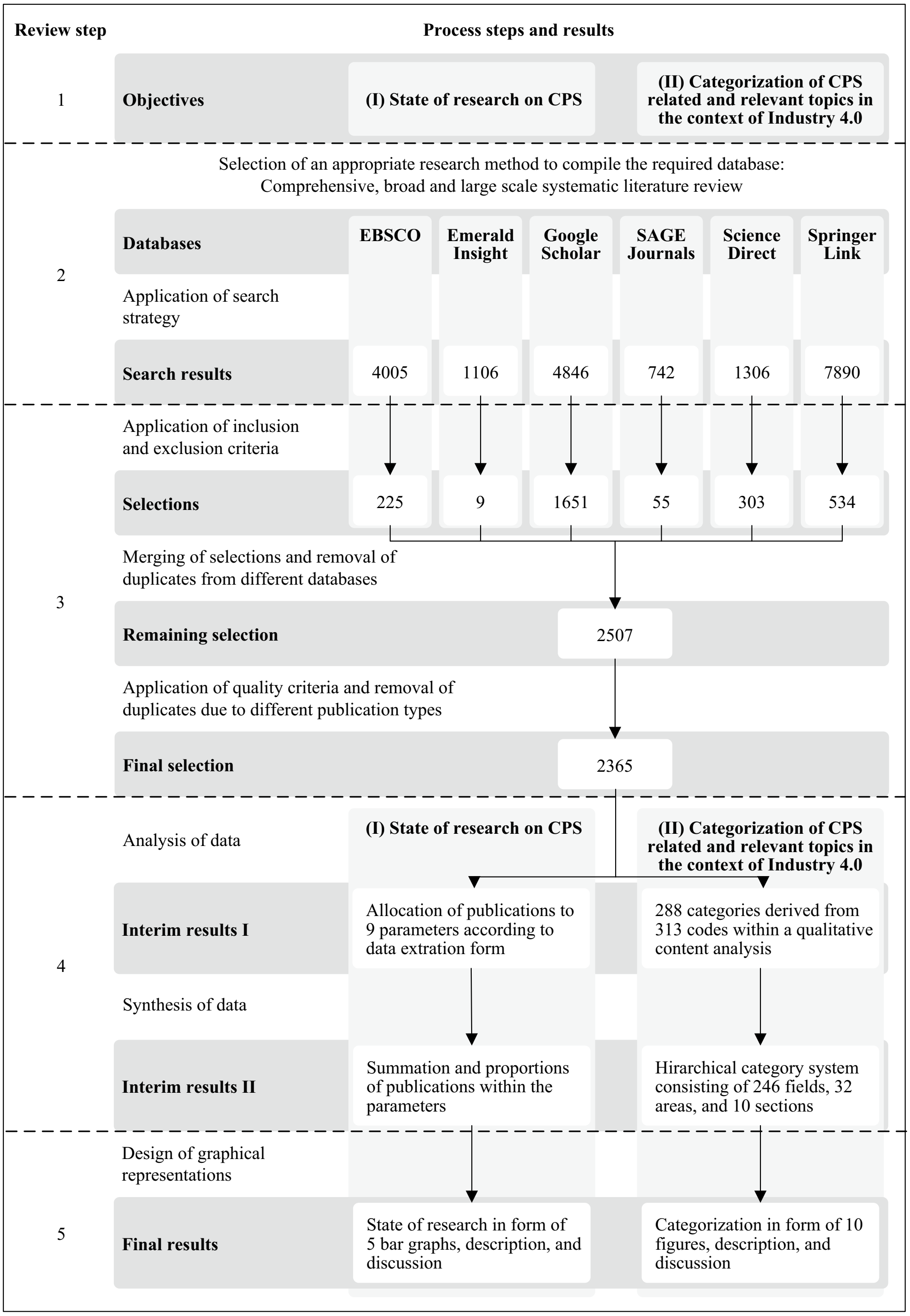
The second step (2) was to identify the relevant literature needed to achieve the defined research objectives, which included screening, selecting, and assessing the search results. For the search, the online databases and library services EBSCO, Emerald Insight, Google Scholar, SAGE Journals, Science Direct, and Springer Link were selected to cover all relevant subject areas. The advanced search function was used in all databases for more comprehensive search options. The keywords were based on the term "cyber-physical systems", considering different spellings in the existing literature. Both synonyms and plural forms were used to ensure an exhaustive search as well as comprehensive and valid results. The complete list of search terms is available in Appendix Table 3. The keywords and their synonyms were combined to search strings by using Boolean operators. The keyword "Industry 4.0" was intentionally omitted despite the thematic focus of the categorization within this context. This approach ensures that CPS sources relevant to the Industry 4.0 domain that do not explicitly contain the term Industry 4.0 in their title, keywords or abstract are also collected and considered. E.g., this becomes evident with terms such as smart factory, smart manufacturing, etc., since these tend to be used synonymously for Industry 4.0 and also for each other. Moreover, there are many papers on niche topics that only address a technical problem, phenomenon, etc., but are relevant to CPS in general, regardless of the respective application domain.

In the third step (3), the search results were screened and selected based on definite inclusion and exclusion criteria. The inclusion criteria were the containment of keywords or synonyms and relatedness to the topic. Exclusion criteria included publication languages different from English or German, inadequacy of outlet[1], or the use of CPS as an abbreviation with a different meaning. Using the described concepts as search terms, the search returned 2777 publications. The procedure was as follows: The first reduction was realized in the databases EBSCO, Google Scholar and Springer Link, where the selection of the option "Source type is different from "Academic Journal"" and "Title does not contain at least one of the keywords or their synonyms" initially reduced the number of papers to be considered. Thereupon, after prior discussion, approval and sample round, it was decided for each source based on title, keywords and the abstract about the consideration based on the stated exclusion criteria. Six researchers in two-person teams

---

[1] Publication type outside of a journal article, monograph, contribution to an edited book, contribution to conference or workshop proceedings, dissertation, or university report.

Fig. 2 Process of the systematic literature review



performed this step of the process. After removing duplicates with the software Citavi 6 and merging the results from all databases, 2507 publications remained. In a final reduction by applying quality criteria[2], the number of publications decreased to 2365. No exclusions were applied with regard to subject-specific selections and rankings of the research outlets, since all themes as well as new, less established research domains had to be considered to achieve a comprehensive overview. In contrast to other systematic literature reviews, a larger number of publications was explicitly considered for analysis because of the topic of CPS itself. First, CPS emerge from the combination of several hardware and software components, rely on complex architectures and

---

[2] Publications that are a description, preface, or foreword of a workshop or conference, none of the keywords or their synonyms existing in the abstract, keywords or full text of the publication, or the main topic of the publication not being in the context of CPS.

Table 1 Steps of the systematic literature review

Review step	Description
1	Formulation of research objectives
2	Search • Development of search strategy (selection of databases, definition of search terms, and options) • Conducting the search by applying search strategy
3	Screening, selection, and assessment of search results • Definition of selection (inclusion and exclusion) and quality criteria • Selection of search results based on selection criteria • Merging of selections of all databases and removal of duplicates • Assessment of quality based on quality criteria and removal in cases of insufficient quality
4	Analysis and synthesis • Creation of data extraction forms • Data analysis • Data synthesis
5	Presentation and interpretation of findings • Presentation of findings • Conclusion

multilayered communication standards, and involve miscellaneous stakeholders (Khaitan & McCalley, 2014). Second, the domain of industrial value creation, with its core of production, is interlinked with many other domains, such as logistics and energy supply, which hold many application scenarios for CPS (Oks et al., 2017). Third and last, since the research field of CPS is highly topical, findings in specific niches can have a universal validity that is relevant to other research disciplines as well.

In step four (4), the selected contributions were analyzed to extract and synthesize the relevant data, however, in different procedures for the two objectives I and II.

Analysis and synthesis for objective I: First, a data extraction form, which had been adapted to the requirements of the research objective, was applied to outline the present state of the research on CPS. The data extraction form, which is displayed below (cf. Table 2), includes both standard information, such as publication type, name of journal, authors, etc., as well as a set of specific parameters, such as dimensions and application domains. In the next step, the sources were analyzed according to the data extraction form. The allocation was performed by the research consortium while ensuring objectivity as is typical for qualitative research by applying inter-coder reliability measures and discussion of results (Mayring, 2015). Concluding, the analysis results were processed quantitatively by summation and proportion calculation.

Table 2 Extracted data

- Publication type
- Name of journal (only for journal articles)
- Publication language
- Publication year
- Author(s)
- Research institution(s)
- Research discipline
- Dimension (technical, organizational, or socio-technical)
- Application domain

Analysis and synthesis for objective II: For the second objective, to elaborate a holistic categorization of CPS related and relevant topics in the context of Industry 4.0. Due to this large variety, we decided to create a categorization as opposed to a classification. According to Jacob's (2004) definition, relevant topics, technologies, concepts, and procedures cannot always be strictly delimited or assigned, and overlapping areas may exist; a classification would require stricter delimitation, hierarchies, and representations (Jacob, 2004). Given the heterogeneity within the field of CPS in Industry 4.0, this did not appear to be expedient. A classification in the form of a taxonomy was equally unsuitable for these reasons (Nickerson et al., 2013). Ontologies, as a comparable approach, focus more on relationships between different phenomena or constructs (Wand & Weber, 2004), however our categorization does not aim to represent encompassing relationships between different items. To compose the categorization, the titles, abstracts, and keywords of the contributions were analyzed for terms of interest regarding CPS in the context of Industry 4.0. These included topics, technologies, concepts, and procedures. Methodically this was conducted by the performance of a structured qualitative content analysis. For this purpose, an inductive code creation approach, following Mayring (2015), was applied. The titles, abstracts, and keywords of all 2365 papers were included in the analysis; relevant passages or words were marked in Citavi 6. A total of 313 codes were created, often by matching words exactly, but also by marking sentences or paragraphs to include content or context. The qualitative content analysis was conducted by five researchers who regularly discussed the codes to ensure a common and consistent understanding and coding procedure. Results were compared and adjusted until a common consensus was reached. Inter-coder reliability measures were also used for quality assurance opposing potential subjectivity in this qualitative research procedure (Mayring, 2015). For the development of the categorization, 288 categories were derived from the 313 codes based on their respective properties. The reduction results from the clustering of similar codes or the omission of codes that were irrelevant or incompatible with the classification system. The 288 categories were arranged into a hierarchy with sub-categories consisting of 246 fields, 32 areas, and 10 sections using Citavi 6. Each field is a specific technology, concept, or procedure. An area is superordinate to this and can be separated, for example, by architecture, value creation process or organizational structure. Sections are overarching subjects into which the areas and fields are classified.

The utilization of software or AI applications was not an option for the development of the categorization either, since it was not a deductive procedure in which all category titles would already have been known, but an inductive one in which the categories first had to be developed from the literature.

In the fifth (5) and final step of the research process, the presentation of the findings is performed.

Presentation and interpretation of findings for objective I: The summed and proportional findings were then converted into bar graphs showing them into proportional, numerical form.

Presentation and interpretation of findings for objective II: The resulting categorization was transferred to a graphical representation for a clearer overview and a more descriptive presentation. In addition, an interactive web tool was created to make the data even more accessible (cf. Appendix Fig. 18). The underlying literature for each category is provided and linked, and the fields and areas can be marked and annotated. Furthermore, a search function has been implemented to enable the direct retrieval of terms and properties. The web tool features a selection of languages, including English and German.

Complementing the graphical representations, the findings in form of the state of research and the categorization are extensively described in Section 4 and discussed in Section 5. The detailed process of the review steps is outlined in Fig. 2.

4 Findings

In the following, the results of the literature review and analysis are presented in two subchapters. First, in Section 4.1, a state of research on CPS is given, which is determined based on the characteristics of the analyzed publications. Second, in Section 4.2, a categorization of CPS related and relevant topics in the context of Industry 4.0 is provided, which organizes them in 10 sections, 32 areas, and 246 fields in detail.

4.1 State of Research on Cyber-Physical Systems

The state of research on cyber-physical systems with regard to the distribution of publications by type is predominantly divided into contributions to edited volumes and conference proceedings (1499) and journal articles (810). The other types, including books, dissertations, and reports, on the other hand, account for a minor proportion of the total, as can be seen in Fig. 3.

In terms of the distribution of the publications according to different scientific disciplines, three are the most prominent. These are computer science (856), computer engineering (808), and engineering (625). Business studies (36), mathematics and physics (26), and medicine (15) also deal with the subject matter, though there are a significantly lower number of publications in these disciplines.

Concerning the distribution of publications according to the disciplines specified in Figs. 4 and 5 shows that, in terms of the dimension of CPS introduced by Oks et al. (2017), the technical is notably the largest, with 2030 contributions. Given the 130 publications in the organizational and 44 in the socio-technical disciplines, it is evident that the topic of CPS has so far been examined primarily from technical and systems design perspectives, while organizational application and systems integration of humans has been of minor interest to date.

When considering the distribution of publications that can be allocated to a specific application domain (an explicit application is described in relation to singularly one domain), as displayed in Fig. 6, a greater variety becomes apparent. The four domains that account for more than 10% of all domain-specific publications (593) are mobility (135), manufacturing (109), energy (104), and healthcare (73). With a cumulative total of 313 contributions focusing on manufacturing, energy, logistics, robotics, safety and hazard defense, maintenance, smart products and coal, oil and gas industry, more than half of domain-specific contributions are relevant to industrial utilization.

A precise examination of the 109 contributions of the application domain manufacturing shows the various utilization potentials of CPS in this context; specific topics and the distribution of the related literature are illustrated in Fig. 7.

4.2 Categorization of Cyber-Physical Systems Related and Relevant Topics in the Context of Industry 4.0

The categorization arranges the CPS related and relevant topics in the context of Industry 4.0 in a structured way. To this end, the findings from the literature are categorized into 10 sections. These include the characteristics and the overall context of industrial CPS as well as the potentials/opportunities and challenges/issues associated with their application. The requirements of industrial CPS, concepts and technologies by which they are accompanied, and their functionality as socio-technical systems are presented. Besides, the architecture of industrial CPS is outlined, and its influence on industrial value creation is characterized. Finally, the potentials of industrial CPS with respect to trans-organizational integration and alliance formation are addressed.

Fig. 3 Distribution of publications by type

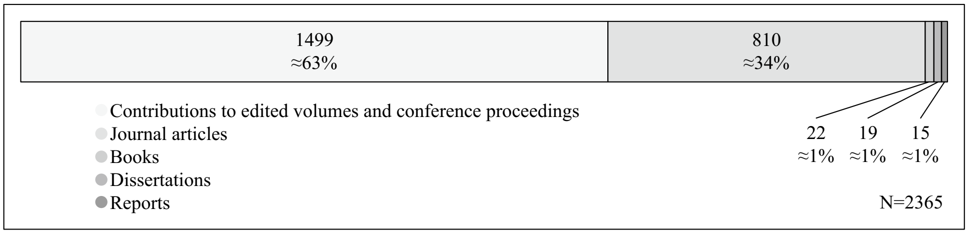


Fig. 4 Distribution of publications by discipline

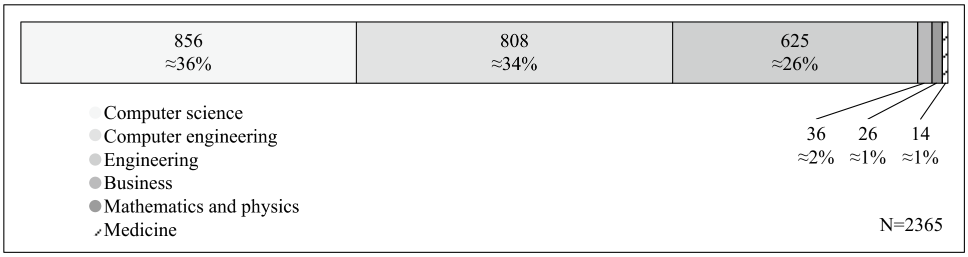


Fig. 5 Distribution of publications by CPS dimension

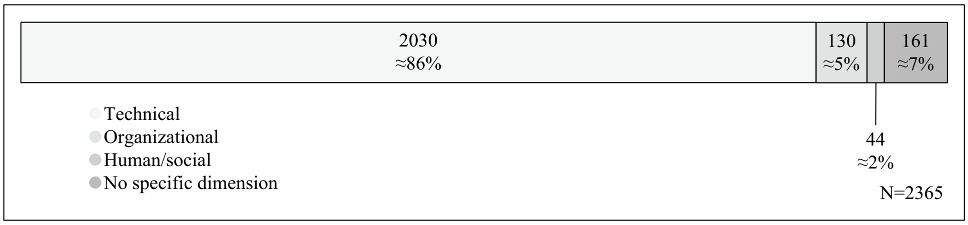


Fig. 6 Distribution of publications by application domain

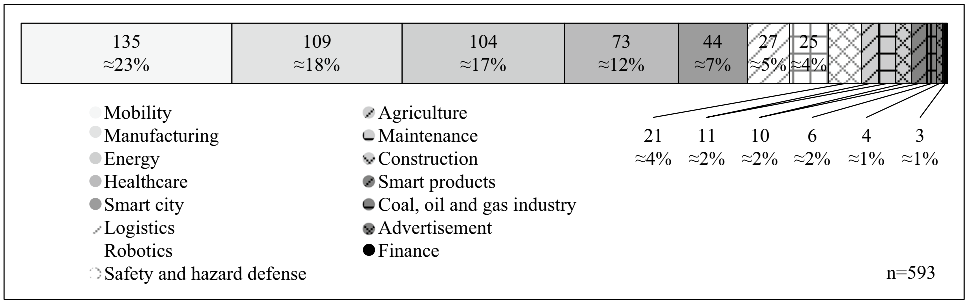
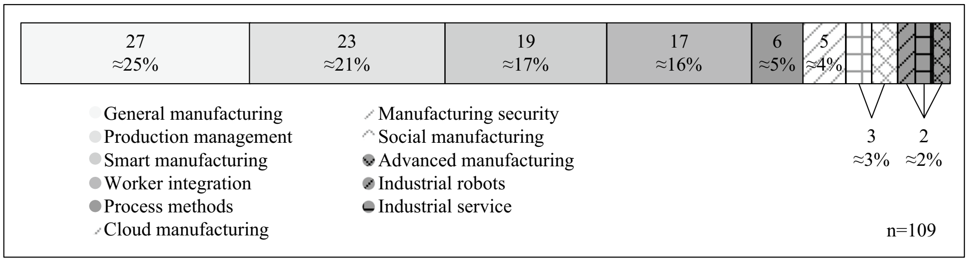


Fig. 7 Distribution of publications in the application domain of manufacturing



To enhance the readability of this sub-section, the categories are marked in italics. Exemplary underlying literature can be found in the Appendix in Table 4. The table is sorted chronologically by occurrence of the categories in the text and contains sample citations of existing research on the respective topics.

The fundamental *characteristics* of CPS apply to the industrial application in the same way that they do to other domains, and are divided into general and the self-characteristics as presented in Fig. 8. General characteristics include *connectivity* and *modularity*; they highlight the comprehensive adaptability of industrial CPS, which can be designed to respond to varying situations and tasks by means of universal interfaces and modular construction. *Real-time capability* and *traceability* ensure that system adaptations can be both performed ad hoc and verifiable in this context. The high degree of autonomy of CPS is reflected in the *self*-characteristics, which describe the abilities of CPS to react autonomously to internal and external influences and control the system state by at least maintaining the system, if not optimizing it by anticipation without external intervention. CPS, therefore, have a high degree of resilience.

The *overall context* in which the systems are situated is what characterizes them specifically as industrial CPS. In the literature, this is widely referred to as *Industry 4.0*, as shown in Fig. 9. Originating from the title of a German governmental funding initiative, Industry 4.0 has become a catchphrase for digitized and interconnected industrial value creation. The firm anchorage of industrial CPS in this context highlights the innovation potential inherent in and relevance of this concept.

The reason for this is apparent due to the *potentials/opportunities* that industrial CPS offer for value creation processes. From an organizational perspective, they cover both production engineering and management aspects while also providing benefits for the users of products and services. In general, processes can be further *automated* and *autonomized*, particularly to the previously discussed characteristics of industrial CPS. Through the continuous monitoring of physical and digital processes and the resulting homogenization, an improved system-wide level of information is achieved, which allows for increases in *efficiency* for both *management* activities and *process* execution. Among other things, this enables *batch/lot size one* production at costs approaching those of mass production, which means that market demand for *product individualization* can be anticipated. Due to universal interfaces and increasing location independence, as well as less hierarchical system architectures, industrial CPS can be set up in *decentralized* structures. Decentralization, in combination with an improved level of information within the overall system, also allows for *complex event processing* with increasing *flexibility*. For example, production and logistics processes can be coordinated with a significantly shorter planning horizon facilitated by *lead time reductions*. The sensor-aided improvement of the level of information regarding the condition of system components allows *fault/failure* scenarios to be detected earlier or even predictive, which leads to *quality improvements* for both production facilities and products. The continuous and extensive backflow of status information from smart products reinforces this trend even further. Among other things, the general rapid increase in the availability of data allows for the development of new,

Fig. 8 Characteristics of industrial CPS

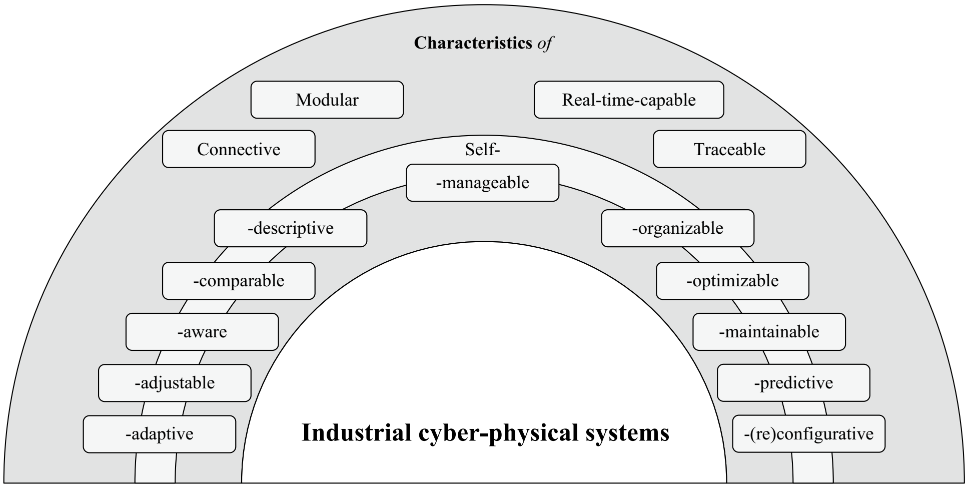
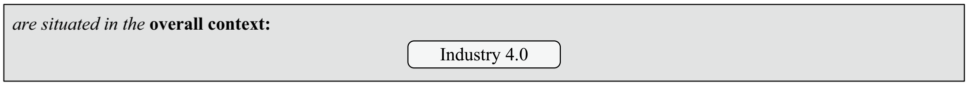


Fig. 9 Overall context of industrial CPS



data-driven *business models.* Alongside this, potentials for market penetration strategies arise in the form of *product portfolio enlargements* and *time-to-market* reductions. An overview of the potentials/opportunities offered by industrial CPS is provided in Fig. 10.

In addition to the vast potentials/opportunities, the implementation of industrial CPS also brings *challenges/issues* with it, including increased system *complexity* resulting from far-reaching changes in system size and structure. In that way, the number of system components (technological, organizational, inter-organizational) can increase significantly due to the connection and interaction of formerly independent and self-sufficient systems as well as the dissolving of system boundaries towards ad-hoc systems of systems. Additionally, system architectures become more multilayered and overall system diversity increases. Alongside the changes in system architectures, industrial CPS also lead to an increase in complexity in the organizational landscape. Linear value creation processes dissolve towards holistic value networks which become increasingly inter-organizational. Also, further organizational units and stakeholder groups are involved with and affected by industrial CPS than before. This complexity is intensified by time-related factors, as, for example, production management becomes more real-time-critical and product life cycles are shortening. Advancing inter-organizational integration in particular can lead to reduced *transparency* concerning system structures, *synchronization* problems, and new challenges for *risk and uncertainty management*. Due to the integration of numerous system components, the continuous monitoring of conditions, and the thereof resulting data throughput rates and volumes, and the inherent real-time feedback loops between sensors and actuators in industrial CPS, *communication* problems, such as *delays* or *jitter*, pose a severe threat to system functionality. As with many digitization matters, the implementation of industrial CPS occasionally arouses *concerns and reservations among employees* due to notions that working conditions might change and certain professions might become obsolete. *High implementation efforts* are an additional challenge/issue. With regard to the acquisition of new production plants or the retrofitting of existing ones to integrate them into industrial CPS and the, in many cases, high *capital* requirement resulting from this, a conclusive cost-benefit calculation is often rather difficult in advance. Particularly in the case of industrial CPS which have trans-organizational structures or are used to facilitate hybrid value creation networks, *juridical matters* arise because responsibilities and liability issues in the event of system failures or manufacturing defects that lead to malfunctioning products cannot always be unequivocally clarified.

Two further challenges/issues that are discussed in detail in the literature on industrial CPS are *safety* and *security*. The field of safety is divided into *hazard defense* and *state*. In hazard defense, strategies are described to prevent system failures through *environmental monitoring* or, in the case of such failures, to facilitate *emergency management*. System *state* control, which attempts to *detect fault/failure* situations before they become safety issues, is closely related. While safety deals with the operational integrity of systems, i.e., the protection of people and the environment from physical damage, security addresses data and information protection within a system. In the context of industrial CPS, this concerns the defense against *threats and vulnerabilities* like *(cyber-) attacks* and the securing of *privacy*, e.g., via preventing *data abuse*. Additionally, practical measures are presented for *attack detection*, *information flow control*, and *access and control message protection* (*cryptography*, *digital signatures, and steganography).* In summary and relation, the challenges/issues associated with industrial CPS are illustrated in Fig. 11.

Industrial CPS are subject to various *requirements*, as listed in Fig. 12, that are necessary or advantageous for their functionality and operation. These include *autonomy*, which ensures the functioning of systems within the defined functional objectives, especially if they cannot be operated from outside in either a planned or unplanned capacity. To this end, systems must be designed in order to be *context-aware* and *sensitive* so that changes in state and status are not only sensed but can also be considered in the superordinate application context and operate according to predefined algorithms. This ensures a high degree of *dependability* and *reliability* with regard to system availability and behavior as well as the value creation processes based on it. This dependable and reliable system *availability* is particularly necessary because, especially in the context of large-scale interconnected systems, (sub-)system failures can have serious consequences, including the

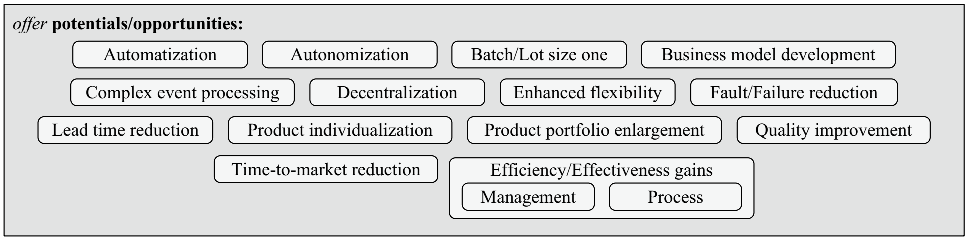


Fig. 10 Potentials/opportunities of industrial CPS

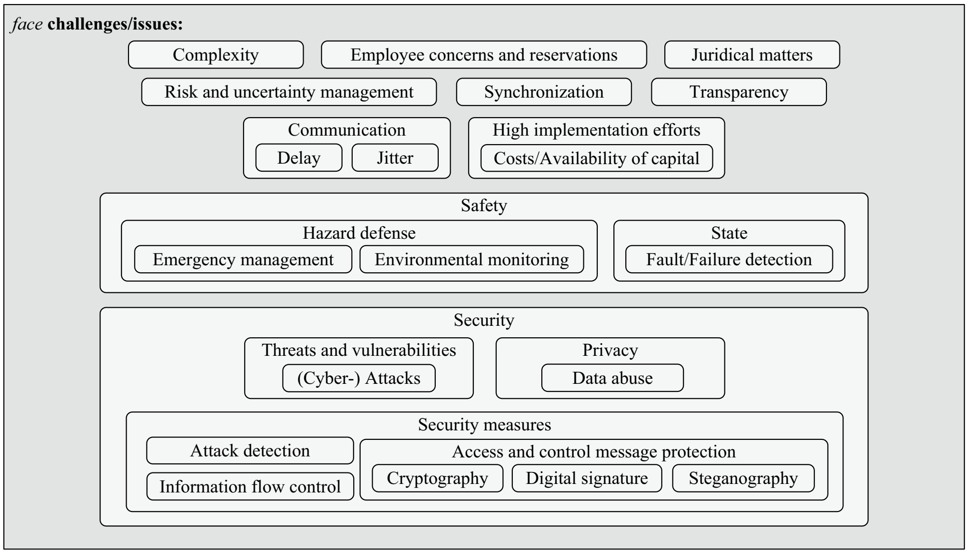


Fig. 11 Challenges/issues of industrial CPS

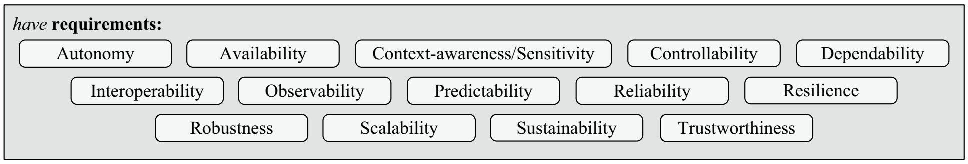


Fig. 12 Requirements of industrial CPS

collapse of entire systems of systems. Availability is also of utmost importance whenever safety-relevant processes are monitored and controlled by the system. In the context of maintaining system functionality under adverse conditions and in critical situations, *robustness* and *resilience* are also essential for industrial CPS. To a certain extent, the systems should be able to cope with environmental changes; their configuration should be able to robustly sustain these conditions. If the environmental changes are so severe that they cannot be handled by robustness, the systems should be so resilient that they adjust and adapt their configurations accordingly. The system state must be *observable*, with a high degree of reliability, and the information output on the state and control processes must be *trustworthy* so that fact-based decisions by administrators are possible at all times. In this context of system monitoring and control, it is also vital to have the most accurate *predictability* of expected system behavior in different situations so that the *controllability* of the system is given, despite its complexity and high degree of automation and autonomy.

