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ORIGINAL ARTICLE

Concept and engineering development of cyber physical production systems: a systematic literature review

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Abstract
Cyber Physical Systems (CPSs) play a crucial role in the Industry 4.0 paradigm. The application of CPSs in production and manufacturing environments gave rise to the term Cyber Physical Production Systems (CPPSs). There is a growing interest in CPPSs, yet research in this area is scattered and needs to be reviewed for understanding their development status and maturity. The aim of this study is to carry out a systematic literature review (SLR) to analyze the current research activities on CPPSs according to their contributions to the engineering life cycle of such production system. Firstly, a method for SLR is presented. Then, literature analysis of CPPSs is conducted to present research activities in the light of the concept development and engineering development stages. Finally, based on the results of the literature analysis, a concept map of CPPSs research is proposed, which depicts the existing research topics in the engineering life cycle of CPPSs. And we exploit it to propose a research agenda of the CPPSs integration process required to ensure their efficient industrial use. Findings of this review can help researchers to examine the maturity of the development status of CPPSs, to discover which phases require improvement, and to know the future research directions for their industrial practices.

Keywords Cyber physical systems · Cyber physical production systems · Industry 4.0 · Concept development · 5C architecture · Industrial engineering

1 Introduction

Driven by the requirements for highly customized products, increasing product complexity, and shorter product lifecycles, etc., manufacturing industry has experienced a number of major transitions, e.g., from mass production to flexible manufacturing, to computer integrated manufacturing, to lean manufacturing, to e-manufacturing, and eventually moving forward to smart manufacturing and Industry 4.0 era. Industry 4.0 is a "strategic initiative" of the German government that was adopted as part of the High-Tech Strategy 2020 Action Plan. An important component of Industry 4.0 is the fusion of the physical and the virtual worlds, which is made possible in part by Cyber Physical Systems (CPSs) [1]. The concept of CPSs can be applied to different domains [2], and this paper focuses on a specific application of CPSs in the production environment, namely Cyber-Physical Production Systems (CPPSs). CPPSs hold great potential to make production systems become intelligent, resilient, and self-adaptive by utilizing the cyber world to realize the distributed collaboration in the physical world [3].

Although CPSs and CPPSs gain more and more research attention in recent years, they are not entirely new concepts and evolve from e-manufacturing. E-manufacturing is a system methodology that enables the manufacturing operations to successfully integrate with the functional objectives of an enterprise through the use of Internet, tether-free (i.e., wireless, web, etc.) and predictive technologies [4]. E-manufacturing integrates data and information from shop floor assets, suppliers, enterprise information systems, and customers, which increases the opportunities for data

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intensive process such as on-line monitoring and tracing the real-time information [5], and real-time decision-making in quick time. Many researchers developed comprehensive e-manufacturing platforms and systems for data integration. For example, Katchasuwanmanee et al. [6] developed an "e-ProMan" system where a large set of data are acquired from both inside and outside the factory by a "Big Data" approach, in order to analyze the correlation between work flow, data flow, and energy flow to manage the use of energy on shop floors.

Both CPPSs and e-manufacturing systems aim to obtain real-time data and information on the production process so that right decisions are made, products are improved, and customer expectations are met. However, CPPSs cover the characteristics of e-manufacturing and enable higher levels of responsiveness, connectedness, and intelligence. Table 1 provides a comparison between e-manufacturing systems and CPPSs from several aspects (adapted from [7]). Especially, compared with the e-manufacturing which processes data and information by programmable and control-oriented machine learning, CPPSs expand the data source to all fields and process big data by deep learning.

1.1 The definition of CPPSs

As the CPPS is a relatively new term, there is no standard and agreed definition. From the literal meaning, CPPS can be explained as: a Cyber system (C), e.g., digital twin, and a Physical system (P), e.g., a shop floor, in a Production environment (P), connect with each other to form bigger Systems (S). The first detailed description of a CPPS was given by Monostori [8] and has been widely cited and broadly accepted in recent years. As a complement to Monostori's description, Cardin [10] added several missing points, including knowledge management, decision making, and adaptability, and adapted it as follows (the complementary part of Monostori's description has been highlighted in bold):

> CPPSs are **systems of systems** of autonomous and cooperative elements connecting with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks, **enhancing decision-making processes in real-time, response to unforeseen conditions and evolution along time**.

Several conclusions can be reached from these definitions: (i) CPPSs are systems of systems, and hence more than just isolated systems because of the complex interactions among them. (ii) They consist of autonomous and cooperative elements, including physical elements (robots, machine tools, etc.), cyber elements, and human, which can be connected or decoupled dependent on different situations. (iii) The connection between systems impacts on all levels of the production lifecycle from processes to logistics. (iv) CPPSs have adaptability under unforeseen conditions. (v) CPPSs are able to carry out decision making or cognitive tasks autonomously.

The notion of CPPS is very wide [10], and it attracts many different research disciplines, such as industrial engineering, mechanical engineering, manufacturing engineering, automation and control, computer science, electrical and electronic engineering, ergonomics, and business and management. In this paper, CPPSs have been studied from the viewpoint of industrial engineering, which according to the Institute of Industrial Engineers in the USA, is "concerned with the design, improvement, and installation of integrated systems of people, material, equipment, information, and energy to make a product or provide a service". Therefore, industrial engineering, more than any other discipline, is concerned with the developments of CPPSs in an integrated manner.

Table 1 Comparison between e-manufacturing systems and CPPSs (adapted from [7])

	E-manufacturing systems	CPPSs
Objective	Integrate manufacturing operations with the functional objectives of an enterprise [4].	Connect autonomous and cooperative elements in situation dependent ways, on and across all levels of production, to enhance decision-making processes in real-time, response to unforeseen conditions and evolution along time [8].
Main characteristics	Digitization, globalization, mobility, collaborative work, and immediacy [9].	Intelligence, connectedness, responsiveness, highly reconfigurability [8].
Data source	Sensors and controllers and networks	All sources.
Network environment	Web-based and tether-free.	Industrial internet, cloud based, Internet of Things (IoT), service-oriented architecture.
Data/information processing capability	Control-oriented machine learning, expert-depended.	Big data analytics, deep learning.
Generality	Application specific.	Generic and opening to customers
Enabling technology	Networked and remote monitoring	CPS

1.2 An overview of existing reviews on CPPSs

The rapidly growing interest in CPPSs from both academics and industry practitioners has suggested the need for a comprehensive review of CPPSs to provide a general understanding of this emergent research area. Over the last few years, review papers on Industry 4.0 [11], smart manufacturing [12], and their enabling technologies, such as CPSs [13], IoT [14], and cloud computing [15], have emerged. However, the number of literature reviews related to CPPSs is comparatively small. The existing literature reviews on CPPSs have been summarized, as shown in Table 2, with the type of review and their focus.

There are two main approaches to review literature: systematic literature review (SLR) and narrative literature review. SLR uses explicit and rigorous criteria to identify, critically evaluate, and synthesize all the literature on a particular topic, and the effect of data extraction bias can be largely minimized [23]. Narrative literature reviews provide a comprehensive analysis of the current knowledge on a topic but do not describe the methods used for selecting specific sources which may lead to difficulties in data reproduction [23]. Both approaches have been used to review the current status of CPPSs, but SLR is relatively rare, with only 2 such.

