A method for supporting the transformation of an existing production system with its integrated Enterprise Information Systems (EISs) into a Cyber Physical Production System (CPPS)

Xuan Wu [a,b,*], Virginie Goepp [b], Ali Siadat [a], François Vernadat [c]

[a] Arts et Metiers Institute of Technology, Université de Lorraine, LCFC, HESAM Université, 57070, Metz, France
[b] INSA Strasbourg, ICube Laboratory, 24 Boulevard de la Victoire, 67084, Strasbourg Cedex, France
[c] University of Lorraine, LGIPM Laboratory, 3 Rue Augustin Fresnel, 57070, Metz, France

A B S T R A C T

Cyber-Physical Systems (CPSs) combine the use of components from the physical and the digital worlds in a synergistic way. Cyber-Physical Production Systems (CPPSs), essential in Industry 4.0, result from the application of CPS principles to production environments. To promote the widespread implementation of CPPSs, it is necessary to study how to transform an existing production system with its integrated Enterprise Information Systems (EISs) into a CPPS. This is a very broad question and the scope of this work is limited to the concept development stage. The purpose of the paper is twofold: (1) to elaborate a meta-model for formalizing the elements that constitute CPPSs, with a particular emphasis on the involved EISs, and (2) to propose a method for supporting the transformation of an existing production system with its integrated EISs into a CPPS. Firstly, a literature review on the transformation methods towards CPPSs is carried out. It concludes that existing studies do not consider all aspects of CPPSs, especially its EISs, and that there is a lack of a method that analyzes the gap between the As-Is system and the To-Be system. As a result, a meta-model describing the main object classes that constitute CPPSs and the interrelationships among these classes, is proposed. Next, a method based on the meta-model is proposed to support the transformation into a CPPS. It provides a checking matrix to immediately visualize which improvement actions in the As-Is system are required. Furthermore, a case study illustrating the use of the method is presented. Finally, the contributions of the study are summarized and future work is highlighted.

1. Introduction

The manufacturing industry is facing challenging trends, such as highly customized products, increasing product complexity and shorter product lifecycles. Cyber Physical Systems (CPSs), which are characterized by a tight interaction of computational and physical elements to provide intelligence, responsiveness and adaptation (Leitão et al., 2016), are part of the solution for tackling the growing challenges that manufacturing industries are facing. The specific application of CPSs to production environments results in Cyber-Physical Production Systems (CPPSs).

* Corresponding author at: INSA Strasbourg, ICube Laboratory, 24 Boulevard de la Victoire, 67084, Strasbourg Cedex, France.

E-mail addresses: xuan.wu@ensam.eu (X. Wu), virginie.goepp@insa-strasbourg.fr (V. Goepp), ali.siadat@ensam.eu (A. Siadat), vernadat30@gmail.com (F. Vernadat).

Although CPPSs can bring many benefits, the real-scale implementation of CPPSs in industrial practices is still in its infancy due to the legacy barrier (Calderón Godoy and González Pérez, 2018). Actually, enterprises are still conservative in adopting new solutions, especially because of the lack of roadmaps and methodologies that support the transformation from legacy systems to a CPPS. Therefore, a comprehensive transformation methodology is required to support industries to move from their legacy systems towards a CPPS.

Transformation approaches are being proposed in recent years, but not many. These approaches either focused on the retrofit of specific elements of CPPSs (i.e., retrofit of machine tools (Lins et al., 2017)) without considering all elements of CPPSs especially Enterprise Information Systems (EISs), or focused on improving some performance of legacy systems without full transformation into CPPSs, as in (Calderón Godoy and González Pérez, 2018; Orellana and Torres, 2019; Di Carlo et al., 2021). Therefore, to the best of the authors' knowledge, no comprehensive methodologies on the transformation from legacy systems to CPPSs have been proposed so far.

Consequently, transformation of legacy systems into CPPSs is an emerging topic that is growing rapidly and deserves more attention. However, this is a very broad topic and includes overwhelming and complex tasks that cannot be simply handled by this paper. While the ultimate goal is to develop a comprehensive methodology for transforming legacy systems into CPPSs, at the moment the paper is a preliminary study positioned at the concept development stage which attempts to provide a partial contribution to this broad topic. The contribution of the paper consists of a meta-model defining all necessary elements of a CPPS, with a particular emphasis on involved EISs, and a method for transforming an existing production system with its integrated EISs into a CPPS to guide industry practitioners in visualizing which elements need to be added and modified to become a real CPPS.

The rest of the paper is organized as follows: In Section 2, we propose the definition of CPPSs and further elaborate the research problem, scope and objective. Section 3 presents the related works of the transformation methods into CPPSs. Section 4 presents the meta-model of CPPSs and Section 5 presents the method for the transformation into a CPPS. Section 6 illustrates the use of this method with a case study. Section 7 concludes the paper by synthesizing the contribution and indicating future research directions.

2. Research context

2.1. The definition of CPPSs

There are many definitions of CPPSs, but there is no consensus on a formal definition. There are two distinct categories of research streams on the definition of CPPSs. As for CPSs in general, the first research stream advocates that a CPPS is the glue (i.e. a middleware layer) that connects the cyber world with the physical world, as in (Wang et al., 2015). The second research stream advocates that a CPPS is a system of systems in which cyber components work seamlessly and in synergy together with physical systems to form a whole to fulfill a common mission, as in (Lee, 2008). We adhere to the second stream. However, the existing definitions are unclear on what a CPPS really is and what it should include, even the widely cited one proposed by Monostori et al. (2016). We therefore propose the following, more concise definition:

A CPPS is a combination of technological agents (including smart products and smart devices), IT agents and humans, collaborating within a synergistic production environment to carry out technical, decision-making or cognitive tasks autonomously, using the best capabilities of each kind of agent involved.

In this definition, technological agents include all physical devices (such as robots and Computer Numeric Control (CNC) machines) as well as products with sensing, computation and control units, therefore being able to receive and send messages and make local decisions. IT agents include hardware (such as computers) and software (such as computer programs and software packages). Humans refer to all kinds of human agents involved in the system.

2.2. Problem statement

According to the definition of CPPSs, EISs, which are made of computers, software, people, processes and data (Romero and Vernadat, 2016), can be considered to be included in CPPSs. EISs are defined as "software systems for business management, encompassing modules supporting organizational functional areas such as planning, manufacturing, sales, marketing, distribution, accounting, financial, human resources management, project management, inventory management, maintenance, transportation and e-business" (Rashid et al., 2002). Nowadays, operations of production systems are realized through various EISs, including customer relationship management (CRM) systems, enterprise resource planning (ERP) systems, manufacturing execution systems (MES), etc. Therefore, when transforming a legacy system into a CPPS, not only its production system needs to be considered, but its involved EIS as well. In this regard, the research problem addressed herein is: "How to transform an existing production system with its integrated EIS into a CPPS in the context of Industry 4.0 or Smart Manufacturing?".

2.3. Research scope and objective

According to systems engineering principles (Kossiakoff et al., 2011; Shortell, 2015; International Organization for Standardization, 2015), a system life cycle development can be divided into three main stages: (1) the concept development stage, which is the initial stage of the formulation and definition of a system concept perceived to best satisfy a valid need; (2) the engineering development stage, which covers the translation of the system concept into hardware, control and software designs; and (3) the post development stage, which includes the production, deployment, operation, and support of the system throughout its useful life. When applying systems engineering principles to CPPSs, a generic transformation process towards a CPPS can be considered as a stepwise process which consists of these three stages. This paper is a preliminary study positioned at the concept development stage.

