# Cyber Physical Production Systems: A Review of Design and Implementation Approaches

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*Abstract* - **Cyber Physical System (CPS) is a very crucial and promising technology in Industry 4.0 context. The application of CPS in the production and manufacturing environment gave rise to the term 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. There is growing interest in CPPSs, yet there is a scarcity of review to document the current status of CPPSs. This review aims to classify the current research activities within CPPSs field with a special focus on design and implementation approaches in view of industrial engineering and to analyze research gaps based on the literature review. Findings of this review can be used as the basis for future research in CPPSs and related topics.**

*Keywords* – **Cyber physical production systems, design approach, implementation approach, industrial engineering, 5C architecture**

## I. INTRODUCTION

The manufacturing industry is facing well-known trends, such as highly customized products, increasing product complexity and shorter product lifecycles. Industry 4.0 and smart factory as the most widespread industrial paradigms, appear on the scene. Industry 4.0 is a general term that includes a series of different technologies, with the Cyber-Physical Systems (CPS) as the core technology [1]. Smart factories utilize the CPS technology to monitor the physical world and make decentralized decisions in the virtual world [2]. Therefore, we can note that the common enabler behind Industry 4.0 and the smart factory is actually the CPS. There are many different definitions of CPS depending on the application scenario. The core idea of CPS is the fusion of the real world and the virtual world by implementing the interaction between physical components and cyber components in distributed networks. CPS have been applied in many fields such as the civil infrastructure the healthcare, the smart home, and so on [3]. This paper focuses on the specific application of CPS in the production environment, namely Cyber-Physical Production Systems (CPPSs).

Fig. 1 shows the change of the number of journal articles and conference articles within the CPPSs field until the end of 2018 in the ISI Web of Science which is one of the most extensive citation databases that includes various publishing houses such as Elsevier, Springer, and IEEE. Considering some authors may use the term CPS and "manufacturing/production systems" to illustrate the research work within the CPPSs field. We set up our bibliographical research using three topics "cyber physical system(s) AND manufacturing systems" OR "cyber physical system(s) AND production systems" OR "cyber physical production system(s)". we note that the research work on CPPSs in literature starts from 2012. The total number of articles, the number of conference articles and journal articles are distinguished by the red solid line, black round dotted line and green dashed line. For the total number of articles, a rapid growth can be noticed from 2012 to 2017. There is a slight decline in 2018 because the journal articles have not been fully published. What is even more remarkable is that the number of journal articles has increased significantly in the last few years. The aim of this figure is to show that the CPPS has been widely studied in literature and the research trend is expected to increase in the upcoming years.

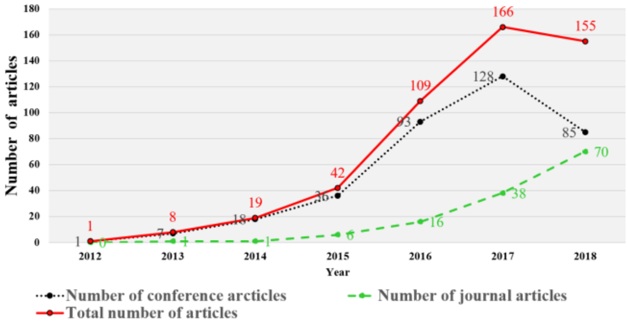

Fig. 1. Distribution of articles per year

As CPPSs is a relatively new term, there is no standard and agreed definition. Most of the researchers just simply describe the concept of CPPSs as the application of CPS in the manufacturing and production field. The most cited, detailed explanation of this concept was given by [4]: "*CPPSs consist of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks*". In this definition, we can conclude several points: (i) CPPSs are systems of systems, more than just isolated systems because of complex interactions among them; (ii) These systems includes autonomous and cooperative elements and can be connected or decoupled according to different situation, which means the subsystems are independent and reconfigurable; (iii) The connection between systems impacts all levels of production lifecycle from manufacturing to logistics. However, in this definition, two important concepts are missing: knowledge management and human resources. On the one hand, knowledge is key for decision making and an automated continuous improvement of CPPSs' operations. On the other hand, although CPPSs can work in an automatic way, humans should have a central and key role instead of being replaced by technologies because humans are the most flexible one who can handle exceptional situations and control the systems when needed. The following definition, suggested by [5], emphasized the missing points: "*A CPPS is a composition of human resources, production equipment and aggregated products towards which it establishes one or several cyber-physically formulated interaction interfaces. These interfaces are used for monitoring and control of the CPPS operations as well as to tap into the knowledge generated both by the human resources, and the equipment, during the production process as well as knowledge generated by its aggregated products throughout their life-cycle*." These two definitions complement each other and cover various aspects of CPPSs.