In order to react to changes and new requirements in industrial CPS-based value creation processes, such as short-term capacity fluctuations or long-term market, production or product-related trends, it is a further requirement of industrial CPS that they are *scalable*, which can be executed briefly. Furthermore, since, as previously mentioned, value creation activities are becoming increasingly interactive and networked both intra- and inter-organizationally, the *interoperability* of individual industrial CPS is also of great interest.

All the requirements mentioned above should be met under the premise of *sustainability* in order to achieve efficiency and effectiveness in economic, ecological, and social dimensions.

In light of the far-reaching and holistic digitization of industrial value creation, a wide range of *complementing concepts and technologies* are being applied. In this, industrial CPS often serve as a linking element that systematically integrates these concepts and technologies in a goal-oriented and application-specific manner. *Big data* analyses are one of these concepts. Based on the widespread utilization of sensor technology in production and in products as such, industrial CPS often generate extensive data *(5 Vs: volume, velocity, variety, value, veracity)*, which can be transferred by algorithm-based analyses such as *pattern detection/recognition* in *smart data* for general optimization purposes, as well as data-driven services and business models (*data as a service*). As often distributed and decentralized systems, industrial CPS use *cloud*, *edge* and *ubiquitous computing* to perform data processing and system control detached from the conventional automation pyramid. In many application scenarios of industrial CPS, the use of *artificial intelligence (AI)*, e.g., as a foundation for the self-characteristics described previously, is suitable. Conventional methods to this end include *reasoning* or *machine learning*. As previously indicated, industrial CPS can be connected ad hoc to

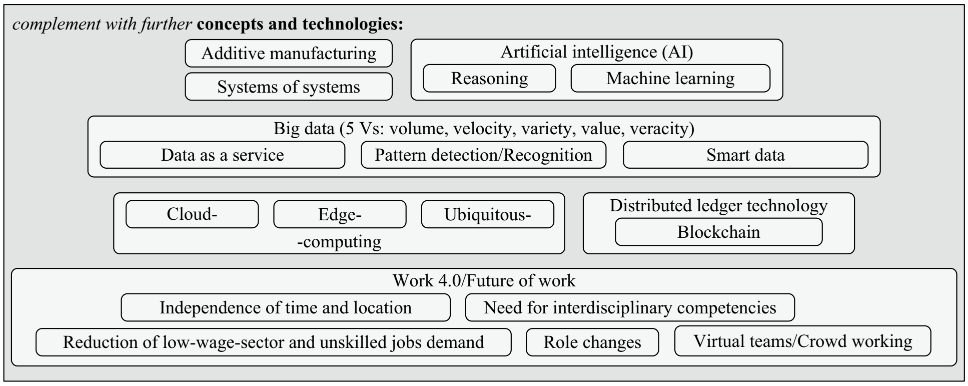


Fig. 13 Complementing concepts and technologies to industrial CPS

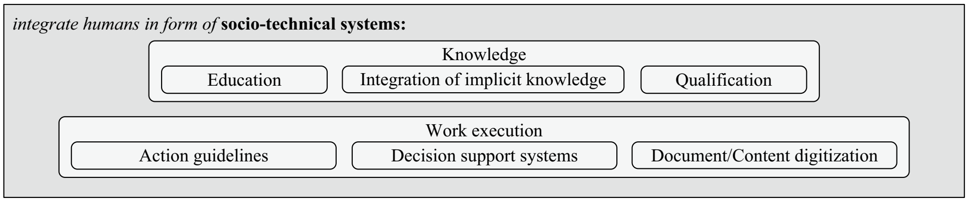


Fig. 14 Industrial CPS as socio-technical systems

systems of systems according to context and task. To ensure integrity in the exchange of data and resources, *distributed ledger technologies*, such as *blockchain*, offer an adequate solution. Another concept that is compatible with industrial CPS is *additive manufacturing*. On the one hand, topics as resource efficiency, availability of spare parts, rapid prototyping, etc. can be addressed via this concept. On the other hand, production processes itself can apply technologies such as 3D printing.

Another concept that goes hand in hand with the digitization of industrial processes is *work 4.0/future of work*, which describes the elaboration of innovative working methods that are either possible or necessary due to technological changes. This may concern the general conditions of work in the industrial sector, which can even allow execution of work *independent of time and location* and in *virtual teams/crowd working*. Additionally, the introduction of industrial CPS is often accompanied by extensive changes in job requirements and professional training. Thus, the *need for interdisciplinary competencies* arises due to increasing system complexity, which is also reflected in a progressive linking and overlapping of disciplines relevant to value creation. Furthermore, the increasing automation associated with industrial CPS in particular leads to a *reduction of low-wage-sector and unskilled jobs demand*. *Role changes* become, therefore, necessary, which often require extensive training measures.

The spectrum of concepts and technologies that complement industrial CPS is shown Fig. 13.

In addition to the primary technical consideration of industrial CPS, the literature also examines the integration of humans in the form of *socio-technical systems*. In the field of production-supporting activities, this affects *work execution*. Due to increasing availability of information and new forms of HCI, information can be provided through various *decision support systems*, e.g., by means of *action guidelines* in maintenance. In addition, media discontinuities are being reduced due to increasing *document/content digitization*. The topic of *knowledge* in relation to industrial CPS is also covered by the literature. Additionally, due to new methods of system-integrated *education* and *qualification*, the *integration of implicit knowledge* can be achieved, making previously person-bound knowledge increasingly available to a wider circle of personnel (e.g., by the creation of action guidelines for machine repairs and further maintenance activities). The socio-technical systems integration of industrial CPS is presented in Fig. 14.

CPS have a common *architecture* with individual specifications depending on the application domain. The architecture of industrial CPS, which is described hereafter, serves as the underlying principle and scheme for the definition of concrete system features and configurations from design alternatives, depending on functional and non-functional requirements, and for the selection of suitable system components. Thereby, industrial CPS are allocated to the superordinate domain of *information technology (IT)*, respectively, *information and communication technology (ICT)*. From this domain, industrial CPS combine technologies and concepts of the *(industrial) internet of things ((I)IoT)* or *web of things (WoT)*, which can be partitioned into a *cyber sphere* and a *physical sphere* according to the underlying logic of CPS. *Software architecture* and the *data* processing of industrial CPS are situated within the cyber sphere while *hardware architecture* and *human-computer interaction (HCI)* exist within the physical sphere. *Network architecture* serves as a connective link between the two spheres.

In the area software architecture, industrial CPS literature covers the following topics: Adequate *operating systems* for the respective system components are analyzed, the design of these systems from a *programming* standpoint with the subfields *algorithms* and *programming languages* as well as *software agents* with further subfields *mobile agents* and *multi-agents*. Further topics are sufficient *middleware* in the form of *data distribution services (DDS)* and *workflow engines*. Beyond that, concepts are presented that allow *dynamic software updating (DSU)* for CPS.

Concerning data in the context of industrial CPS, the following focal points receive particular attention in the literature. First, the data *acquisition* by sensors is discussed. This data can then be *aggregated* with existing data or *fused* with data from external sources. The resulting data sets are analyzed and evaluated by *processing*. The literature also examines how data *traffic*, in the form of *dissemination*, *exchange*, and *transmission*, can be performed both within a system but in exchange with other systems. With regard to the qualitative aspects of data, their *quality* and *reliability* are considered. Further topics are data *recovery* and the concept of *supervisory control and data acquisition (SCADA)*.

The domain of hardware architecture contains the components that physically constitute industrial CPS. These are mainly *embedded systems* that are extended by *sensors* that continuously record physical environmental conditions. The resulting data is processed by *processors* and *field programmable gate arrays (FPGA)*. The subsequent operation of *actuators*, which, in turn, affect the physical environment, is carried out by *controllers*. *Identifiers* ensure the individual identifiability of each system component. Furthermore, passive components can be integrated into industrial CPS via *radio-frequency identification (RFID)* technologies, such as *near field communication (NFC)*. In addition, the field of *robotics* is receiving a considerable amount of attention in the context of industrial CPS.

In the area of HCI, the integration of humans in industrial CPS is addressed. Against this backdrop, the literature deals, among other things, with the support of humans in the performance of physical work. E.g., *cobots* or *collaborative robotics* are used to enable humans and machines to carry out tasks jointly in order to integrate the respective superior skills optimally. Technology can also be worn on the human body as *wearables*; these wearables can provide physical support, as seen with *(powered) exoskeletons*, or can be used to provide information in the form of *augmented reality (AR)* and *virtual reality (VR)* devices. In the field of *user interfaces* of industrial CPS, the literature deals with different forms of *human-machine-interfaces (HMI)* and *graphical user interfaces (GUI)*, which can be operated via *gesture control* or *voice control*. In the overall context of HCI, *unrestrained human-machine collaboration* combined with the highest standards of *workplace safety* is of particular importance.

The network architecture of industrial CPS draws on a variety of established technologies and concepts and adapts them to the specifics inherent in industrial CPS as needed. In general, the network architecture provides the link between the cyber sphere and the physical sphere and enables the transfer of signals and data. The literature on industrial CPS deals extensively with the subject of how network architectures can be designed in these systems and what requirements they have to meet, and a great deal of attention is paid to the *networks* themselves. Different types of networks and their suitability for a variety of applications due to differences in transmission power, range, and data transfer rates are considered. The first worth mentioning are *sensor networks (SN)*, which can be divided into *mobile actuator/sensor networks (MASN)*, *wireless sensor networks (WSN)* and *wireless sensor and actuator networks (WSAN)*. These network types are used to link sensors and actuators and to ensure the transfer of measured environmental values and coordinated actuator behavior. *Controller area networks (CAN)* are used as a serial bus system and are particularly useful in safety-relevant areas. For short-distance applications, *wireless personal area networks (WPAN)*, such as *Bluetooth* or *wireless personal body networks (WPBN)*, offer the advantage that interference with other networks can be reduced and that there is a low power requirement for transmitting units. For large-scale coverage, the pervasive *wireless local area networks (WLAN)* are used. For the integration of geographically remote system units, *wide area networks (WAN)* are used in form of *long range wide area networks (LoRaWAN)* and *low power wide area networks (LPWAN)*, which offer high energy efficiency. *Cellular networks* with *LTE* and *5G* standards are also used for interconnecting widely separated system units, especially if those are mobile. Depending on the type of network and application, different *protocols* are used to determine the communication syntax. In the context of industrial CPS, *IP*, *MAC*, *message queue telemetry transport (MQTT)*, *TCP*, and *TCP/IP* are mentioned in the literature. *Dynamic spectrum access* for the optimization of frequency spectra of connections and *routing* for the coordination of message streams are also being considered, as they can help to handle increased data volumes in a system-efficient manner. The subject of plant networking is also receiving a large amount of interest; therefore, *plug-and-produce* and *(standardized) interfaces* that enable the interoperability of diverse production plants with minimal setup effort are of great importance in the process of industrial CPS development. In this context of *machine-to-machine communication (M2M)*, the *OPC Unified Architecture (OPC UA)* provides a

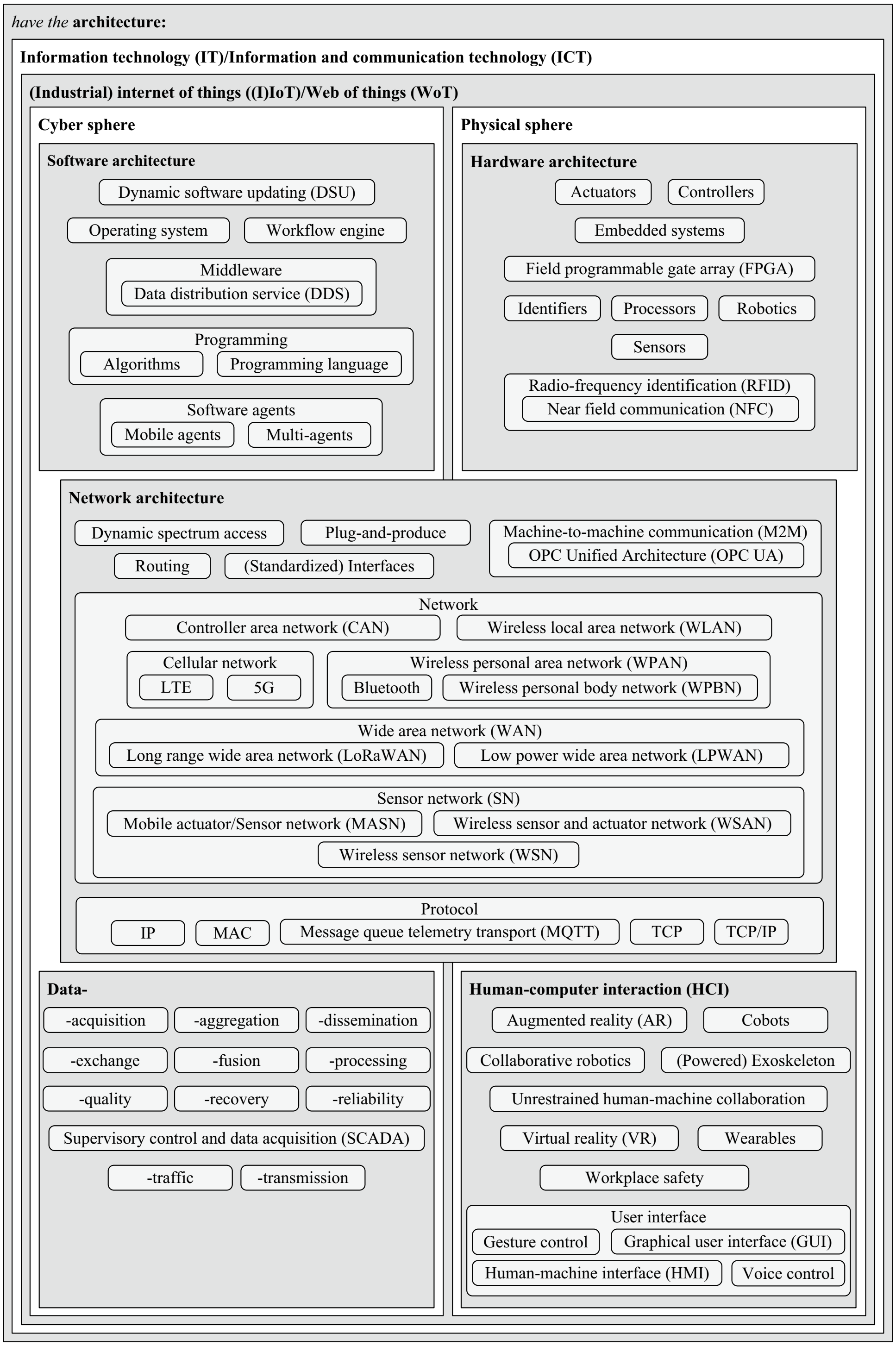


Fig. 15 Architecture of industrial CPS

platform-independent, service-oriented architecture (SOA) for the exchange of machine data.

Figure 15 provides a holistic visualization of the architecture underlying industrial CPS.

Within the realization of the already described potentials through the application of CPS they transform *industrial value creation*. This applies to all sequential stages and organizational levels in value chains and value networks; they can be broken down into the *pre-production stage*, *production stage*, and *product in use stage*.

Already in the pre-production stage, the *monitoring* of raw, auxiliary, and operating materials, as well as of supplier parts and construction groups intended for later production begins. Through the continuous collection and consolidation of data on *smart (raw)materials/components*, information regarding *condition*, *processing*, and *transport* becomes available in form of digital twins, already in the earliest stages of the value chain and is manipulation-proof passed on across organizational boundaries. This applies both to newly extracted raw materials and to *reprocessed* and *renewed* materials and components within the scope of *lifecycle management*.

In the production stage, the transformation of industrial value creation is discussed in the context of the *holistic concepts, digital factory*, *smart factory*, and *smart manufacturing*. Manufacturing systems that use CPS in their processes are referred to as *cyber-physical production systems (CPPS)*. In the literature, CPPS are examined from different focal points; specifically, *production system development*, *production execution*, and *production support* can be clustered.

Production system development describes all activities and procedures on the way to a CPS-based production system. In the subarea *design*, the planning and development of the production processes takes place. Within the *design space exploration*, the options and alternatives for the future system configuration are discussed and structured. The subsequent IT design process can be carried out with different *system level design methodologies*. With *component-based* development, the aim is to design standardized components that can be used several times in different applications of modular systems with the same or related requirements, minimizing the amount of effort required. *Contract-based* development is particularly important when a large number of modules from various providers are combined into a single system. Hereby, the definition of formal contracts for the use of standardized interfaces ensures compatibility. *Model-based* design and development is used in particular when the intended system has a high degree of complexity. By using predefined models with advanced functional characteristics, systems can be simulated and tested in detail, even before physical engineering. Due to the previously discussed challenges associated with CPS, such as complexity, method-combining procedures are feasible. If these are participative, co-creative, or open, the term *co-design* is used.

Simulation is used to determine the behavior and performance, as well as the safety and security, of CPPS before they are constructed and launched. In this process, *modeling* is used to create a physical or digital representation of the system or its individual parts. Deliberate reductions and omissions lead to an individual abstraction of the original. Depending on the application purpose, models can take the form of formal descriptions, physical objects or computer-based virtualizations. In *co-simulation*, different simulation tools that use different models, each of which represents subsystems, are interconnected to enable a holistic system simulation. This procedure is particularly suitable for CPPS since components and systems from different (technical) disciplines are combined in this process. Due to the ongoing digitization and increasing automation of production through the establishment of CPS, production control continues to receive a great deal of attention in the literature. For programmable logic controllers (PLC), which are used to control systems, robots, and actuators, *hardware-in-the-loop simulation* is applied to make them operational before they are directly connected to the hardware to be controlled.

For the subsequent *engineering* of CPPS, two initial situations can be distinguished: *Greenfield*, when a completely new production system is designed, and *brownfield/retrofit*, when an existing production system is upgraded to a CPPS. In the literature, the following activities are described for both cases with the specifics that the respective initial situation entails. In *requirements engineering*, the first step is to define the characteristics and general parameters that the system should fulfill. One of the factors that affect the requirements for CPPS is *product line engineering*, which, therefore, should be considered in close connection with production line engineering. Depending on the selection of the hardware to be utilized, *software engineering* should be adjusted accordingly. For the combination and iterative adaptation of CPPS hardware and software, it is advantageous to *prototype* them before integrating them into a consistent CPPS.

In the production execution stage, the plants are operated. *Manufacturing* is an essential part of this. In this area, the literature deals with the effects of implementing industrial CPS on *production management* with the subfields *process control* and *process management*. It is also described how the application of industrial CPS enables *advanced manufacturing*, which refers to the execution of particularly complex production processes for the manufacturing of equally complex products, both of which are only possible through the use of digital technologies and concepts. Moreover, *cloud manufacturing*, which describes a less organization- and location-bound value creation through flexible, virtual production networks, benefits from the utilization of industrial CPS. Another topic that receives attention in the context of CPS-based manufacturing is *industrial services*. This includes *service composition*, which is concerned with the arrangement and orchestration of service bundles, often from various providers, that are combined to form integrated service systems. One service to be highlighted in this field is *maintenance*. Due to the many degrees of freedom regarding potential events and their resolution, processes related to maintenance are difficult to optimize. However, based on live sensor data and results of big data analytics, *condition-based* and *predictive* maintenance procedures can increasingly be implemented in CPPS with great optimization potential.

Overall, i.e., beyond the maintenance application, industrial CPS, with their sensors and actuators, offer vast potentials for reforming *monitoring/control* in production. *Condition monitoring* enables a meaningful and comprehensive status overview to be obtained in real-time for all equipped system components, including both production infrastructure and production parts. *Event processing* is focused on the continuity and real-time capability through the application of industrial CPS. This enables a reliable *event-triggered control*, in which events are reacted to mostly automatically with adequate measures when they occur. To prevent adverse events, *predictive control* uses the ability to recognize trends and patterns in data and take countermeasures before critical values are reached. Also, for the field of *fuzzy control*, industrial CPS offer implications for the definition of control variables as well as for the already known SCADA.

In addition to the usage of monitoring/control, the exorbitant increase in status information, and data sets generated by industrial CPS, sensor technology can also be exploited for *analysis*. *Testing* is carried out, among other activities in this area, all of which can be largely automated by *model-based testing* with optimized *testbed* conditions. These test activities can examine hardware and software as well as processes in production plants and production output. Additionally, the literature deals with *validation* and *verification* as a means for requirements fulfilment with the subfields *model checking* and *runtime verification*. In supplement to this, *eigen analysis* is explicitly mentioned.

The third and last subject area concerning CPPS is constituted by production support, including the area *logistics*. Here, the whole context of *material handling* within an organization but also beyond its borders is examined. Especially for *warehouse systems*, industrial CPS offer far-reaching application potentials, which allow for optimizations in warehouse volumes and processes through increased transparency. In addition to warehousing, internal logistics also benefit in the form of *automated guided vehicles (AGV)*, which ensure highly automated, event-based, and system-integrated flows of materials into production. With the establishment of *intelligent transportation systems (ITS)*, industrial CPS are also applied in logistics between geographically dispersed production sites of an organization or different organizations in a value chain, which results in *supply chain optimization*, including the *delivery* of final products to vendors and end-users.

Another area involved in production support is the *smart grid* integration of plants. The integration of industrial CPS in the *power supply* of production facilities affects the general *energy efficiency* of these facilities by better incorporating energy requirements, availability, and costs into production planning and execution. In addition, methods such as *energy harvesting* from physical processes of industrial CPS and *battery management* in less grid-dependent production processes offer opportunities to improve energy balances.

In the third stage, the product in use stage, industrial CPS are used to feed back relevant information regarding product performance into the CPPS. In particular, *smart products*, which, due to their integrated sensor and actuator technology, enable information and data generation similar to that of the production systems that manufacture them, allow monitoring *throughout the entire product life cycle (product usage data)*. This continuously collected information regarding the *condition* and *usage* of the products is a highly valuable source for the evaluation and possible adjustment of product planning and production execution parameters.

By the holistic approach of *lifecycle management*, *recycling* or *downcycling* is applied at the end of product use, in the course of which the data collected over the entire product lifecycle in the form of a digital twin is, at best, reintroduced into the reprocessing or renewal in the new pre-production stage.

Apart from the subjects that can be clearly assigned to the individual stages, there are also those that are relevant *across company/organization boundaries throughout the entire value chain*. These include the *digital twin*, which combines the industrial CPS-based information of the entire lifecycles of both production plants and products. The *integrated supply chain*, which merges inter-organizational logistics processes due to increased transparency from industrial CPS, is another example of an activity that takes place across company/organization boundaries throughout the entire value chain. In this, procedures such as *ad-hoc connectivity* increase the *interoperability* of production systems, facilities, and services, which expands the potential realization of industrial CPS. In this context, the increasing establishment of *platform ecosystems*, which enable the linking of heterogeneous services and hardware to industrial CPS in the form of systems of systems, is particularly noteworthy.

A general overview of how CPS transform industrial value creation is shown in Fig. 16.

The application potentials of industrial CPS across company/organizational boundaries offer opportunities for *horizontal and vertical integration/operational and strategic alliances*. The *horizontal integration* can either be performed within a *company/organization* between production sites, departments, manufacturing sectors, etc., which previously operated largely independently, or along the value chain/within the value network across organizational boundaries, both upstream and downstream.

The cooperation between companies/organizations or their organizational units can be performed at the *operational* or *strategic level (vertical integration)*. While integration at the operational level is mostly about technical and procedural cooperation, which coordinate the execution of value creation activities, sometimes automated, ad-hoc and for short periods of time, those at the strategic level represent rather long-term alliances between two or more partners, which closely interconnect their industrial CPS and related processes.

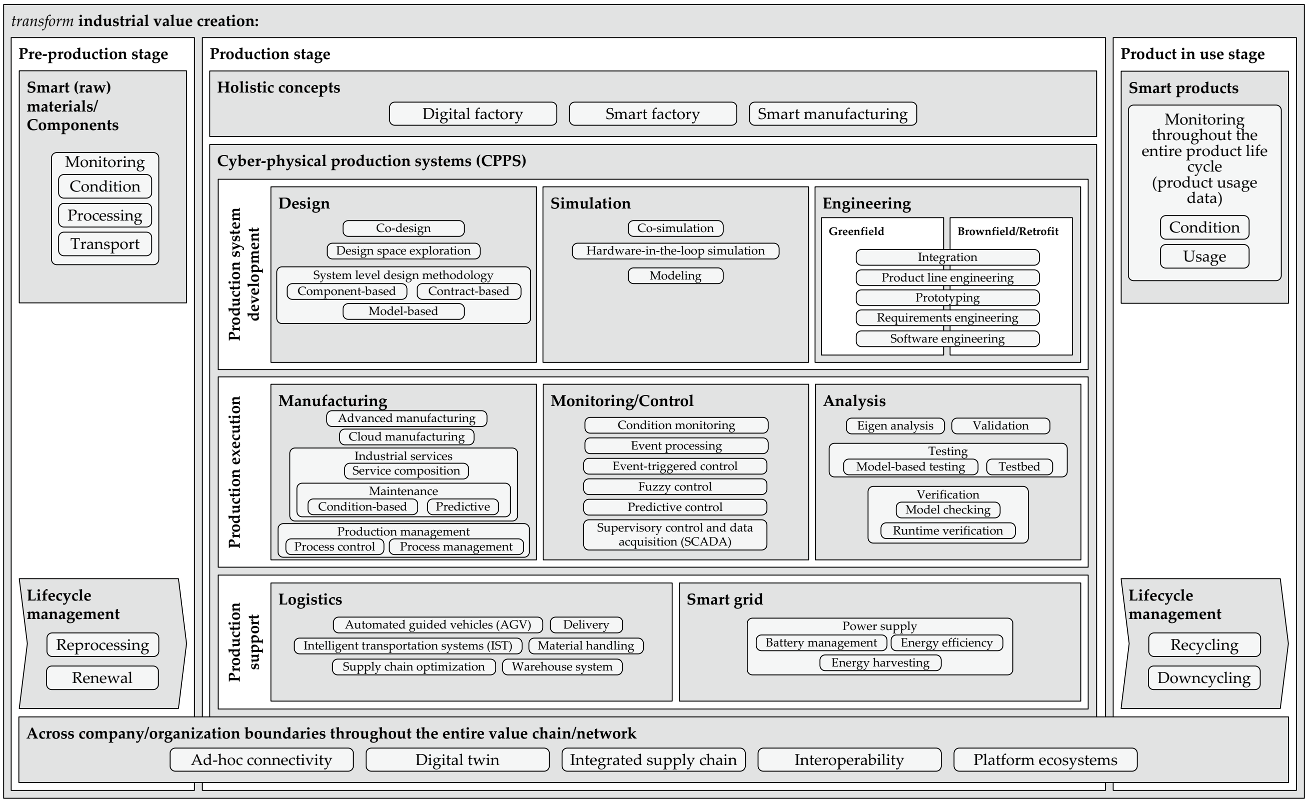
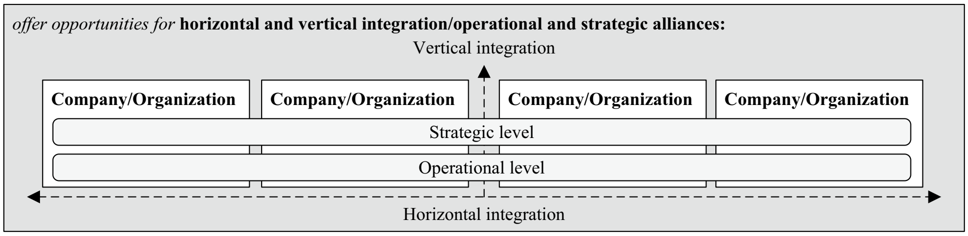


Fig. 16 Value creation based on industrial CPS

Fig. 17 Organizational integration and strategic alliances based on industrial CPS



The schematics of these integrations and alliances are shown in Fig. 17.