The objective of this work is to propose, for the concept development stage, a method to support the transformation of an existing production system with its integrated EIS into a CPPS. First of all, due to the complexity and structural opacity of CPPSs, a model needs to be set up for a common understanding of CPPSs, especially the elements of involved EISs. Therefore, in this work, a meta-model of CPPSs has been elaborated by defining the necessary elements that constitute a CPPS and their interrelationships. Then, by instantiating the meta-model, a method for the transformation of an existing production system with its integrated EISs into a CPPS is proposed. This method provides a detailed process to guide people in analyzing the gap between As-Is systems and To-Be systems and, therefore, to identify which elements need to be added or modified for future implementation. The proposed method gives a transformation matrix to help industry practitioners to understand the current status of existing production systems and visualize what should be improved to move towards CPPSs.

3. Related works on transformation methods

As stated in Section 2.3, the research scope of the paper is concept development. Therefore, this section presents an overview of transformation methods relevant for the concept development stage and identifies the research gap.

Wu et al. (2020) have already proposed a systematic literature review of existing approaches used in the concept development stage of CPPSs. We refer to some of the articles they reviewed but reanalyze them from the perspective of transformation. According to this review, there are many architectures for CPPSs, including standard architectures (such as the widely recognized RAMI 4.0 (Adolphs et al., 2015) and IIRA (Lin et al., 2015)), multilayer architectures (such as the most popular 5C Architecture (Lee et al., 2015)), and architectures with specific design concerns (such as a human-centered architecture (Francalanza et al., 2017)). Although these architectures provide generic structuring guidelines for implementing CPPSs, they do not deal with brownfield

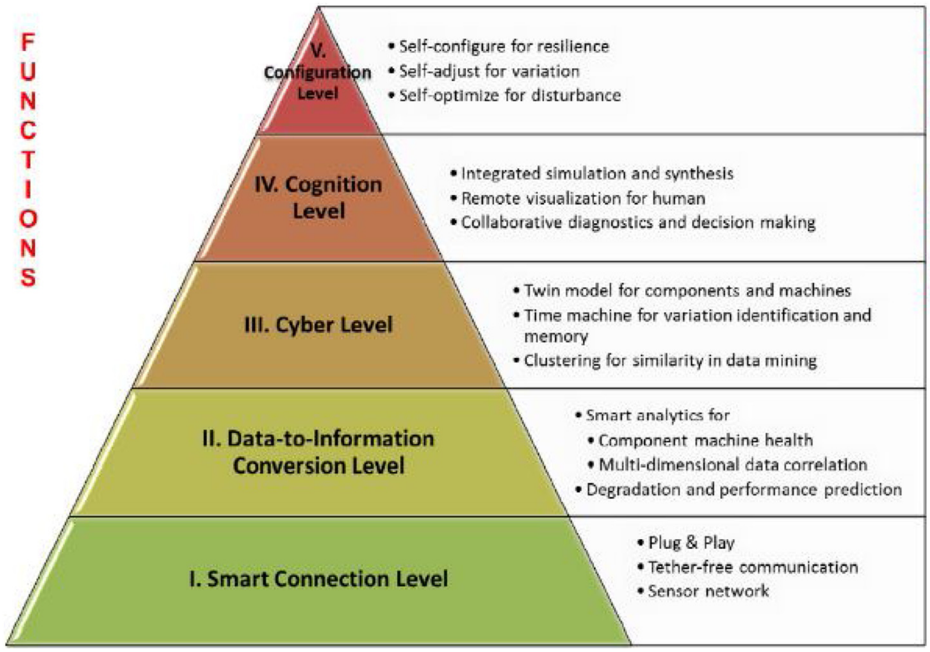


Fig. 1. 5C Architecture for the implementation of CPSs (Lee et al., 2015).

implementations that is to say created on top of legacy systems rather than starting from scratch (Etz et al., 2020). For example, although the RAMI 4.0 includes concepts and standards for an Industry 4.0 implementation, it does not suggest a way to transform old equipment into modern CPSs.

There are some methods dedicated to the transformation into CPPSs. Lass and Gronau (2020) propose a CPS component concept including architecture model and hardware proposal, which allows the combination of classic PLC programming and implementation of complex algorithms to successfully transform existing, non-CPS plants, into a CPPS. Etz et al. (2020) propose an architecture detailing how to design and implement an OPC UA gateway for a legacy robot system in order to allow seamless communication across machines within a smart manufacturing environment. Lins et al. (2017) propose a method for retrofitting existing CNC machines, which depicts in detail the functional requirements, the design parameters, data model and the system architecture. Khan et al. (2020) propose an architecture for the cloud migration that can be applied to legacy industrial SCADA systems. These transformation methods are specific to certain devices and do not consider all the aspects of CPPSs but only part of its technological agents and IT agents. To be more precise, existing studies concerning technological agents of CPPSs aim at adding new technologies (such as communication gateways) to existing devices and ingesting data and information of control functions to the cloud for storage and processing. The existing studies concerning IT agents of CPPSs focus on transforming enterprise applications into cloud-based services. The ignored aspects, such as human and business processes, are mainly those covered by Enterprise Information Systems (EISs) in CPPSs. Therefore, in this study, a meta-model is proposed to define all necessary elements in CPPSs, including its integrated EIS at a detailed level.

There are some studies that are not restricted to specific types of devices. For example, (Lins et al., 2018; Lins and Oliveira, 2020) define three components of the transition to CPPSs: infrastructure, communication and application and propose the retrofitting process according to these components. However, they do not consider the status of the existing system and do not analyze the gap between the target system and the legacy one. The transformation can be implemented by (1) either adding new functionality that was not available when it was originally designed, such as adding new communication protocols; or (2) modifying existing components, such as exchange of old computers by faster processing units. They all aim to enhance specific elements of legacy systems in order to increase new functionalities. However, due to the complexity and structural opacity of CPPSs, it is difficult to figure out which new elements are added and which old elements are affected. Therefore, in this paper, a method is proposed to support manufacturing industries to visualize which elements need to be added and modified to move towards CPPSs.

4. Meta-model of CPPSs

This section presents a meta-model that specifies the main object classes of CPPSs and their interrelationships. The following sub-sections present how to extract classes and how to establish their interrelationships for setting up the meta-model.

4.1. Object classes in a CPPS

The object classes in a CPPS are extracted from two parts: the 5C Architecture (Lee et al., 2015) and enterprise modelling standards (ISO 19439, 2006ISO 19439, 2006; ISO 19440, 2020ISO 19440, 2020).

(1) Object classes extracted from the 5C Architecture

Lee et al. (2015) proposed the 5C Architecture for implementing CPSs, as shown in Fig. 1. It can equally be extended to CPPSs. Because the 5C Architecture is the most popular and broadly accepted architecture, it is proposed to use it as a reference to specify the object classes in a CPPS.

At the smart connection level (C1 level), all the physical devices, such as machines and robots, are connected and communicate to one another through communication protocols and standards, so that data can be acquired from a variety of sources and stored in the data center. At the data-to-information conversion level (C2 level), meaningful data can be inferred from a large volume of raw

Table 1
Object Classes extracted from the 5C Architecture.