Moreover, according to Table 2, most reviews focus on a specific research topic: the root of CPPSs [8], integration approaches in CPPSs [16], international standards and patent portfolios of CPSs in manufacturing [18], monitoring and control of ICPSs [19], programming approaches of ICPSs [20], the classification of CPPSs applications [10], production planning and scheduling in CPPSs [21], and the role of connectivity and control systems in CPPSs [22]. Only two give a more general perspective. Wang et al. [17] outline the characteristics of CPSs, representative examples, and future research directions. Monostori et al. [3] introduce the concept, characteristics, expectations, challenges, and case studies of CPPSs.

Therefore, one can note that existing literature reviews of CPPSs either focus on a specific research topic or on general topics including the concept, characteristics, expectations, challenges, and case studies of CPPSs. However, CPPSs research is scattered and needs to be structured for understanding their maturity and to suggest future research directions for their further development. Indeed, none of the reviews investigated the development status of CPPSs according to their

Table 2 Summary of the existing literature reviews on CPPSs

Reference Authors and year	Review type	Focus of the literature review
Monostori, 2014 [8]	Narrative literature review	Description of the root, expectations and challenges of CPPSs.
Schmidt et al., 2015 [16]	Narrative literature review	Review of the existing integration approaches and integration types in CPPSs.
Wang et al., 2015 [17]	Narrative literature review	Review of the current status and the latest advancements of CPSs in manufacturing, including definitions, characteristics and applications.
Monostori et al., 2016 [3]	Narrative literature review	Review of CPSs in manufacturing from the viewpoint of Manufacturing Science and Technology (MST), including the concept, characteristics, expectations, challenges and case studies.
Trappey et al., 2016 [18]	Systematic literature review	Review of the international standards, and patent portfolios in CPSs.
Jiang et al., 2018 [19]	Narrative literature review	Review of the recent advancements of Industrial Cyber Physical Systems (ICPSs) in monitoring, fault diagnosis and control approaches by data-driven realization.
Atmojo and Vyatkin, 2018 [20]	Narrative literature review	Review of programming approaches for ICPSs and analysis of their capabilities.
Cardin, 2019 [10]	Narrative literature review	Proposition of a framework for classifying CPPSs applications according to several items, including cognitive abilities, application extent, interaction with human operators, distribution of intelligence and network technologies.
Rossit et al., 2019 [21]	Narrative literature review	Review of the most salient contributions on scheduling in CPPSs.
Rojas and Rauch, 2019 [22]	Systematic literature review	Review of the current trends in CPPSs with a special focus on the role of connectivity and control systems in production.

engineering life cycle. It is our interest to contribute with this. In addition, SLR of CPPSs is currently rare, and we decide to apply SLR in our work because it is based on a systematic, replicable, and less biased approach.

1.3 Research objectives and review scope

The aim of this article is to carry out a SLR to investigate the development status of CPPSs according to their engineering life cycle. This review can help researchers to examine the maturity of the development status of CPPSs, to discover which phases require improvement, and to know the future research directions. By doing this, we work out a map to analyze existing works on CPPSs. So, we exploit it to propose a research agenda of the CPPSs integration process required to ensure their efficient industrial use.

According to system engineering principles [24], the life cycle of CPPSs can be divided into 3 broad stages and 8 distinct phases, as shown in Fig. 1. The "Concept development" stage identifies needs for a system, explores potential system concepts, and defines specific system architectures to satisfy users' needs. The "Engineering development" stage validates the use of any unproven technologies, implements the system functional design into hardware and software components, integrates these components into an operating system, and evaluates the system in a realistic operational environment. The "post development" stage includes production, deployment, operation, and support. In this paper, we focus on the concept development and engineering development stages. In the former stage, articles are reviewed according to three phases: needs analysis, concept exploration and concept definition. In the latter stage, we propose to exploit the five levels of the classical 5C architecture for CPSs [25] to review articles, as shown in Fig. 2.

The rest of the paper is structured as follows. Section 2 introduces the research method for conducting a SLR. Section 3 presents a literature analysis of CPPSs based on their three phases in the concept development stage and the 5C architecture in the engineering development stage. A research agenda regarding the integration issues in CPPSs is proposed in Section 4, and finally, the conclusion is summarized in Section 5.

2 Method for systematic literature review

For our SLR, we adopt the framework proposed by Brocke et al. [26] which comprises 5 main steps, as shown in Fig. 3. We detail our SLR process as follows.

Step I: Definition of review scope

Step I is used to define an appropriate scope and flavor of the review. Here, it has been established in the introduction that our research focus is the concept development and engineering development stages within CPPSs from the viewpoint of industrial engineering.

Step II: Conceptualization of topic

Step II defines the keywords used for searching articles. Since the term CPPS means the application of CPSs in manufacturing and production environments, some authors may use the term ICPSs (Industrial Cyber Physical Systems) as well as the combination of "CPSs" and "manufacturing systems/production systems/smart manufacturing/intelligent manufacturing/smart factory" to illustrate the same work within the field of CPPSs. Therefore, three queries were finally identified:

- Query 1: "cyber physical production system*"
- Query 2: "industrial cyber physical system*"
- Query 3: "cyber physical system*" AND ("manufacturing system*" OR "production system*" OR "smart manufacturing" OR "intelligent manufacturing" OR "smart factory")

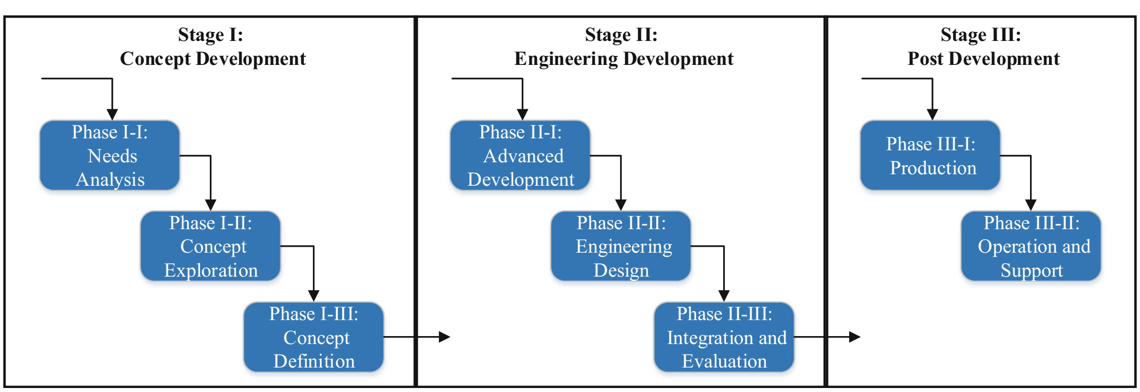

Fig. 1 System life cycle model according to system engineering principles [24]