5 Discussion and Outlook

In the final Section of this study, the results are discussed, contributions to extant research, highlighted and limitations pointed out. Finally, a concluding and prospective outlook is given.

5.1 Contributions

The contribution of this study is twofold. First, it provides insight into the existing literature on CPS by organizing 2365 publications according to discipline, CPS dimension, and application field. Second, the resulting data set was analyzed and transferred into a categorization of CPS related and relevant topics in the context of Industry 4.0. Thereby, this study contributes by complementing the existing topic-specific reviews and categorizations. In addition to the general category formation, the industrial CPS architecture by incorporating technological, data-driven, and socio-technical views as well as the overview of value creation on the basis of this concept, are particularly noteworthy. Thus, our results enhance the CPS concept map of Asare et al. (2012), whose overview comes the closest to the scope of this work, significantly and set the focus on industrial CPS.

Both contributions thus provide new knowledge to the research on CPS in the context of Industry 4.0. The state of research first provides insights into the distributions of publications by discipline (cf. Figs. 4 and 5). Most originate from computer science, computer engineering, and engineering, meaning that the subject area has so far been considered from a highly technical perspective. The business, value creation, and information systems perspectives have therefore been somewhat neglected, which implicates great potential for future research in these areas. It is not surprising that research was initially conducted from a technical perspective, as technological developments for specific problems are developed first and then other application scenarios or generalization potentials are considered. At this point, we are at a frontier of information systems research, which can be more involved here to contextualize the technical developments in a larger context, e.g., business, socio-technical, development with the user/stakeholder, and value creation. This is also reflected in the state of research on CPS dimensions (cf. Fig. 5). So far, there have been primarily technical studies and only a few from the organizational and human/social disciplines.

The application domains for CPS are wide ranging (cf. Fig. 6). It can therefore be confirmed that CPS are a general purpose technology. Nevertheless, it is noteworthy that many applications are in the domain of smart manufacturing. Here, a distinction can be made between discrete and process manufacturing (Ning et al., 2017; Zhang et al., 2020). There have been and are several public funding programs and initiatives in these areas due to the feasible potential. This can also be linked to fact that the application of CPS is easier to realize in an organization (on meso level) than in an overarching system.

Furthermore, the manufacturing domain was examined in more detail (cf. Fig. 7). There, as well, the application fields for CPS are wide ranging, and there are a large number of applications in industry in general. Related work by Monostori et al. (2016) also highlights the relevance of CPS in manufacturing. The literature thus suggests that we can assume far-reaching changes that qualify for an industrial revolution.

In addition to the state of research, the categorization of industrial CPS also provides several new insights for research on CPS in the context of Industry 4.0. As compared to existing taxonomies, reviews, and categorizations (cf. Section 2), our study is much more comprehensive and provides a detailed categorization and analysis of industrial CPS. We arrange our findings into 10 sections, the key conclusions of which are summarized below.

With regard to the *characteristics* of industrial CPS, it is apparent that CPS are a further development of systems that are oriented toward autonomous operation and independent action (cf. Fig. 8). This aspect is supported by Berger et al. (2021), who examined CPPS from a self-organizing systems' perspective. Our results also show that CPS are clearly an *enabler for Industry 4.0*. Figure 10 shows that CPS have far-reaching *potential* that is relevant for industry, consumers, and the common good, in terms of sustainability, for example. There is also a large number of *challenges* to be overcome, particularly in the areas of safety and security, which is not surprising given the increased openness and interaction of entities and systems (cf. Fig. 11). Our results also contribute to an extension of the works of Liu et al. (2017) and Hofer (2018). For CPS to function properly, numerous *requirements* must be fulfilled (cf. Fig. 12). This point was also taken up by other authors, e.g., Asare et al. (2012), who also mentioned a few requirements in their concept map. In addition, CPS are a concept that can be seen as a hub of various *complementary concepts and technologies* of the digital age. CPS can only unfold their potential through interaction with these concepts and technologies (cf. Fig. 13). The relevance of CPS to complementary concepts in the context of digitalized industrial value creation has also been stated by (Kim, 2017). As shown in Fig. 14, CPS integrate humans in the form of *socio-technical systems* that require a user- and stakeholder-centric consideration. The *architecture* of CPS can be characterized as highly complex, which is also supported by other authors who described CPS architectures (Hofer, 2018; Lee et al., 2015; Pivoto et al., 2021). The architecture suggested by this study integrates software, hardware, network, data processing, and HCI components (cf. Fig. 15). CPS also offer application potential for the entire *industrial value creation* network (cf. Fig. 16). The interconnectivity and general network character of CPS generates potential for operational and strategic *alliances* with other organizations and entities (cf. Fig. 17).

The categorization of CPS related and relevant topics in the context of Industry 4.0 described above offers a variety of possible applications in practice. First, it provides an overview of the existing state of concepts and technologies in the area of industrial CPS. Thus, the categorization also serves as means of analyzing potential by documenting and evaluating existing technologies and systems and performing compatibility checks. In addition, it can be used for strategy development. Thus, organization-specific potentials and limitations regarding digitization and Industry 4.0 can be narrowed down. It can also help develop retrofit or greenfield digitization strategies. Furthermore, the categorization enables CPS design by facilitating the selection of system-relevant technologies and concepts as well as the definition of interfaces and standards. Finally, it can be used in education and training, for example through user-centered formats for knowledge transfer, in the context of system implementations, and digitization activities.

The architecture in Fig. 15 and the value creation based on industrial CPS in Fig. 16 go far beyond existing categorizations and can also be used as a design tool; a fully functional web tool was developed to that end. The web tool enables users to better comprehend industrial CPS and capture their architecture and use across the entire industrial value chain. Specifically, the tool can be applied within established methods or in the form of a canvas in workshops.

5.2 Future Work

The planned continuation of the research work is threefold: First, the state of knowledge and the categorization shall be updated by periodic repetitions of the review. On the one hand, this will allow new research foci, concepts, technologies, etc. to be observed in order to integrate them into the existing findings. On the other hand, trends, changes in thematic emphases, etc. can be identified over time, which allows statements to be made about the development of the research landscape and the implementation and application state of CPS in the context of Industry 4.0.

In addition to the scientific literature, funding projects and best practices from industry related to industrial CPS will be systematically analyzed. These can then underpin the individual topics in the categorization, particularly in the artifact *Industry 4.0 Compendium*, which is a functional web tool of the categorization (cf. Appendix Fig. 18), as a supplement to the scientific literature, and increase the added value for users from practice. Thus, this extension contributes to the managerial contribution. The respective systematic search and analysis process of funding projects and best practices has already started.

Furthermore, the extensive literature dataset provides an opportunity to undertake deductive—including software-assisted—analyses in order to elaborate quantitative measures and weighted links of the identified categories. In this way, the present qualitative findings of the study could be supplemented by quantitative ones, which would facilitate a more comprehensive interpretation.

5.3 Limitations

The limitations of our study are primarily determined by the subject area and the methodology. With industrial CPS, we are exploring a still relatively young and dynamic field of research. As a result, findings are constantly increasing as new developments and studies are being undertaken and published. Thus, the data presented here is only a snapshot representing the state of research and categorization of industrial CPS at one point in time. New findings and developments may have emerged in the meantime that would affect the results of this study.

The systematic literature review is influenced by the selection of literature databases and search engines. We aimed to make a selection that is as comprehensive as possible, including different disciplines and leading publishers. Search strings also influence the results of literature searches; we therefore attempted to search for publications on CPS as broadly and comprehensively as possible by using a wide variety of spellings.

The third limitation of our study results from the exclusive consideration of title, keywords, and abstract for the structured qualitative content analysis. In our opinion, this has no impact on the categorization, but it cannot be guaranteed that our approach did not necessarily exploit the complete amount of information.

5.4 Outlook

The final goal of our study is to provide an outlook on how research on and the use of industrial CPS can be further advanced. As our results show, interdisciplinary approaches are advisable or even necessary for this purpose due to the interwoven and wide-ranging characteristics of the topic. Therefore, the aim of research should be to break down existing silos and collaborate with related disciplines to develop methods and concepts that bring the topic of industrial CPS further into application. Specifically, information systems research has the potential to play a central role. Due to its interdisciplinary approaches, information systems research should act as a link between the disciplines and the entire body of knowledge, especially regarding system design, development, and implementation. This leads to the implication for information systems research to further contribute to the implementation and application of Industry 4.0 by transferring and adapting specific insular knowledge about CPS to value creating applications.

Since the introduction of the concept of CPS, there have been many vision papers and agendas on the subject. Therefore, we suggest an interim assessment and investigation of the current state of knowledge and implementation to determine the further implementation capabilities of scenarios foreseen in agendas and vision papers. Moreover, it is advisable to aim and research towards analogy building in order to enable the transfer of results and knowledge from other disciplines regarding CPS to be applied in industry, but also to make the extensive knowledge from the industrial domain available to other disciplines.

We believe that our categorization of industrial CPS can enhance the knowledge transfer into practice. It can particularly contribute to the design and development of new industrial CPS applications. Through the Industry 4.0 Compendium web tool (cf. Appendix Fig. 18), the results of this study have been made available to the research and practice community in an application-oriented manner (Oks & Jalowski, 2020); it offers search, selection, and note-taking functions. These features help reduce the plethora and complexity of information, making it more accessible and thus fostering CPS-oriented activities in the context of Industry 4.0.

Appendix

Table 3 Search terms

Language	Keywords	Synonyms
English	Cyber-physical	• Cyber physical • Cyberphysical
	Cyber-physical system	• Cyber physical system • Cyberphysical system • Cyber-physical systems • Cyber physical systems • Cyberphysical systems
German	CPS	-
	Cyber-physisches System	• Cyber physisches System • Cyberphysisches System • Cyber-physische Systeme • Cyber physische Systeme • Cyberphysische Systeme
	Cyber-physikalisches System	• Cyber physikalisches System • Cyberphysikalisches System • Cyber-physikalische Systeme • Cyber physikalische Systeme • Cyberphysikalische Systeme

Table 4 Categories with exemplary underlying literature

Categories (fields, areas, and sections)	Exemplary literature
Characteristics	
Connective	• Chen, X., Sun, J., & Sun, M. (2014). A Hybrid Model of Connectors in Cyber-Physical Systems. In S. Merz & J. Pang (Eds.), *Lecture Notes in Computer Science: Vol. 8829. Formal Methods and Software Engineering* (pp. 59–74). Springer. https://doi.org/10.1007/978-3-319-11737-9_5 • Reppa, V., Polycarpou, M. M., & Panayiotou, C. G. (2015). Distributed sensor fault diagnosis for a network of interconnected cyberphysical systems. *IEEE Transactions on Control of Network Systems*, *2*(1), 11–23. https://doi.org/10.1109/TCNS.2014.2367362
Modular	• González-Nalda, P., Etxeberria-Agiriano, I., Calvo, I., & Otero, M. C. (2016). A modular CPS architecture design based on ROS and Docker. *International Journal on Interactive Design and Manufacturing*, *11*(4). Advance online publication. https://doi.org/10.1007/s12008-016-0313-8 • Suh, D., Jeon, K., Chang, S., Kim, J., & Kim, J. (2015). Auto-localized multimedia platform based on a modular cyber physical system aligned in a two-dimensional grid. *Cluster Computing*, *18*(4), 1449–1464. https://doi.org/10.1007/s10586-015-0479-z
Real-time-capable	• Alsaydia, O. M. A., & Hameed, M. M. (2016). Design and analysis a real time cyber physical cloud computing system. *Imperial Journal of Interdisciplinary Research*, *2*(9), 279–283. • Lu, C., Saifullah, A., Li, B., Sha, M., Gonzalez, H., Gunatilaka, D., Wu, C., Nie, L., & Chen, Y. (2016). Real-time wireless sensor-actuator networks for industrial cyber-physical systems. *Proceedings of the IEEE*, *104*(5), 1013–1024. https://doi.org/10.1109/JPROC.2015.2497161
Traceable	• Huang, J., Zhu, Y., Cheng, B., Lin, C., & Chen, J. (2016). A PetriNet-based approach for supporting traceability in cyber-physical manufacturing systems. *Sensors*, *16*(3). https://doi.org/10.3390/s16030382 • Mohajerin Esfahani, P., Vrakopoulou, M., Andersson, G., & Lygeros, J. (2012). A tractable nonlinear fault detection and isolation technique with application to the cyber-physical security of power systems. In *51st IEEE Annual Conference on Decision and Control (CDC)* (pp. 3433–3438). https://doi.org/10.1109/CDC.2012.6426269
Self-characteristics	• Bordel, B., Alcarria, R., Martín, D., Robles, T., & de Rivera, D. S. (2016). Self-configuration in humanized cyber-physical systems. *Journal of Ambient Intelligence and Humanized Computing, 8.* Advance online publication. https://doi.org/10.1007/s12652-016-0410-3 • Dai, W., Dubinin, V. N., Christensen, J. H., Vyatkin, V., & Guan, X. (2017). Towards self-manageable and adaptive industrial cyber-physical systems with knowledge-driven autonomic service management. *IEEE Transactions on Industrial Informatics*, *13*(2). https://doi.org/10.1109/TII.2016.2595401 • Dutt, N., Jantsch, A., & Sarma, S. (2015). Self-aware cyber-physical systems-on-chip. In *IEEE/ACM International Conference on Computer-Aided Design (ICCAD)* (pp. 46-50). https://doi.org/10.1109/ICCAD.2015.7372548 • Smirnov, A., Kashevnik, A., & Shilov, N. (2015). Cyber-physical-social system self-organization: ontology-based multi-level approach and case study In. *9th IEEE International Conference on Self-Adaptive and Self-Organizing Systems* (pp. 168–169). https://doi.org/10.1109/SASO.2015.29
Overall context	
Industry 4.0	• Jazdi, N. (2014). Cyber physical systems in the context of Industry 4.0. *IEEE International Conference on Automation, Quality and Testing, Robotics*, 1–4. https://doi.org/10.1109/AQTR.2014.6857843 • Mosterman, P. J., & Zander, J. (2016). Industry 4.0 as a cyber-physical system study. *Software & Systems Modeling*, *15*(1), 17–29. https://doi.org/10.1007/s10270-015-0493-x
Potentials/Opportunities	
Automated	• Kao, H.-A., Jin, W., Siegel, D., & Lee, J. (2015). A cyber physical interface for automation systems - Methodology and examples. *Machines*, *3*(2), 93–106. https://doi.org/10.3390/machines3020093 • Leitão, P., Colombo, A. W., & Karnouskos, S. (2016). Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges. *Computers in Industry*, *81*, 11–25. https://doi.org/10.1016/j.compind.2015.08.004

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Automatization	• Duarte, R. P., Neto, H., & Vestias, M. (2016). XtokaxtikoX: A stochastic computing-based autonomous cyber-physical system. In *IEEE International Conference on Rebooting Computing (ICRC)* (pp. 1–7). https://doi.org/10.1109/ICRC.2016.7738716 • Gronau, N. (2016). Determinants of an appropriate degree of autonomy in a cyber-physical production system. *Procedia CIRP*, *52*, 1–5. https://doi.org/10.1016/j.procir.2016.07.063
Efficiency gains	• Bayhan, H., Meißner, M., Kaiser, P., Meyer, M., & Hompel, M. ten (2020). Presentation of a novel real-time production supply concept with cyber-physical systems and efficiency validation by process status indicators. *The International Journal of Advanced Manufacturing Technology*, *108*, 527–537. https://doi.org/10.1007/s00170-020-05373-z
Effectiveness gains	• Rocher, G., Tigli, J.-Y., Lavirotte, S., & Le Thanh, N. (2020). Effectiveness assessment of cyber-physical systems. *International Journal of Approximate Reasoning*, *118*, 112–132. https://doi.org/10.1016/j.ijar.2019.12.002
Management	• Schuh, G., Potente, T., Thomas, C., & Hempel, T. (2014). Short-term cyber-physical production management. *Procedia CIRP*, *25*, 154–160. https://doi.org/10.1016/j.procir.2014.10.024
Process	• Song, Z., Labalette, P., Burger, R., Klein, W., Nair, S., Suresh, S., Shen, L., & Canedo, A. (2015). Model-based cyber-physical system integration in the process industry. In Q.-S. Jia (Ed.), *IEEE International Conference on Automation Science and Engineering (CASE)* (pp. 1012–1017). https://doi.org/10.1109/CoASE.2015.7294231
Batch/Lot size one	• Bauernhansl, T., Tzempetonidou, M., Rossmeissl, T., Groß, E., & Siegert, J. (2018). Requirements for designing a cyber-physical system for competence development. *Procedia Manufacturing*, *23*, 201–206. https://doi.org/10.1016/j.promfg.2018.04.017 • Niemueller, T., Lakemeyer, G., Reuter, S., Jeschke, S., & Ferrein, A. (2017). Benchmarking of cyber-physical systems in industrial robotics. In C. Brecher, D. B. Rawat, H. Song, & S. Jeschke (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications* (pp. 193–207). Academic Press. https://doi.org/10.1016/b978-0-12-803801-7.00013-4
Product individualization	• Jiang, P., Leng, J., Ding, K., Gu, P., & Koren, Y. (2016). Social manufacturing as a sustainable paradigm for mass individualization. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *230*(10), 1961–1968. https://doi.org/10.1177/0954405416666903 • Tan, C., Hu, S. J., Chung, H., Barton, K., Piya, C., Ramani, K., & Banu, M. (2017). Product personalization enabled by assembly architecture and cyber physical systems. *CIRP Annals*, *66*(1), 33–36. https://doi.org/10.1016/j.cirp.2017.04.106
Decentralization	• Li, H., Lai, L., & Poor, H. V. (2012). Multicast routing for decentralized control of cyber physical systems with an application in smart grid. *IEEE Journal on Selected Areas in Communications*, *30*(6), 1097–1107. https://doi.org/10.1109/JSAC.2012.120708 • Schuhmacher, J., & Hummel, V. (2016). Decentralized control of logistic processes in cyber-physical production systems at the example of ESB Logistics Learning Factory. *Procedia CIRP*, *54*, 19–24. https://doi.org/10.1016/j.procir.2016.04.095
Complex event processing	• Babiceanu, R. F., & Seker, R. (2015). Manufacturing cyber-physical systems enabled by complex event processing and big data environments: A framework for development. In T. Borangiu, D. Trentesaux, & A. Thomas (Eds.), *Studies in Computational Intelligence: Vol. 594. Service orientation in holonic and multi-agent manufacturing* (pp. 165–173). Springer. https://doi.org/10.1007/978-3-319-15159-5_16 • Klein, R., Rilling, S., Usov, A., & Xie, J. (2013). Using complex event processing for modelling and simulation of cyber-physical systems. *International Journal of Critical Infrastructures*, *9*(1/2), 148. https://doi.org/10.1504/IJCIS.2013.051610
Enhanced flexibility	• Boschi, F., Zanetti, C., Tavola, G., & Taisch, M. (2016). Functional requirements for reconfigurable and flexible cyber-physical system. In *42nd Annual Conference of the IEEE Industrial Electronics Society* (pp. 5717-5722). https://doi.org/10.1109/IECON.2016.7794018 • Rosenthal, F., Jung, M., Zitterbart, M., & Hanebeck, U. D. (2019). CoCPN – Towards flexible and adaptive cyber-physical systems through cooperation. In *16th IEEE Annual Consumer Communications & Networking Conference (CCNC)* (pp. 1-6). https://doi.org/10.1109/CCNC.2019.8651882
Lead time reductions	• Barros, A. C., Azevedo, A., Rodrigues, J. C., Marques, A., Toscano, C., & Simões, A. C. (2017). Implementing cyber-physical systems in manufacturing. In *The 47th International Conference on Computers & Industrial Engineering*. 1–9. • Kolberg, D., & Zühlke, D. (2015). Lean automation enabled by Industry 4.0 technologies. *IFAC-PapersOnLine*, *48*(3), 1870–1875. https://doi.org/10.1016/j.ifacol.2015.06.359
Fault/Failure reduction	• Alippi, C., Ntalampiras, S., & Roveri, M. (2016). Model-free fault detection and isolation in large-scale cyber-physical systems. *IEEE Transactions on Emerging Topics in Computational Intelligence*, *1*(1), 61-71. https://doi.org/10.1109/TETCI.2016.2641452 • Zhang, Z., An, W., & Shao, F. (2016). Cascading failures on reliability in cyber-physical system. *IEEE Transactions on Reliability*, *65*(4), 1745–1754. https://doi.org/10.1109/TR.2016.2606125
Quality improvement	• Bonci, A., Pirani, M., & Longhi, S. (2019). Tiny cyber-physical systems for performance improvement in the factory of the future. *IEEE Transactions on Industrial Informatics*, *15*(3), 1598–1608. https://doi.org/10.1109/TII.2018.2855747 • Regan, G., McCaffery, F., Paul, P. C., Reich, J., Armengaud, E., Kaypmaz, C., Zeller, M., Guo, J.Z., Longo, S., O'Carroll, E., & Sorokos, I. (2020). Quality improvement mechanism for cyber physical systems - An evaluation. *Journal of Software: Evolution and Process*, *32*(11). https://doi.org/10.1002/smr.2295
Business model development	• Rauch, E., Seidenstricker, S., Dallasega, P., & Hämmerl, R. (2016). Collaborative cloud manufacturing: Design of business model innovations enabled by cyberphysical systems in distributed manufacturing systems. *Journal of Engineering*, *2016*(3), 1–12. https://doi.org/10.1155/2016/1308639 • Rudtsch, V., Gausemeier, J., Gesing, J., Mittag, T., & Peter, S. (2014). Pattern-based business model development for cyber-physical production systems. *Procedia CIRP*, *25*, 313–319. https://doi.org/10.1016/j.procir.2014.10.044
Product portfolio enlargement	• Meixner, K., Rabiser, R., & Biffl, S. (2019). Towards modeling variability of products, processes and resources in cyber-physical production systems engineering. In C. Salinesi & T. Ziadi (Eds.), *Proceedings of the 23rd International Systems and Software Product Line Conference volume B – SPLC'19*, (pp. 49-56). ACM Press. https://doi.org/10.1145/3307630.3342411 • Tan, C., Hu, S. J., Chung, H., Barton, K., Piya, C., Ramani, K., & Banu, M. (2017). Product personalization enabled by assembly architecture and cyber physical systems. *CIRP Annals*, *66*(1), 33–36. https://doi.org/10.1016/j.cirp.2017.04.106
Time-to-market reduction	• Canedo, A., Schwarzenbach, E., & Al Faruque, M. A. (2013). Context-sensitive synthesis of executable functional models of cyber-physical systems. In C. Lu, P. R. Kumar, & R. Stoleru (Eds.), *2013 ACM/IEEE International Conference on Cyber-Physical Systems* (p. 99-108). IEEE. https://doi.org/10.1145/2502524.2502539 • Villalonga, A., Castano, F., Beruvides, G., Haber, R., Strzelczak, S., & Kossakowska, J. (2019). Visual analytics framework for condition monitoring in cyber-physical systems. In *23rd International Conference on System Theory, Control and Computing (ICSTCC)* (pp. 55-60). https://doi.org/10.1109/ICSTCC.2019.8885611

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Challenges/Issues	
Complexity	• Kim, J.-C., We, K.-S., & Lee, C.-G. (2011). How resource componentizing for addressing the mega-complexity of cyber-physical systems. In *17th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications* (pp. 61–66). https://doi.org/10.1109/RTCSA.2011.35 • Liang, G., & Zhang, L. (2015). Extension of model for research and design of complex cyber physical system. In M. S. P. Babu (Ed.), *6th IEEE International Conference on Software Engineering and Service Science* (pp. 478–481). IEEE. https://doi.org/10.1109/ICSESS.2015.7339101
Transparency	• Dahlmanns, M., Pennekamp, J., Fink, I. B., Schoolmann, B., Wehrle, K., & Henze, M. (2021). Transparent end-to-end security for publish/subscribe communication in cyber-physical systems. In M. Gupta, M. Abdelsalam, & S. Mittal (Eds.), *Proceedings of the 2021 ACM Workshop on Secure and Trustworthy Cyber-Physical Systems* (pp. 78–87). ACM. https://doi.org/10.1145/3445969.3450423 • Lee, J., Bagheri, B., & Kao, H.-A. (2014). Recent advances and trends of cyber-physical systems and big data analytics in industrial informatics. In C. E. Pereira (Ed.), *12th IEEE International Conference on Industrial Informatics*. IEEE. https://doi.org/10.13140/2.1.1464.1920
Synchronization	• Andrade, H. A., Derler, P., Eidson, J. C., Li-Baboud, Y.-S., Shrivastava, A., Stanton, K. B., & Weiss, M. (2015). Towards a reconfigurable distributed testbed to enable advanced research and development of timing and synchronization in cyber-physical systems. In *International Conference on ReConFigurable Computing and FPGAs (ReConFig)* (pp. 1-6). https://doi.org/10.1109/ReConFig.2015.7393352 • Deng, X., & Yang, Y. (2013). Communication synchronization in cluster-based sensor networks for cyber-physical systems. *IEEE Transactions on Emerging Topics in Computing*, *1*(1), 98–110. https://doi.org/10.1109/TETC.2013.2273219
Risk and uncertainty management	• Axelrod, C. W. (2013). Managing the risks of cyber-physical systems. In *IEEE Long Island Systems, Applications and Technology Conference (LISAT)* (pp. 1–6). https://doi.org/10.1109/LISAT.2013.6578215 • Pereira, A., Rodrigues, N., Barbosa, J., & Leitão, P. (2013). Trust and risk management towards resilient large-scale cyber-physical systems. In *22nd IEEE International Symposium on Industrial Electronics (ISIE)* (pp. 1–6). https://doi.org/10.1109/ISIE.2013.6563837
Communication	• Elattar, M., Wendt, V., & Jasperneite, J. (2017). Communications for cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 347–372). Springer. https://doi.org/10.1007/978-3-319-42559-7_13 • Henneke, D., Elattar, M., & Jasperneite, J. (2015). Communication patterns for cyber-physical systems. In *2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA)* (pp. 1–4). https://doi.org/10.1109/ETFA.2015.7301623
Delay	• Nandanwar, A., Behera, L., Shukla, A., & Karki, H. (2016). Delay constrained utility maximization in cyber physical system with mobile robotic networks. In *42nd Annual Conference of the IEEE Industrial Electronics Society* (pp. 4884-4889). https://doi.org/10.1109/IECON.2016.7793926 • Shen, B., Zhou, X., & Kim, M. (2016). Mixed scheduling with heterogeneous delay constraints in cyber-physical systems. *Future Generation Computer Systems*, *61*, 108–117. https://doi.org/10.1016/j.future.2015.10.021
Jitter	• Gawand, H. L., Bhattacharjee, A. K., & Roy, K. (2014). Real time jitters and cyber physical system. *International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, 2004–2008. https://doi.org/10.1109/ICACCI.2014.6968505 • Zhang, X.-L., & Liu, P. (2015). A new delay jitter smoothing algorithm based on pareto distribution in cyber-physical systems. *Wireless Networks*, *21*(6), 1913–1923. https://doi.org/10.1007/s11276-015-0891-6
Employee concerns and reservations	• Dressler, F. (2018). Cyber physical social systems: Towards deeply integrated hybridized systems. *International Conference on Computing, Networking and Communications (ICNC)*, 420–424. https://doi.org/10.1109/ICCNC.2018.8390404 • Waschull, S., Bokhorst, J., Molleman, E., & Wortmann, J. C. (2020). Work design in future industrial production: Transforming towards cyber-physical systems. *Computers & Industrial Engineering*, *139*, 105,679. https://doi.org/10.1016/j.cie.2019.01.053
High implementation efforts	• Horváth, I., & Gerritsen, B. H. M. (2012). Cyber-physical systems: Concepts, technologies and implementation principles. In *TMCE 2012*. • Hu, F., Lu, Y., Vasilakos, A. V., Hao, Q., Ma, R., Patil, Y., Zhang, T., Lu, J., Li, X., & Xiong, N. N. (2016). Robust cyber–physical systems: Concept, models, and implementation. *Future Generation Computer Systems*, *56*, 449–475. https://doi.org/10.1016/j.future.2015.06.006
Costs/Availability of capital	• Bajaj, N., Nuzzo, P., Masin, M., & Sangiovanni-Vincentelli, A. L. (2015). Optimized selection of reliable and cost-effective cyber-physical system architectures. In *Design, Automation & Test in Europe Conference & Exhibition (DATE)* (pp. 561–566). https://doi.org/10.7873/DATE.2015.0913 • Shin, S. Y., Chaouch, K., Nejati, S., Sabetzadeh, M., Briand, L. C., & Zimmer, F. (2021). Uncertainty-aware specification and analysis for hardware-in-the-loop testing of cyber-physical systems. *Journal of Systems and Software*, *171*. https://doi.org/10.1016/j.jss.2020.110813
Juridical matters	• Brecher, C., Ecker, C., Herfs, W., Obdenbusch, M., Jeschke, S., Hoffmann, M., & Meisen, T. (2016). The need of dynamic and adaptive data models for cyber-physical production systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications* (pp. 321–338). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00021-3 • Husic, M., & Hozdic, E. (2014). Legal aspects of the implementation of cyber-physical systems in production industry. In *18th International Research/Expert Conference*.
Safety	• Khalid, A., Kirisci, P., Ghrairi, Z., Pannek, J., & Thoben, K.-D. (2017). Safety requirements in collaborative human–robot cyber-physical system. In M. Freitag, H. Kotzab, & J. Pannek (Eds.), *Lecture Notes in Logistics. Dynamics in Logistics* (pp. 41–51). Springer. https://doi.org/10.1007/978-3-319-45117-6_4 • Trapp, M., Schneider, D., & Liggesmeyer, P. (2013). A safety roadmap to cyber-physical systems. In J. Münch, K. Schmid, & H. D. Rombach (Eds.), *Perspectives on the Future of Software Engineering: Essays in Honor of Dieter Rombach* (pp. 81–94). Springer. https://doi.org/10.1007/978-3-642-37395-4_6
Security	• Brazell, J. B. (2014). The need for a transdisciplinary approach to security of cyber physical infrastructure. In S. C. Suh, U. J. Tanik, J. N. Carbone, (A) Eroglu, & (B) Thurasingham (Eds.), *Applied Cyber-Physical Systems* (pp. 5–14). Springer. https://doi.org/10.1007/978-1-4614-7336-7_2 • Dong, P., Han, Y., Guo, X., & Xie, F. (2015). A systematic review of studies on cyber physical system security. *International Journal of Security and Its Applications*, *9*(1), 155–164. https://doi.org/10.14257/ijsia.2015.9.1.17
Hazard defense	• Horn, D., Ali, N., & Hong, J. E. (2019). Towards enhancement of fault traceability among multiple hazard analyses in cyber-physical systems. In *43rd IEEE Annual Computer Software and Applications Conference (COMPSAC)* (pp. 458–464). https://doi.org/10.1109/COMPSAC.2019.10249 • Liu, H., & Wang, L. (2020). Remote human–robot collaboration: A cyber–physical system application for hazard manufacturing environment. *Journal of Manufacturing Systems*, *54*, 24–34. https://doi.org/10.1016/j.jmsy.2019.11.001