Levels	Object Classes extracted from the 5C architecture
C1	Product, Component, Machine, Production System, Sensor, Controller, EIS Software Package, Raw Data, Communication Protocol, Data Acquisition Technology, Data Storage Technology, Central Server
C2	Meaningful data, Data Preprocessing Technology
C3	Information Hub, Data Analysis Technology
C4	Information, Presentation Interface, Human, Decision
C5	(nil)

data by data preprocessing technologies. At the cyber level (C3 level), data is transformed into useful information by data analysis technologies and a Digital Twin (DT) of the physical world is created. At the cognition level (C4 level), the extracted information is delivered to end-users for decision making through presentation interfaces. At the configuration level (C5 level), a series of decisions about actions are applied to the physical system and achieve self-configuration and self-adaptiveness in response to external environmental changes.

Based on the description of each level of the 5C Architecture obtained from (Lee et al., 2015), a set of key-nouns (in bold) have been extracted to become the object classes. For example, part of the description of the connection level is "acquiring **data** from **machines** and their **components** is the first step and the data might be directly measured by **sensors** or obtained from **controllers** or **EIS software**" (Lee et al., 2015). From this sentence, the following classes are identified: *data*, *machine*, *component*, *sensor*, *controller* and *EIS software package*. The process for extracting the object classes at the other levels is the same, therefore we do not detail them anymore. One thing worth mentioning is that C1 to C4 levels already include all the classes and there are no new classes at the C5 level because it only applies the decisions made at the C4 level to the C1 level. Smart products, which are important objects in the definition of CPPSs, are not emphasized in the 5C Architecture. Therefore, a new object class "Product" is added at the connection level. The results of all the extracted object classes for the five levels are shown in Table 1.

To reach a consensus on the meaning of these classes, "Communication Protocol" and "Presentation Interface" are specifically explained in detail because these two classes are prone to be misunderstood due to their names. The communication protocols are defined as the entirety of communication hardware and software. "Presentation interface" is used as an umbrella class that enables the human-system interaction. It includes cognitive assistance software that supports information and knowledge management, and devices that translate human input into electronic signals and vice versa. A cognitive assistance software is able to observe and analyze information and recommend appropriate actions in real-time.

(2) Object classes extracted from enterprise modelling standards

EISs can be regarded as multidimensional information processing objects, which include three main dimensions (Reix et al., 2016): (1) an informational dimension: EISs are representations of the environment through a set of data; (2) a technological dimension: EISs are systems that carry out the processes of collecting, storing and processing information, which consist of hardware and software; (3) an organizational dimension: EISs support business processes and decision-making processes, which require actors and technological resources.

From this description, it can be concluded that the 5C Architecture only covers the informational and technological dimension of EIS, such as integrated software packages like ERP systems, but does not cover the organizational dimension. Therefore, it is proposed to build the other object classes of EIS on the basis of the enterprise modeling standards ISO 19439 (2006) and ISO 19440 (2020), which precisely define a set of enterprise modeling constructs. Among these constructs, the relevant ones are selected as the necessary object classes for representing EIS, as shown in Table 2. Informational, technological and organizational dimensions of EIS are distinguished by three colors: pink, blue and orange.

Combining the object classes extracted from the 5C architecture and enterprise modeling standards, the meta-model, shown in Fig. 2, has been elaborated as a Unified Modelling Language (UML) object class diagram. Object classes of the EISs domain are highlighted using three colors (pink, blue and orange) corresponding to the three dimensions (respectively, informational, technological and organizational) usually covered in most EISs.

4.2. Interrelationships between object classes

The interrelationships between the object classes extracted from the 5C Architecture can be inferred and obtained from the description of this architecture. In the same way, the interrelationships between the object classes extracted from enterprise modelling standards can be derived directly from these standards. Therefore, these interrelationships are not described herein. Only the interrelationships between the classes extracted from the 5C Architecture and those extracted from the enterprise modelling standards are detailed. According to the three dimensions of EISs, these interrelationships are also categorized into three kinds (respectively, informational, technological and organizational relationships) as shown in Table 3 and are highlighted with three colors (pink, blue and orange) in Fig. 2.

- The technological relationships mean that EISs provide hardware, software and datarelated capabilities (such as data storage and processing capabilities) to perform the processes of collecting, storing and processing data.
- The informational relationships mean that data and information are stored in EIS databases and represented by EIS interfaces.
- The organizational relationships mean that EISs support the business processes and decision-making processes in production systems through humans and other technological resources.

5. A method for transforming an existing production system with its integrated EIS into a CPPS

By instantiating the meta-model, a method for the transformation of an existing production system with its integrated EISs into a CPPS is proposed in this section. The instantiation principles of the meta-model are first described. Then, based on these principles, a method for the transformation is presented.

5.1. Instantiation principles of the meta-model

Instantiation principles of the meta-model are described as follows, which gives guidance for the instantiation process:

- Principle 1: Classes extracted from the 5C Architecture should be instantiated layer by layer from the C1 level to the C5 level, as the 5C Architecture gives a sequential workflow for the implementation of CPSs. That is to say, if classes at the C1 level are not instantiated, it is impossible to instantiate classes at the C2 level and the same goes for other levels.
- Principle 2: At each level, the classes extracted from the 5C Architecture should be instantiated first and then the EIS classes

Table 2
Selection of the object classes for EIS from the enterprise modeling constructs.

EIS dimensions	Enterprise modeling constructs	Object classes in EIS (✗:exclude; ✓:include)	Reasons for including or excluding
Informational dimension	Enterprise Object	✗	The object classes *Raw Data*, *Meaningful Data* and *Information* specified in the 5C Architecture can better represent the informational dimension.
	Enterprise Object View	✗	
	Order	✗	
	Product	✗	
Technological dimension	Resource	✓	Represents software, hardware and human resources
	Capability	✓	Represents ICT capabilities that are needed to support the execution of tasks
	Functional Entity	✗	Is only a specialization of the class *Resource*, which is already selected
	Operational Role	✗	Only represents the human skills to perform operational tasks, so the class *Person Role* that can represent all the human skills is selected
Organizational dimension	Domain	✓	Represents the functional area of an EIS
	Business Process	✓	Represents a partially ordered set of business processes or enterprise activities, or both
	Enterprise Activity	✓	Represents the lowest level of process functionality that is needed to realize a basic task within a business process
	Event	✓	Represents the initiation of a state change in the enterprise, which shall trigger business processes or enterprise activities or both
	Person Profile	✓	Represents the human skills available to serve the organizational and operational tasks
	Organizational Role	✗	Only represents the human skills to perform organizational tasks, so the class *Person Role* that can represent all the human skills is selected
	Organization Unit	✓	Represents the formal, hierarchical or administrative structure of an enterprise, or some combination thereof.
	Decision Center	✓	Represents the decisional structure of an enterprise