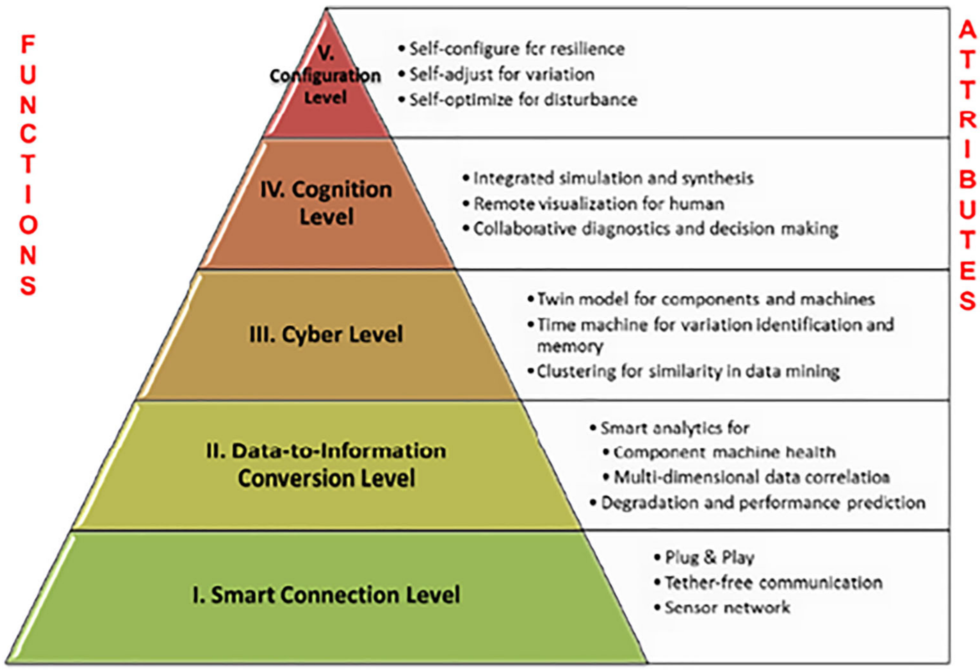

Fig. 2 5C architecture for CPSs [25]

Step III: Literature search

This step involves the search process. It is developed by first going through relevant data sources. To have access to a wide range of academic and conference publications, the ISI Web of Science database was selected. We combined the abovementioned three queries with the Boolean "OR" to search the ISI Web of Science database in "Topic" (equal to "title"+"abstract"+"keyword") until the end of 2019. A limitation to English papers was set because we intended to consider only internationally recognized work. The initial search queries resulted in a total of 1102 papers.

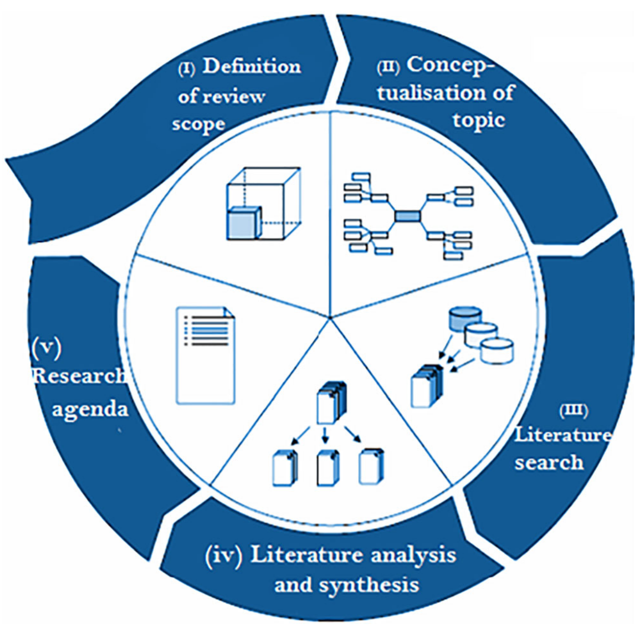

Fig. 3 Framework for literature review [26]

Step IV: Literature analysis and synthesis

We import the 1102 records obtained from Web of Science into Rayyan QCRI (http://rayyan.qcri.org), a free online application that can help researchers working on SLR. Then, we set up explicit exclusion criteria, as shown in Table 3, including five main exclusion criteria, together with their subsets. Once inclusion and exclusion criteria have been outlined, Rayyan can help to expedite the screening work. As Rayyan is a rather simplistic interface, we use it as a platform for labeling papers, making include/exclude decisions, sharing results, and collaborating reviews among co-authors. However, only the abstract/title screening can be performed automatically by Rayyan. The full-text screening has been undertaken using "manual" methods according to the exclusion reasons in Table 3 and checked by co-authors to reduce the subjective judgment. After the full-text screening, a total number of 100 papers were selected for the final literature analysis.

According to the aim and research activities in each phase of life cycle development model (Fig. 1) and the 5C architecture (Fig. 2), we analyzed the contributions of the 100 articles and categorized them into two main categories (concept development, 46 articles, and engineering development category, 54 articles) and eight sub-categories (needs analysis, 3 articles; concept exploration, 17 articles; concept definition, 26 articles; smart connection, 21 articles; data-to-information conversion, 5 articles; cyber, 20 articles; cognition, 6 articles; and configuration, 2 articles). The literature review process is

Table 3 Exclusion criteria

Exclusion criteria	Criteria explanation
Without Full Text (WFT)	There is no access to full texts.
Editorial Material (EM)	Excluding the editorial material as only journal articles and conference articles are included.
Non-Related (NR)	NR1: review articles.
	NR2: The term CPSs is not used in manufacturing and production environments.
	NR3: The term CPSs is only used as the background or future research direction.
	NR4: The term CPSs is only used as a short point of reference or as a collateral research topic.
	NR5: The topic is not related to the three phases in the concept development stage and the 5C levels.
Similar Articles (SA)	If there are two similar articles (one is a journal, the other is a conference) written by the same authors, the conference article is excluded. If there are several similar conference articles written by the same authors, only the most recent one is included and the others are excluded.
Similar Topics (ST)	If there are several articles discussing the same topic, only the article with the highest citations is included.

shown in Fig. 4. It presents a breakdown of each stage, the number of selected articles and reference lists in each category. The corresponding literature analysis will be presented in Section 3.

Step V: Research agenda

Based on the literature analysis, we propose a concept map of CPPSs research in Section 4. This map is exploited to work out a research agenda of the integration process in CPPSs for their industrial use.

3 Literature analysis and synthesis

3.1 Concept development stage

3.1.1 Needs analysis phase

The objective of the needs analysis phase is to show that there are operational needs of the development of a new system or the evolution of an existing system, and those needs can be fulfilled with affordable cost and acceptable level of risk [24].

According to the literature screening results, research in CPPSs pays less attention to the early needs analysis phase and only 3 articles were found for this phase. Firstly, compared to the traditional production systems, the degree of automation in CPPSs increases significantly and the operator's tasks shift to monitoring and supervision of CPPSs. Therefore, new requirements for Human-Machine Interface (HMI) development become increasingly important. Wittenberg [27] analyzed human-CPSs interaction requirements and mainly presented the user-requirements for the usage of mobile devices, such as tablets with augmented reality and an application for data glasses. Secondly, the overall aim of CPPSs is to save costs, increase efficiency, and improve product quality, which requires the development of quality control systems. Albers et al. [28] defined the technical requirements for the quality control system, including requirements to controlled variable, requirements to correcting variable, requirements to controller, and requirements to acquisition of process and product quality data. Thirdly, due to the complexity of CPPSs, the process from modern industry to the successful smart factory should be treated as an evolution and an analysis of the requirements towards implementation of the smart factory is necessary. Odważny et al. [29] analyzed and listed a set of requirements for implementing the smart factory concept, such as the access to technologies and qualified staff, the ability to organize aggregation of data of production process, and the readiness to integration within a company.