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
State	• Roth, M., & Liggesmeyer, P. (2013). Modeling and analysis of safety-critical cyber physical systems using state/event fault trees. In *32nd International Conference on Computer Safety, Reliability and Security*. • Sistla, A. P., Žefran, M., & Feng, Y. (2012). Runtime monitoring of stochastic cyber-physical systems with hybrid state. In S. Khurshid & K. Sen (Eds.), *Lecture Notes in Computer Science: Vol. 7186. Runtime Verification*, (pp. 276–293). Springer. https://doi.org/10.1007/978-3-642-29860-8_21
Environmental monitoring	• Mois, G., Sanislav, T., & Folea, S. C. (2016). A cyber-physical system for environmental monitoring. *IEEE Transactions on Instrumentation and Measurement*, *65*(6), 1463–1471. https://doi.org/10.1109/TIM.2016.2526669 • Sanislav, T., Mois, G., Folea, S. C., Miclea, L., Gambardella, G., & Prinetto, P. (2014). A cloud-based cyber-physical system for environmental monitoring. In *2014 3rd Mediterranean Conference on Embedded Computing (MECO)* (pp. 6–9). https://doi.org/10.1109/MECO.2014.6862654
Emergency management	• Gelenbe, E., & Wu, F.-J. (2013). Future research on cyber-physical emergency management systems. *Future Internet*, *5*(3), 336–354. https://doi.org/10.3390/fi5030336 • Wu, G., Lu, D., Xia, F., & Yao, L. (2011). A fault-tolerant emergency-aware access control scheme for cyber-physical systems. *Information Technology and Control*, *40*(1), 29–40. https://doi.org/10.5755/j01.itc.40.1.190
Fault/Failure detection	• Abid, M., Khan, A. Q., Rehan, M., & Haroon-ur-Rasheed (2014). TS fuzzy approach for fault detection in nonlinear cyber physical systems. In Z. H. Khan, A. B. M. S. Ali, & Z. Riaz (Eds.), *Studies in Computational Intelligence: Vol. 540. Computational Intelligence for Decision Support in Cyber-Physical Systems* (pp. 421–447). Springer. https://doi.org/10.1007/978-981-4585-36-1_14 • Alippi, C., Ntalampiras, S., & Roveri, M. (2016). Model-free fault detection and isolation in large-scale cyber-physical systems. *IEEE Transactions on Emerging Topics in Computational Intelligence*, *1*(1), 61-71. https://doi.org/10.1109/TETCI.2016.2641452
Threats and vulnerabilities	• DeSmit, Z., Elhabashy, A. E., Wells, L. J., & Camelio, J. A. (2016). Cyber-physical vulnerability assessment in manufacturing systems. *Procedia Manufacturing*, *5*, 1060–1074. https://doi.org/10.1016/j.promfg.2016.08.075 • Fernandez, E. B. (2016). Preventing and unifying threats in cyberphysical systems. In *17th IEEE International Symposium on High Assurance Systems Engineering (HASE)* (pp. 292-293). https://doi.org/10.1109/HASE.2016.50
(Cyber-) Attacks	• Chen, C.-M., Hsiao, H.-W., Yang, P.-Y., & Ou, Y.-H. (2013). Defending malicious attacks in cyber physical systems. In *1st IEEE International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)* (pp. 13-18). https://doi.org/10.1109/CPSNA.2013.6614240 • Gawand, H. L., Bhattacharjee, A. K., & Roy, K. (2015). Online monitoring of a cyber physical system against control aware cyber attacks. *Procedia Computer Science*, *70*, 238–244. https://doi.org/10.1016/j.procs.2015.10.079
Privacy	• Fink, G. A., Edgar, T. W., Rice, T. R., MacDonald, D. G., & Crawford, C. E. (2016). Security and privacy in cyber-physical systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications* (pp. 129–141). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00009-2 • Zhang, H., Shu, Y., Cheng, P., & Chen, J. (2016). Privacy and performance trade-off in cyber-physical systems. *IEEE Network*, *30*(2), 62–66. https://doi.org/10.1109/MNET.2016.7437026
Data abuse	• Alguliyev, R., Imamverdiyev, Y., & Sukhostat, L. (2018). Cyber-physical systems and their security issues. *Computers in Industry*, *100*, 212–223. https://doi.org/10.1016/j.compind.2018.04.017 • Gudivada, V. N., Ramaswamy, S., & Srinivasan, S. (2018). Data management issues in cyber-physical systems. *Transportation Cyber-Physical Systems*, 173–200. https://doi.org/10.1016/B978-0-12-814295-0.00007-1
Attack detection	• Chen, Y., Kar, S., & Moura, J. M. F. (2016). Dynamic attack detection in cyber-physical systems with side initial state information. *IEEE Transactions on Automatic Control*, *62*(9), 4618-4624 https://doi.org/10.1109/TAC.2016.2626267
Information flow control	• Akella, R., Tang, H., & McMillin, B. M. (2010). Analysis of information flow security in cyber–physical systems. *International Journal of Critical Infrastructure Protection*, *3*(3-4), 157–173. https://doi.org/10.1016/j.ijcip.2010.09.001
Access and control message protection	• Misra, S., Krishna, P. V., Saritha, V., Agarwal, H., Shu, L., & Obaidat, M. S. (2015). Efficient medium access control for cyber–physical systems with heterogeneous networks. *IEEE Systems Journal*, *9*(1), 22–30. https://doi.org/10.1109/JSYST.2013.2253421
Cryptography, digital signatures, and steganography	• Vegh, L., & Miclea, L. (2015). Improving the security of a cyber-physical system using cryptography, steganography and digital signatures. *International Journal of Computer and Information Technology*, *4*(2), 427–434. https://ijcit.com/archives/volume4/issue2/Paper040229.pdf
Requirements	
Autonomy	• Hong, I., Youn, H., Chun, I.-G., & Lee, E. (2014). Autonomic computing framework for cyber-physical systems. In V. V. Das (Ed.), *Computer Science Series: Vol. 1, Computation and Communication Technologies: Third International Conference on Advances in Computing, Control, and Telecommunication Technologies (ACT 2011)* (pp. 140–143). Curran. • Theuer, H., & Lass, S. (2016). Mastering complexity with autonomous production processes. *Procedia CIRP*, *52*, 41–45. https://doi.org/10.1016/j.procir.2016.07.058
Context-awareness/Sensitivity	• Canedo, A., Schwarzenbach, E., & Al Faruque, M. A. (2013). Context-sensitive synthesis of executable functional models of cyber-physical systems. In C. Lu, P. R. Kumar, & R. Stoleru (Eds.), *2013 ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)* (p. 99-108). https://doi.org/10.1145/2502524.2502539 • Timonen, J. (2015). Improving situational awareness of cyber physical systems based on operator's goals. In C. Onwubiko (Ed.), *2015 International Conference on Cyber Situational Awareness, Data Analytics and Assessment (CyberSA)* (pp. 1-6). https://doi.org/10.1109/CyberSA.2015.7166121
Dependability	• Sanislav, T., Mois, G., & Miclea, L. (2016). An approach to model dependability of cyber-physical systems. *Microprocessors and Microsystems*, *41*, 67–76. https://doi.org/10.1016/j.micpro.2015.11.021 • Soubiran, E., Guenab, F., Cancila, D., Koudri, A., & Wouters, L. (2016). Ensuring dependability and performance for CPS design: Application to a signaling system. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications* (pp. 363–375). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00023-7
Reliability	• Ge, L., Wang, S., Wang, X., & Liang, D. (2016). Analytical FRTU deployment approach for reliability improvement of integrated cyber-physical distribution systems. *IET Generation, Transmission & Distribution*, *10*(11), 2631–2639. https://doi.org/10.1049/iet-gtd.2015.1050 • Hazra, A., Dasgupta, P., & Chakrabarti, P. P. (2016). Formal assessment of reliability specifications in embedded cyber-physical systems. *Journal of Applied Logic*, *18*, 71–104. https://doi.org/10.1016/j.jal.2016.09.001

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Availability	• Parvin, S., Hussain, F. K., Hussain, O. K., Thein, T., & Park, J. S. (2013). Multi-cyber framework for availability enhancement of cyber physical systems. *Computing*, *95*(10-11), 927–948. https://doi.org/10.1007/s00607-012-0227-7 • Wang, Z., Jin, Y., Yang, S., Han, J., & Lu, J. (2021). An improved genetic algorithm for safety and availability checking in cyber-physical systems. *IEEE Access*, *9*, 56,869–56,880. https://doi.org/10.1109/ACCESS.2021.3072635
Robustness	• Rungger, M., & Tabuada, P. (2013). A symbolic approach to the design of robust cyber-physical systems. In *52nd IEEE Annual Conference on Decision and Control (CDC)* (pp. 3932–3937). https://doi.org/10.1109/CDC.2013.6760490 • Tabuada, P., Caliskan, S. Y., Rungger, M., & Majumdar, R. (2014). Towards robustness for cyber-physical systems. *IEEE Transactions on Automatic Control*, *59*(12), 3151–3163. https://doi.org/10.1109/TAC.2014.2351632
Resilience	• Bujorianu, M. L., & Piterman, N. (2015). A modelling framework for cyber-physical system resilience. In C. Berger & M. R. Mousavi (Eds.), *Information Systems and Applications, incl. Internet/Web, and HCI: Vol. 9361. Cyber Physical Systems. Design, Modeling, and Evaluation* (pp. 67–82). Springer. https://doi.org/10.1007/978-3-319-25141-7_6 • Woo, H., Yi, J., Browne, J. C., Mok, A. K., Atkins, E. M., & Xie, F. (2008). Design and Development Methodology for Resilient Cyber-Physical Systems. In *28th International Conference on Distributed Computing Systems Workshops* (pp. 525–528). IEEE. https://doi.org/10.1109/ICDCS.Workshops.2008.62
Observability	• Cam, H. (2014). Controllability and Observability of Risk and Resilience in Cyber-Physical Cloud Systems. In S. Jajodia, K. Kant, P. Samarati, A. Singhal, V. Swarup, & C. Wang (Eds.), *Secure Cloud Computing* (pp. 325–343). Springer. https://doi.org/10.1007/978-1-4614-9278-8_15 • Chen, Y., Kar, S., & Moura, J. M. F. (2015). Cyber-physical systems: Dynamic sensor attacks and strong observability. In *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* (pp. 1752–1756). IEEE. https://doi.org/10.1109/ICASSP.2015.7178271
Trustworthiness	• Boyes, H. A. (2013). Trustworthy cyber-physical systems – A review. In *System Safety: The 8th IET System Safety Conference incorporating the Cyber Security Conference 2013*. IET. https://doi.org/10.1049/cp.2013.1707 • David, M. W., Yerkes, C. R., Simmons, M. E., & Franceschini, W. (2016). Towards trustworthy smart cyber-physical systems. In K.-Y. Lam, C.-H. Chi, & S. Qing (Eds.), *Lecture Notes in Computer Science: Vol. 9977. Information and Communications Security* (pp. 392–399). Springer. https://doi.org/10.1007/978-3-319-50011-9_30
Predictability	• Mubeen, S., Lisova, E., & Vulgarakis Feljan, A. (2020). Timing predictability and security in safety-critical industrial cyber-physical systems: A position paper. *Applied Sciences*, *10*(9), 3125. https://doi.org/10.3390/app10093125 • Sun, B., Li, X., Wan, B., Wang, C., Zhou, X., & Chen, X. (2016). Definitions of predictability for cyber physical systems. *Journal of Systems Architecture*, *63*, 48–60. https://doi.org/10.1016/j.sysarc.2016.01.007
Controllability	• Alcaraz, C., & Lopez, J. (2016). Safeguarding structural controllability in cyber-physical control systems. In I. G. Askoxylakis, S. Ioannidis, S. K. Katsikas, & C. Meadows (Eds.), *Lecture Notes in Computer Science: Vol. 9879. Computer Security – ESORICS 2016* (pp. 471–489). Springer. https://doi.org/10.1007/978-3-319-45741-3_24 • Jiang, Y., Yin, S., & Kaynak, O. (2018). Data-driven monitoring and safety control of industrial cyber-physical systems: Basics and beyond. *IEEE Access*, *6*, 47,374–47,384. https://doi.org/10.1109/ACCESS.2018.2866403
Interoperability	• Bermejo Munoz, J., Galan, S. G., Lopez, L. R., Prado, R. P., Munoz, J. E., Grimstad, T., & Lopez, D. R. (2012). Interoperability in large scale cyber-physical systems. In *17th IEEE Conference on Emerging Technologies & Factory Automation (ETFA)* (pp. 1–6). IEEE. https://doi.org/10.1109/ETFA.2012.6489788 • Schilberg, D., Hoffmann, M., Schmitz, S., & Meisen, T. (2017). Interoperability in smart automation of cyber physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 261–286). Springer. https://doi.org/10.1007/978-3-319-42559-7_10
Scalability	• García-Valls, M., Calva-Urrego, C., de la Puente, Juan A., & Alonso, A. (2016). Adjusting middleware knobs to assess scalability limits of distributed cyber-physical systems. *Computer Standards & Interfaces.* Advance online publication. https://doi.org/10.1016/j.csi.2016.11.003 • Padmanabh, K. (2013). On the Scalability of a Cyber Physical System. *Journal of the Indian Institute of Science*, *93*(3), 499–509. http://journal.iisc.ernet.in/index.php/iisc/article/download/2169/3045
Sustainability	• Estevez, C., & Wu, J. (2016). Green cyber-physical systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications.* (pp. 225–237). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00015-8 • Song, Z., & Moon, Y. (2016). Assessing sustainability benefits of cybermanufacturing systems. *The International Journal of Advanced Manufacturing Technology.* Advance online publication. https://doi.org/10.1007/s00170-016-9428-0
Concepts and technologies	
Big data	• Hahanov, V. I., Miz, V., Litvinova, E. I., Mishchenko, A., & Shcherbin, D. (2015). Big Data driven cyber physical systems. In *13th International Conference on the Experience of Designing and Application of CAD Systems in Microelectronics (CADSM)* (pp. 76–80). IEEE. https://doi.org/10.1109/CADSM.2015.7230800 • Jara, A. J., Genoud, D., & Bocchi, Y. (2014). Big data for cyber physical systems: An analysis of challenges, solutions and opportunities. In *8th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS)* (pp. 376–380). IEEE. https://doi.org/10.1109/IMIS.2014.139
Pattern detection/Recognition	• Bhuiyan, M. Z. A., Wu, J., Weiss, G. M., Hayajneh, T., Wang, T., & Wang, G. (2020). Event detection through differential pattern mining in cyber-physical systems. *IEEE Transactions on Big Data*, *6*(4), 652–665. https://doi.org/10.1109/TBDATA.2017.2731838 • Spezzano, G., & Vinci, A. (2015). Pattern detection in cyber-physical systems. *Procedia Computer Science*, *52*, 1016–1021. https://doi.org/10.1016/j.procs.2015.05.096
Smart data	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2 • Tao, F., Qi, Q., Wang, L., & Nee, A. (2019). Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Data as a service	• Marini, A., & Bianchini, D. (2016). Big data as a service for monitoring cyber-physical production systems. In T. Claus, F. Herrmann, M. Manitz, & O. Rose (Eds.), *Proceedings, 30th European Conference on Modelling and Simulation ECMS 2016.* European Council for Modelling and Simulation. https://doi.org/10.7148/2016-0579 • Quadri, I., Bagnato, A., Brosse, E., & Sadovykh, A. (2015). Modeling methodologies for cyber-physical systems: Research field study on inherent and future challenges. *Ada User Journal*, *36*(4), 246–253. https://pure.au.dk/portal/files/107182954/Modeling_methodologies_for_Cyber_Physical_Systems.pdf
Cloud computing	• Glotfelter, P., Eichelberger, T., & Martin, P. J. (2014). Physicloud: A cloud-computing framework for programming cyber-physical systems. In *IEEE Conference on Control Applications (CCA)* (pp. 1533–1538). IEEE. https://doi.org/10.1109/CCA.2014.6981542
Edge computing	• Rodríguez, A., Valverde, J., Portilla, J., Otero, A., Riesgo, T., & La Torre, E. de (2018). Fpga-Based High-Performance Embedded Systems for Adaptive Edge Computing in Cyber-Physical Systems: The ARTICo³ Framework. *Sensors*, *18*(6). https://doi.org/10.3390/s18061877
Ubiquitous computing	• Chen, H. (2017). Theoretical foundations for cyber-physical systems: A literature review. *Journal of Industrial Integration and Management*, *02*(03). https://doi.org/10.1142/S2424862217500130
Artificial intelligence (AI)	• Lv, Z., Chen, D., Lou, R., & Alazab, A. (2021). Artificial intelligence for securing industrial-based cyber–physical systems. *Future Generation Computer Systems*, *117*, 291–298. https://doi.org/10.1016/j.future.2020.12.001 • Radanliev, P., Roure, D. de, van Kleek, M., Santos, O., & Ani, U. (2020). Artificial intelligence in cyber physical systems. *AI & Society*, 1–14. https://doi.org/10.1007/s00146-020-01049-0
Reasoning	• Håkansson, A., Hartung, R. L., & Moradian, E. (2015). Reasoning strategies in smart cyber-physical systems. *Procedia Computer Science*, *60*, 1575–1584. https://doi.org/10.1016/j.procs.2015.08.267 • Tepjit, S., Horváth, I., & Rusák, Z. (2019). The state of framework development for implementing reasoning mechanisms in smart cyber-physical systems: A literature review. *Journal of Computational Design and Engineering*, *6*(4), 527–541. https://doi.org/10.1016/j.jcde.2019.04.002
Machine learning	• O'Donovan, P., Gallagher, C., Bruton, K., & O'Sullivan, D. T. (2018). A fog computing industrial cyber-physical system for embedded low-latency machine learning Industry 4.0 applications. *Manufacturing Letters*, *15*, 139–142. https://doi.org/10.1016/j.mfglet.2018.01.005 • Olowononi, F. O., Rawat, D. B., & Liu, C. (2021). Resilient machine learning for networked cyber physical systems: A survey for machine learning security to securing machine learning for CPS. *IEEE Communications Surveys & Tutorials*, *23*(1), 524–552. https://doi.org/10.1109/COMST.2020.3036778
Systems of systems	• Díaz, J., Pérez, J., Pérez, J., & Garbajosa, J. (2016). Conceptualizing a framework for cyber-physical systems of systems development and deployment. In R. Bahsoon & R. Weinreich (Eds.), *Proccedings of the 10th European Conference on Software Architecture Workshops - ECSAW '16* (pp. 1–7). ACM Press. https://doi.org/10.1145/2993412.3004852 • Lucia, S., Kögel, M., Zometa, P., Quevedo, D. E., & Findeisen, R. (2016). Predictive control, embedded cyberphysical systems and systems of systems – A perspective. *Annual Reviews in Control*, *41*, 193–207. https://doi.org/10.1016/j.arcontrol.2016.04.002
Distributed ledger technologies	• Arsenjev, D., Baskakov, D., & Shkodyrev, V. (2019). Distributed ledger technology and cyber-physical systems. Multi-agent Systems. Concepts and Trends. In S. Misra, O. Gervasi, B. Murgante, E. Stankova, V. Korkhov, C. Torre, A. M. A.C. Roche, D. Taniar, B. O. Apduhan, & E. Tarantino (Eds.), *Lecture Notes in Computer Science: Vol. 11,620. Computational Science and Its Applications – ICCSA 2019* (pp. 618–630). Springer. https://doi.org/10.1007/978-3-030-24296-1_50 • Lebioda, A., Lachenmaier, J., & Burkhardt, D. (2019). Control of cyber-physical production systems: A concept to increase the trustworthiness within multi-agent systems with distributed ledger technology. In *PACIS 2019*.
Blockchain	• Lee, J., Azamfar, M., & Singh, J. (2019). A blockchain enabled cyber-physical system architecture for Industry 4.0 manufacturing systems. *Manufacturing Letters*, *20*, 34–39. https://doi.org/10.1016/j.mfglet.2019.05.003 • Rathore, H., Mohamed, A., & Guizani, M. (2020). A survey of blockchain enabled cyber-physical systems. *Sensors*, *20*(1). https://doi.org/10.3390/s20010282
Additive manufacturing	• Gupta, N., Tiwari, A., Bukkapatnam, S. T. S., & Karri, R. (2020). Additive manufacturing cyber-physical system: Supply chain cybersecurity and risks. *IEEE Access*, *8*, 47,322–47,333. https://doi.org/10.1109/ACCESS.2020.2978815 • Rokka Chhetri, S., & Al Faruque, M. A. (2017). Side channels of cyber-physical systems: Case study in additive manufacturing. *IEEE Design & Test*, *34*(4), 18–25. https://doi.org/10.1109/MDAT.2017.2682225
Work 4.0/Future of work	• Al-Ani, A. (2017). Cps and the worker: Reorientation and requalification? In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 563–574). Springer. https://doi.org/10.1007/978-3-319-42559-7_23 • Beckett, R. C., & Daberkow, T. (2019). Work 4.0 and the identification of complex competence sets. In *MWAIS 2019 Proceedings*.
Independence of time and location	• Wärzner, A., Hartner-Tiefenthaler, M., & Koeszegi, S. T. (2017). Working anywhere and working anyhow? In Y. Blount & M. Gloet (Eds.), *Advances in human resources management and organizational development (AHRMOD). Anywhere working and the new era of telecommuting* (pp. 90–112). IGI Global. https://doi.org/10.4018/978-1-5225-2328-4.ch004
Virtual teams/Crowd working	• Valenduc, é., & Vendramin, P. (2016). Work in the digital economy: Sorting the old from the new.*ETUI Research Paper – Working Paper 2016.03.* https://doi.org/10.2139/ssrn.2770405
Need for interdisciplinary competencies	• Letmathe, P., & Schinner, M. (2017). Competence management in the age of cyber physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 595–614). Springer. https://doi.org/10.1007/978-3-319-42559-7_25
Reduction of low-wage-sector and unskilled jobs demand	• Krzywdzinski, M. (2017). Automation, skill requirements and labour-use strategies: High-wage and low-wage approaches to high-tech manufacturing in the automotive industry. *New Technology, Work and Employment*, *32*(3), 247–267. https://doi.org/10.1111/ntwe.12100
Role changes	• Fantini, P., Pinzone, M., & Taisch, M. (2020). Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Computers & Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2018.01.025
Socio-technical systems	
Work execution	• Bousdekis, A., Apostolou, D., & Mentzas, G. (2020). A human cyber physical system framework for operator 4.0 – artificial intelligence symbiosis. *Manufacturing Letters*, *25*, 10–15. https://doi.org/10.1016/j.mfglet.2020.06.001 • Krugh, M., & Mears, L. (2018). A complementary cyber-human systems framework for Industry 4.0 cyber-physical systems. *Manufacturing Letters*, *15*, 89–92. https://doi.org/10.1016/j.mfglet.2018.01.003