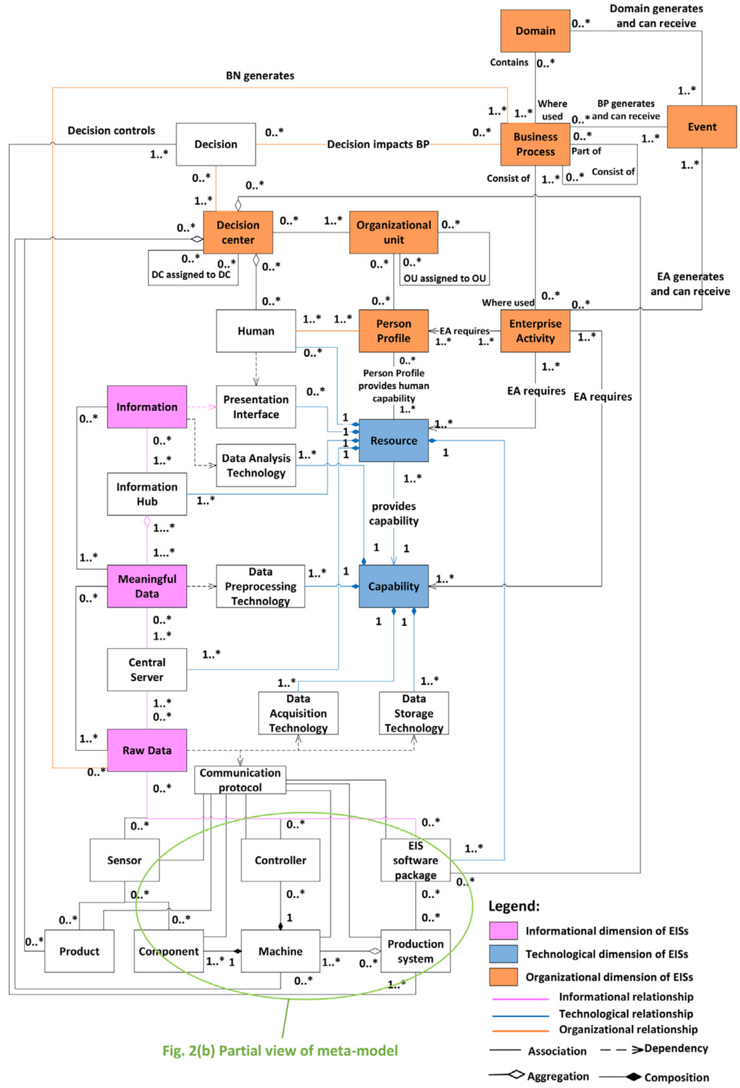
associated with the technological, informational and organizational relationships at this level should be instantiated. This way, the technological relationships are first considered, then the informational relationships and finally the organizational relationships. Indeed, if there are no technological relationships, it is impossible to obtain data/information and to have an informational relationship. Also, if there are no informational relationships, it is impossible to support efficiently business processes and decision making and to have an organizational relationship.

Combining Principle 1 and Principle 2, the instantiation process starts with the C1 level, and goes further with the EIS classes associated with the technological, informational and organizational relationships at the C1 level. Then, this instantiation loop moves to the C2 level and repeats until the C5 level.

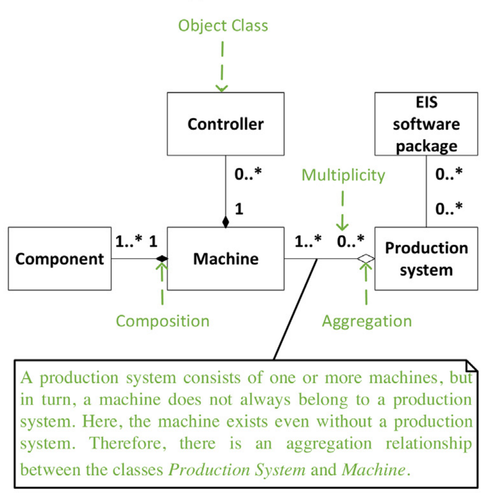
5.2. *Method for transforming a production system into a CPPS*

In this section, based on instantiating the meta-model, a method for the transformation into a CPPS is proposed as shown in Fig. 3.

- Step I: Understand the existing production system (As-Is system), including its composition, functionalities, used technologies, architectures and production processes.
- Step II: Define To-Be system requirements, which is a formal description of the target system specification. System requirements can then be broken down into basic functions, and each of them can be fulfilled by dedicated classes in a CPPS, which form the component requirements. Wu et al. (2020) conducted a systematic literature review on the existing works on the requirement analysis of CPPSs, which could be used as a reference to carry out this activity.



(a)



(b)

Fig. 2. Meta-model of CPPSs. a) A global view of meta-model. b) A partial view of meta-model.

Table 3
Interrelationships between object classes extracted from the 5C Architecture and object classes extracted from enterprise modelling standards.

Level	Technological relationships	Informational relationships	Organizational relationships
C1	Resource & (EIS software package, Central Server), Capability & (Data Acquisition Technology, Data Storage Technology)	EIS software package & Raw Data, Raw Data & Central Server	(nil)
C2	Data Preprocessing Technology & Capability	Central Server & Meaningful Data	(nil)
C3	Capability & Data Analysis Technology, Resource & Information Hub	Meaningful Data & Information Hub	(nil)
C4	Resource & (Presentation Interface, Human)	Information & (Information Hub & Presentation Interface)	Human & Person Profile, Decision Center & Decision
C5	(nil)	(nil)	Decision & Business Process, Business Process & Raw Data

- The technological relationships mean that EISs provide hardware, software and data-related capabilities (such as data storage and processing capabilities) to perform the processes of collecting, storing and processing data.
- The informational relationships mean that data and information are stored in EIS databases and represented by EIS interfaces.
- The organizational relationships mean that EISs support the business processes and decision-making processes in production systems through humans and other technological resources.

• Step III: Perform gap analysis by instantiating the meta-model. In the transformation context, it means mapping the As-Is system with the meta-model. This enables firstly to identify the missing classes or those that need to be modified according to the To-Be system requirements, and then to instantiate the corresponding object classes. In this work, because the focus is on concept development, the instantiation of the object classes is considered as the investigation of possible solution options according to the component requirements and the choice of the optimal solution, without the detailed design and implementation. According to the principles defined in Section 5.1, the instantiation process of the meta-model is shown in Fig. 4. At each level, there are four kinds of mapping activities (mapping the 5C classes, mapping the EIS classes associated with the technological, informational and organizational relationships) and one instantiation activity. The use of the 5C Architecture is intended to assist the CPPS transformation process in the different levels of maturity, but it is not necessary to implement all five levels. If all requirements can be met at a given level, the transformation process ends; otherwise, it goes to the next level until the C5 level. Therefore, at the end of each level, there is a checking activity to see whether it is required to go to the next level according to the To-Be system requirements.

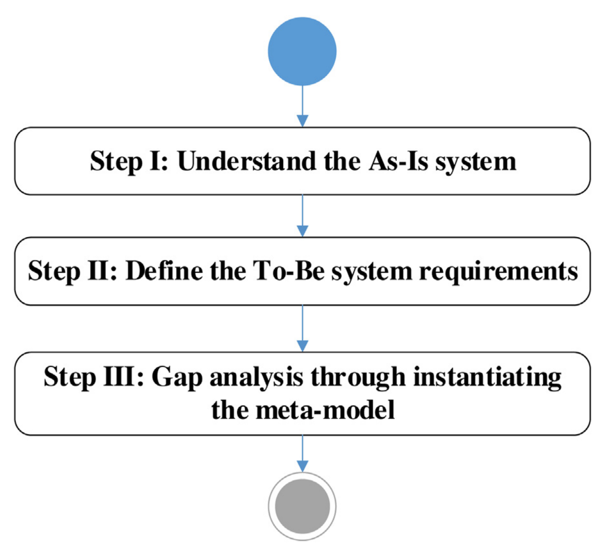


Fig. 3. Method for transforming a production system into a CPPS.