3.1.2 Concept exploration phase

The concept exploration phase translates operational requirements into system and subsystem functions, explores a range of feasible architectures, and evaluates the conformity of system concepts with operational objectives [24].

There are several standard architectures that can be adopted as conceptual architectures for CPPSs, such as RAMI 4.0 (Reference Architectural Model Industrial), IIRA (Industrial Internet Reference Architecture), IBM Industry 4.0, and NIST service-oriented smart manufacturing system architecture. RAMI 4.0 [30] and IIRA [31] are two of the most popular and widely recognized architectures. They put the concepts of vertical integration, horizontal integration, end-to-end engineering, and life cycle together and are regarded as promising architectures for CPPSs.

Apart from the standard architectures, many specific architectures of CPPS are also proposed in the literature. These are generally multi-layer architectures. The most widespread one, as mentioned in Section 1.3, is the 5C architecture for CPS proposed by Lee et al. [25]. It consists of five levels, namely, the connection, conversion, cyber, cognition, and configuration levels. Jiang [32] proposed an 8C architecture by adding

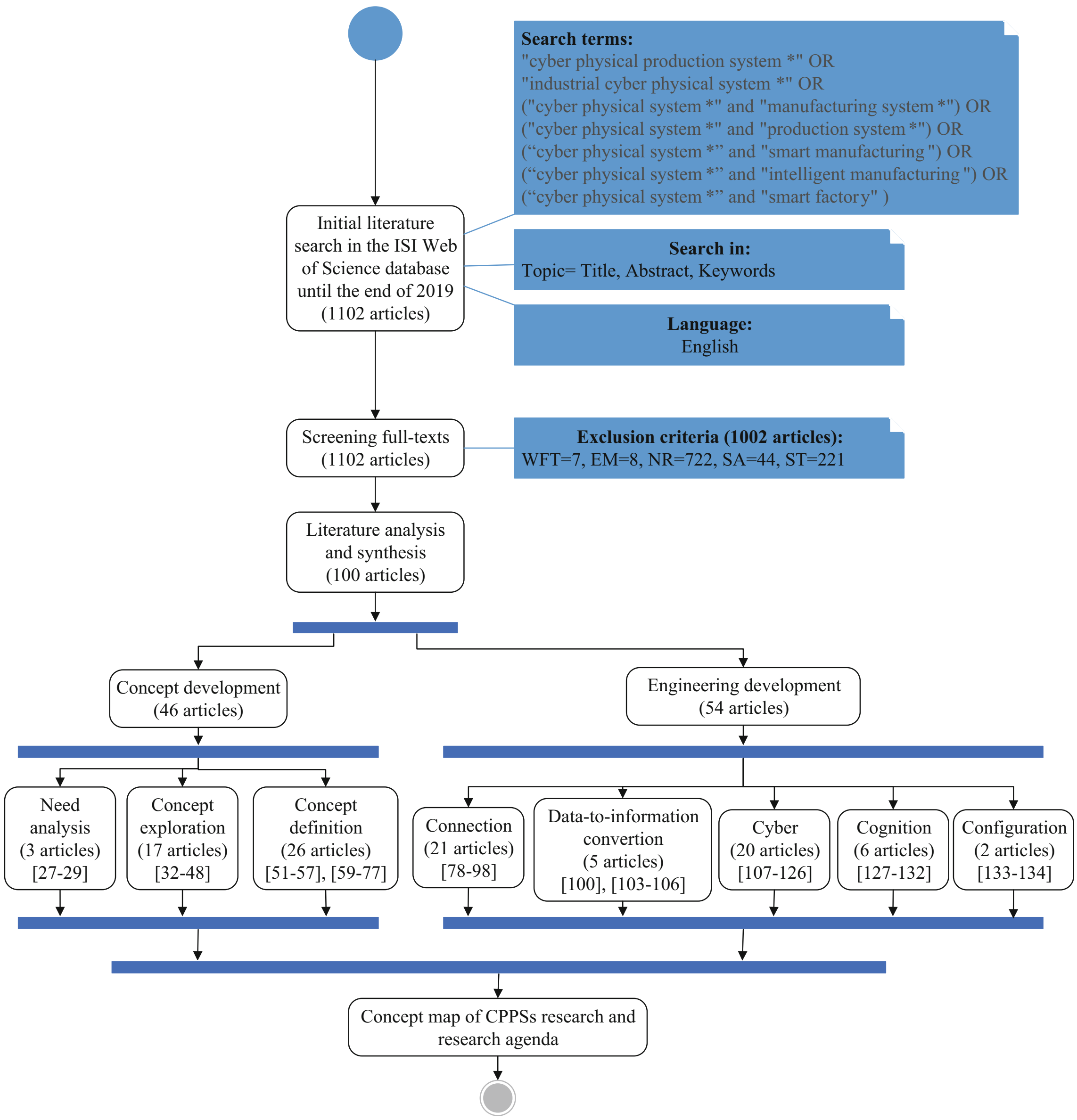

Fig. 4 Literature review process

another 3C (coalition, customer, and content) facets to the 5C architecture to emphasize the horizontal integration. Authors in [33–39] proposed their own multi-layer architectures which basically consist of four layers or a subset of them: a physical layer, a cyber layer, a communication layer, and a cloud layer. The physical layer contains all the physical elements involved in manufacturing systems. The cyber layer is the virtual representation of the physical space. The communication layer establishes the communication technologies between the physical layer and the cyber layer. The cloud layer contains cloud storage, information exchange services, and various software applications. Concerning these multi-layer architectures, we found that the authors did not indicate clearly if these architectures have any mapping to the standard ones, such as RAMI 4.0 and IIRA. As RAMI 4.0 and IIRA are relatively comprehensive architectures covering various critical aspects of Industry 4.0, these specific architectures could be considered to cover a subset of the standard architectures. Therefore, further studies of the mapping relationships are needed.

Some authors proposed architectures which took some specific design concerns of CPPSs into account, the most common being human factors. Pirvu et al. [40] proposed the anthropocentric cyber-physical system architecture that integrates the physical component, the cyber component, and the human component. Humans embody highly developed intelligence, such as understanding, learning, and adapting, and they can provide knowledge for the design of CPPSs' architectures [41]. Moreover, the way CPPSs and humans interact may be different, from the lowest automation (production systems just provide data to humans, who in turn make all the decisions) to full automation (CPPSs make decisions automatically and humans just supervise CPPSs) [42, 43]. The objectives of CPPSs are not removing humans, but to fully interact with humans. Thus, humans should play a much more important role than is the case at the moment, and further investigations of human's position in CPPSs are necessary. Apart from the human-centered design concerns, there are also many other design concerns for architectures, such as big data-centric, fog-enabled, and product-centric concerns. A few notable examples are as follows. Wang et al. [44] proposed a cloud-based and big data-centric framework for the smart factory, which enables transparency to supervisory control and coordinates self-organization process of manufacturing resources to achieve both high flexibility and efficiency. Wu et al. [45] introduced a fog-enabled architecture that enables large-scale, geographically distributed online machine and process monitoring, diagnosis, and prognosis in the context of data-driven CPPSs. Miranda et al. [46] developed a CPPS framework based on Sensing, Smart, and Sustainable Product Development (S^3 Product). Weyer et al. [47] presented a framework for interactions between CPS and multi-disciplinary simulation along the production life-cycle.