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Decision support systems	• Kumar, R., Rogall, C., Thiede, S., Herrmann, C., & Sangwan, K. S. (2021). Development of a decision support system for 3D printing processes based on cyber physical production systems. *Procedia CIRP*, *98*, 348–353. https://doi.org/10.1016/j.procir.2021.01.115 • Salama, S., & Eltawil, A. B. (2018). A decision support system architecture based on simulation optimization for cyber-physical systems. *Procedia Manufacturing*, *26*, 1147–1158. https://doi.org/10.1016/j.promfg.2018.07.151
Action guidelines	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). Rollen, Views und Schnittstellen - Implikationen zur stakeholderzentrierten Entwicklung Sozio-Cyber-Physischer Systeme. In A. C. Bullinger-Hoffmann (Ed.), *Arbeitswissenschaft und Innovationsmanagement. Abschlussveröffentlichung: S-CPS: Ressourcen-Cockpit für Sozio-Cyber-Physische Systeme* (pp. 61–80). aw&I. https://doi.org/10.14464/awir.v1i0.107
Document/Content digitization	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2
Knowledge	• Emmanouilidis, C., Pistofidis, P., Bertoncelj, L., Katsouros, V., Fournaris, A., Koulamas, C., & Ruiz-Carcel, C. (2019). Enabling the human in the loop: Linked data and knowledge in industrial cyber-physical systems. *Annual Reviews in Control*, *47*, 249–265. https://doi.org/10.1016/j.arcontrol.2019.03.004 • Panfilenko, D., Poller, P., Sonntag, D., Zillner, S., & Schneider, M. (2016). BPMN for knowledge acquisition and anomaly handling in CPS for smart factories. In *21th IEEE Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 1–4). IEEE. https://doi.org/10.1109/ETFA.2016.7733686
Education	• Oks, S. J., Jalowski, M., Zansinger, N., & Möslein, K. M. (2021). Die Rolle von Industrie 4.0-Demonstratoren in der digitalen Transformation: Eine Standpunktbestimmung am Portable Industrial Demonstrator for Cyber-Physical Systems (PID4CPS). In K. Wilbers & L. Windelband (Eds.), *Texte zur Wirtschaftspädagogik und Personalentwicklung: Vol. 26. Lernfabriken an beruflichen Schulen – Gewerblich-technische und kaufmännische Perspektiven* (119-57). epubli. • Plateaux, R., Penas, O., Choley, J.-Y., Mhenni, F., Hammadi, M., & Louni, F. (2016). Evolution from mechatronics to cyber physical systems: An educational point of view. In *11th France-Japan & 9th Europe-Asia Congress on Mechatronics (MECATRONICS) /17th International Conference on Research and Education in Mechatronics (REM)* (pp. 360-366). https://doi.org/10.1109/MECATRONICS.2016.7547169
Qualification	• Makio-Marusik, E., Ahmad, B., Harrison, R., Makio, J., & Colombo, A. W. (2018). Competences of cyber physical systems engineers — Survey results. In *IEEE Industrial Cyber-Physical Systems (ICPS)* (pp. 491–496). IEEE. https://doi.org/10.1109/ICPHYS.2018.8390754 • Törngren, M., Bensalem, S., McDermid, J., Passerone, R., Sangiovanni-Vincentelli, A., & Schätz, B. (2015). Education and training challenges in the era of cyber-physical systems. In M. Törngren & M. E. Grimheden (Eds.), *Workshop on Embedded and Cyber-Physical Systems Education (WESE)* (pp. 1–5). The Association for Computing Machinery. https://doi.org/10.1145/2832920.2832928
Integration of implicit knowledge	• Böhle, F., & Huchler, N. (2016). Cyber-physical systems and human action: A re-definition of distributed agency between humans and technology, using the example of explicit and implicit knowledge. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications.* (pp. 115–127). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00008-0 • Sanin, C., Haoxi, Z., Shafiq, I., Waris, M. M., Silva de Oliveira, C., & Szczerbicki, E. (2019). Experience based knowledge representation for internet of things and cyber physical systems with case studies. *Future Generation Computer Systems*, *92*, 604–616. https://doi.org/10.1016/j.future.2018.01.062
Architecture	
Information technology (IT)/Information and communication technology (ICT)	• Marwedel, P., & Engel, M. (2016). Cyber-physical systems: Opportunities, challenges and (some) solutions. In A. Guerrieri, A. Rovella, G. Fortino, & V. Loscri (Eds.), *Internet of Things. Management of Cyber Physical Objects in the Future Internet of Things: Methods, Architectures and Applications* (pp. 1–30). Springer. https://doi.org/10.1007/978-3-319-26869-9_1 • Park, K.-J., Zheng, R., & Liu, X. (2012). Cyber-physical systems: Milestones and research challenges. *Computer Communications*, *36*(1), 1–7. https://doi.org/10.1016/j.comcom.2012.09.006
(Industrial) internet of things ((I)IoT)	• Berger, U., Selka, J., Ampatzopoulos, A., & Klabuhn, J. (2017). Manufacturing cyber-physical systems (industrial internet of things). In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 423–445). Springer. https://doi.org/10.1007/978-3-319-42559-7_16
Web of things (WoT)	• Dillon, T. S., Zhuge, H., Wu, C., Singh, J., & Chang, E. (2011). Web-of-things framework for cyber-physical systems. *Concurrency and Computation: Practice and Experience*, *23*(9), 905–923. https://doi.org/10.1002/cpe.1629
Cyber sphere	• Alur, R. (2015). *Principles of cyber-physical systems*. The MIT Press. • Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2
Physical sphere	• Alur, R. (2015). *Principles of cyber-physical systems*. The MIT Press. • Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2
Software architecture	• Abdelwahed, S., Kandasamy, N., & Gokhale, A. S. (2007). High confidence software for cyber-physical systems. In A. S. Gokhale, J. Gray, & R. K. Smith (Eds.), *Proceedings of the 2007 workshop on Automating service quality Held at the International Conference on Automated Software Engineering (ASE)* (pp. 1–3). ACM. https://doi.org/10.1145/1314483.1314484 • Mosterman, P. J., & Zander, J. (2016). Cyber-physical systems challenges: A needs analysis for collaborating embedded software systems. *Software & Systems Modeling*, *15*(1), 5–16. https://doi.org/10.1007/s10270-015-0469-x
Data processing	• Jirkovsky, V., Obitko, M., & Marik, V. (2016). Understanding data heterogeneity in the context of cyber-physical systems integration: Transactions on industrial informatics. *IEEE Transactions on Industrial Informatics*, *13*(2), 660-667. https://doi.org/10.1109/TII.2016.2596101 • Yuan, Y., Tang, X., Zhou, W., Pan, W., Li, X., Zhang, H.-T., Ding, H., & Goncalves, J. (2019). Data driven discovery of cyber physical systems. *Nature Communications*, *10*(1), 4894. https://doi.org/10.1038/s41467-019-12490-1

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Hardware architecture	• Greenwood, G. W., Gallagher, J. C., & Matson, E. T. (2015). Cyber-physical systems: The next generation of evolvable hardware research and applications. In H. Handa, H. Ishibuchi, Y.-S. Ong, & K. C. Tan (Eds.), *Proceedings in Adaptation, Learning and Optimization: Vol. 1. Proceedings of the 18th Asia Pacific Symposium on Intelligent and Evolutionary Systems* (pp. 285–296). Springer. https://doi.org/10.1007/978-3-319-13359-1_23 • Marwedel, P. (2021). *Embedded System Design*. Springer. https://doi.org/10.1007/978-3-030-60910-8
Human-computer interaction (HCI)	• Gladden, M. E. (2019). Novel forms of "magical" human-computer interaction within the cyber-physical smart workplace: Implications for usability and user experience. *International Journal of Research Studies in Management*, *8*(1). https://doi.org/10.5861/ijrsm.2019.4001 • Ludwig, T., Kotthaus, C., & Pipek, V. (2017). Should I try turning it off and on again? In I. R. Management Association (Ed.), *3D Printing* (pp. 282–295). IGI Global. https://doi.org/10.4018/978-1-5225-1677-4.ch015
Network architecture	• Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001 • Švéda, M., & Ryšavý, O. (2013). Dependable cyber-physical systems networking: An approach for real-time, software intensive systems. *IFAC Proceedings Volumes*, *46*(28), 116–119. https://doi.org/10.3182/20130925-3-CZ-3023.00010
Operating systems	• Du, X.-Z., Qiao, J.-Z., Lin, S.-K., & Tang, X.-C. (2012). The design of node operating system for cyber physical systems. *Procedia Engineering*, *29*, 3717–3721. https://doi.org/10.1016/j.proeng.2012.01.559 • Schätz, B. (2016). Platforms for cyber-physical systems – Fractal operating system and integrated development environment for the physical world. In *2016 3rd International Workshop on Emerging Ideas and Trends in Engineering of Cyber-Physical Systems (EITEC)* (pp. 1–4). IEEE. https://doi.org/10.1109/EITEC.2016.7503688
Programming	• Peter, S., Momtaz, F., & Givargis, T. (2015). From the browser to the remote physical lab: Programming cyber-physical systems. In *IEEE Frontiers in Education Conference (FIE)* (pp. 1–7). IEEE. https://doi.org/10.1109/FIE.2015.7344228 • Vicaire, P. A., Hoque, E., Xie, Z., & Stankovic, J. A. (2012). Bundle: A group-based programming abstraction for cyber-physical systems. *IEEE Transactions on Industrial Informatics*, *8*(2), 379–392. https://doi.org/10.1109/TII.2011.2166772
Algorithms	• Benhai, Z., Yuan, Y., Hongyan, M., Dapeng, Y., & Libo, X. (2016). Research on optimal ELSF real-time scheduling algorithm for CPS. In *Proceedings of the the 28th Chinese Control and Decision Conference (2016 CCDC)* (pp. 6867–6871). IEEE. https://doi.org/10.1109/CCDC.2016.7532235 • Yang, J., Zhang, X., & Wang, D. (2016). A decision level fusion algorithm for time series in cyber physical system. In Y. Wang (Ed.), *Lecture Notes in Computer Science: Vol. 9784. Big Data Computing and Communications* (pp. 409–420). Springer. https://doi.org/10.1007/978-3-319-42553-5_35
Programming language	• Burns, A. (2016). Why the expressive power of programming languages such as Ada is needed for future cyber physical systems. In M. Bertogna, L. M. Pinho, & E. Quiñoñes (Eds.), *Lecture Notes in Computer Science: Vol. 9695. Reliable Software Technologies – Ada-Europe 2016* (pp. 3–11). Springer. https://doi.org/10.1007/978-3-319-39083-3_1 • Soulier, P., Li, D., & Williams, J. R. (2015). A survey of language-based approaches to cyber-physical and embedded system development. *Tsinghua Science and Technology*, *20*(2), 130–141. https://doi.org/10.1109/TST.2015.7085626
Software agents	• Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., & Colombo, A. W. (2016). Smart agents in industrial cyber–physical systems. *Proceedings of the IEEE*, *104*(5), 1086–1101. https://doi.org/10.1109/JPROC.2016.2521931 • Lin, J., Sedigh, S., & Miller, A. (2011). A semantic agent framework for cyber-physical systems. In A. Elçi, M. T. Koné, & M. A. Orgun (Eds.), *Studies in Computational Intelligence: Vol. 344. Semantic Agent Systems: Foundations and Applications* (pp. 189–213). Springer. https://doi.org/10.1007/978-3-642-18308-9_9
Mobile agents	• Li, H., Peng, J., Zhang, X., & Huang, Z. (2017). Flocking of mobile agents using a new interaction model: A cyber-physical perspective. *IEEE Access*, *5*, 2665–2675. https://doi.org/10.1109/ACCESS.2017.2669438
Multi-agents	• Vogel-Heuser, B., Diedrich, C., Pantforder, D., & Göhner, P. (2014). Coupling heterogeneous production systems by a multi-agent based cyber-physical production system. In C. E. Pereira (Ed.), *12th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 713–719). IEEE. https://doi.org/10.1109/INDIN.2014.6945601 • Wang, S., Wan, J., Zhang, D., Di Li, & Zhang, C. (2016). Towards smart factory for Industry 4.0: A self-organized multi-agent system with big data based feedback and coordination. *Computer Networks*, *101*, 158–168. https://doi.org/10.1016/j.comnet.2015.12.017
Middleware	• Cappa-Banda, L., & García-Valls, M. (2016). Experimenting with a load-aware communication middleware for CPS domains. In S. Latifi (Ed.), *Advances in Intelligent Systems and Computing: Vol. 448. Information Technology: New Generations* (pp. 763–772). Springer. https://doi.org/10.1007/978-3-319-32467-8_66 • Shin, D.-H., He, S., & Zhang, J. (2016). Robust and cost-effective design of cyber-physical systems: An optimal middleware deployment approach. *IEEE/ACM Transactions on Networking*, *24*(2), 1081–1094. https://doi.org/10.1109/TNET.2015.2403862
Data distribution services (DDS)	• Kang, W., Kapitanova, K., & Son, S. H. (2012). RDDS: A real-time data distribution service for cyber-physical systems. *IEEE Transactions on Industrial Informatics*, *8*(2), 393–405. https://doi.org/10.1109/TII.2012.2183878 • Lee, W., Chung, S., Cho, S., Joe, I., & Park, J. (2015). A discovery support scheme for inter-domain DDS gateways in cyber-physical systems. In J. J. Park, H.-C. Chao, H. R. Arabnia, & N. Y. Yen (Eds.), *Lecture Notes in Electrical Engineering: Vol. 352. Advanced Multimedia and Ubiquitous Engineering: Future Information Technology* (pp. 39–44). Springer. https://doi.org/10.1007/978-3-662-47487-7_6
Workflow engine	• Chen, W.-C., & Shih, C.-S. (2011). Erwf: Embedded real-time workflow engine for user-centric cyber-physical systems. In *17th IEEE International Conference on Parallel and Distributed Systems (ICPADS)* (pp. 713–720). IEEE. https://doi.org/10.1109/ICPADS.2011.60 • Polter, M., Katranuschkov, P., & Scherer, R. (2020). A generic workflow engine for iterative, simulation-based non-linear system identifications. In *2020 Winter Simulation Conference (WSC)* (pp. 2671–2682). IEEE. https://doi.org/10.1109/WSC48552.2020.9384096
Dynamic software updating (DSU)	• Kang, S., Chun, I., & Kim, W.-T. (2014). Dynamic software updating for cyber-physical systems. In *18th IEEE International Symposium on Consumer Electronics (ISCE)* (pp. 1–3). IEEE. https://doi.org/10.1109/ISCE.2014.6884473 • Park, M. J., Kim, D. K., Kim, W.-T., & Park, S.-M. (2010). Dynamic software updates in cyber-physical systems. In *International Conference on Information and Communication Technology Convergence (ICTC)* (pp. 425–426). IEEE. https://doi.org/10.1109/ICTC.2010.5674807

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Data acquisition	• Dai, W., Zhang, Z., Wang, P., Vyatkin, V., & Christensen, J. H. (2017). Service-oriented data acquisition and management for industrial cyber-physical systems. In *15th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 759–764). IEEE. https://doi.org/10.1109/INDIN.2017.8104867 • Huang, W., Dai, W., Wang, P., & Vyatkin, V. (2017). Real-time data acquisition support for IEC 61,499 based industrial cyber-physical systems. In *43rd Annual Conference of the IEEE Industrial Electronics Society (IECON)* (pp. 6689–6694). IEEE. https://doi.org/10.1109/IECON.2017.8217168
Data aggregation	• Ren, J., Wu, G., Su, X., Cui, G., Xia, F., & Obaidat, M. S. (2016). Learning automata-based data aggregation tree construction framework for cyber-physical systems. *IEEE Systems Journal*, *12*(2), 1467-1479. https://doi.org/10.1109/JSYST.2015.2507577 • Stojmenovic, I. (2014). Machine-to-machine communications with in-network data aggregation, processing, and actuation for large-scale cyber-physical systems. *IEEE Internet of Things Journal*, *1*(2), 122–128. https://doi.org/10.1109/JIOT.2014.2311693
Data fusion	• Kühnert, C., & Arango, I. M. (2017). A generic data fusion and analysis platform for cyber-physical systems. In J. Beyerer, O. Niggemann, & C. Kühnert (Eds.), *Technologien für die intelligente Automation. Machine Learning for Cyber Physical Systems: Selected papers from the International Conference ML4CPS 2016* (pp. 45–54). Springer. https://doi.org/10.1007/978-3-662-53806-7_6 • Li, H., Zhang, L., Xiao, T., & Dong, J. (2015). Data fusion and simulation-based planning and control in cyber physical system for digital assembly of aeroplane. *International Journal of Modeling, Simulation, and Scientific Computing*, *6*(3). https://doi.org/10.1142/S1793962315500270
Data processing	• Kos, A., Tomažič, S., Salom, J., Trifunovic, N., Valero, M., & Milutinovic, V. (2015). New benchmarking methodology and programming model for big data processing. *International Journal of Distributed Sensor Networks*, *11*(8), 1–7. https://doi.org/10.1155/2015/271752 • Stojmenovic, I. (2014). Machine-to-machine communications with in-network data aggregation, processing, and actuation for large-scale cyber-physical systems. *IEEE Internet of Things Journal*, *1*(2), 122–128. https://doi.org/10.1109/JIOT.2014.2311693
Data traffic	• Li, H. (2012). Data traffic scheduling for cyber physical systems with application in voltage control of microgrids. In *IEEE Global Communications Conference (GLOBECOM)* (pp. 3334–3339). IEEE. https://doi.org/10.1109/GLOCOM.2012.6503629 • Qu, C., Chen, W., Song, J. B., & Li, H. (2015). Distributed data traffic scheduling with awareness of dynamics state in cyber physical systems with application in smart grid. *IEEE Transactions on Smart Grid*, *6*(6), 2895–2905. https://doi.org/10.1109/TSG.2015.2399247
Data dissemination	• Bodkhe, U., & Tanwar, S. (2020). Taxonomy of secure data dissemination techniques for IoT environment. *IET Software*, *14*(6), 563–571. https://doi.org/10.1049/iet-sen.2020.0006 • Li, K., Kurunathan, H., Severino, R., & Tovar, E. (2018). Cooperative key generation for data dissemination in cyber-physical systems. In *9th ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)* (pp. 331–332). IEEE. https://doi.org/10.1109/ICCPS.2018.00039
Data exchange	• Lien, S.-Y., & Cheng, S.-M. (2013). Resource-optimal network resilience for real-time data exchanges in Cyber-Physical Systems. In *24th IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)* (pp. 1603–1608). IEEE. https://doi.org/10.1109/PIMRC.2013.6666398 • Müller, R., Vette, M., Hörauf, L., & Speicher, C. (2016). Consistent data usage and exchange between virtuality and reality to manage complexities in assembly planning. *Procedia CIRP*, *44*, 73–78. https://doi.org/10.1016/j.procir.2016.02.126
Data transmission	• Fang, K., & Guo, B. (2015). An efficient data transmission strategy for cyber-physical systems in the complicated environment. In *2015 7th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC)* (Vol. 2, pp. 541–545). IEEE. https://doi.org/10.1109/IHMSC.2015.164 • França, R. P., Iano, Y., Monteiro, A. C. B., & Arthur, R. (2021). Applying a methodology in data transmission of discrete events from the perspective of cyber-physical systems environments. In V. Sugumaran, A. K. Luhach, & A. Elçi (Eds.), *Advances in Systems Analysis, Software Engineering, and High Performance Computing. Artificial Intelligence Paradigms for Smart Cyber-Physical Systems* (pp. 278–300). IGI Global. https://doi.org/10.4018/978-1-7998-5101-1.ch013
Data quality	• Sha, K., & Zeadally, S. (2015). Data quality challenges in cyber-physical systems. *Journal of Data and Information Quality*, *6*(2-3), 1–4. https://doi.org/10.1145/2740965 • Song, Z., Sun, Y., Wan, J., & Liang, P. (2016). Data quality management for service-oriented manufacturing cyber-physical systems. *Computers & Electrical Engineering.* Advance online publication. https://doi.org/10.1016/j.compeleceng.2016.08.010
Data reliability	• Wang, D. (2017). Data reliability challenge of cyber-physical systems. In C. Brecher, D. B. Rawat, H. Song, & S. Jeschke (Eds.), *Cyber-physical systems: Foundations, principles and applications* (pp. 91–101). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00006-7
Data recovery	• Nower, N., Tan, Y., & Lim, Y. (2015). Incomplete feedback data recovery scheme with Kalman filter for real-time cyber-physical systems. In *7th International Conference on Ubiquitous and Future Networks (ICUFN)* (pp. 845–850). IEEE. https://doi.org/10.1109/ICUFN.2015.7182663
Supervisory control and data acquisition (SCADA)	• Segovia, M., Cavalli, A. R., Cuppens, N., & Garcia-Alfaro, J. (2019). A study on mitigation techniques for SCADA-driven cyber-physical systems (position paper). In N. Zincir-Heywood, G. Bonfante, M. Debbabi, & J. Garcia-Alfaro (Eds.), *Lecture Notes in Computer Science: Vol 11,358. Foundations and Practice of Security* (pp. 257–264). Springer. https://doi.org/10.1007/978-3-030-18419-3_17 • Stefanov, A., Liu, C.-C., Govindarasu, M., & Wu, S.-S. (2015). SCADA modeling for performance and vulnerability assessment of integrated cyber-physical systems. *International Transactions on Electrical Energy Systems*, *25*(3), 498–519. https://doi.org/10.1002/etep.1862
Embedded systems	• Bonakdarpour, B. (2008). Challenges in transformation of existing real-time embedded systems to cyber-physical systems. *ACM SIGBED Review*, *5*(1), 1–2. https://doi.org/10.1145/1366283.1366294 • Lee, E. A. (2009). Introducing embedded systems: A cyber-physical approach. In P. Marwedel (Ed.), *Proceedings of the 2009 Workshop on Embedded Systems Education* (pp. 1–2). ACM. https://doi.org/10.1145/1719010.1719011
Sensors	• Ashok, P., Krishnamoorthy, G., & Tesar, D. (2011). Guidelines for managing sensors in cyber physical systems with multiple sensors. *Journal of Sensors*, *2011*, 1–15. https://doi.org/10.1155/2011/321709 • Dunets, R., Klym, H., & Kochan, R. (2016). Models of hardware integration of sensors elements with cyber-physical systems. In *13th International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET)*. https://doi.org/10.1109/TCSET.2016.7452033
Processors	• Adyanthaya, S., Geilen, M., Basten, T., Schiffelers, R., Theelen, B., & Voeten, J. (2013). Fast multiprocessor scheduling with fixed task binding of large scale industrial cyber physical systems. In *Euromicro Conference on Digital System Design* (pp. 979–988). IEEE. https://doi.org/10.1109/DSD.2013.111 • Craven, S., Long, D., & Smith, J. (2010). Open source precision timed soft processor for cyber physical system applications. In V. Prasanna (Ed.), *International Conference on Reconfigurable Computing and FPGAs (ReConFig)* (pp. 448–451). IEEE. https://doi.org/10.1109/ReConFig.2010.72

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Field programmable gate array (FPGA)	• Grimm, T., Janssen, B., Navarro, O., & Hübner, M. (2015). The value of FPGAs as reconfigurable hardware enabling cyber-physical systems. In *20th IEEE Conference on Emerging Technologies & Factory Automation (ETFA)* (pp. 1–8). IEEE. https://doi.org/10.1109/ETFA.2015.7301496 • Sarma, S., & Dutt, N. (2014). Fpga emulation and prototyping of a cyberphysical-system-on-chip (CPSoC). In *25th IEEE International Symposium on Rapid System Prototyping (RSP)* (pp. 121–127). IEEE. https://doi.org/10.1109/RSP.2014.6966902
Actuators	• Cheng, S.-T., & Chou, J.-H. (2012). Fuzzy-based actuators controlling for minimizing power consumption in cyber-physical system. In L. Barolli (Ed.), *26th IEEE International Conference on Advanced Information Networking and Applications (AINA)* (pp. 160–166). IEEE. https://doi.org/10.1109/AINA.2012.109 • Taha, A. F., Gatsis, N., Summers, T., & Nugroho, S. A. (2019). Time-varying sensor and actuator selection for uncertain cyber-physical systems. *IEEE Transactions on Control of Network Systems*, *6*(2), 750–762. https://doi.org/10.1109/TCNS.2018.2873229
Controllers	• Goswami, D., Schneider, R., & Chakraborty, S. (2011). Co-design of cyber-physical systems via controllers with flexible delay constraints. In *Proceedings of the 16th Asia and South Pacific Design Automation Conference* (pp. 225–230). IEEE. https://doi.org/10.1109/ASPDAC.2011.5722188 • Reniers, M., van de Mortel-Fronczak, J., & Roelofs, K. (2017). Model-based engineering of supervisory controllers for cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 111–136). Springer. https://doi.org/10.1007/978-3-319-42559-7_5
Identifiers	• Huang, X., & Dong, J. (2019). Reliable control of cyber-physical systems under sensor and actuator attacks: An identifier-critic based integral sliding-mode control approach. *Neurocomputing*, *361*, 229–242. https://doi.org/10.1016/j.neucom.2019.06.069
Radio-frequency identification (RFID)	• Huebner, A., Facchi, C., Meyer, M., & Janicke, H. (2013). RFID systems from a cyber-physical systems perspective. In M. Kucera (Ed.), *2013 proceedings of the 11th Workshop on Intelligent Solutions in Embedded Systems (WISES)* (pp. 1–6). IEEE. • Wu, N., & Li, X. (2011). RFID applications in cyber-physical system. In C. Turcu (Ed.), *Deploying RFID - Challenges, Solutions, and Open Issues*. InTech. https://doi.org/10.5772/17464
Near field communication (NFC)	• Katiyar, K., Gupta, H., & Gupta, A. (2014). Integrating contactless near field communication and context-aware systems: Improved internet-of-things and cyberphysical systems. In *5th International Conference - Confluence The Next Generation Information Technology Summit (Confluence)*.
Robotics	• Khalid, A., Kirisci, P., Ghrairi, Z., Thoben, K.-D., & Pannek, J. (2016). A methodology to develop collaborative robotic cyber physical systems for production environments. *Logistics Research*, *9*(1). https://doi.org/10.1007/s12159-016-0151-x • Michniewicz, J., & Reinhart, G. (2014). Cyber-physical robotics – Automated analysis, programming and configuration of robot cells based on cyber-physical-systems. *Procedia Technology*, *15*, 566–575. https://doi.org/10.1016/j.protcy.2014.09.017
Cobots/Collaborative robotics	• Khalid, A., Kirisci, P., Ghrairi, Z., Pannek, J., & Thoben, K.-D. (2017). Safety requirements in collaborative human–robot cyber-physical system. In M. Freitag, H. Kotzab, & J. Pannek (Eds.), *Lecture Notes in Logistics. Dynamics in Logistics* (pp. 41–51). Springer. https://doi.org/10.1007/978-3-319-45117-6_4 • Rodić, A., Stevanović, I., & Jovanović, M. (2019). Smart cyber-physical system to enhance flexibility of production and improve collaborative robot capabilities – Mechanical design and control concept. In N. A. Aspragathos, P. N. Koustoumpardis, & V. C. Moulianitis (Eds.), *Mechanisms and Machine Science: Vol 67. Advances in Service and Industrial Robotics* (pp. 627–639). Springer. https://doi.org/10.1007/978-3-030-00232-9_66
Wearables	• Jóźwiak, L. (2017). Advanced mobile and wearable systems. *Microprocessors and Microsystems*, *50*, 202–221. https://doi.org/10.1016/j.micpro.2017.03.008 • Yelizarov, A. A., Nazarov, I. V., Skuridin, A. A., Yakimenko, S. I., & Ikonnikova, D. M. (2020). Features of wireless charging of mobile and wearable devices for the IoT and cyber physical systems. In *2020 International Conference on Engineering Management of Communication and Technology (EMCTECH)* (pp. 1–4). IEEE. https://doi.org/10.1109/EMCTECH49634.2020.9261567
(Powered) Exoskeletons	• Bances, E., Schneider, U., Siegert, J., & Bauernhansl, T. (2020). Exoskeletons towards Industrie 4.0: Benefits and challenges of the IoT communication architecture. *Procedia Manufacturing*, *42*, 49–56. https://doi.org/10.1016/j.promfg.2020.02.087
Augmented reality (AR)	• Lukman Khalid, C. M., Fathi, M. S., & Mohamed, Z. (2014). Integration of cyber-physical systems technology with augmented reality in the pre-construction stage. In *2nd International Conference on Technology, Informatics, Management, Engineering & Environment (TIME-E)* (pp. 151–156). IEEE. https://doi.org/10.1109/TIME-E.2014.7011609 • Scheuermann, C., Meissgeier, F., Bruegge, B., & Verclas, S. (2016). Mobile augmented reality based annotation system: A cyber-physical human system. In L. T. de Paolis & A. Mongelli (Eds.), *Lecture Notes in Computer Science: Vol. 9768. Augmented Reality, Virtual Reality, and Computer Graphics* (pp. 267–280). Springer. https://doi.org/10.1007/978-3-319-40621-3_20
Virtual reality (VR)	• Frontoni, E., Loncarski, J., Pierdicca, R., Bernardini, M., & Sasso, M. (2018). Cyber physical systems for Industry 4.0: Towards real time virtual reality in smart manufacturing. In L. T. de Paolis & P. Bourdot (Eds.), *Lecture Notes in Computer Science: Vol 10,851. Augmented Reality, Virtual Reality, and Computer Graphics* (pp. 422–434). Springer. https://doi.org/10.1007/978-3-319-95282-6_31 • Mikkonen, T., Kemell, K.-K., Kettunen, P., & Abrahamsson, P. (2019). Exploring virtual reality as an integrated development environment for cyber-physical systems. In *45th Euromicro Conference on Software Engineering and Advanced Applications (SEAA)* (pp. 121–125). IEEE. https://doi.org/10.1109/SEAA.2019.00027
User interface	• Paelke, V., & Röcker, C. (2015). User interfaces for cyber-physical systems: Challenges and possible approaches. In A. Marcus (Ed.), *Lecture Notes in Computer Science: Vol. 9186. Design, User Experience, and Usability* (pp. 75–85). Springer. https://doi.org/10.1007/978-3-319-20886-2_8 • Sonntag, D., Zillner, S., van der Smagt, P., & Lörincz, A. (2017). Overview of the CPS for smart factories project: Deep learning, knowledge acquisition, anomaly detection and intelligent user interfaces. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 487–504). Springer. https://doi.org/10.1007/978-3-319-42559-7_19
Human-machine-interface (HMI)	• Pedersen, N., Bojsen, T., & Madsen, J. (2017). Co-simulation of cyber physical systems with HMI for human in the loop investigation. In *TMS/DEVS Symposium on Theory of Modeling & Simulation* (pp. 1-12). Society for Modeling and Simulation International (SCS). https://doi.org/10.22360/springsim.2017.tmsdevs.012 • Wittenberg, C. (2016). Human-CPS interaction - Requirements and human-machine interaction methods for the Industry 4.0. *IFAC-PapersOnLine*, *49*(19), 420–425. https://doi.org/10.1016/j.ifacol.2016.10.602