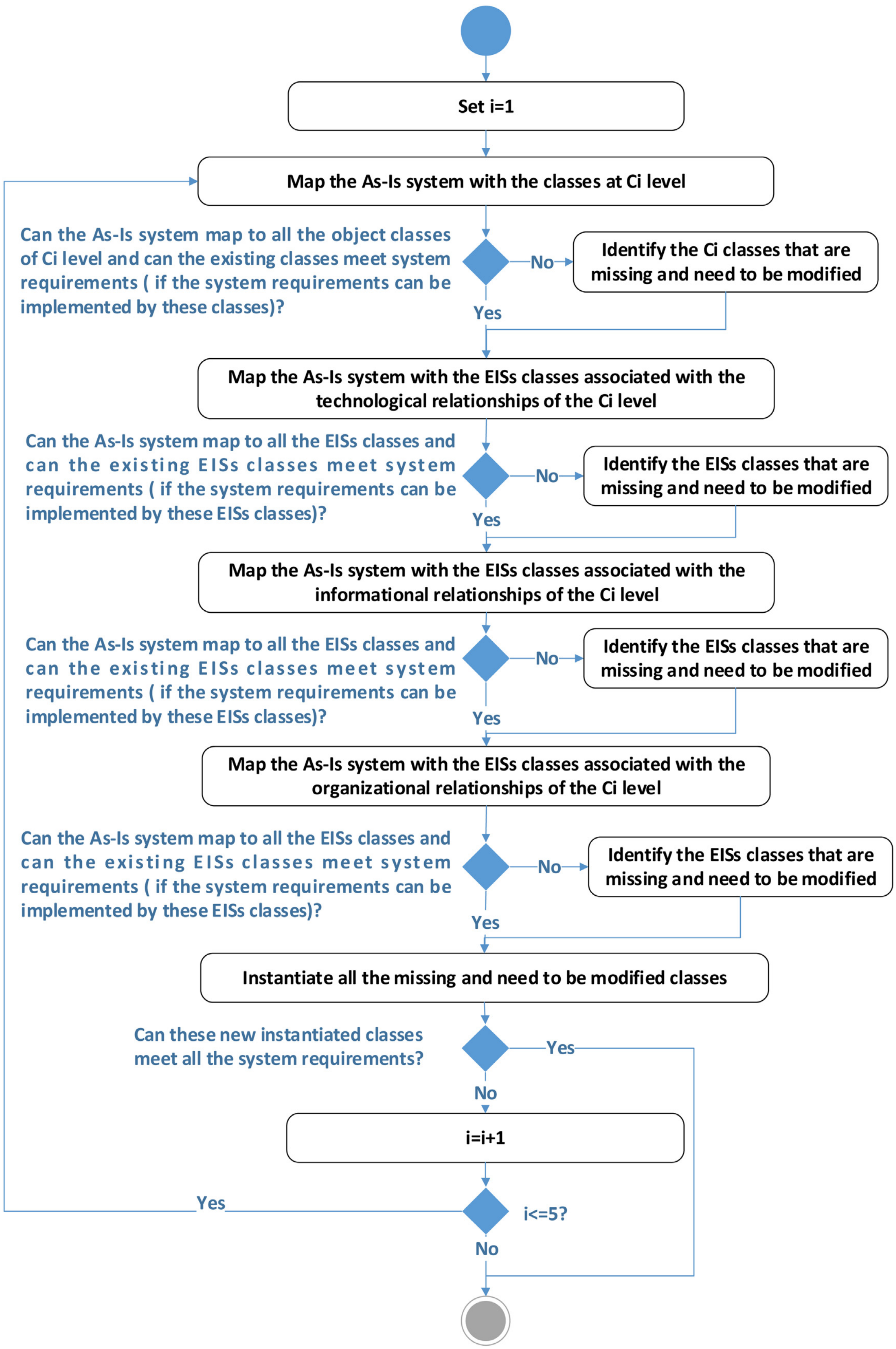


Fig. 4. Meta-model instantiation process.

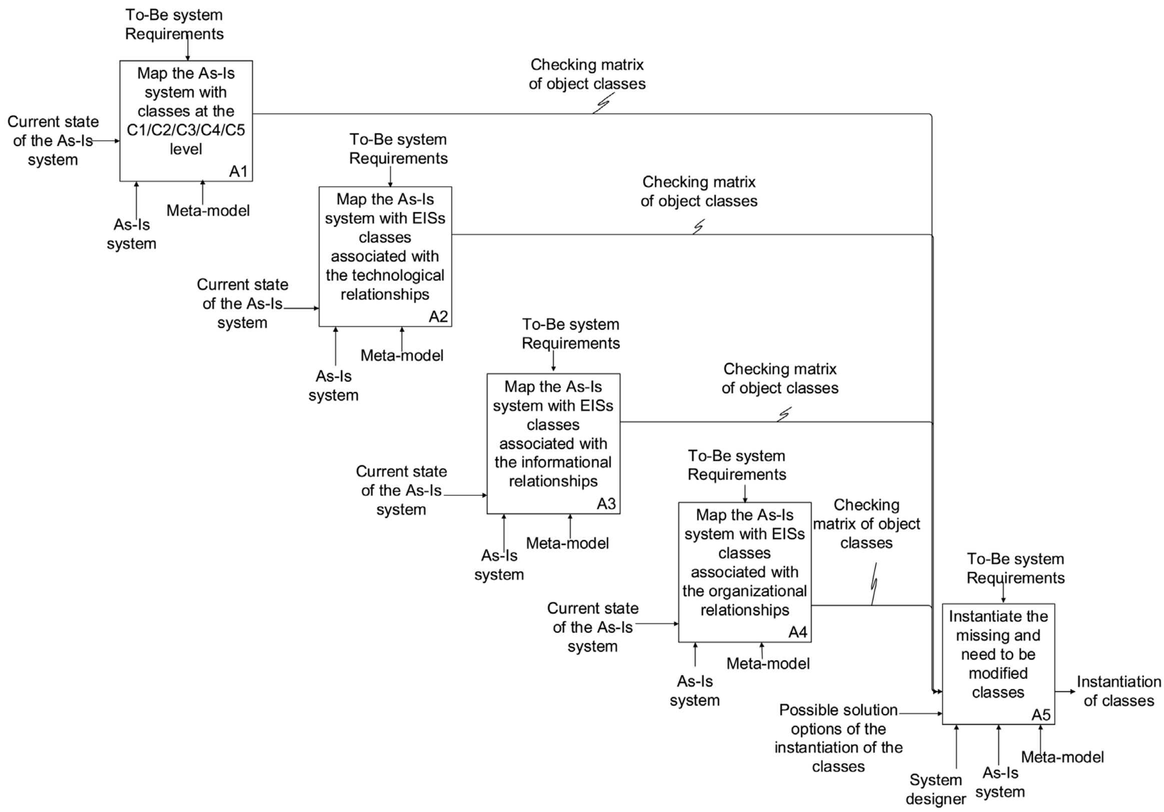


Fig. 5. Activity A0 – To instantiate the meta-model.

To better understand the activities of the instantiation process of Fig. 4, an IDEF0 diagram (Fig. 5) is proposed to analyze the data required by each activity, including inputs, outputs, resources (or mechanisms) supporting the activity, and constraints (controls) required for the activity. There are five activities that are consistent with the activities in Fig. 4. After each mapping activity, a checking matrix of the object classes is proposed to immediately visualize the gap between the As-Is and To-Be system, as shown in Table 4. This matrix is structured in rows and columns. The columns represent the object classes in the meta-model. Meanwhile, the rows describe the instantiation of the As-Is system and To-be system and the three states of classes (to be created, to be modified, and no modification) of object classes. Each class should have one and only one state.