After exploring a range of feasible architectures, it is mandatory to evaluate all architectural alternatives of the highly constrained design space defined by the systems operational objectives. The Design Space Exploration (DSE) can be used to offer a set of high-quality implementations from which one or more solutions can be selected for later definition. Bakakeu et al. [48] presented a multi-objective DSE method that takes the hardware architecture of a production system and the data analytics algorithms as input and automatically generates different solutions to efficiently compute data analytics algorithms on the shop floor. This approach allowed users to evaluate architectures during the design phase and to analyze the performance of the resulting system.

3.1.3 Concept definition phase

The aim of the concept definition phase is to select a preferred system configuration, to define functions and interactions of the component levels, to synthesize alternative technological approaches, and to conduct system simulations to confirm that the selected concept meets requirements [24]. The architectures explored in the previous phase can be defined by several manufacturing paradigms including MAS (Multi-Agent Systems), HMS (Holonic Manufacturing Systems), and SOA (Service-Oriented Architectures). As CPPSs are complex, model-driven approaches are also popular for the concept definition. After defining the concept, simulation and validation approaches are necessary to confirm system requirements. These three topics are discussed as follows.

MAS, HMS, and SOA In dynamic manufacturing environments, CPPSs need capabilities to react to disturbances and maintain system stability. These capabilities can be realized by MAS, HMS, and SOA.

The term agent refers to an intelligent entity that can perform tasks autonomously [49]. An agent enjoys very similar properties to a CPPS, characterized by autonomy, flexibility, robustness, and adaptability. Vogel-Heuser et al. [50] identified that the inherent characteristics of agent technologies can provide sufficient means to realize CPPSs. The interaction of multiple agents can form a decentralized system called MAS, a popular architecture for the design of distributed CPPSs. Zhang et al. [51] proposed a CPPS for the manufacturing shop floor based on agent technology. The framework consists of three agents, namely a smart machine agent, a self-organizing agent, and a self-adaptive agent. These can allocate resources according to the production requirements and adjust when exceptions occur. Cruz Salazar et al. [52] gathered, evaluated, and compared more than twenty MAS patterns. From the analysis of design patterns, a CPPS architecture that fulfills requirements related to the RAMI 4.0 was identified. Agents can implement dynamic reconfiguration in a collaborative manner; however, without global coordination, load-unbalance problems may occur due to the different abilities of individual agents. In this context, Li et al. [53] proposed intelligent evaluation and control algorithms to improve load-balance with the assistance of big data feedback. Agent-based technologies have also been used as the implementation support for bio-inspired design principles, such as a bio-inspired self-organizing architecture for shop floors [54] and a bio-inspired self-aware health monitoring architecture for distributed industrial systems[55]. Moreover, MAS is often applied for distributed production planning and control as well as process supervision [56, 57].

HMS refers to a distributed control architecture consisting of a set of autonomous holons. The term holon has dualistic character: it is a part of some bigger whole, but consists of parts [58]. Holons can represent a set of abstract entities in the manufacturing paradigm, including resources, orders, products, and staff. MAS has been widely used as implementing framework for control models in HMS. For example, Woo et al. [59] presented a data analytics platform for manufacturing systems that advances the framework of HMS with the use of agent technology. Although HMS and MAS, as enablers for CPPSs, provide flexibility, autonomous, and adaptability, there are still some limitations. In CPPSs, agents (holons) can negotiate among themselves to cope with unexpected interrupts. As a result, the system becomes more resilient. However, it will also make the system become more complicated and difficult to manage. Therefore, a simple management method to realize interaction is needed.

A SOA offers many benefits such as interoperability, reusability, loose-coupling, and lower complexity [60]. Various

SOAs have been developed and implemented over the past decade, but they were mostly designed for software engineering applications and SOA use in manufacturing is in its infancy. In order to implement a SOA in CPPSs, the manufacturing functions or applications should be encapsulated as standard services and how the services can be discovered, described, orchestrated, and shared should be defined. Dai et al. [61] introduced a knowledge-driven service orchestration engine to achieve semantic context-aware service compositions for flexible data acquisition and reconfiguration. However, interfaces to Information Systems (IS) are yet to be implemented. Lu et al. [62] proposed a smart manufacturing architecture which integrates the entire manufacturing ecosystems, including IT (Information Technologies), OT (Operation Technologies), and supply chain logistic systems, on a single manufacturing service bus. As an extended work, Lu and Ju [63] further proposed a semantic modeling framework for easy development, usage, and dynamic composition of cyber physical manufacturing services. Tao and Qi [64] proposed an IT-driven service-oriented framework for promoting smart manufacturing. Recent research [65] has adopted services in HMS, which gives rise to a new concept: Service-oriented Holonic Manufacturing Systems (SoHMS).

Model-driven design approaches The design of CPPSs is extremely complex due to its heterogeneity and integration scale. However, model-driven design will help to reduce its overall complexity. In this context, model-driven approaches are used for CPPSs by many researchers. For example, Zhang [66] proposed a software-defined approach to model CPPSs based on Modelica Modeling Language (ModelicaML). Kannengiesser and Muller [67] proposed a multi-level method for modeling CPPSs based on semantic web standards.

The general architectures explored in the "concept exploration" phase only gives design guidelines at a high-level point of view. Therefore, they require additional formal techniques to model and specify the components involved in CPPSs. Choi and Kang [68] proposed to implement the 5C architecture using technologies such as PM (Process Mining), DES (Discrete Event Simulation), and VR (Virtual Reality). Contreras et al. [69] proposed to implement RAMI 4.0 using technologies including OPC UA (Object Linking and Embedding (OLE) for Process Control Unified Architecture) protocol, FDI (Field Device Integration) standard, and AutomationML (Automation Markup Language). Pisching et al. [70] proposed a technique derived from petri nets to define components and functionalities of a production system according to the RAMI 4.0 architecture.

The top layers of RAMI 4.0, the "business" and "functional" layers, are expected to provide standard runtimes for executable business processes in the connected world [71]. Some work related to these two layers has already been conducted. Suri et al. [72] proposed a model-based approach to design business strategies and the corresponding operational processes using the Business Motivation Model (BMM) and Business Process Modeling and Notation (BPMN). Neubauer et al. [73] proposed a Subject-oriented Process Management (S-BPM) approach to integrate business and production processes across organizational control layers. Rudtsch et al. [74] proposed a methodology for the pattern-based development and realization of business models in CPS.