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Graphical user interface (GUI)	• Wan, K., Alagar, V., & Wei, B. (2013). Intelligent graphical user interface for managing resource knowledge in cyber physical systems. In M. Wang (Ed.), *Lecture Notes in Computer Science: Vol. 8041. Knowledge Science, Engineering and Management* (pp. 89–103). Springer. https://doi.org/10.1007/978-3-642-39787-5_8
Gesture control	• Horváth, G., & Erdős, G. (2017). Gesture control of cyber physical systems. *Procedia CIRP*, *63*, 184–188. https://doi.org/10.1016/j.procir.2017.03.312
Voice control	• Afanasev, M. Y., Fedosov, Y. V., Andreev, Y. S., Krylova, A. A., Shorokhov, S. A., Zimenko, K. V., & Kolesnikov, M. V. (2019). A concept for integration of voice assistant and modular cyber-physical production system. In *17th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 27–32). IEEE. https://doi.org/10.1109/INDIN41052.2019.8972015
Unrestrained human-machine collaboration	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2
Workplace safety	• Ceesay, E. N., Myers, K., & Watters, P. A. (2018). Human-centered strategies for cyber-physical systems security. *ICST Transactions on Security and Safety*, *4*(14). https://doi.org/10.4108/eai.15-5-2018.154773 • Nikolakis, N., Maratos, V., & Makris, S. (2019). A cyber physical system (CPS) approach for safe human-robot collaboration in a shared workplace. *Robotics and Computer-Integrated Manufacturing*, *56*, 233–243. https://doi.org/10.1016/j.rcim.2018.10.003
Network	• Akkaya, I., Liu, Y., & Lee, E. A. (2015). Modeling and simulation of network aspects for distributed cyber-physical energy systems. In S. K. Khaitan, J. D. McCalley, & C.-C. Liu (Eds.), *Power Systems. Cyber Physical Systems Approach to Smart Electric Power Grid* (pp. 1–23). Springer. https://doi.org/10.1007/978-3-662-45928-7_1 • Liu, Y., & Guan, Y. (2012). Distributed network and system monitoring for securing cyber-physical infrastructure. In S. K. Das, K. Kant, & N. Zhang (Eds.), *Handbook on Securing Cyber-Physical Critical Infrastructure* (pp. 455–479). Morgan Kaufmann. https://doi.org/10.1016/B978-0-12-415815-3.00018-2
Sensor network (SN)	• Garay, J. R. B., & Kofuji, S. T. (2010). Architecture for sensor networks in cyber-physical system. In C. E. Velásquez (Ed.), *Ieee Latin-American Conference on Communications (LATINCOM)* (pp. 1–6). IEEE. https://doi.org/10.1109/LATINCOM.2010.5641126 • Liu, Q., Chang, Y., & Jia, X. (2012). Real-time data aggregation for contention-based sensor networks in cyber-physical systems. In X. Wang, R. Zheng, T. Jing, & K. Xing (Eds.), *Lecture Notes in Computer Science: Vol. 7405. Wireless Algorithms, Systems, and Applications* (pp. 520–531). Springer. https://doi.org/10.1007/978-3-642-31869-6_45
Mobile actuator/sensor network (MASN)	• Nielsen, J., Rock, L., Rogers, B., Dalia, A., Adams, J., & Chen, Y. (2010). Automated social coordination of cyber-physical systems with mobile actuator and sensor networks. In *IEEE/ASME International Conference on Mechatronics and Embedded Systems and Applications (MESA)* (pp. 554–559). IEEE. https://doi.org/10.1109/MESA.2010.5552016 • Tricaud, C., & Chen, Y. (2009). Optimal mobile actuator/sensor network motion strategy for parameter estimation in a class of cyber physical systems. In *2009 American Control Conference* (pp. 367–372). IEEE. https://doi.org/10.1109/ACC.2009.5160289
Wireless sensor network (WSN)	• Jabeur, N., Sahli, N., & Zeadally, S. (2015). Enabling cyber physical systems with wireless sensor networking technologies, multiagent system paradigm, and natural ecosystems. *Mobile Information Systems*, *2015*(6), 1–15. https://doi.org/10.1155/2015/908315 • Lin, C.-Y., Zeadally, S., Chen, T.-S., & Chang, C.-Y. (2012). Enabling cyber physical systems with wireless sensor networking technologies. *International Journal of Distributed Sensor Networks*, *2012*, 1–21. https://doi.org/10.1155/2012/489794
Wireless sensor and actuator network (WSAN)	• Lu, C., Saifullah, A., Li, B., Sha, M., Gonzalez, H., Gunatilaka, D., Wu, C., Nie, L., & Chen, Y. (2016). Real-time wireless sensor-actuator networks for industrial cyber-physical systems. *Proceedings of the IEEE*, *104*(5), 1013–1024. https://doi.org/10.1109/JPROC.2015.2497161 • Mariappan, R., Reddy, P., & Wu, C. (2015). Cyber physical system using intelligent wireless sensor actuator networks for disaster recovery. In *2015 International Conference on Computational Intelligence and Communication Networks (CICN)* (pp. 95–99). IEEE. https://doi.org/10.1109/CICN.2015.28
Controller area network (CAN)	• Liping, C., Xiaoping, W., Xiong, G., Hongchang, Z., Fanli, Z., Bin, G., & Lei, W. (2012). Modeling and simulating CAN-based cyber-physical systems in modelica. In *6th IEEE International Conference on Software Security and Reliability Companion (SERE-C)* (pp. 152–157). IEEE. https://doi.org/10.1109/SERE-C.2012.31 • Shen, B., Zhou, X., & Wang, R. (2014). Ber analysis for controller area network impaired by the impulse noise in cyber-physical systems. In *IEEE International Conference on Computer and Information Technology (CIT)* (pp. 425–429). IEEE. https://doi.org/10.1109/CIT.2014.99
Wireless personal area network (WPAN)	• Devesh, M., Kant, A. K., Suchit, Y. R., Tanuja, P., & Kumar, S. N. (2020). Fruition of CPS and IoT in context of Industry 4.0. In S. Choudhury, R. Mishra, R. G. Mishra, & A. Kumar (Eds.), *Advances in Intelligent Systems and Computing: Vol. 989. Intelligent Communication, Control and Devices* (pp. 367–375). Springer. https://doi.org/10.1007/978-981-13-8618-3_39
Bluetooth	• Netland, Ø., & Skavhaug, A. (2016). Control of cyber-physical systems using bluetooth low energy and distributed slave microcontrollers. In A. Skavhaug (Ed.), *Lecture Notes in Computer Science: Vol. 9923. Computer Safety, Reliability, and Security* (pp. 256–267). Springer. https://doi.org/10.1007/978-3-319-45480-1_21
Wireless personal body network (WPBN)	• Dmitriev, Y. A. (2013). Separation of chaotic signals during their incoherent reception using a reference chaos generator. *Technical Physics Letters*, *39*(4), 353–356. https://doi.org/10.1134/S1063785013040044
Wireless local area network (WLAN)	• Cao, X., Liu, L., Shen, W., Laha, A., Tang, J., & Cheng, Y. (2015). Real-time misbehavior detection and mitigation in cyber-physical systems over WLANs. *IEEE Transactions on Industrial Informatics*, *13*(1), 186-197. https://doi.org/10.1109/TII.2015.2499123
Wide area network (WAN)	• Schmidt, D. C., White, J., & Gill, C. D. (2014). Elastic infrastructure to support computing clouds for large-scale cyber-physical systems. In *17th IEEE International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing* (pp. 56–63). IEEE. https://doi.org/10.1109/ISORC.2014.61
Long range wide area network (LoRaWAN)	• Pianini, D., Elzanaty, A., Giorgetti, A., & Chiani, M. (2018). Emerging distributed programming paradigm for cyber-physical systems over LoRaWANs. In *IEEE Globecom Workshops (GC Wkshps)* (pp. 1–6). IEEE. https://doi.org/10.1109/GLOCOMW.2018.8644518
Low power wide area network (LPWAN)	• Kim, D.-Y., Kim, S., Hassan, H., & Park, J. H. (2017). Radio resource management for data transmission in low power wide area networks integrated with large scale cyber physical systems. *Cluster Computing*, *20*(2), 1831–1842. https://doi.org/10.1007/s10586-017-0841-4
Cellular network	• Yang, A.-M., Yang, X.-L., Chang, J.-C., Bai, B., Kong, F.-B., & Ran, Q.-B. (2018). Research on a fusion scheme of cellular network and wireless sensor for cyber physical social systems. *IEEE Access*, *6*, 18,786–18,794. https://doi.org/10.1109/ACCESS.2018.2816565
LTE	• Elattar, M., Dürkop, L., & Jasperneite, J. (2015). Utilizing LTE QoS features to provide a reliable access network for cyber-physical systems. In *13th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 956–961). IEEE. https://doi.org/10.1109/INDIN.2015.7281864

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
5G	• Condoluci, M., Dohler, M., & Araniti, G. (2016). Machine-type communications over 5G systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications. A volume in Intelligent Data-Centric Systems* (pp. 75–89). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00005-5
Protocol	• Cai, Y., & Qi, D. (2015). Control protocols design for cyber-physical systems. In B. Xu (Ed.), *Proceedings of 2015 IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC 2015)* (pp. 668–671). IEEE. https://doi.org/10.1109/IAEAC.2015.7428638
IP	• Park, S. O., Do, T. H., Jeong, Y.-S., & Kim, S. J. (2013). A dynamic control middleware for cyber physical systems on an IPv6-based global network. *International Journal of Communication Systems*, *26*(6), 690–704. https://doi.org/10.1002/dac.1382
MAC	• Xia, F., & Rahim, A. (2015). MAC Protocols for Cyber-Physical Systems. *SpringerBriefs in Computer Science*. Springer. https://doi.org/10.1007/978-3-662-46361-1 • Zheng, M., Lin, J., Liang, W., & Yu, H. (2015). A priority-aware frequency domain polling MAC protocol for OFDMA-based networks in cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica*, *2*(4), 412–421. https://doi.org/10.1109/JAS.2015.7296536
Message queue telemetry transport (MQTT)	• Garcia, C. A., Montalvo-Lopez, W., & Garcia, M. V. (2020). Human-robot collaboration based on cyber-physical production system and MQTT. *Procedia Manufacturing*, *42*, 315–321. https://doi.org/10.1016/j.promfg.2020.02.088 • Jo, H.-C., & Jin, H.-W. (2015). Adaptive periodic communication over MQTT for large-scale cyber-physical systems. In J. Ng (Ed.), *2015 IEEE 3rd International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA)* (pp. 66–69). IEEE. https://doi.org/10.1109/CPSNA.2015.21
TCP	• Hewage, K., Duquennoy, S., Iyer, V., & Voigt, T. (2015). Enabling TCP in mobile cyber-physical systems. In *12th IEEE International Conference on Mobile Ad Hoc and Sensor Systems* (pp. 289–297). IEEE. https://doi.org/10.1109/MASS.2015.38
TCP/IP	• Schoeberl, M., & Pedersen, R. U. (2018). tpIP: A time-predictable TCP/IP stack for cyber-physical systems. In *21st IEEE International Symposium on Real-Time Distributed Computing (ISORC)* (pp. 75–82). IEEE. https://doi.org/10.1109/ISORC.2018.00018 • Sveda, M., & Vrba, R. (2013). Cyber-physical systems networking with TCP/IP: A security application approach. In *IEEE AFRICON* (pp. 1–5). IEEE. https://doi.org/10.1109/AFRCON.2013.6757652
Dynamic spectrum access	• Rawat, D. B., Reddy, S., Sharma, N., Bista, B. B., & Shetty, S. (2015). Cloud-assisted GPS-driven dynamic spectrum access in cognitive radio vehicular networks for transportation cyber physical systems. In *IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 1942–1947). IEEE. https://doi.org/10.1109/WCNC.2015.7127765 • Si, P., Yu, F. R., & Zhang, Y. (2013). Qos- and security-aware dynamic spectrum management for cyber-physical surveillance system. In *IEEE Global Communications Conference (GLOBECOM)* (pp. 962–967). IEEE. https://doi.org/10.1109/GLOCOM.2013.6831198
Routing	• Gao, Z., Ren, J., Wang, C., Huang, K., Wang, H., & Liu, Y. (2013). A genetic ant colony algorithm for routing in CPS heterogeneous network. *International Journal of Computer Applications in Technology*, *48*(4), 288. https://doi.org/10.1504/IJCAT.2013.058351 • Xiang, X., Liu, W., Liu, A., Xiong, N. N., Zeng, Z., & Cai, Z. (2019). Adaptive duty cycle control–based opportunistic routing scheme to reduce delay in cyber physical systems. *International Journal of Distributed Sensor Networks*, *15*(4). https://doi.org/10.1177/1550147719841870
Plug-and-produce	• Otto, J., Henning, S., & Niggemann, O. (2014). Why cyber-physical production systems need a descriptive engineering approach – A case study in plug & produce. *Procedia Technology*, *15*, 295–302. https://doi.org/10.1016/j.protcy.2014.09.083 • Páscoa, F., Pereira, I., Ferreira, P., & Lohse, N. (2017). Redundant and decentralised directory facilitator for resilient plug and produce cyber physical production systems. In T. Borangiu, D. Trentesaux, (A) Thomas, P. Leitão, & J. (B) Oliveira (Eds.), *Studies in Computational Intelligence: Vol. 694. Service Orientation in Holonic and Multi-Agent Manufacturing* (pp. 71–79). Springer. https://doi.org/10.1007/978-3-319-51100-9_7
(Standardized) Interfaces	• Leitão, P., Barbosa, J., Papadopoulou, M.-E. C., & Venieris, I. S. (2015). Standardization in cyber-physical systems: The ARUM case. In *IEEE International Conference on Industrial Technology (ICIT)* (pp. 2988–2993). IEEE. https://doi.org/10.1109/ICIT.2015.7125539
Machine-to-machine communication (M2M)	• Chen, S., Ma, M., & Luo, Z. (2015). An authentication framework for multi-domain machine-to-machine communication in cyber-physical systems. In *IEEE Globecom workshops (GC wkshps)* (pp. 1–6). IEEE. https://doi.org/10.1109/GLOCOMW.2015.7414062 • Wan, J., Yan, H., Liu, Q., Zhou, K., Lu, R., & Di Li (2013). Enabling cyber-physical systems with machine-to-machine technologies. *International Journal of Ad Hoc and Ubiquitous Computing*, *13*(3/4), 187. https://doi.org/10.1504/IJAHUC.2013.055454
OPC Unified Architecture (OPC UA)	• Lam, A. N., & Haugen, O. (2019). Implementing OPC-UA services for industrial cyber-physical systems in service-oriented architecture. In *45th Annual Conference of the IEEE Industrial Electronics Society (IECON)* (pp. 5486–5492). IEEE. https://doi.org/10.1109/IECON.2019.8926972 • Müller, M., Wings, E., & Bergmann, L. (2017). Developing open source cyber-physical systems for service-oriented architectures using OPC UA. In *15th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 83–88). IEEE. https://doi.org/10.1109/INDIN.2017.8104751
Industrial value creation	
Pre-production stage, production stage, and product in use stage	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2
Monitoring	• Mörth, O., Emmanouilidis, C., Hafner, N., & Schadler, M. (2020). Cyber-physical systems for performance monitoring in production intralogistics. *Computers & Industrial Engineering*, *142*. https://doi.org/10.1016/j.cie.2020.106333 • Yin, S., Rodriguez-Andina, J. J., & Jiang, Y. (2019). Real-time monitoring and control of industrial cyberphysical systems: With integrated plant-wide monitoring and control framework. *IEEE Industrial Electronics Magazine*, *13*(4), 38–47. https://doi.org/10.1109/MIE.2019.2938025
Smart (raw)materials/ Components	• Culler, D., & Long, J. (2016). A prototype smart materials warehouse application implemented using custom mobile robots and open source vision technology developed using EmguCV. *Procedia Manufacturing*, *5*, 1092–1106. https://doi.org/10.1016/j.promfg.2016.08.080 • Kassim, A., Horváth, I., & van der Vegte, W. F. (2016). Prototyping a cyber-physical affordance exploration system for smart materials: Implementation and integration of hardware, software and cyberware ingredients. In I. Horváth, J.-P. Pernot, & Z. Rusák (Eds.), *Tools and methods of competitive engineering* (pp. 25–40). University of Technology.
Condition	• Majdani, F., Petrovski, A., & Doolan, D. (2016). Designing a context-aware cyber physical system for smart conditional monitoring of platform equipment. In C. Jayne & L. Iliadis (Eds.), *Communications in Computer and Information Science: Vol. 629. Engineering Applications of Neural Networks* (pp. 198–210). Springer. https://doi.org/10.1007/978-3-319-44188-7_15 • Villalonga, A., Castano, F., Beruvides, G., Haber, R., Strzelczak, S., & Kossakowska, J. (2019). Visual analytics framework for condition monitoring in cyber-physical systems. In *23rd International Conference on System Theory, Control and Computing (ICSTCC)* (pp. 55–60). IEEE. https://doi.org/10.1109/ICSTCC.2019.8885611

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Processing	• Parashchuk, I., & Kotenko, I. (2019). Formulation of a system of indicators of information protection quality in automatic systems of numerical control machines for advanced material processing. *Materials Today: Proceedings*, *19*, 1835–1840. https://doi.org/10.1016/j.matpr.2019.07.023
Transport	• Möller, D. P., & Vakilzadian, H. (2016). Cyber-physical systems in smart transportation. In *IEEE International Conference on Autonomic Computing (ICAC)* (pp. 776–781). IEEE. https://doi.org/10.1109/EIT.2016.7535338
Reprocessing/Renewal	• Tozanlı, Ö., & Kongar, E. (2020). Integration of Industry 4.0 principles into reverse logistics operations for improved value creation: A case study of a mattress recycling company. In A. Erkollar (Ed.), *Enterprise & Business Management* (pp. 1–26). Tectum. https://doi.org/10.5771/9783828872301-1
Lifecycle management	• Smetana, S., Seebold, C., & Heinz, V. (2018). Neural network, blockchain, and modular complex system: The evolution of cyber-physical systems for material flow analysis and life cycle assessment. *Resources, Conservation and Recycling*, *133*, 229–230. https://doi.org/10.1016/j.resconrec.2018.02.020 • Barthelmey, A., Störkle, D., Kuhlenkötter, B., & Deuse, J. (2014). Cyber physical systems for life cycle continuous technical documentation of manufacturing facilities. *Procedia CIRP*, *17*, 207–211. https://doi.org/10.1016/j.procir.2014.01.050 • Thoben, K.-D., Pöppelbuß, J., Wellsandt, S., Teucke, M., & Werthmann, D. (2014). Considerations on a Lifecycle Model for Cyber-Physical System Platforms. In B. Grabot, B. Vallespir, S. Gomes, A. Bouras, & D. Kiritsis (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 438. Advances in Production Management Systems: Innovative and Knowledge-Based Production Management in a Global-Local World* (pp. 85–92). Springer. https://doi.org/10.1007/978-3-662-44739-0_11
Digital factory	• Ciavotta, M., Maso, G. D., Rovere, D., Tsvetanov, R., & Menato, S. (2020). Towards the digital factory: A microservices-based middleware for real-to-digital synchronization. In A. Bucchiarone, N. Dragoni, S. Dustdar, P. Lago, M. Mazzara, V. Rivera, & A. Sadovykh (Eds.), *Microservices* (pp. 273–297). Springer. https://doi.org/10.1007/978-3-030-31646-4_11
Smart factory	• Chen, G., Wang, P., Feng, B., Li, Y., & Liu, D. (2020). The framework design of smart factory in discrete manufacturing industry based on cyber-physical system. *International Journal of Computer Integrated Manufacturing*, *33*(1), 79–101. https://doi.org/10.1080/0951192X.2019.1699254 • Sinha, D., & Roy, R. (2020). Reviewing cyber-physical system as a part of smart factory in Industry 4.0. *IEEE Engineering Management Review*, *48*(2), 103–117. https://doi.org/10.1109/EMR.2020.2992606
Smart manufacturing	• Tao, F., Qi, Q., Wang, L., & Nee, A. (2019). Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014 • Yao, X., Zhou, J., Lin, Y., Li, Y., Yu, H., & Liu, Y. (2019). Smart manufacturing based on cyber-physical systems and beyond. *Journal of Intelligent Manufacturing*, *30*(8), 2805–2817. https://doi.org/10.1007/s10845-017-1384-5
Cyber-physical production systems (CPPS)	• Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP*, *17*, 9–13. https://doi.org/10.1016/j.procir.2014.03.115 • Ribeiro, L. (2017). Cyber-physical production systems' design challenges. In *26th IEEE International Symposium on Industrial Electronics (ISIE)* (pp. 1189–1194). IEEE. https://doi.org/10.1109/ISIE.2017.8001414
Production system development	• Chun, I.-G., Kim, J., Kim, W.-T., & Lee, E. (2011). Self-managed system development method for cyber-physical systems. In T. Kim, H. Adeli, A. Stoica, & B.-H. Kang (Eds.), *Communications in Computer and Information Science: Vol. 256. Control and Automation, and Energy System Engineering* (pp. 191–194). Springer. https://doi.org/10.1007/978-3-642-26010-0_23 • Thramboulidis, K. (2015). A cyber–physical system-based approach for industrial automation systems. *Computers in Industry*, *72*, 92–102. https://doi.org/10.1016/j.compind.2015.04.006
Production execution	• Chiraga, N., Walker, A., Bright, G., & Onunka, C. (2017). Factory communication system for customer-based production execution: An empirical study on the manufacturing system entropy. In *13th IEEE International Conference on Control & Automation (ICCA)* (pp. 660–665). IEEE. https://doi.org/10.1109/ICCA.2017.8003138 • Lu, Y., Peng, T., & Xu, X. (2019). Energy-efficient cyber-physical production network: Architecture and technologies. *Computers & Industrial Engineering*, *129*, 56–66. https://doi.org/10.1016/j.cie.2019.01.025
Production support	• Schuh, G., Stich, V., Reuter, C., Blum, M., Brambring, F., Hempel, T., Reschke, J., & Schiemann, D. (2017). Cyber physical production control. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 519–539). Springer. https://doi.org/10.1007/978-3-319-42559-7_21
Design	• Ruan, J., Yu, W., Yang, Y., & Hu, J. (2015). Design and realize of tire production process monitoring system based on cyber-physical systems. In *International Conference on Computer Science and Mechanical Automation* (pp. 175–179). IEEE. https://doi.org/10.1109/CSMA.2015.42 • Turetskyy, A., Wessel, J., Herrmann, C., & Thiede, S. (2021). Battery production design using multi-output machine learning models. *Energy Storage Materials*, *38*, 93–112. https://doi.org/10.1016/j.ensm.2021.03.002
Design space exploration	• Mühleis, N., Glaß, M., Zhang, L., & Teich, J. (2011). A co-simulation approach for control performance analysis during design space exploration of cyber-physical systems. *ACM SIGBED Review*, *8*(2), 23–26. https://doi.org/10.1145/2000367.2000372 • Zhou, Y., & Baras, J. S. (2013). CPS modeling integration hub and design space exploration with application to microrobotics. In D. C. Tarraf (Ed.), *Lecture Notes in Control and Information Sciences: Vol. 449. Control of Cyber-Physical Systems* (pp. 23–42). Springer. https://doi.org/10.1007/978-3-319-01159-2_2
System level design methodology	• Attarzadeh-Niaki, S.-H., & Sander, I. (2016). An extensible modeling methodology for embedded and cyber-physical system design. *Simulation*, *92*(8), 771–794. https://doi.org/10.1177/0037549716659753 • Zeng, J., Yang, L. T., Lin, M., Ning, H., & Ma, J. (2016). A survey: Cyber-physical-social systems and their system-level designmethodology. *Future Generation Computer Systems.* Advance online publication. https://doi.org/10.1016/j.future.2016.06.034
Component-based	• Blech, J. O., & Herrmann, P. (2015). Behavioral types for component-based development of cyber-physical systems. In D. Bianculli, R. Calinescu, & B. Rumpe (Eds.), *Lecture Notes in Computer Science: Vol. 9509. Software Engineering and Formal Methods* (pp. 43–52). Springer. https://doi.org/10.1007/978-3-662-49224-6_5 • Crnkovic, I., Malavolta, I., Muccini, H., & Sharaf, M. (2016). On the use of component-based principles and practices for architecting cyber-physical systems. In *19th International ACM SIGSOFT Symposium on Component-Based Software Engineering (CBSE)*. https://doi.org/10.1109/CBSE.2016.9