6. Case study

To illustrate the use of the method, an academic case study is presented to clarify each step of the method. As the method is positioned at the concept development stage, this case study refrains from deeper technological details. In addition, as the case study is for illustrating the use of the method, not for technological validation in industry cases, it is a simplified case inspired by a production line of the LS2N Laboratory at the University of Nantes, France.

6.1. As-Is description of a production system

Let us consider an example of an As-Is production system mainly consisting of three articulated ABB industrial robots, three CNC machine tools, computer and shop floor Kanban, MES, humans, warehouse (storing parts and manufactured products) and parts, as shown in Fig. 6. The pick and place operations between the conveyor and the CNC machine tools is performed by the robots. Robot #1 also performs the load and unload work between the warehouse and the conveyor.

In this system, the CNC machine tools and robots form a shop floor-level IoT. The detailed configuration of the As-Is system is shown in Fig. 7. The robotic arm has a controller with a serial interface and is fully actuated with each DOF (Degree of Freedom) by a motor. A Raspberry Pi board is connected to the robot controller via an RS-232 cable to a Serial converter, and software created in Python with a user interface is responsible for continuously sending and receiving data to/from the robot serial interface. The Raspberry Pi board has an SSH (Secure Shell) remote access interface, a secure communication protocol that can be used to exchange data over an Ethernet network. USB cameras are fixed on robots to recognize the object and position of parts. Embedded boards (Raspberry Pi) are also configured for CNC machines, with remote communication capabilities similar to those implemented in the robot. Vibration sensors are fixed on the spindle of CNC machines to receive the vibration value. By collecting vibration data, it is possible to monitor machines running conditions and manage predictive maintenance. Local databases deployed on each embedded board store the real-time data and the pre-processed data, while a MES database deployed in the cloud stores order data, production rules, historical data and other engineered data. Meanwhile, preprocessed data from the local databases is further synchronized to the MES database. For local data processing, the real-time data acquired from different data sources is first cleaned to eliminate inaccurate and duplicated data. The Sorted Neighborhood Method (SNM) and K-means clustering algorithms are used to realize data cleansing (Ding et al., 2019). Then, a Fast Fourier Transform (FFT) is used for feature extraction (Ding et al., 2019), which could be treated as the machine health indicators. After this, the meaningful data is extracted and uploaded through the shop floor network to the public database for backup. The generated information, including production progress and machine status, is visualized in shop floor

Table 4
Checking matrix of object classes.

Object classes in the meta model		Instantiation of object classes		State of object classes		
		As-Is system	To-Be system	To be created	To be modified	No modification
C1	Product					
	Component					
	Sensor					
	Machine					
	Controller					
	Production System					
	EIS software package					
	Communication Protocol					
	Data Acquisition Technology					
	Data Storage Technology					
	Central Server					
	Raw Data					
C2	Meaningful data					
	Data Preprocessing Technology					
C3	Information Hub					
	Data Analysis Technologies					
C4	Information					
	Presentation Interface					
	Human					
	Decision					
Informational dimension of EIS	Raw Data					
	Meaningful Data					
	Information					
Technological dimension of EIS	Resource					
	Capability					
Organizational dimension of EIS	Domain					
	Event					
	Business Process					
	Enterprise Activity					
	Person Profile					
	Decision Center					
	Organizational Unit					

Kanban's for shop-floor managers and operators to make decisions and take actions. An MES can store manufacturing data, monitor production processes and display production status to humans.

This production system does not implement the connectedness of all the elements within the industrial network for data interaction and sharing, which results in the inability to obtain information from the surrounding environment and to respond to internal and external changes. Therefore, the system must be transformed into a CPPS to have connectedness, intelligence and responsiveness.

6.2. Transformation of the As-Is system into a CPPS

The transformation of the As-Is system into a CPPS can be implemented by adding new elements or modifying existing elements. However, due to the complexity of CPPSs, it is difficult to figure out which new elements should be added and which old elements are affected. The method proposed in Section 5 gives, for concept development, a detailed process for transforming existing production systems with its integrated EISs into CPPSs. There are three steps for the transformation process from the As-Is system to the CPPS as follows:

(1) Step I: Understand the As-Is system

According to the description of the As-Is system in Section 6.1, machines (including CNC machine tools and industrial robots) network access (including interfaces, protocols, etc.) has been configured, together with the intelligence of machines. However, the connection of parts to the industrial network and the intelligence of parts has not been configured. The parts to be manufactured should have their local intelligence to know how they are manufactured, what kinds of resources they need and what the current manufacturing work-in-progress is. Besides, the autonomous interaction between parts and machines has not been carried out in the As-Is system and those should be interconnected within the industrial network for data interaction and sharing.

With the aid of MES, in the As-Is system, operators can perceive the real-time production data and monitor the production statuses. However, when there is interference, such as the breakdown of machines and new orders insertion, the operation will stop and wait for shop floor managers and operators to make decisions, which is centralized and with low efficiency.

(2) Step II: Define system requirements.

According to the problems identified for the As-Is system in step I, three requirements for the To-Be system are stated, as shown in Table 5.

(3) Step III: Instantiate the meta-model. According to Fig. 4, there are four mapping activities and an instantiation activity at each level.

At the C1 level, after the four mapping activities between the As-Is system and the meta-model, their mapping results are shown in Table 6. The technological relationships between EIS classes and other classes of CPPSs mean that databases and computer programs are deployed to collect and store data. The informational relationships mean that data about production orders are obtained from MES and real-time data are input to local databases.

Then, the instantiations of each object class in the As-Is system are checked one by one to see if the new system requirements

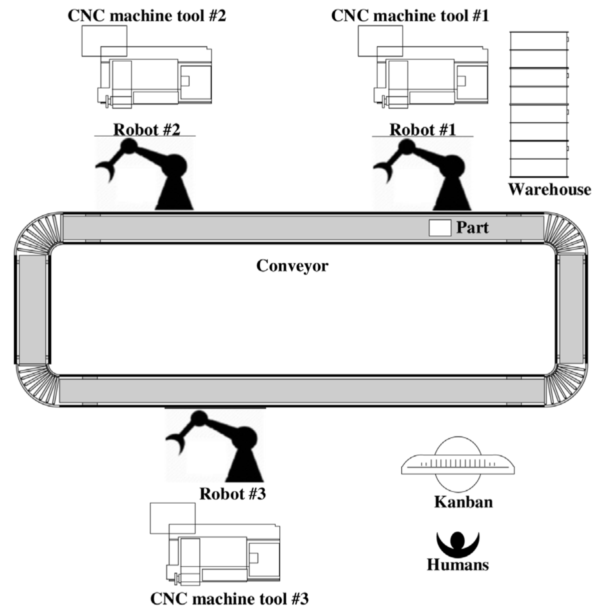


Fig. 6. Layout of As-Is system.