Simulation and validation Simulation is important for getting an insight into CPPSs and for analyzing their behaviors under various situations. There are essentially two commonly used simulation approaches for CPPSs.

The first is the co-simulation approach, which can realize the global simulation of a coupled system by the composition of simulators. In co-simulation, the modeling is done in a distributed manner on subsystems without having the coupled system in mind [75]. The need for co-simulation of CPPSs arises as CPPSs are systems of systems and each subsystem pertains to a specialized domain. Using co-simulation, each subsystem within a larger system is simulated independently using the most suitable technique. For example, co-simulations approaches for CPPSs were presented by Neghina et al. [75] and Havard et al. [76].

The second approach is agent-based simulation, a promising method for simulating characteristics of complex CPPSs. For example, Novák et al. [77] used a multi agent paradigm to simulate CPPSs, which simplifies synchronization and improves the stability of simulations.

3.2 Engineering development stage—5C architecture

The concept development stage is the initial stage of the formulation and definition of a system concept, while the engineering development stage translates the system concept into a validated physical system design. The 5C architecture, in which the technologies are developed and validated, software and hardware subsystems are engineered, and the total system is integrated in an operational environment, is used to detail the tasks in the engineering development stage. The research focus at each level is illustrated as follows.

3.2.1 Smart connection level

This level achieves integration between different elements in the physical space such as sensors, controllers and machine tools. Liu et al. [78] implemented an application of vertical integration of various systems including machine tools, robots, AGVs, air-move systems, and storage systems. Ding and Jiang [79] presented a hardware-software integrated platform for production interactions among stakeholders. Suri et al. [80] proposed a model-based approach for modular system integrations.

Because of the added connectivity in CPPSs, all devices in the production network may suffer from potential external attacks. Vargas Martínez and Vogel-Heuser [81] addressed this issue by introducing a reactive protection concept. Etz et al. [82] designed an integrated safety architecture that enables safety communication in heterogeneous production lines. Yin et al. [83] introduced blockchain technology to ensure machine-to-machine communications in CPPSs. Toublanc et al. [84] proposed a demonstrator for security on sensor/actuator network in industrial applications.

Appropriate communication protocols and standards play an important role in the integration of CPPSs. Therefore, much work has been done concerning this issue, including the OPC UA protocol for vertical interoperability [85], ethernet standard enabled real-time processing for factory networks [86], MQ Telemetry Transport (MQTT) protocol for real-time data monitoring and controlling [87], IO-Link standard for factory automation communication [88], AutomationML standard for data exchange [89], oneM2M standard for semantic interoperability [90], Low Power Wide Area Network (LPWAN) applied to the sensor network for data transmission [91], a middleware for data aggregation between shop floor and IS [92], and a CPPS gateway for integrating high availability communication interfaces [93].

Since different elements in CPPSs are able to generate enormous amounts of data about the ongoing production processes, big data acquisition and storage approaches are required. Marini and Bianchini [94] described a data-as-a-service approach to deal with big data storage. Silva et al. [95] presented a sensor integration solution that allows for automatic data acquisition. Dai et al. [96] adopted a service-oriented data acquisition approach. Ding et al. [97] proposed a Radio Frequency Identification (RFID)-enabled manufacturing system to collect real-time production and transportation data. In order to achieve reliable and accurate data acquisition, Deng et al. [98] proposed data cleansing algorithms for energy-saving.

3.2.2 Data-to-information conversion level

With the increasing connections of systems, enormous amounts of data will be constantly generated. Considering an increasing amount and complexity of data, appropriate tools and methodologies, such as data processing, big data analysis, and data mining, are required to extract information [99, 100]. Different types of data analysis methods, including clustering, decision trees, and Bayesian statistics, were reviewed by Xu and Duan [101].

Regardless as to how data is processed, the era of big data enables enterprises to make effective use of data, realize a data-driven strategy, and enhance the value of data. In this way, the competitiveness of enterprises improves significantly. Data-driven manufacturing has attracted extensive research efforts and provides a full range of value-added services to enterprises, including smart design, smart planning and process optimization, material distribution and tracking, manufacturing process monitoring, product quality control, and smart equipment maintenance [102]. Some examples are as follows: Wan et al. [103] implemented a manufacturing big data solution for active preventive maintenance. Niggemann et al. [104] outlined a data-driven approach to extract the most relevant information for anomaly detection and diagnosis. Kißkalt et al. [105] described a machine learning approach for data-driven process and condition monitoring systems. Lee et al. [106] implemented a CPPS to predict the quality of metal casting by several machine learning algorithms such as decision trees, random forest, artificial neural networks, and support vector machines.

3.2.3 Cyber level

This level is a central information hub, which aggregates all the information from various sources to form a cyber space [25]. Some researchers noticed the importance of resource sharing and management, and a series of such research topics have been proposed, such as resource sharing [107] as well as resource definition, matching, and management [108–110].

Having massive amounts of information gathered, specific analytics have to be used to extract additional information [25]. For example, the self-comparative information of machine is available for evolution. Haubeck et al. [111] proposed to enhance evolution on the cyber level of CPPSs by using inherent experience of machines that were augmented by additional experience of similar machines at potentially remote locations.

Due to the increasing connectivity to external networks, CPPSs are easily targeted by cyber-attacks. Therefore, the cyber security of CPPSs is an important research topic. Security techniques can be grouped into (i) monitoring and detecting, for example, a cross-layer anomaly detection approach by fusing evidence from a wide range of monitored parameters was presented by Sandor et al. [112], and (ii) defense techniques, for example, Khalid et al. [113] proposed a security mechanism based on a two-pronged strategy for a collaborative robotic cyber-physical system.

The digital twin, which builds the link between the physical and cyber worlds, is a very important research focus. Many researchers studied the technologies, tools, and approaches for realizing digital twins, such as cloud computing technologies [114], virtual engineering tools [115], multi-modal data acquisition approaches [116], resource virtualization technologies [117], open source approaches [118], and a digital twin-based CPPS frameworks [119]. The benefits of digital twins of real-time data acquisition and the subsequent simulation-based data processing were demonstrated by Uhlemann et al. [120]. Digital twins cover all life cycle activities and processes from design, production, utilization to service [121]. Therefore, a specific digital twin application can be assigned to multiple purposes:

- Design, simulation, and verification: Liu et al. [122] presented a digital twin-driven methodology for rapid individualized designing of manufacturing systems and discussed how the digital twin applied in simulating and verifying the properties and system behaviors.
- Production Planning and Control (PPC): Kück et al. [123] proposed a digital twin-driven simulation based approach for the adaptive scheduling and control of dynamic manufacturing systems. In addition, an approach for developing a human digital twin, which takes part in decentralized production planning and control, was described by Graessler and Poehler [124].
- Monitoring and prediction: digital twins can be used for continuous monitoring to discover undesirable situations in a proactive manner and to predict outcomes based on real-time data [125].
- Managing and optimization: in the design phase, digital twins can be used to optimize design Fs and improve design models. In the production phase, the whole manufacturing process can be controlled in real time and optimized by digital twins [126].