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Contract-based	• Cancila, D., Zaatiti, H., & Passerone, R. (2015). Cyber-physical system and contract-based design. In M. Törngren & M. E. Grimheden (Eds.), *Workshop on Embedded and Cyber-Physical Systems Education* (pp. 1–4). The Association for Computing Machinery. https://doi.org/10.1145/2832920.2832924 • Westman, J., & Nyberg, M. (2014). Environment-centric contracts for design of cyber-physical systems. In J. Dingel, W. Schulte, I. Ramos, S. Abrahão, & E. Insfran (Eds.), *Lecture Notes in Computer Science: Vol. 8767. Model-Driven Engineering Languages and Systems* (pp. 218–234). Springer. https://doi.org/10.1007/978-3-319-11653-2_14
Model-based	• Al Faruque, M. A., & Ahourai, F. (2015). A model-based design of cyber-physical energy systems. In *20th Asia and South Pacific Design Automation Conference* (pp. 97–104). IEEE. https://doi.org/10.1109/ASPDAC.2014.6742873 • Molina, J. M., Damm, M., Haase, J., Holleis, E., & Grimm, C. (2014). Model based design of distributed embedded cyber physical systems. In J. Haase (Ed.), *Lecture Notes in Electrical Engineering: Vol. 265. Models, Methods, and Tools for Complex Chip Design* (pp. 127–143). Springer. https://doi.org/10.1007/978-3-319-01418-0_8
Co-design	• Goswami, D., Schneider, R., & Chakraborty, S. (2011). Co-design of cyber-physical systems via controllers with flexible delay constraints. In *Proceedings of the 16th Asia and South Pacific Design Automation Conference* (pp. 225–230). IEEE Press. https://doi.org/10.1109/ASPDAC.2011.5722188 • Lin, M., Pan, Y., Yang, L. T., Guo, M., & Zheng, N. (2013). Scheduling co-design for reliability and energy in cyber-physical systems. *IEEE Transactions on Emerging Topics in Computing*, *1*(2), 353–365. https://doi.org/10.1109/TETC.2013.2274042
Simulation	• Chu, C.-T., & Shih, C.-S. (2013). CPSSim: Simulation framework for large-scale cyber-physical systems. In *1st IEEE International Conference on Cyber-Physical Systems, Networks, and Applications (CPSNA 2013).* IEEE. https://doi.org/10.1109/CPSNA.2013.6614245 • van Tran, H., Truong, T. P., Nguyen, K. T., Huynh, H. X., & Pottier, B. (2016). A federated approach for simulations in cyber-physical systems. In P. C. Vinh & V. Alagar (Eds.), *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering: Vol. 165. Context-Aware Systems and Applications* (pp. 165–176). Springer. https://doi.org/10.1007/978-3-319-29236-6_17
Modeling	• Simko, G., Levendovszky, T., Maroti, M., & Sztipanovits, J. (2014). Towards a theory for cyber-physical systems modeling. In R. Lämmel & W. Taha (Eds.), *Proceedings of the 4th ACM SIGBED International Workshop on Design, Modeling, and Evaluation of Cyber-Physical Systems* (pp. 56–61). ACM. https://doi.org/10.1145/2593458.2593463 • Zhang, Y., Shi, J., Zhang, T., Liu, X., & Qian, Z. (2015). Modeling and checking for cyber–physical system based on hybrid interface automata. *Pervasive and Mobile Computing*, *24*, 179–193. https://doi.org/10.1016/j.pmcj.2015.07.008
Co-simulation	• Mühleis, N., Glaß, M., Zhang, L., & Teich, J. (2011). A co-simulation approach for control performance analysis during design space exploration of cyber-physical systems. *ACM SIGBED Review*, *8*(2), 23–26. https://doi.org/10.1145/2000367.2000372 • Wang, B., & Baras, J. S. (2013). Hybridsim: A modeling and co-simulation toolchain for cyber-physical systems. In A. Verbraeck (Ed.), *17th IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications (DS-RT)* (pp. 33–40). IEEE. https://doi.org/10.1109/DS-RT.2013.12
Hardware-in-the-loop simulation	• Kim, M.-J., Kang, S., Kim, W.-T., & Chun, I.-G. (2013). Human-interactive hardware-in-the-loop simulation framework for cyber-physical systems. In *Second International Conference on Informatics & Applications (ICIA)* (pp. 198–202). IEEE. https://doi.org/10.1109/ICoIA.2013.6650255 • Shin, S. Y., Chaouch, K., Nejati, S., Sabetzadeh, M., Briand, L. C., & Zimmer, F. (2021). Uncertainty-aware specification and analysis for hardware-in-the-loop testing of cyber-physical systems. *Journal of Systems and Software*, *171*. https://doi.org/10.1016/j.jss.2020.110813
Engineering	• Barnard Feeney, A., Frechette, S., & Srinivasan, V. (2017). Cyber-physical systems engineering for manufacturing. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things* (pp. 81–110). Springer. https://doi.org/10.1007/978-3-319-42559-7_4 • Yue, T., Ali, S., & Selic, B. (2015). Cyber-physical system product line engineering: Comprehensive domain analysis and experience report. In D. C. Schmidt (Ed.), *Proceedings of the 19th International Conference on Software Product Line* (pp. 338–347). ACM. https://doi.org/10.1145/2791060.2791067
Greenfield	• Pilsan, H. O., Amann, R., & Gerstenberg, M. (2019). Realization of a small IIoT node: A greenfield approach. In *20th International Conference on Research and Education in Mechatronics (REM)* (pp. 1–5). IEEE. https://doi.org/10.1109/REM.2019.8744088
Brownfield/Retrofit	• Bader, S. R., Wolff, C., Vössing, M., & Schmidt, J.-P. (2018). Towards enabling cyber-physical systems in brownfield environments. In G. Satzger, L. Patrício, M. Zaki, N. Kühl, & P. Hottum (Eds.), *Lecture Notes in Business Information Processing: Vol. 331. Exploring Service Science* (pp. 165–176). Springer. https://doi.org/10.1007/978-3-030-00713-3_13 • Lins, T., & Oliveira, R. A. R. (2020). Cyber-physical production systems retrofitting in context of Industry 4.0. *Computers & Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2019.106193
Requirements engineering	• Penzenstadler, B., & Eckhardt, J. (2012). A requirements engineering content model for cyber-physical systems. In *2nd IEEE Workshop on Requirements Engineering for Systems, Services, and Systems-of-Systems (RESS)* (pp. 20–29). IEEE. https://doi.org/10.1109/RES4.2012.6347692 • Wiesner, S., Gorldt, C., Soeken, M., Thoben, K.-D., & Drechsler, R. (2014). Requirements engineering for cyber-physical systems. In B. Grabot, B. Vallespir, S. Gomes, A. Bouras, & D. Kiritsis (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 438. Advances in Production Management Systems: Innovative and Knowledge-Based Production Management in a Global-Local World* (pp. 281–288). Springer. https://doi.org/10.1007/978-3-662-44739-0_35
Product line engineering	• Iglesias, A., Lu, H., Arellano, C., Yue, T., Ali, S., & Sagardui, G. (2017). Product line engineering of monitoring functionality in industrial cyber-physical systems. In M. Cohen, M. Acher, L. Fuentes, D. Schall, J. Bosch, R. Capilla, E. Bagheri, Y. Xiong, J. Troya, A. Ruiz-Cortéz, & D. Benavides (Eds.), *Proceedings of the 21st International Systems and Software Product Line Conference - Volume A* (pp. 195–204). ACM. https://doi.org/10.1145/3106195.3106223 • Yue, T., Ali, S., & Selic, B. (2015). Cyber-physical system product line engineering: Comprehensive domain analysis and experience report. In D. C. Schmidt (Ed.), *Proceedings of the 19th International Conference on Software Product Line* (pp. 338–347). ACM. https://doi.org/10.1145/2791060.2791067
Software engineering	• Bures, T., Krikava, F., Mordinyi, R., Pronios, N., Weyns, D., Berger, C., Biffl, S., Daun, M., Gabor, T., Garlan, D., Gerostathopoulos, I., & Julien, C., (2015). Software engineering for smart cyber-physical systems - Towards a research agenda. *ACM SIGSOFT Software Engineering Notes*, *40*(6), 28–32. https://doi.org/10.1145/2830719.2830736 • Dziwok, S., Gerking, C., Becker, S., Thiele, S., Heinzemann, C., & Pohlmann, U. (2014). A tool suite for the model-driven software engineering of cyber-physical systems. In S. C. Cheung, A. Orso, & M.-A. Storey (Eds.), *22nd ACM SIGSOFT International Symposium on the Foundations of Software Engineering (FSE 2014)* (pp. 715–718). ACM. https://doi.org/10.1145/2635868.2661665

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Prototyping	• Beghi, A., Marcuzzi, F., & Rampazzo, M. (2016). A virtual laboratory for the prototyping of cyber-physical systems. *IFAC-PapersOnLine*, *49*(6), 63–68. https://doi.org/10.1016/j.ifacol.2016.07.154 • Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., & Colombo, A. W. (2016). Smart agents in industrial cyber–physical systems. *Proceedings of the IEEE*, *104*(5), 1086–1101. https://doi.org/10.1109/JPROC.2016.2521931
Manufacturing	• Berger, U., Selka, J., Ampatzopoulos, A., & Klabuhn, J. (2017). Manufacturing cyber-physical systems (industrial internet of things). In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things* (pp. 423–445). Springer. https://doi.org/10.1007/978-3-319-42559-7_16 • Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology*, *65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005
Production management	• Schuh, G., Potente, T., Thomas, C., & Hempel, T. (2014). Short-term cyber-physical production management. *Procedia CIRP*, *25*, 154–160. https://doi.org/10.1016/j.procir.2014.10.024 • Xing, B. (2015). Optimization in production management: Economic load dispatch of cyber physical power system using artificial bee colony. In C. Kahraman & S. Çevik Onar (Eds.), *Intelligent Systems Reference Library: Vol. 87. Intelligent Techniques in Engineering Management* (pp. 275–293). Springer. https://doi.org/10.1007/978-3-319-17906-3_12
Process control	• Diaz, J., Bielza, C., Ocaña, J. L., & Larrañaga, P. (2016). Development of a cyber-physical system based on selective gaussian naïve bayes model for a self-predict laser surface heat treatment process control. In O. Niggemann & J. Beyerer (Eds.), *Technologien für die intelligente Automation. Machine Learning for Cyber Physical Systems* (pp. 1–8). Springer. https://doi.org/10.1007/978-3-662-48838-6_1 • Wang, Y., Vuran, M. C., & Goddard, S. (2008). Cyber-physical systems in industrial process control. *ACM SIGBED Review*, *5*(1), 1–2. https://doi.org/10.1145/1366283.1366295
Process management	• Kammerer, K., Pryss, R., Sommer, K., & Reichert, M. (2018). Towards context-aware process guidance in cyber-physical systems with augmented reality. In *4th International Workshop on Requirements Engineering for Self-Adaptive, Collaborative, and Cyber Physical Systems (RESACS)* (pp. 44–51). IEEE. https://doi.org/10.1109/RESACS.2018.00013
Advanced manufacturing	• Pombo, I., Godino, L., Sánchez, J. A., & Lizarralde, R. (2020). Expectations and limitations of cyber-physical systems (CPS) for advanced manufacturing: A view from the grinding industry. *Future Internet*, *12*(9), 159. https://doi.org/10.3390/fi12090159 • Trappey, A. J. C., Trappey, C. V., Govindarajan, U. H., Sun, J. J., & Chuang, A. C. (2016). A review of technology standards and patent portfolios for enabling cyber-physical systems in advanced manufacturing. *IEEE Access*, *4*, 7356–7382. https://doi.org/10.1109/ACCESS.2016.2619360
Cloud manufacturing	• Morgan, J., & O'Donnell, G. E. (2015). The cyber physical implementation of cloud manufactuirng monitoring systems. *Procedia CIRP*, *33*, 29–34. https://doi.org/10.1016/j.procir.2015.06.007 • Yu, C., Xu, X., & Lu, Y. (2015). Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing – Concepts and relationships. *Manufacturing Letters*, *6*, 5–9. https://doi.org/10.1016/j.mfglet.2015.11.005
Industrial services	• Gajdzik, B. (2020). Development of business models and their key components in the context of cyber-physical production systems in Industry 4.0. In A. Jablonski & M. Jablonski (Eds.), *Scalability and sustainability of business models in circular, sharing and networked economies* (pp. 73–94). Cambridge Scholars Publis. • Herterich, M. M., Uebernickel, F., & Brenner, W. (2015). The impact of cyber-physical systems on industrial services in manufacturing. *Procedia CIRP*, *30*, 323–328. https://doi.org/10.1016/j.procir.2015.02.110
Service composition	• Fuchs, J., Oks, S. J., & Franke, J. (2019). Platform-based service composition for manufacturing: A conceptualization. *Procedia CIRP*, *81*, 541–546. https://doi.org/10.1016/j.procir.2019.03.152 • Huang, J., Bastani, F. B., Yen, I.-L., & Zhang, W. (2010). A framework for efficient service composition in cyber-physical systems. In *5th IEEE International Symposium on Service Oriented System Engineering (SOSE)* (pp. 291–298). IEEE. https://doi.org/10.1109/SOSE.2010.46
Maintenance	• Jantunen, E., Zurutuza, U., Ferreira, L. L., & Varga, P. (2016). Optimising maintenance: What are the expectations for cyber physical systems. In *3rd International Workshop on Emerging Ideas and Trends in Engineering of Cyber-Physical Systems (EITEC)* (pp. 53–58). IEEE. https://doi.org/10.1109/EITEC.2016.7503697 • Lee, J., & Bagheri, B. (2015). Cyber-physical systems in future maintenance. In J. Amadi-Echendu, C. Hoohlo, & J. Mathew (Eds.), *Lecture Notes in Mechanical Engineering. 9th WCEAM Research Papers* (pp. 299–305). Springer. https://doi.org/10.1007/978-3-319-15536-4_25
Condition-based	• Larrinaga, F., Fernandez, J., Zugasti, E., Garitano, I., Zurutuza, U., Anasagasti, M., & Mondragon, M. (2018). Implementation of a reference architecture for cyber physical systems to support condition based maintenance. In *5th International Conference on Control, Decision and Information Technologies (CoDIT)* (pp. 773–778). IEEE. https://doi.org/10.1109/CoDIT.2018.8394825 • Mbuli, J., Trentesaux, D., Clarhaut, J., & Branger, G. (2017). Decision support in condition-based maintenance of a fleet of cyber-physical systems: A fuzzy logic approach. In *Intelligent Systems Conference (IntelliSys)* (pp. 82–89). IEEE. https://doi.org/10.1109/IntelliSys.2017.8324362
Predictive	• Bampoula, X., Siaterlis, G., Nikolakis, N., & Alexopoulos, K. (2021). A deep learning model for predictive maintenance in cyber-physical production systems using LSTM autoencoders. *Sensors*, *21*(3). https://doi.org/10.3390/s21030972 • Yang, F.-N., & Lin, H.-Y. (2019). Development of a predictive maintenance platform for cyber-physical systems. In *IEEE International Conference on Industrial Cyber Physical Systems (ICPS)* (pp. 331–335). IEEE. https://doi.org/10.1109/ICPHYS.2019.8780144
Monitoring/Control	• Niggemann, O., Biswas, G., Kinnebrew, J. S., Khorasgani, H., Volgmann, S., & Bunte, A. (2015). Data-driven monitoring of cyber-physical systems leveraging on big data and the internet-of-things for diagnosis and control. In Y. Pencolé, L. Travé-Massuyès, & P. Dague (Chairs), *26th International Workshop on Principles of Diagnosis (DX15)*. • Srewil, Y., & Scherer, R. J. (2013). Effective construction process monitoring and control through a collaborative cyber-physical approach. In L. M. Camarinha-Matos & R. J. Scherer (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 408. Collaborative Systems for Reindustrialization* (pp. 172–179). Springer. https://doi.org/10.1007/978-3-642-40543-3_19
Condition monitoring	• Fleischmann, H., Kohl, J., & Franke, J. (2016). A reference architecture for the development of socio-cyber-physical condition monitoring systems. In *11th Systems of Systems Engineering Conference (SoSE)* (pp. 1–6). IEEE. https://doi.org/10.1109/SYSOSE.2016.7542963 • Villalonga, A., Castano, F., Beruvides, G., Haber, R., Strzelczak, S., & Kossakowska, J. (2019). Visual analytics framework for condition monitoring in cyber-physical systems. In *23rd International Conference on System Theory, Control and Computing (ICSTCC)* (pp. 55–60). IEEE. https://doi.org/10.1109/ICSTCC.2019.8885611

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Event processing	• Babiceanu, R. F., & Seker, R. (2015). Manufacturing cyber-physical systems enabled by complex event processing and big data environments: A framework for development. In T. Borangiu, D. Trentesaux, & A. Thomas (Eds.), *Studies in Computational Intelligence: Vol. 594. Service orientation in holonic and multi-agent manufacturing* (pp. 165–173). Springer. https://doi.org/10.1007/978-3-319-15159-5_16 • Vegh, L., & Miclea, L. (2016). Secure and efficient communication in cyber-physical systems through cryptography and complex event processing. In *International Conference on Communications (COMM)* (pp. 273–276). IEEE. https://doi.org/10.1109/ICComm.2016.7528290
Event-triggered control	• An, J., Yao, J., Zhou, H., & Hu, F. (2013). A better understanding of event-triggered control from a CPS perspective. In *International Conference on Parallel and Distributed Systems (ICPADS)* (pp. 257–264). IEEE. https://doi.org/10.1109/ICPADS.2013.45 • Zeng, X., & Hui, Q. (2015). Energy-event-triggered hybrid supervisory control for cyber-physical network systems. *IEEE Transactions on Automatic Control*, *60*(11), 3083–3088. https://doi.org/10.1109/TAC.2015.2409900
Predictive control	• Lucia, S., Kögel, M., Zometa, P., Quevedo, D. E., & Findeisen, R. (2016). Predictive control, embedded cyberphysical systems and systems of systems – A perspective. *Annual Reviews in Control*, *41*, 193–207. https://doi.org/10.1016/j.arcontrol.2016.04.002 • Zhang, K., Sprinkle, J., & Sanfelice, R. G. (2016). Computationally aware switching criteria for hybrid model predictive control of cyber-physical systems. *IEEE Transactions on Automation Science and Engineering*, *13*(2), 479–490. https://doi.org/10.1109/TASE.2016.2523341
Fuzzy control	• Cheng, S.-T., & Chou, J.-H. (2016). Fuzzy control to improve energy-economizing in cyber-physical systems. *Applied Artificial Intelligence*, *30*(1), 1–15. https://doi.org/10.1080/08839514.2015.1121065 • Voskoglou, M. G. (2020). Fuzzy control in cyber-physical systems. *International Journal of Cyber-Physical Systems*, *2*(2), 46–58. https://doi.org/10.4018/IJCPS.2020070103
Analysis	• Hahn, A., Thomas, R. K., Lozano, I., & Cárdenas, A. A. (2015). A multi-layered and kill-chain based security analysis framework for cyber-physical systems. *International Journal of Critical Infrastructure Protection*, *11*, 39–50. https://doi.org/10.1016/j.ijcip.2015.08.003 • Michniewicz, J., & Reinhart, G. (2014). Cyber-physical robotics – Automated analysis, programming and configuration of robot cells based on cyber-physical-systems. *Procedia Technology*, *15*, 566–575. https://doi.org/10.1016/j.protcy.2014.09.017
Testing	• Abbas, H., Hoxha, B., Fainekos, G., & Ueda, K. (2014). Robustness-guided temporal logic testing and verification for Stochastic Cyber-Physical Systems. In *4th IEEE Annual International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)* (pp. 1–6). IEEE. https://doi.org/10.1109/CYBER.2014.6917426 • Abbaspour Asadollah, S., Inam, R., & Hansson, H. (2015). A survey on testing for cyber physical system. In K. El-Fakih, G. Barlas, & N. Yevtushenko (Eds.), *Lecture Notes in Computer Science: Vol. 9447. Testing Software and Systems* (pp. 194–207). Springer. https://doi.org/10.1007/978-3-319-25945-1_12
Model-based testing	• Aerts, A., Reniers, M., & Mousavi, M. R. (2016). Model-based testing of cyber-physical systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications.* (pp. 287–304). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00019-5 • Zander, J. (2013). Model-based testing for execution algorithms in the simulation of cyber-physical systems. In *IEEE AUTOTESTCON* (pp. 1–7). IEEE. https://doi.org/10.1109/AUTEST.2013.6645058
Testbed	• Chen, B., Butler-Purry, K. L., Goulart, A., & Kundur, D. (2014). Implementing a real-time cyber-physical system test bed in RTDS and OPNET. In *North American Power Symposium (NAPS)* (pp. 1–6). IEEE. https://doi.org/10.1109/NAPS.2014.6965381 • Matena, V., Bures, T., Gerostathopoulos, I., & Hnetynka, P. (2016). Model problem and testbed for experiments with adaptation in smart cyber-physical systems. *11th International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS)* Association for Computing Machinery. https://doi.org/10.1145/2897053.2897065
Validation	• Arrieta, A., Sagardui, G., & Etxeberria, L. (2014). Towards the automatic generation and management of plant models for the validation of highly configurable cyber-physical systems. In *IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 1–8). IEEE. https://doi.org/10.1109/ETFA.2014.7005090 • Arrieta, A., Wang, S., Sagardui, G., & Etxeberria, L. (2016). Search-based test case selection of cyber-physical system product lines for simulation-based validation. In H. Mei (Ed.), *Proceedings of the 20th International Systems and Software Product Line Conference on - SPLC* (pp. 297–306). ACM Press. https://doi.org/10.1145/2934466.2946046
Verification	• Malecha, G., Ricketts, D., Alvarez, M. M., & Lerner, S. (2016). Towards foundational verification of cyber-physical systems. In *Science of Security for Cyber-Physical Systems Workshop (SOSCYPS)*. https://doi.org/10.1109/SOSCYPS.2016.7580000 • Zheng, X., & Julien, C. (2015). Verification and validation in cyber physical systems: Research challenges and a way forward. In *International Workshop on Software Engineering for Smart Cyber-Physical Systems* (pp. 15–18). IEEE. https://doi.org/10.1109/SEsCPS.2015.11
Model checking	• Bak, S., & Chaki, S. (2016). Verifying cyber-physical systems by combining software model checking with hybrid systems reachability. In *Proceedings of the International Conference on Embedded Software (EMSOFT)* (pp. 1–10). ACM. https://doi.org/10.1145/2968478.2968490 • Zhang, Y., Liu, X., Shi, J., Zhang, T., & Qian, Z. (2014). Scenario-based behavioral nonexistent consistency checking for cyber-physical systems. In *8th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS)* (pp. 58–65). IEEE. https://doi.org/10.1109/IMIS.2014.8
Runtime verification	• Garcia-Valls, M., Perez-Palacin, D., & Mirandola, R. (2014). Time-sensitive adaptation in CPS through run-time configuration generation and verification. In *38th IEEE Annual Computer Software and Applications Conference* (pp. 332–337). IEEE. https://doi.org/10.1109/COMPSAC.2014.55 • Yu, K., Chen, Z., & Dong, W. (2014). A predictive runtime verification framework for cyber-physical systems. In *8th IEEE International Conference on Software Security and Reliability - companion (SERE-C)* (pp. 223–227). IEEE. https://doi.org/10.1109/SERE-C.2014.43
Eigen analysis	• Ye, H., Gao, W., Mou, Q., & Liu, Y. (2017). Iterative infinitesimal generator discretization-based method for eigen-analysis of large delayed cyber-physical power system. *Electric Power Systems Research*, *143*, 389–399. https://doi.org/10.1016/j.epsr.2016.10.016
Logistics	• Lewandowski, M., Gath, M., Werthmann, D., & Lawo, M. (2013). Agent-based control for material handling systems in in-house logistics - Towards cyber-physical systems in in-house-logistics utilizing real size. In *Smart SysTech 2013: European Conference on Smart Objects, Systems and Technologies* (pp. 1–5). VDE Verlag. • Schuhmacher, J., & Hummel, V. (2016). Decentralized control of logistic processes in cyber-physical production systems at the example of ESB Logistics Learning Factory. *Procedia CIRP*, *54*, 19–24. https://doi.org/10.1016/j.procir.2016.04.095

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Material handling	• Orestis K. Efthymiou, & Ponis, S. T. (2019). Current status of Industry 4.0 in material handling automation and in-house logistics. Advance online publication. https://doi.org/10.5281/zenodo.3566333 • Zhang, Y., Zhu, Z., & Lv, J. (2018). CPS-based smart control model for shopfloor material handling. *IEEE Transactions on Industrial Informatics*, *14*(4), 1764–1775. https://doi.org/10.1109/TII.2017.2759319
Warehouse systems	• Basile, F., Chiacchio, P., Coppola, J., & Gerbasio, D. (2015). Automated warehouse systems: A cyber-physical system perspective. In *2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA)* (pp. 1–4). IEEE. https://doi.org/10.1109/ETFA.2015.7301597
Automated guided vehicles (AGV)	• Farooq, B., Bao, J., Raza, H., Sun, Y., & Ma, Q. (2021). Flow-shop path planning for multi-automated guided vehicles in intelligent textile spinning cyber-physical production systems dynamic environment. *Journal of Manufacturing Systems*, *59*, 98–116. https://doi.org/10.1016/j.jmsy.2021.01.009 • Mehami, J., Nawi, M., & Zhong, R. Y. (2018). Smart automated guided vehicles for manufacturing in the context of industry 4.0. *Procedia Manufacturing*, *26*, 1077–1086. https://doi.org/10.1016/j.promfg.2018.07.144
Intelligent transportation systems (ITS)	• Gokhale, A. S., McDonald, M., Drager, S., & McKeever, W. (2010). A cyber physical systems perspective on the real-time and reliable dissemination of information in intelligent transportation systems. *Network Protocols and Algorithms*, *2*(3), 116–136. https://doi.org/10.5296/npa.v2i3.480 • Rawat, D. B., Bajracharya, C., & Yan, G. (2015). Towards intelligent transportation cyber-physical systems: Real-time computing and communications perspectives. In *Southeastcon* (pp. 1–6). IEEE. https://doi.org/10.1109/SECON.2015.7132923
Supply chain optimization	• Frazzon, E. M., Silva, L. S., & Hurtado, P. A. (2015). Synchronizing and improving supply chains through the application of cyber-physical systems. *IFAC-PapersOnLine*, *48*(3), 2059–2064. https://doi.org/10.1016/j.ifacol.2015.06.392
Delivery	• Sanjab, A., Saad, W., & Basar, T. (2017). Prospect theory for enhanced cyber-physical security of drone delivery systems: A network interdiction game. In *IEEE International Conference on Communications (ICC)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICC.2017.7996862
Smart grid	• Karnouskos, S. (2011). Cyber-physical systems in the smartgrid. In *9th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 20–23). IEEE. https://doi.org/10.1109/INDIN.2011.6034829 • Macana, C. A., Quijano, N., & Mojica-Nava, E. (2011). A survey on cyber physical energy systems and their applications on smart grids. In M. V. Gualteros (Ed.), *IEEE PES Conference on Innovative Smart Grid Technologies Latin America* (pp. 1–7). IEEE. https://doi.org/10.1109/ISGT-LA.2011.6083194
Power supply	• Guo, J., Liu, W., Syed, F. R., & Zhang, J. (2019). Reliability assessment of a cyber physical microgrid system in island mode. *CSEE Journal of Power and Energy Systems.* Advance online publication. https://doi.org/10.17775/CSEEJPES.2017.00770
Energy efficiency	• Cao, J., & Li, H. (2009). Energy-efficient structuralized clustering for sensor-based cyber physical systems. In *Symposia and workshops on ubiquitous, autonomic and trusted computing* (pp. 234–239). IEEE. https://doi.org/10.1109/UIC-ATC.2009.26 • Parolini, L., Sinopoli, B., Krogh, B. H., & Wang, Z. (2012). A cyber–physical systems approach to data center modeling and control for energy efficiency. *Proceedings of the IEEE*, *100*(1), 254–268. https://doi.org/10.1109/JPROC.2011.2161244
Energy harvesting	• Erol-Kantarci, M., Illig, D. W., Rumbaugh, L. K., & Jemison, W. D. (2016). Energy-harvesting low-power devices in cyber-physical systems. In H. Song, D. B. Rawat, S. Jeschke, & C. Brecher (Eds.), *Intelligent Data Centric Systems. Cyber-Physical Systems: Foundations, Principles and Applications.* (pp. 55–74). Academic Press. https://doi.org/10.1016/B978-0-12-803801-7.00004-3 • Zhao, M., Li, Q., Xie, M., Liu, Y., Hu, J., & Xue, C. J. (2015). Software assisted non-volatile register reduction for energy harvesting based cyber-physical system. In *Design, Automation & Test in Europe Conference & Exhibition (DATE)* (pp. 567–572). IEEE. https://doi.org/10.7873/DATE.2015.0619
Battery management	• Man, K. L., Ting, T. O., Krilavicius, T., Wan, K., Chen, C., Chang, J., & Poon, S. H. (2012). Towards a hybrid approach to SoC estimation for a smart Battery Management System (BMS) and battery supported Cyber-Physical Systems (CPS). In A. Kajackas (Ed.), *2nd Baltic Congress on Future Internet Communications (BCFIC)* (pp. 113–116). IEEE. https://doi.org/10.1109/BCFIC.2012.6217989 • Zhang, F., & Shi, Z. (2009). Optimal and adaptive battery discharge strategies for cyber-physical systems. In *48th IEEE Conference on Decision and Control (CDC)* (pp. 6232–6237). IEEE. https://doi.org/10.1109/CDC.2009.5400561
Smart products	• Barbosa, J., Leitao, P., Trentesaux, D., Colombo, A. W., & Karnouskos, S. (2016). Cross benefits from cyber-physical systems and intelligent products for future smart industries. In *14th IEEE International Conference on Industrial Informatics (INDIN)* (pp. 504–509). IEEE. https://doi.org/10.1109/INDIN.2016.7819214 • Riel, A., Kreiner, C., Macher, G., & Messnarz, R. (2017). Integrated design for tackling safety and security challenges of smart products and digital manufacturing. *CIRP Annals - Manufacturing Technology*, *66*(1), 177–180. https://doi.org/10.1016/j.cirp.2017.04.037
Monitoring throughout the entire product life cycle (product usage data)	• Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Springer Series in Wireless Technology. Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-42559-7_2 • Shangguan, D., Chen, L., & Ding, J. (2019). A hierarchical digital twin model framework for dynamic cyber-physical system design. *Proceedings of the 5th International Conference on Mechatronics and Robotics Engineering (ICMRE)* (pp. 123–129). ACM Press. https://doi.org/10.1145/3314493.3314504
Condition	• El Hamdi, S., Abouabdellah, A., & Oudani, M. (2019). Industry 4.0: Fundamentals and main challenges. In *International Colloquium on Logistics and Supply Chain Management (LOGISTIQUA)* (pp. 1–5). IEEE. https://doi.org/10.1109/LOGISTIQUA.2019.8907280
Usage	• Nazarenko, A. A., & Camarinha-Matos, L. M. (2020). The role of digital twins in collaborative cyber-physical systems. In L. M. Camarinha-Matos, N. Farhadi, F. Lopes, & H. Pereira (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 577. Technological Innovation for Life Improvement* (pp. 191–205). Springer. https://doi.org/10.1007/978-3-030-45124-0_18
Recycling	• Sharpe, R. G., Goodall, P. A., Neal, A. D., Conway, P. P., & West, A. A. (2018). Cyber-physical systems in the re-use, refurbishment and recycling of used electrical and electronic equipment. *Journal of Cleaner Production*, *170*, 351–361. https://doi.org/10.1016/j.jclepro.2017.09.087
Downcycling	• Keivanpour, S., & Kadi, D. A. (2018). Perspectives for application of the internet of things and big data analytics on end of life aircraft treatment. *International Journal of Sustainable Aviation*, *4*(3/4), 202. https://doi.org/10.1504/IJSA.2018.098423
Across company/organization boundaries throughout the entire value chain/network	• Mendhurwar, S., & Mishra, R. (2021). 'Un'-blocking the Industry 4.0 value chain with cyber-physical social thinking. *Enterprise Information Systems*, 1–48. https://doi.org/10.1080/17517575.2021.1930189