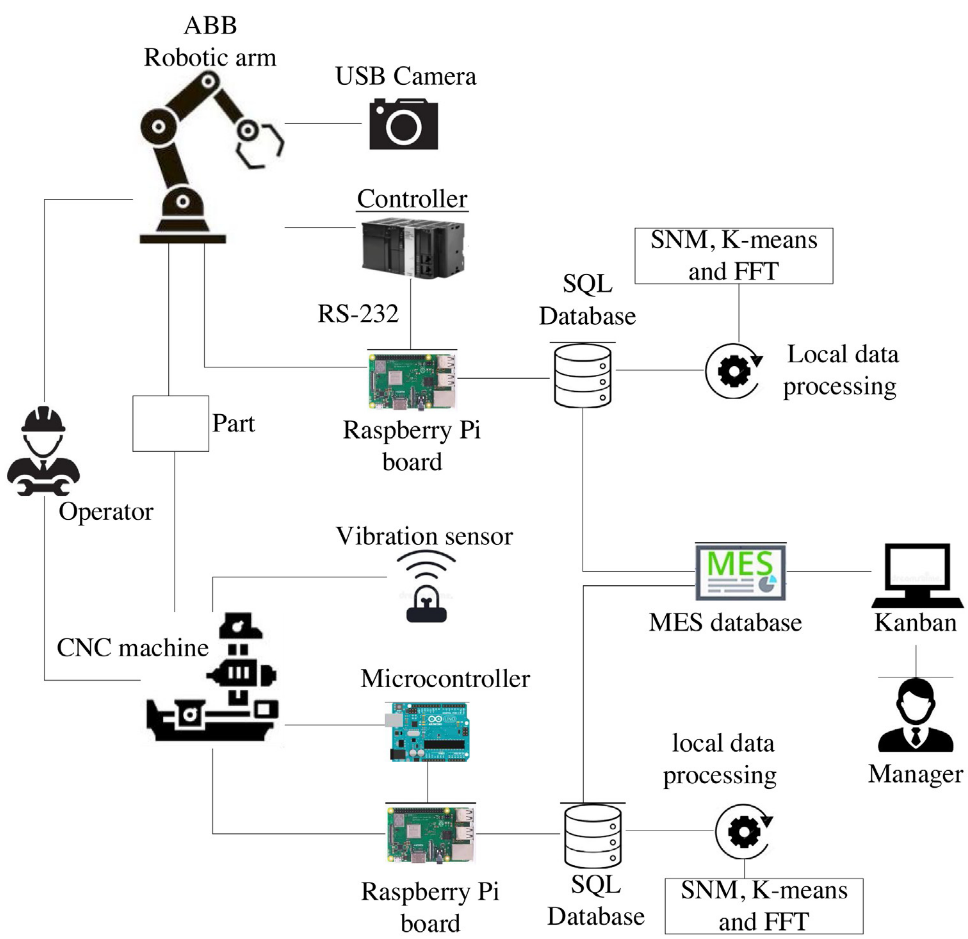


Fig. 7. As-Is system configuration.

Table 5
CPPSs Requirements statement.

ID	Requirements
RQ1	Connectedness of parts to the industrial network and the autonomous interaction between parts and machines within the industrial network for information interaction and sharing.
RQ2	Intelligence of parts: parts can acquire information from their environment (capabilities and states about machines and the sequence of manufacturing operations and their current progress, including which kind of machine performs a certain operation and how is the production progressing) and make decisions about production scheduling autonomously.
RQ3	Autonomous production scheduling to respond quickly to unexpected events or disturbances.

Table 6
Mapping between the As-Is system and object classes in the meta-model.

Object Classes at the C1 level	Instantiations of the object classes in the As-Is system
Product	Parts
Component	Robotic arm, spindle of CNC machine
Sensor	USB Camera, vibration sensor
Machine	ABB Robot arms, CNC machine
Controller	Controller of robot, micro-controller of CNC machine
Production System	As-Is system
EIS software package	MES
Communication Protocol	Ethernet, RS 232, SSH, cable, router
Data Acquisition Technology	Hardware: sensor, controller Software: computer programs
Data Storage Technology	Hardware: embedded board (Raspberry Pi), computer. Software: database (SQL)
Central Server	Local database provided by embedded board
Raw Data	Data from vibration sensor, camera, controller and MES

are met. To meet RQ1 and RQ2, the existing instantiation of the class "Data acquisition technology", "Data storage technology", "Raw data" needs to be modified for acquiring data of parts and connect parts to the industrial network. RFID technologies and embedded board for parts can implement the intelligence of parts and their communication with machines. The result is shown in the checking matrix (Table 7). As the RQ3 has not been met yet, the transformation process goes to the next level. From the C2 level to the C5 level, the transformation process is the same as at the C1 level. The new requirement is to implement responsive production scheduling. The As-Is system only has local data processing. For global data analysis in the cloud, a decision tree can be used to infer the cause of the interference. Then, knowledge-based reasoning (KBR), Deep Neural Network (DNN) and the non-dominant sorting genetic algorithm (NSGA-II) can further be used to generate responsive production scheduling strategies (Ding et al., 2019). The checking matrix of states of object classes and their instantiation is shown in Table 8. The To-Be system configuration is shown in Fig. 8, where changes are highlighted in red.

6.3. Results

Through the creation and modification of object classes, the centralized and human-intervened manufacturing operations control in the As-Is production system can be replaced by a decentralized and autonomous one in the To-Be system.

In the To-Be system, autonomous production scheduling is as follows.

(1) When an order is received, detailed information of the part type (such as manufacturing requirements, quantity and quality) is written in an RFID tag attached to the part. The manufacturing operations for each part are generated based on the above data.
(2) Parts will announce their next operation to all the machines and each machine can decide whether it can process the part or not. On this basis, parts and machines can autonomously interact with each other to decide the optimal production sequences dynamically and react to disturbances collaboratively. For example, after calculating the real-time data of spindle speed and vibration based on a decision tree, a dominant disturbance

Table 7
Checking matrix of object classes and their instantiation.

	Object classes	Instantiation of object classes		States of object classes	
	As-Is system	To-Be system	To be created	To be modified	No modification
C1	Product	Parts			
	Component	Robotic arm, spindle of CNC machine			√
	Sensor	USB Camera, vibration sensor			√
	Machine	ABB Robot, CNC machine			√
	Controller	Controller of robot, micro-controller of CNC machine			√
	Production System	As-Is system	To-Be system	√	
	EIS software package	MES			√
	Communication Protocol	Ethernet, RS 232, SSH, cable, router			√
	Data Acquisition Technology	• Hardware: sensors, controllers; • Software: computer programs –	RFID	√	
	Data Storage Technology	• Hardware: Raspberry Pi, computer; • Software: database –	Embedded board of parts (Raspberry Pi)	√	
	Central Server	Local databases provided by embedded boards			√
	Raw Data	Data from vibration sensor, camera, controller and MES –	Data from RFID	√	
Technological dimension of EIS	Resource	Computer, local database, MES			√
	Capability	Data acquisition and storage capability	New data acquisition and storage capability of parts data	√	

Table 8
Checking matrix of object classes and their instantiation.