Existing digital twin applications are mainly developed for simulation, anomalies monitoring, and prediction purposes, and very few of them take autonomous feedback control from a cyber object to a physical object into account. Real digital twins should have both physical-to-cyber data exchange and cyber-to-physical data exchange. Therefore, more research efforts should be made to implement bidirectional automated data exchange between physical objects and cyber objects.

3.2.4 Cognition level

Since abundant information is available, the cognition level can generate comprehensive knowledge of CPPSs [25]. Appropriate presentation tools are needed to transfer knowledge to users. Zinnikus et al. [127] presented a 3D visualization tool to help humans repair occurring faults. Fischer et al. [128] presented a speech interaction system that provides maintenance information for workers over wireless headphones and a microphone. Constantinescu et al. [129] presented human-system interfaces to proactively provide the required information at the right time based on the users' context during the modeling and simulation activity.

To support correct and efficient decision making, relevant knowledge should be provided to humans depending on the current context. Hoos et al. [130] addressed this problem by introducing the concept of a decision packet that enables operators to find problem solving knowledge. Rahm et al. [131] provided a self-learning assistance system for operators, technicians, and maintenance teams to enhance their fault diagnosis and correction capabilities. Galaske and Anderi [132] presented a simulation-based decision support for the disruption management process in a resilient CPPS. By evaluating each disruption event scenario, the best strategy, including the expected impact on production processes, will be recommended to decision-makers.

3.2.5 Configuration level

In this level, the decisions made at the cognition level will be applied to the physical space [25]. This can achieve resilience control and adjustment, especially the self-X properties, where X is a placeholder for "one or more desirable properties of a system subjected to a variable operation condition", such as self-adjustment, self-configuration, and self-optimization, in response to external environmental changes. For example, Grundstein et al. [133] presented an Autonomous Production Control method (APC) for manufacturing processes, which acted autonomously and kept the resilience of CPPSs. Scholze and Barata [134] presented a context awareness approach for self-optimization of flexible manufacturing processes.

This level has the highest requirements of self-X capabilities. Research efforts towards this level are relatively rare. Moreover, the total integration of these 5 levels in CPPSs does not exist currently within the scope of the author's knowledge.

4 Concept map of CPPS research and research agenda

Based on the results of the literature analysis, we propose a concept map, as shown in Fig. 5. It gives a holistic perspective on the research topics of CPPSs in the concept development and engineering development stages. Findings of this review can help researchers to examine the maturity of the development status of CPPSs and to discover which phases require improvement.

Currently, research on the concept and engineering development of CPPSs focuses on the concept definition, technology validation, and prototype test in a lab level. The objective of CPPSs applications is to reach the industrial application level. However, the application of CPPSs in industrial practices is still in its infancy. One of the main obstacles is the integration approaches in CPPSs. Therefore, this section proposes future research directions of CPPSs on the 8 categories we set up in Section 3, with a special focus on the integration issues.

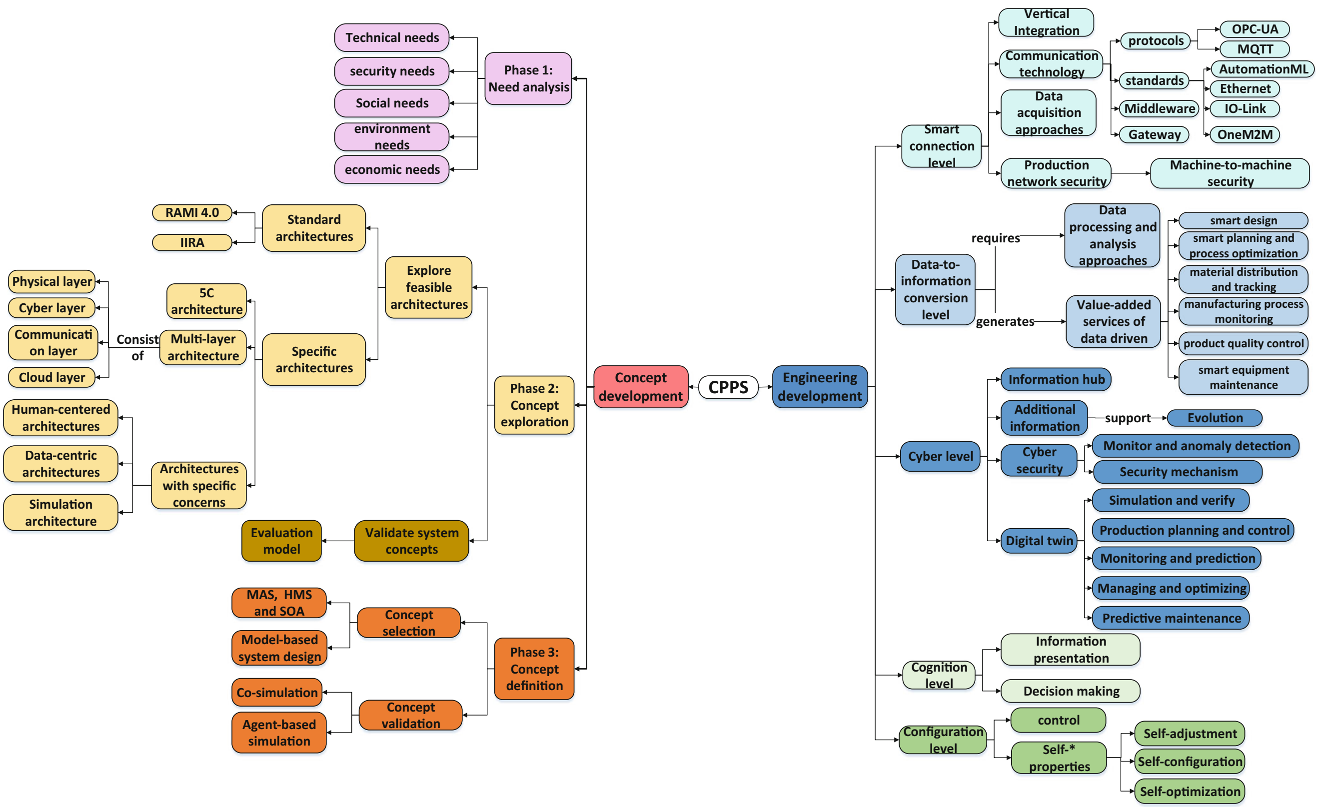

Fig. 5 A concept map of CPPSs research topics

4.1 Concept development stage

During the concept development stage, different communities (e.g., mechanical engineers, electrical engineers, software engineers) develop CPPSs' concept from their specific domain knowledge. Therefore, specified interactions and interfaces between various disciplines and involved components for mutual communication understanding are needed. This gives rise to the issue of the multidisciplinary integration in CPPSs. In the concept development stage, we propose future research directions regarding the issue of multidisciplinary integration in CPPSs as follows.