Table 4 (continued)

Categories (fields, areas, and sections)	Exemplary literature
Digital twin	• Biesinger, F., Meike, D., Kraß, B., & Weyrich, M. (2019). A digital twin for production planning based on cyber-physical systems: A case study for a cyber-physical system-based creation of a digital twin. *Procedia CIRP*, *79*, 355–360. https://doi.org/10.1016/j.procir.2019.02.087 • Tao, F., Qi, Q., Wang, L., & Nee, A. (2019). Digital twins and cyber–physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. *Engineering*, *5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014
Integrated supply chain	• Dekkers, R., Ivanov, D., & Sokolov, B. (2012). The inter-disciplinary modelling of supply chains in the context of collaborative multi-structural cyber-physical networks. *Journal of Manufacturing Technology Management*, *23*(8), 976–997. https://doi.org/10.1108/17410381211276835
Ad-hoc connectivity	• J, J. J., & W, M. W. (2020). Industrial Internet of Things (IIoT) – An IoT integrated services for Industry 4.0: A review. *International Journal of Applied Science & Engineering*, *8*(1). https://doi.org/10.30954/2322-0465.1.2020.5 • Xu, Z., Liu, X., Zhang, G., He, W., Dai, G., & Shu, W. (2008). A certificateless signature scheme for mobile wireless cyber-physical systems. In *28th International Conference on Distributed Computing Systems Workshops* (pp. 489–494). IEEE. https://doi.org/10.1109/ICDCS.Workshops.2008.84
Interoperability	• Fatima, I., Malik, S. U. R., Anjum, A., & Ahmad, N. (2020). Cyber physical systems and IoT: Architectural practices, interoperability, and transformation. *IT Professional*, *22*(3), 46–54. https://doi.org/10.1109/MITP.2019.2912604 • Givehchi, O., Landsdorf, K., Simoens, P., & Colombo, A. W. (2017). Interoperability for industrial cyber-physical systems: An approach for legacy systems. *IEEE Transactions on Industrial Informatics*, *13*(6), 3370–3378. https://doi.org/10.1109/TII.2017.2740434
Platform ecosystems	• Hodapp, D., Hawlitschek, F., & Kramer, D. (2019). Value co-creation in nascent platform ecosystems: A delphi study in the context of the internet of things. In *40th International Conference on Information Systems (ICIS)*. • Petrik, D., & Herzwurm, G. (2018). Platform ecosystems for the industrial internet of things – a software intensive business perspective. In S. Hyrynsalmi, A. Suominen, C. Jud, X. Wang, J. Bosch, & J. Münch (Eds.), *Proceedings of International Workshop on Software-intensive Business: Start-ups, Ecosystems and Platforms(SiBW 2018)*.
Horizontal and vertical integration/Operational and strategic alliances	
Horizontal integration	• Lukoki, V., Varela, L., & Machado, J. (2020). Simulation of vertical and horizontal integration of cyber-physical systems. In *7th International Conference on Control, Decision and Information Technologies (CoDIT)* (pp. 282–287). IEEE. https://doi.org/10.1109/CoDIT49905.2020.9263876 • Wolf, T., Zink, M., & Nagurney, A. (2013). The cyber-physical marketplace: A framework for large-scale horizontal integration in distributed cyber-physical systems. In *33rd IEEE International Conference on Distributed Computing Systems workshops (ICDCSW)* (pp. 296–302). IEEE. https://doi.org/10.1109/ICDCSW.2013.22
Vertical integration (Operational/Strategic level)	• Lukoki, V., Varela, L., & Machado, J. (2020). Simulation of vertical and horizontal integration of cyber-physical systems. In *7th International Conference on Control, Decision and Information Technologies (CoDIT)* (pp. 282–287). IEEE. https://doi.org/10.1109/CoDIT49905.2020.9263876

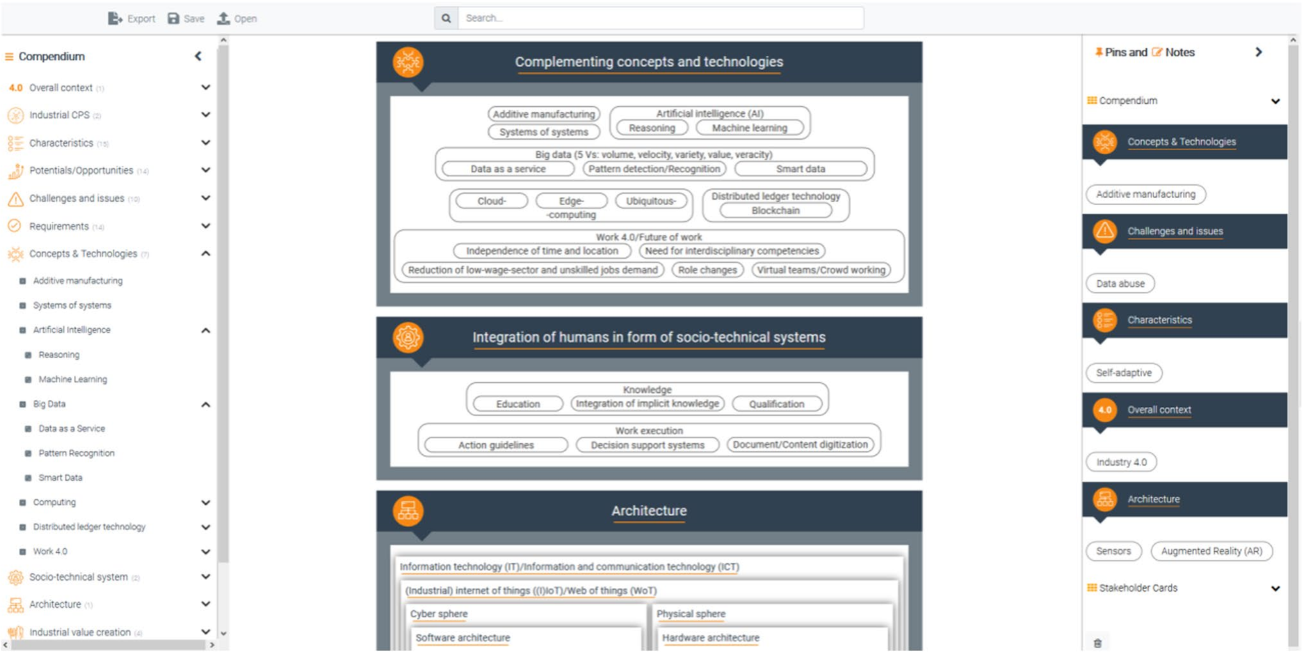


Fig. 18 Web tool *Industry 4.0 Compendium*

Acknowledgements The research presented in this paper was partially funded by the German Federal Ministry of Education and Research in the course of the project “ConSensE” (FKZ 02J19B062) as well as by the Friedrich-Alexander-Universität Erlangen-Nürnberg within the Emerging Fields Initiative “Sustainable Smart Industry”.

Funding Open Access funding enabled and organized by Projekt DEAL. The research leading to these results received funding from the German Federal Ministry of Education and Research in the course of the project “ConSensE” under Grant Agreement No FKZ 02J19B062 as well as by the Friedrich-Alexander-Universität Erlangen-Nürnberg within the Emerging Fields Initiative “Sustainable Smart Industry”.

Declarations

Competing Interests All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. Nor are there any other types of conflicting or competing interests.

References

Alur, R. (2015). *Principles of cyber-physical systems*. The MIT Press

Asare, P., Bakirtzis, G., Bernard, R., Broman, D., Lee, E. A., Prinsloo, G., & Sunder, S. S. (2012). *Cyber-Physical Systems - a Concept Map*. http://CyberPhysicalSystems.org

Berger, S., Häckel, B., & Häfner, L. (2021). Organizing self-organizing systems: A terminology, taxonomy, and reference model for entities in cyber-physical production systems. *Information Systems Frontiers, 23*(2), 391–414. https://doi.org/10.1007/s10796-019-09952-8.

Biesinger, F., Meike, D., Kraß, B., & Weyrich, M. (2019). A digital twin for production planning based on cyber-physical systems: A case study for a cyber-physical system-based creation of a digital twin. *Procedia CIRP, 79,* 355–360. https://doi.org/10.1016/j.procir.2019.02.087

Bresnahan, T. (2010). General purpose technologies. In K. J. Arrow & M. D. Intriligator (Eds.), *Handbook of the economics of innovation* (Vol. 2, pp. 761–791). Elsevier. https://doi.org/10.1016/S0169-7218(10)02002-2

Burns, T., Cosgrove, J., & Doyle, F. (2019). A Review of Interoperability Standards for Industry 4.0. *Procedia Manufacturing, 38,* 646–653. https://doi.org/10.1016/j.promfg.2020.01.083.

Calinescu, R., Camara, J., & Paterson, C. (2019). Socio-cyber-physical systems: Models, opportunities, open challenges. In *5th IEEE/ACM International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS)* (pp. 2–6). IEEE. https://doi.org/10.1109/SEsCPS.2019.00008

Cardin, O. (2019). Classification of cyber-physical production systems applications: Proposition of an analysis framework. *Computers in Industry, 104,* 11–21. https://doi.org/10.1016/j.compind.2018.10.002.

Chaâri, R., Ellouze, F., Koubâa, A., Qureshi, B., Pereira, N., Youssef, H., & Tovar, E. (2016). Cyber-physical systems clouds: A survey. *Computer Networks, 108,* 260–278. https://doi.org/10.1016/j.comnet.2016.08.017.

Chen, H. (2017). Applications of cyber-physical system: a literature review. *Journal of Industrial Integration and Management, 02*(03), 1750012–1750028. https://doi.org/10.1142/S2424862217500129.

Chen, H. (2017). Theoretical foundations for cyber-physical systems: A literature review. *Journal of Industrial Integration and Management, 2*(3), 1750013–1750027. https://doi.org/10.1142/S2424862217500130.

Colledani, M., Coupek, D., Verl, A., Aichele, J., & Yemane, A. (2018). A cyber-physical system for quality-oriented assembly of automotive electric motors. *CIRP Journal of Manufacturing Science and Technology, 20,* 12–22. https://doi.org/10.1016/j.cirpj.2017.09.001.

Colombo, A. W., Karnouskos, S., Kaynak, O., Shi, Y., & Yin, S. (2017). Industrial cyberphysical systems: A backbone of the fourth industrial revolution. *IEEE Industrial Electronics Magazine, 11*(1), 6–16. https://doi.org/10.1109/MIE.2017.2648857.

Dafflon, B., Moalla, N., & Ouzrout, Y. (2021). The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review. *The International Journal of Advanced Manufacturing Technology, 113*(7–8), 2395–2412. https://doi.org/10.1007/s00170-020-06572-4.

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In D. A. Buchanan, & A. Bryman (Eds.), *The SAGE Handbook of Organizational Research Methods* (pp. 671–689). SAGE

Geisberger, E., & Broy, M. (2015). *Living in a networked world: Integrated research agenda, cyber-physical systems (AgendaCPS)* (Acatech Study)

Gil, M., Albert, M., Fons, J., & Pelechano, V. (2019). Designing human-in-the-loop autonomous cyber-physical systems. *International Journal of Human-Computer Studies, 130,* 21–39. https://doi.org/10.1016/j.ijhcs.2019.04.006.

Gürdür, D., & Asplund, F. (2018). A systematic review to merge discourses: Interoperability, integration and cyber-physical systems. *Journal of Industrial Information Integration, 9,* 14–23. https://doi.org/10.1016/j.jii.2017.12.001.

Gürdür, D., El-Khoury, J., Seceleanu, T., & Lednicki, L. (2016). Making interoperability visible: Data visualization of cyber-physical systems development tool chains. *Journal of Industrial Information Integration, 4,* 26–34. https://doi.org/10.1016/j.jii.2016.09.002.

Gürdür Broo, D., Boman, U., & Törngren, M. (2021). Cyber-physical systems research and education in 2030: Scenarios and strategies. *Journal of Industrial Information Integration, 21,* 100192. https://doi.org/10.1016/j.jii.2020.100192.

Haque, S. A., Aziz, S. M., & Rahman, M. (2014). Review of cyber-physical system in healthcare. *International Journal of Distributed Sensor Networks, 2014,* 1–20. https://doi.org/10.1155/2014/217415.

Hehenberger, P., Vogel-Heuser, B., Bradley, D., Eynard, B., Tomiyama, T., & Achiche, S. (2016). Design, modelling, simulation, and integration of cyber physical systems: Methods and applications. *Computers in Industry, 82,* 273–289. https://doi.org/10.1016/j.compind.2016.05.006.

Hermann, M., Pentek, T., & Otto, B. (2016). Design principles for Industrie 4.0 Scenarios. In *49th Hawaii International Conference on System Sciences (HICSS)* (pp. 3928–3937). IEEE. https://doi.org/10.1109/HICSS.2016.488

Hofer, F. (2018). Architecture, technologies and challenges for cyber-physical systems in industry 4.0: A systematic mapping study. In M. Oivo, D. Méndez, & A. Mockus (Eds.), *Proceedings of the 12th ACM/IEEE International Symposium on Empirical Software Engineering and Measurement* (pp. 1–10). ACM. https://doi.org/10.1145/3239235.3239242

Huang, G., Chen, J., & Khojasteh, Y. (2021). A cyber-physical system deployment based on pull strategies for one-of-a-kind production with limited resources. *Journal of Intelligent Manufacturing, 32*(2), 579–596. https://doi.org/10.1007/s10845-020-01589-8.

Humayed, A., Lin, J., Li, F., & Luo, B. (2017). Cyber-physical systems security—A survey. *IEEE Internet of Things Journal, 4*(6), 1802–1831. https://doi.org/10.1109/JIOT.2017.2703172.

Jacob, E. K. (2004). Classification and categorization: A difference that makes a difference. *Library Trends, 52*(3), 515–540.

Jiang, Y., Yin, S., & Kaynak, O. (2018). Data-driven monitoring and safety control of industrial cyber-physical Systems: Basics and beyond. *IEEE Access, 6,* 47374–47384. https://doi.org/10.1109/ACCESS.2018.2866403.

Khaitan, S. K., & McCalley, J. D. (2014). Design techniques and applications of cyberphysical systems: A survey. *IEEE Systems Journal, 9*(2), 1–16. https://doi.org/10.1109/JSYST.2014.2322503.

Kim, J. H. (2017). A review of cyber-physical system research relevant to the emerging IT trends: Industry 4.0, IoT, Big Data, and cloud computing. *Journal of Industrial Integration and Management, 2*(3), 1750011–1750022. https://doi.org/10.1142/S2424862217500117.

Lasi, H., Fettke, P., Kemper, H. G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering, 6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4.

Lee, E. A. (2006). Cyber-physical systems - are computing foundations adequate? In *NSF Workshop On Cyber-Physical Systems: Research Motivation, Techniques and Roadmap*, 1–9

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters, 3,* 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001.

Lei, Y., Rao, Y., Wu, J., & Lin, C. H. (2020). BIM based cyber-physical systems for intelligent disaster prevention. *Journal of Industrial Information Integration, 20,* 100171. https://doi.org/10.1016/j.jii.2020.100171.

Li, L. (2018). China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0." *Technological Forecasting and Social Change, 135,* 66–74. https://doi.org/10.1016/j.techfore.2017.05.028.

Liao, H., Wang, B., Li, B., & Weyman-Jones, T. (2016). ICT as a general-purpose technology: The productivity of ICT in the United States revisited. *Information Economics & Policy, 36,* 10–25. https://doi.org/10.1016/j.infoecopol.2016.05.001.

Liu, Y., Peng, Y., Wang, B., Yao, S., & Liu, Z. (2017). Review on cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica, 4*(1), 27–40. https://doi.org/10.1109/JAS.2017.7510349.

Lozano, C. V., & Vijayan, K. K. (2020). Literature review on cyber physical systems design. *Procedia Manufacturing, 45*, 295–300. https://doi.org/10.1016/j.promfg.2020.04.020

Lu, C., Saifullah, A., Li, B., Sha, M., Gonzalez, H., Gunatilaka, D., & Chen, Y. (2016). Real-time wireless sensor-actuator networks for industrial cyber-physical systems. *Proceedings of the IEEE, 104*(5), 1013–1024. https://doi.org/10.1109/JPROC.2015.2497161

Lu, Y. (2017). Cyber physical system (CPS)-based Industry 4.0: A survey. *Journal of Industrial Integration and Management, 2*(3), 1750014–1750057. https://doi.org/10.1142/S2424862217500142.

Ma, S., Zhang, Y., Lv, J., Yang, H., & Wu, J. (2019). Energy-cyber-physical system enabled management for energy-intensive manufacturing industries. *Journal of Cleaner Production, 226,* 892–903. https://doi.org/10.1016/j.jclepro.2019.04.134.

Marini, A., & Bianchini, D. (2016). Big Data as a service for monitoring cyber-physical production systems. In T. Claus, F. Herrmann, M. Manitz, & O. Rose (Eds.), *Proceedings, 30th European conference on modelling and simulation ECMS 2016.* European Council for Modelling and Simulation. https://doi.org/10.7148/2016-0579

Mayring, P. (2015). Qualitative content analysis: Theoretical background and procedures. In A. Bikner-Ahsbahs, C. Knipping, & N. Presmeg (Eds.), *Advances in Mathematics Education: Approaches to Qualitative Research in Mathematics Education* (pp. 365–380). Springer. https://doi.org/10.1007/978-94-017-9181-6_13

Meesublak, K., & Klinsukont, T. (2020). A cyber-physical system approach for predictive maintenance. In *IEEE International Conference on Smart Internet of Things (SmartIoT)* (pp. 337–341). IEEE. https://doi.org/10.1109/SmartIoT49966.2020.00061

Monostori, L. (2014). Cyber-physical production systems: Roots, Expectations and R&D Challenges. *Procedia CIRP, 17,* 9–13. https://doi.org/10.1016/j.procir.2014.03.115.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology, 65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005.

Muccini, H., Sharaf, M., & Weyns, D. (2016). Self-adaptation for cyber-physical systems: A systematic literature review. In *11th international symposium on software engineering for adaptive and self-managing systems (SEAMS)* (pp. 75–81). IEEE Computer Society; The Association for Computing Machinery. https://doi.org/10.1145/2897053.2897069

Napoleone, A., Macchi, M., & Pozzetti, A. (2020). A review on the characteristics of cyber-physical systems for the future smart factories. *Journal of Manufacturing Systems, 54,* 305–335. https://doi.org/10.1016/j.jmsy.2020.01.007.

Nickerson, R. C., Varshney, U., & Muntermann, J. (2013). A method for taxonomy development and its application in information systems. *European Journal of Information Systems, 22*(3), 336–359. https://doi.org/10.1057/ejis.2012.26.

Ning, Z., Hou, W., Hu, X., & Gong, X. (2017). A cloud-supported cps approach to control decision of process manufacturing: 3D ONoC. In *13th IEEE Conference on Automation Science and Engineering (CASE)* (pp. 458–463). IEEE. https://doi.org/10.1109/COASE.2017.8256147

Oks, S. J., Fritzsche, A., & Möslein, K. M. (2017). An application map for industrial cyber-physical systems. In S. Jeschke, C. Brecher, H. Song, & D. B. Rawat (Eds.), *Industrial Internet of Things: Cybermanufacturing Systems* (pp. 21–46). Springer International Publishing. https://doi.org/10.1007/978-3-319-42559-7_2

Oks, S. J., Fritzsche, A., & Möslein, K. M. (2018). Engineering industrial cyber-physical systems: An application map based method. *Procedia CIRP, 72,* 456–461. https://doi.org/10.1016/j.procir.2018.03.126.

Oks, S. J., & Jalowski, M. (2020). QuartRevo Industry 4.0 Compendium. https://quartrevo.de/#compendiumAnchor

Pivoto, D. G., de Almeida, L. F., Righi, D. R., Rodrigues, R., Lugli, J. J., & Alberti, A. M. (2021). Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. *Journal of Manufacturing Systems, 58,* 176–192. https://doi.org/10.1016/j.jmsy.2020.11.017.

Rajkumar, R., Lee, I., Sha, L., & Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. In S. Sapatnekar (Ed.), *Proceedings of the 47th Design Automation Conference - DAC '10* (pp. 731–736). ACM Press. https://doi.org/10.1145/1837274.1837461

Rojas, R. A., & Rauch, E. (2019). From a literature review to a conceptual framework of enablers for smart manufacturing control. *The International Journal of Advanced Manufacturing Technology, 104*(1–4), 517–533. https://doi.org/10.1007/s00170-019-03854-4.

Rosenberg, N., & Trajtenberg, M. (2009). A general-purpose technology at work: The Corliss steam engine in the late-nineteenth-century United States. In N. Rosenberg (Ed.), *Studies on Science and the Innovation Process* (pp. 97–135). WORLD SCIENTIFIC. https://doi.org/10.1142/9789814273596_0006

Tao, H., Bhuiyan, M. Z. A., Rahman, M. A., Wang, T., Wu, J., Salih, S. Q., & Hayajneh, T. (2020). TrustData: Trustworthy and secured data collection for event detection in industrial cyber-physical system. *IEEE Transactions on Industrial Informatics, 16*(5), 3311–3321. https://doi.org/10.1109/TII.2019.2950192.

Thoben, K. D., Wiesner, S., & Wuest, T. (2017). "Industrie 4.0" and Smart Manufacturing – A review of research issues and application examples. *International Journal of Automation Technology, 11*(1), 4–16. https://doi.org/10.20965/ijat.2017.p0004.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management, 14*(3), 207–222

Trunzer, E., Wullenweber, A., & Vogel-Heuser, B. (2020). Graphical modeling notation for data collection and analysis architectures in cyber-physical systems of systems. *Journal of Industrial Information Integration, 19,* 100155–100165. https://doi.org/10.1016/j.jii.2020.100155.

Vogel-Heuser, B., & Hess, D. (2016). Guest Editorial Industry 4.0–Prerequisites and Visions. *IEEE Transactions on Automation Science and Engineering, 13*(2), 411–413. https://doi.org/10.1109/TASE.2016.2523639.

Vom Brocke, J., Simons, A., Riemer, K., Niehaves, B., Plattfaut, R., & Cleven, A. (2015). Standing on the shoulders of giants: Challenges and recommendations of literature search in information systems research. *Communications of the Association for Information Systems*, *37*. https://doi.org/10.17705/1CAIS.03709

Wand, Y., & Weber, R. (2004). Reflection: Ontology in information systems. *Journal of Database Management, 15*(2), 3–6.

Wu, X., Goepp, V., & Siadat, A. (2020). Concept and engineering development of cyber physical production systems: a systematic literature review. *The International Journal of Advanced Manufacturing Technology, 111*(1–2), 243–261. https://doi.org/10.1007/s00170-020-06110-2.

Xu, L. D., & Duan, L. (2019). Big data for cyber physical systems in industry 4.0: A survey. *Enterprise Information Systems, 13*(2), 148–169. https://doi.org/10.1080/17517575.2018.1442934.

Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: state of the art and future trends. *International Journal of Production Research, 56*(8), 2941–2962. https://doi.org/10.1080/00207543.2018.1444806.

Zhang, C., Chen, Y., Chen, H., & Chong, D. (2021). Industry 4.0 and its implementation: A review. *Information Systems Frontiers*. https://doi.org/10.1007/s10796-021-10153-5.

Zhang, C., Wang, Z., Ding, K., Chan, F. T., & Ji, W. (2020). An energy-aware cyber physical system for energy: Big data analysis and recessive production anomalies detection in discrete manufacturing workshops. *International Journal of Production Research, 58*(23), 7059–7077. https://doi.org/10.1080/00207543.2020.1748904.

Zhao, W., Jiang, C., Gao, H., Yang, S., & Luo, X. (2021). Blockchain-enabled cyber–physical systems: A review. *IEEE Internet of Things Journal, 8*(6), 4023–4034. https://doi.org/10.1109/JIOT.2020.3014864.

Sascha Julian Oks is a senior researcher at the Chair of Information Systems, Innovation & Value Creation at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). He graduated from Universität Bayreuth and Stellenbosch University with a bachelor's and master's degree in business administration. In the context of the digital transformation of industrial value creation, his research focuses on the engineering and implementation process of industrial cyber-physical systems (CPS). Furthermore, in several Design Science Research (DSR) studies, together with colleagues, he has designed and developed the Industry 4.0 demonstrator "PID4CPS" and complementary web tools to systematically foster the stakeholder-centered design of digitization strategies and artifacts. His work has been published in notable information systems and engineering journals and books as well as in CIRP and IEEE proceedings.

Max Jalowski is a research fellow at the Chair of Information Systems, Innovation & Value Creation at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). He received his doctorate at FAU and prior to that, graduated with a master of science in computer science. His research focuses on digital innovation, designing technologies, persuasive technology, and user behavior in creative processes. He has led and participated in various research projects on human-computer and human-robot interaction, business model development for artificial intelligence-based products and services. His teaching focuses on designing and analyzing innovation technology, cyber-physical systems (CPS), and business model development. His research has been presented at high-ranking international conferences and published in journals and CIRP and LNCS proceedings.

Michael Lechner is a member of the steering committee at the Institute of Manufacturing Technology at Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). He studied technology and management and subsequently obtained a Ph.D. for his investigations on the heat treatment of aluminum sheet materials. His current research focuses on sheet metal forming with a focus on customized material properties and digitization. For his scientific work he has received various grants and awards (e.g., International Karl Kolle Prize).

Stefan Mirschberger is currently working at Deloitte Consulting where he supports clients in process management and digital transformation, especially in the automotive industry. Before that, he was working as a research assistant at the Chair of Information Systems, Innovation & Value Creation at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). His research focuses on cyber-physical systems (CPS).

Marion Merklein is ordinaria of the Institute of Manufacturing Technology at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). Numerous prestigious awards underscore her achievements as a scientist, such as the Heinz Maier-Leibniz Prize of the DFG (2004), the VDI Ring of Honor and the Cramer-Klett Prize, the Otto Kienzle Commemorative Medal of the Scientific Society for Production Engineering (2007), and the Sydney H. Melbourne Award of the American Society of Automotive Engineers (SAE), the American Iron and Steel Institute (AISI) (2009), and the Gottfried Wilhelm Leibniz (2013). Moreover, she is member of numerous different national and international research associations (e.g., CIRP) and the Bavarian Ethics Council.

Birgit Vogel-Heuser is a full professor and director of the Institute of Automation and Information Systems at the Technical University of Munich (TUM). Her main research interests are systems engineering, software engineering, and modeling of distributed and reliable embedded systems. She is core member of TUM's MDSI (Munich Data Science Institute), member of TUM's MIRMI (Munich Institute of Robotics and Machine Intelligence), member of the German Academy of Science and Engineering, chair of the VDI/VDE working group on industrial agents, vice chair of the IFAC TC 3.1 computers in control, and was coordinator of the Collaborative Research Centre (CRC) 768: Managing cycles in innovation processes – integrated development of product-service systems based on technical products.

Kathrin M. Möslein is a professor of information systems with a focus on innovation and value creation at FAU's School of Business, Economics and Society. She is currently president of the European Academy of Management (EURAM), a member of the German Rectors' Conference's Standing Committee on Transfer and Cooperation, a member of the Board of Leipziger Stiftung für Innovation und Technologietransfer, and a research professor and academic director of the Center for Leading Innovation and Cooperation (CLIC) at HHL - Leipzig Graduate School of Management. She has been researching, teaching and consulting in the field of strategic innovation and innovation systems since the early 1990s. Her current research focuses on the implementation of innovation strategies and technologies as well as leadership systems in service organizations.