	Object classes	Instantiation of object classes		States of object classes		
	As-Is system	To-Be system	To be created	To be modified	No modification	
C2	Data Preprocessing Technology	Data cleaning and feature extraction algorithms (SNM and FFT)				√
	Meaningful Data	Meaningful data of machine			√	
		–	Meaningful data of parts			
C3	Information Hub	MES database				√
	Data Analysis Technology	–	Algorithms for production scheduling strategies (decision tree, KBR and NSGA-II)	√		
C4	Presentation Interface	Shop floor Kanban, assistance software with algorithms				√
	Information	Production progress, machine status			√	
		–	Abnormal alarms, the cause of the interference and responsive production scheduling strategies			
EIS	Human	Shop-floor operators and managers	Managers		√	
	Decision	Central decisions made by humans: manufacturing operation sequence	Local decisions made automatically by products and machines: specific commands decomposed by the scheduling strategy, which are decentralized on each machine and part		√	
	Resource	Computer, database, shop-floor Kanban, Shop-floor operators and managers	Computer, database, shop-floor Kanban and managers		√	
	Capability	Data acquisition, storage, processing and analysis capability	New data acquisition, storage, processing and analysis capability		√	
	Event	Interference, such as the shutdown of machines and new order insertion				√
	Domain	Production scheduling				√
	Business Process	Centralized production scheduling	Autonomous production scheduling		√	
	Enterprise Activity	Design production schedules, allocate production resources and assign jobs by humans	Design production schedules, allocate production resources and assign jobs autonomously		√	
	Person Profile	High problem-solving skills, operational skills	Low problem-solving skills, leadership and organizational skills		√	
	Decision Center	Human	Parts, machines, human		√	
	Organizational Unit	Production planning department				√

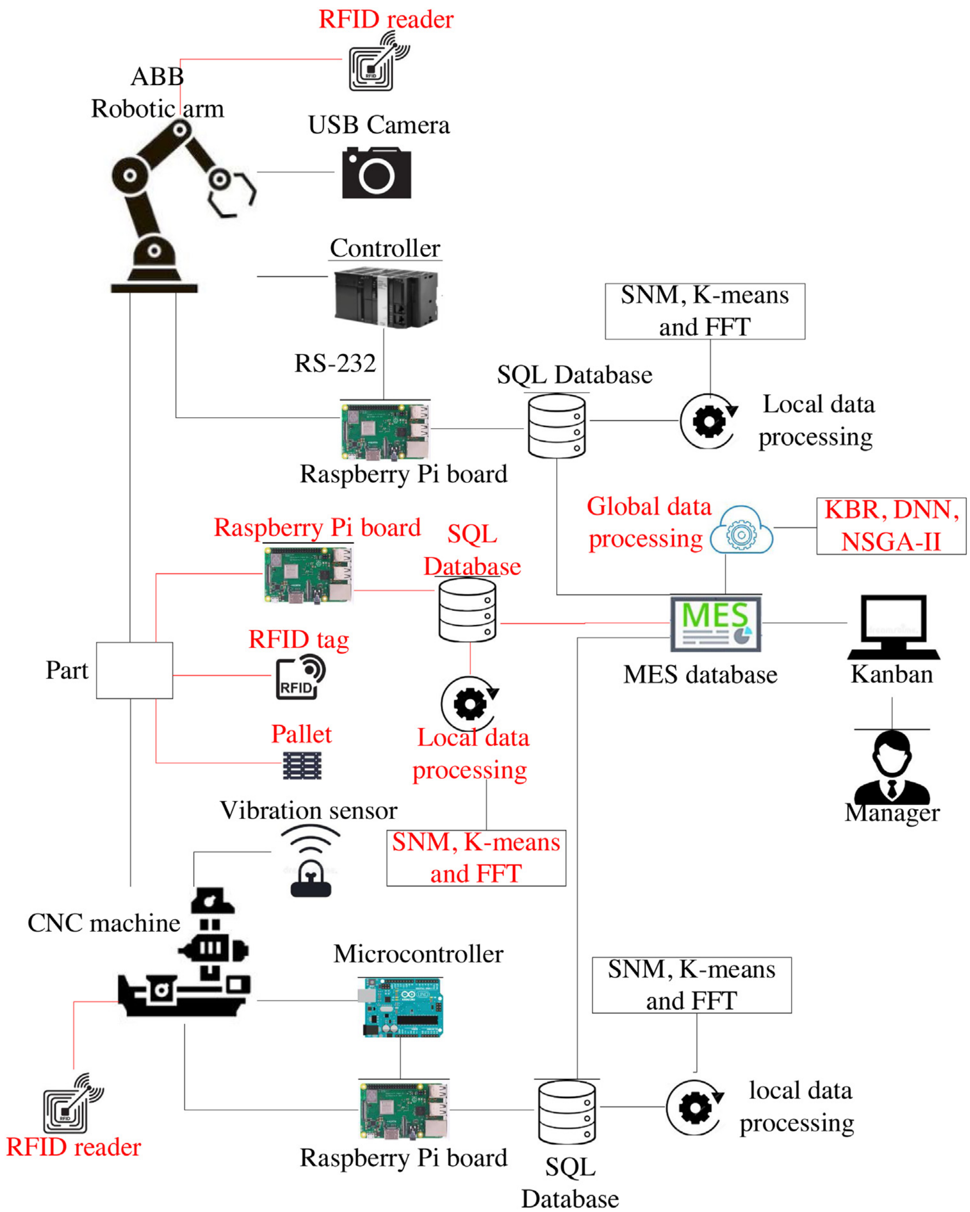


Fig. 8. To-Be system configuration.

is reasoned out that the CNC machine #1 has shut down. To keep normal manufacturing operations, machine #1 will broadcast a message about its shutdown to the other machines. Thus, the other machines can give their responsive messages to machine #1 on whether they can or cannot undertake the task. Finally, a scheduling strategy that recommends machine #2 to undertake the task of machine #1 is applied to the production system.

(3) Once all the manufacturing operations are finished, a product is generated for delivery.

From this example, one can note that some decisions on production scheduling, which are traditionally made in EISs by humans, could be managed by CPPS, by adding intelligence capabilities to the elements of CPPS. This will minimize response times, increase the flexibility and autonomy of the entire system, make the system self-aware and self-configurable and have minimal intervention from humans.

7. Conclusion and outlook

CPPSs can be considered as extremely important advances in the development of production systems to progress towards Smart Manufacturing or Industry 4.0. Transformation solutions of legacy systems into CPPSs are being proposed by academics. However, existing studies only focused on the transformation of specific elements of CPPSs (i.e., retrofit of machine tools), without considering all elements of CPPSs especially involved EISs. This work aims to propose a method for supporting the transformation of an existing production system with its EISs into a true CPPS.

The contributions of this work are: (1) According to the 5C Architecture and the enterprise modelling standards, a meta-model that describes the main object classes that constitute CPPSs is proposed. In particular, it includes three dimensions of EISs: informational, technological and organizational dimensions, respectively; and (2) by instantiating the meta-model, a method for supporting the transformation of an existing production system with its integrated EISs into a CPPS is proposed. As a result, a checking matrix is proposed, which is a useful tool to immediately visualize which elements are needed to be added and modified in the As-Is system. This work provides the first attempt to pave the way for the development of urgently needed CPPSs transformation methodologies.

As future work, further exploration and enhancement of the method are needed to ensure its applicability to real-world and large case applications. More specifically, the next step needs to move forward from the concept development stage to the engineering development stage of the system life cycle. As we have already identified three dimensions of EISs to be considered in the transformation, we will study how to transform them, especially the organizational dimension of EISs. In the organizational dimension, we will address the following question: how to transform the decision-making process of EISs? It may include these sub questions: which decisions can automatically be made by CPPSs components locally? which decisions have to be made by humans? What are the impacts of these local decisions on business processes? We will explore potential architectures, techniques and tools to support this transformation.

CRediT authorship contribution statement

Xuan Wu: Methodology, Validation, Writing - Original Draft, Writing - Review & Editing. **Virginie Goepp:** Methodology, Validation, Writing - Review & Editing, Supervision. **Ali Siadat:** Validation, Writing - Review & Editing, Supervision. **François Vernadat:** Methodology, Writing - Review & Editing, Supervision.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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