4.1.1 Need analysis phase

Research on the "needs analysis" phase is relatively rare and focuses mainly on technical needs. In the future, many other needs should also be considered, such as performance needs, environmental needs, legal needs, and economic needs. Some existing reviews and guidelines for requirements engineering (RE) could be potential solutions. For example, Weidmann et al. [135] reviewed the methods of RE in mechatronics in the following four steps: elicitation, documentation, structuring and consolidation, and managing. Fritz et al. [136] proposed a guideline for the RE process of small- and medium-sized enterprises (SMEs) regarding the CPSs. Moreover, the multidisciplinary collaboration creates new challenges for needs analysis as the complexity of systems leaves needs fragmented among different disciplines and sometimes the needs are conflict, unstable, or not fully defined. Therefore, in future work, a way has to be found for the collaborative and consistent description of needs between different stakeholders, as well as their validation and evolution. This could be addressed by a common standard or natural language, such as natural language processing [137] and model-based graphic language [138]. In this way, domain barriers can be greatly reduced or fully removed.

4.1.2 Concept exploration phase

In the "concept exploration" phase, many specific architectures for CPPSs are proposed, but integrated design architectures need to be investigated in which the designers take all engineering disciplines into consideration simultaneously. The RAMI 4.0 provides such a holistic view for all the important aspects that are needed by different stakeholders. It combines three core dimensions in a cuboidal space, covering the whole life cycle from development to disposal and resource recovery and multiple layer integration from asset to business as well as the connection from products to the IoT and services. But RAMI 4.0 only provides general guidelines on a high-level point of view, without any specific development approaches. Each production system requires a different and specific architecture according to their specific requirements. In order that the research community does not confuse themselves and users by multiple architectures, they need to build their specific architectures based on RAMI 4.0 and give the mapping relationships between them.

4.1.3 Concept definition phase

In the "concept definition" phase, many studies have instantiated the general architectures according to some specific technologies, and the most popular being MAS, HMS, and SOA. However, one can note that these technologies have already been developed in the past decades and addressed the same objectives as CPPSs. The novelty of CPPSs lies not in establishing new technologies but in combining existing technologies, such as MAS, SOA, IoT, cloud computing, and big data. Therefore, the future research focus is to connect the dots between the existing isolated technologies as they are not consistently aggregated, which requires a multidisciplinary system integration that across lifecycle phases.

4.2 Engineering development stage

In the engineering development stage of CPPSs, manufacturing technologies, ICT technologies, system devices, data, processes, and subsystems should be integrated together in an operating environment. The existing work we reviewed has addressed some integration issues such as device integration [78], system integration [80], and data integration [89]. However, the full integration of Enterprise Information Systems (EISs) in CPPS has not been addressed yet. As EISs can make effective decisions, improve the business processes, and make the enterprise more competitive, the integration of EISs in CPPSs is one of the main issues that make production systems to be self-configured, self-adjusted, and self-optimized.

The integration of EISs in CPPSs can be analyzed from three dimensions: (1) an informational integration, which deals with the exchange of data and information between EISs software packages and CPPSs components; (2) a technological integration, which uses interoperability technologies or interfaces provided by EISs to perform collecting, storing, and processing data in CPPSs; (3) an organizational integration which deals with the way CPPSs impact business and decision-making processes supported by EISs. The organizational integration is a new perspective for CPPSs as it concerns the impacts of CPPSs on organization and business processes. The informational and technological links need to be implemented first to ensure the operation of CPPSs, and then, if we want CPPSs to operate efficiently and autonomously, the organizational link need to be implemented. Since the term CPPS has high Information and Communication Technology (ICT) connotation, the informational and technological dimension integrations have, to some extent, been addressed in CPPSs research. However, the organizational integration, perhaps the most complex and challenging, has not been studied in literature yet. Therefore, we propose the following research directions for these three dimensions of integration at each level of the 5C architecture.

4.2.1 Smart connection level

This level mainly concerns the technological integration. The diversity of systems and communication technologies is the reason for the high complexity and configuration difficulties of integrating EISs and CPPSs. Therefore, standardization and semantic interoperability could be useful to improve the integration issue. Besides, up to now, the implementation of CPPSs at this level is mainly at the component level and plant level. The connection across organizational level has not been fully implemented and more factors need to be considered, especially the social aspects (e.g., data sharing principles among different enterprises).

4.2.2 Data-to-information conversion level

This level mainly concerns the informational integration. Concerning the branch of the data processing and analysis approaches in the concept map, there are lots of methods. But what useful data from CPPSs can be integrated effectively into EIS has not been addressed and need to be investigated in future work. While all data can be easily retrieved thanks to the ICT capabilities of CPPSs, this indeed makes no sense because only useful data that can support the business processes and contribute to the overall performance of the organization should be retrieved. As we already have all heterogeneous data, ontologies could be used to define the relationships between data and impacted business processes.

4.2.3 Cyber level

This level mainly concerns the informational and technological integration. As the cyber level is a central information hub that gathers all information from various sources, it provides EISs with access to additional information that has not been available previously. One future direction concerning the branch of the additional information in the concept map is to investigate how to extract additional information to improve the EISs in terms of business processes and its evolution. Knowledge-based modeling and methods of reasoning could be used to extract information that are useful for EISs.

4.2.4 Cognition level

This level covers all three dimensions of integration. Concerning the branch of decision making in the concept map, one future direction of the organizational integration is to figure out how to decentralize part of the decisions that are currently made in the EISs field to CPPSs' components (such as smart machines and smart products). This decentralization could ensure that decisions can be made at the right level quickly. The start point could be to investigate the intelligence of CPPSs' components, the necessary functions of EISs, which decisions can be automatically run by CPPSs, and which decisions have to be made in EISs.

4.2.5 Configuration level

This level covers all three dimensions of integration. Concerning the branch of self-configuration, one conceivable research direction of the organizational integration is to implement the dynamic reconfigurability between CPPSs and EISs. The reconfigurability is twofold: on the one hand, if the configuration of CPPSs (e.g., the layout of CPPSs) changes, the organization and business processes will be changed automatically. On the other hand, if new functionalities of EISs are needed, CPPSs can configure themselves automatically to meet these new requirements. The digital twin could be a solution to implement such dynamic reconfigurability as the change of state of the physical object will have impacts on the state of the cyber object automatically and vice versa in digital twins. But as the best of our knowledge, there is no study about dynamic reconfigurability between CPPSs and EISs through digital twins.

5 Conclusion

We have reviewed the academic progress of CPPSs in their concept and engineering development stages, using a SLR method. Firstly, 100 papers until the end of 2019 were selected and categorized into 8 categories: needs analysis, concept exploration, concept definition, connection level, data-to-information conversion, cyber, cognition, and configuration. Then, a literature analysis was conducted to present research topics and approaches in each category. Finally, a concept map of existing research topics on CPPSs and future research directions on these 8 categories in the concept map was proposed with a special focus on the integration issues. Limitations of the paper result from its scope and the applied review method. First, papers were only collected from the multidisciplinary database ISI Web of Science. Second, because of the search criteria restricted to only conference and journal articles, existing researches published in books or reports were excluded. From a completeness point of view, this review could be more comprehensive if more databases, books, reports, and other relevant publications could be taken into account.

In conclusion, despite some limitations, this literature review has reported the current status of CPPSs in their concept and engineering development stages and proposed future research directions regarding the integration issues. Findings of this review not only help researchers to examine the maturity of the development status of CPPSs, but also point out the future research directions for their industrial practices from the perspective of industrial engineering.

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Compliance with ethical standards

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