The notion of CPPSs is very wide and aggregate many different research disciplines. Its development can be categorized into three distinct communities in parallel: (i) The industrial engineering community, mainly focuses on CPPSs engineering and implementation approaches, by adopting systems engineering methods. (ii) The computer science community, mainly concentrates on information technology and development methods of software systems. (iii) The electrical engineering community, mainly focuses on hardware in CPPSs, such as sensors. In this paper, we study CPPSs in view of industrial engineering.

CPPSs can be regarded as a significant evolution in the manufacturing and production systems. The challenge in the future is to prove the advantages CPPSs bring to the industry. Therefore, it is important to develop approaches for the design and implementation of CPPSs. Many methods on specific technical issues emerge in recent years. However, as far as we know, there is a lack of efforts to review the design and implementation approaches of CPPSs. The rapidly growing interest from both academics and practitioners in CPPSs has urged such need to help newcomers have a general understanding of this emergent research area and therefore choose the proper approaches in future studies. Therefore, the purpose of this paper is to review the design and implementation approaches of CPPSs in literature and to analyze research gaps.

## II. REVIEW OF CPPS DESIGN AND IMPLEMENTATION APPROACHES

After reading the journal articles we found in section I, classifications for CPPSs design and implementation approaches were set up manually instead of automatically by some tools. Within the scope of this paper, it is not possible to integrate all the articles. Therefore, our study exhibits some representative articles to explain the classifications and show the current developments available in literature.

### *A. CPPSs design approaches*

The design of CPPS is extremely challenging due to the involvement of multiple fields and the complex interactions in distributed environments. In this regard, modelling & simulation approaches are the most popular and useful ones for CPPSs design. We identify four modelling approaches as follows.

#### 1) *Architecture-based modelling approaches*

In view of industrial engineering, an architecture should address the organizational structure of a system including its design principles, components and relationships. There are some established architectures and standards that can be used as the references for the conceptual design of CPPSs. The Reference Architectural Model Industrial (RAMI 4.0) and the Industrial Internet Reference Architecture (IIRA) are two of the most popular and widely recognized architectures.

The RAMI 4.0 [6] describes the connection between IT, manufacturers/plants and product life cycle by using a layer model (including three axes: the layer axis, value stream axis, and hierarchy axis). It formalizes manufacturing resources as 'Industry 4.0 component' [7] which comprises asset and Asset Administration Shell (AAS). The asset can be anything in the physical world, e.g. a sensor. The AAS is the mapping of assets to the virtual world and illustrates its functionalities. With reference to the RAMI 4.0, a multi-level method for modelling CPPSs was proposed in [8], where RAMI 4.0 was used on the meta-model level, the model level, and the instance level to form a concrete CPPS. This contributed to the lifecycle management.

The IIRA [9] is a standard architecture of designing Industrial Internet Systems (IIS), which is developed by the industrial internet consortium. With reference to the IIRA function viewpoint, a three-tier architecture that includes the edge, platform and enterprise tier was presented, as in [10].

RAMI 4.0 and IIRA synthesize the three kinds of integrations (vertical integration, horizontal integration and end-to-end integration), and also consider the whole life cycle, which refer to as promising architectures for CPPSs. However, they are not sufficient architectures because they did not address how humans interacted with CPPSs.

#### 2) *Agent-based modelling & simulation approaches*

The term agent refers to an intelligent entity that can perform tasks autonomously [11]. An agent enjoys very similar properties with a CPPS, which is characterized by autonomy, flexibility, robustness, adaptability and so on. Thus, the agent-based modelling & simulation approaches can be seen as a very promising means for simulating characteristics of complex CPPSs. For example, a simulation approach was presented in [12] that evaluated the self-organizing potential of CPPSs.

The interaction of multiple agents can form decentralized systems, called Multi Agent Systems (MAS), which is a popular architecture for the design of distributed CPPSs [13]. A MAS is are often applied for distributed production planning and control of CPPSs, as in [14], [15]. Although MAS brings many benefits, there are still some limitations. In the CPPSs, each resource (such as machines) represents an intelligent agent, and these agents can negotiate among themselves to cope with unexpected interrupts, so as to make the system more resilient. But it will also make the system become complicated, which will be difficult to be managed. therefore, a simple management method to realize interaction is needed.

#### 3) *Human-centered modelling approaches*

Nowadays, more and more researchers start to discover the importance of humans and they acknowledge humans should be central elements in CPPSs. Reference [16] presented an anthropocentric cyber-physical reference model that consisted of a physical component, cyber component and human component where the human was an element that affected the behaviors of the system throughout its whole life cycle. Moreover, humans embody the highly developed intelligence, such as understanding, learning and adapting, that can provide design knowledge for CPPSs, as explained in [17], [18]. In the CPPS paradigm, human tasks will be different. Workers will face plentiful computerized interfaces, make more complex decisions and coordinate the autonomous production. Collectively, the human work tasks, work areas and interaction ways with machines will be different. The objectives of CPPSs is not removing humans, but to fully involving humans by using their intelligence.

#### 4) *Modelling for integration approaches of specific design concerns*

There are some modeling approaches that enable to integrate into the design of CPPSs' specific concerns such as process management, business strategies, different engineering stages, co-simulation and so on. One such example was provided by [19], that depicted the Subject-oriented Process Management (S-BPM) approach for vertical integration of the business and production processes.

### B. *CPPSs Implementation Approaches*

The 5C architecture of CPS, proposed by [2], provided a guideline for implementing CPSs from the initial data acquisition, to information gathered, to the final system control, and it can be extended to CPPSs. As shown in Fig. 2, it includes five levels: smart connection level, data-to-information conversion level, cyber level, cognition level and configuration level. The smart connection level (level I) is the physical world, levels II–IV are the cyber world, while the configuration level (level V) is the feedback from the cyber world to the physical world. We categorize the CPPSs implementation approaches through the lens of 5C levels.

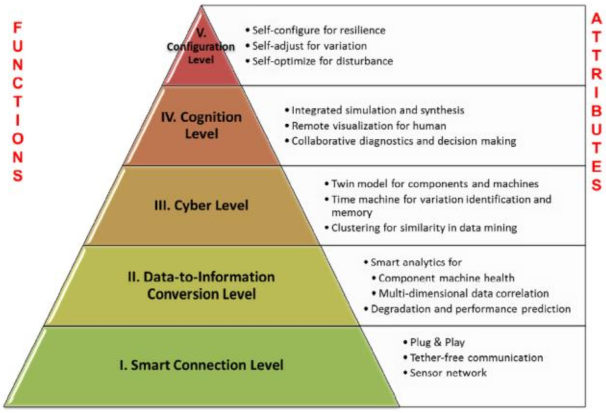

Fig. 2. 5C architecture for implementation of CPSs [2]

#### 1) *Smart Connection Level*

This level achieves integrations between different elements in the physical space such as sensors, controllers and machine tools.

There are two important factors in this level to improve the implementation of CPPSs. First, the communication in CPPSs demands standard protocols, interfaces and information model, such as the IEC 61499 standard. An example was presented in [20], that establishes communication with different elements by integrating different interfaces and connections to sensors and actuators. Second, since different elements in CPPSs are able to generate huge amounts of data about the ongoing production processes, data acquisition approaches [21] and data cleansing algorithms [22] are research topics.

#### 2) *Data-to-Information Conversion Level*

This level converts data to meaningful information. Considering an increasing amount and complexity of data, tools and methodologies such as data processing [23], big data analysis [24] and data mining approaches are proposed to get the valuable information.

#### 3) *Cyber Level*

This level is a central information hub, which aggregate all the information from various sources to form a cyber space. Some researchers noticed the importance of collaborative manufacturing network. One example was given by [25], presenting an intelligent collaborative platform to manage the production network. With the current trend of increased connectivity to external networks, CPPSs are increasingly targeted by cyber-attacks. Therefore, the cyber security is another important research area. On the one hand, in the early attack stage, there should be ways to monitor and detect abnormal behavior [26]. On the other hand, defense mechanisms should be enhanced to ensure security [27].

Moreover, a digital twin is the most important research focus at this level. Digital twin is the virtualization of the physical resources in the cyber world. The idea of a digital twin is widely used to simulate properties and behaviors of systems. Reference [28] developed three digital twins (a product, a process and an operation digital twin) that can simulate the state and behaviour of the corresponding physical object for optimizing production processes.

4) *Cognition Level*: Since abundant information is available, this level can generate comprehensive knowledge of the system. The research focus is developing appropriate presentation tools that can show the knowledge to experts for further decisions making. One such example is illustrated in [29]. Besides, in this level CPPSs are able to diagnose their own state and predict the potential failure, as in [30].

5) *Configuration Level*: The configuration level can apply the right decisions made in the cognition level to the physical space, therefore implementing a resilience control. It can achieve control and adjustment, especially the self-X properties (X is a placeholder for describing the desirable characteristics of a system in response to changing environments), such as self-adjustment, self-configuration and self-optimization, in response to external environmental changes. One such example was given in [31], presenting an Autonomous Production Control method (APC) of manufacturing processes, which includes all control tasks and their interdependencies. The APC method acts autonomously and keeps the resilience of CPPSs.

## III. DISCUSSION

As previously reviewed, there has been a great deal of efforts toward CPPSs design and implementation approaches. However, there are still research gaps.

➢ CPPSs change the traditional Computer Integrated Manufacturing (CIM) pyramid that has hierarchical layers into a decentralized architecture, which will have an impact on the structure of centralized Information Systems (IS). An IS-centric architecture for CPPSs should be designed, and the place and new role of IS in these architectures should be analyzed.

➢ The most significant difference between CPPSs and traditional production systems lies in the digital twin. In the digital twin, the physical object's change of state should have an automatic impact on the cyber object's state and vice versa. However, the concept of "Digital Twin" is easily confused with the concepts of "Digital Model" and "Digital Shadow" that don't implement the bidirectional dynamic impacts between physical objects and cyber objects. Therefore, the digital twin should be put into more research efforts.

➢ As [4] pointed out, one of the most important characteristics of CPPSs is intelligence, which can be defined as follows: *elements are able to acquire information from their surroundings and act autonomously*. Intelligence can widely distribute throughout the entire CPPSs. The "connection level" and "data-to-information level" can achieve the intelligence through physical elements, such as machines, products and conveyors. In the "cyber level", the digital twin can achieve intelligence because it is dynamically linked to the physical object. In other words, the physical object's change of state will have an automatic impact on the cyber object's state and vice versa. This is the most significant difference between CPPSs and traditional production systems. However, the "cognition Level" and "configuration Level" haven't implemented the intelligence.

➢ The research efforts on the configuration level are extremely rare because this level has the highest requirements with self-X capabilities which is the most difficult to achieve. Moreover, the total integration of 5 levels in CPPSs does not exist currently within the scope of the authors' knowledge.

➢ The industrial practices of CPPSs are still at its infancy and difficult to implement. One of the major obstacles lies in the integrative link between CPPSs and Enterprise Information Systems (EIS) which rely on software such as the Manufacturing Execution System (MES). This link has long been, and often still is, confused with information technologies due to the influence of the computer science community. While it is true the link in its broad sense is surely first of all a technological one which leverages the latest information technologies to combine the digital and physical world, more importantly is an organizational link to better support the decision making and business processes. Therefore, this link is the integration of all elements including data, information technologies, people and business processes.

## IV. CONCLUSION

There has been a great deal of efforts from both academics and industry practitioners towards CPPSs, yet there is a scarcity of literature review to document the CPPSs design and implementation approaches. This paper provides such a review in view of industrial engineering to help researchers and practitioners have a general understanding of this emergent research area and therefore choose the proper approaches and technologies in future research.

In this paper, four different CPPSs design approaches are identified, focusing either on a specific way of modelling (architecture or agent-based, human-centered), or integration approaches from specific design concerns. Then, a review of CPPSs implementation approaches is identified through the lens of 5C architecture levels. At last, this paper analyzes the research gaps and points out possible directions for future research.

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