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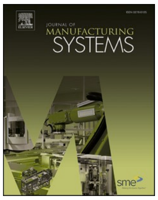

Review

Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review

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ABSTRACT

The industrial scenario is undergoing exponential changes, mainly due to the different technologies that emerge quickly and the ever increasing demand. As a consequence, the number of processing devices and systems in the industries' architectures is also increasing. Entities connectivity, physical/virtual joint functioning, interactivity, interoperability, self-organization, smart decision making, among other factors are fundamental to foster Industry 4.0 (I4.0) potential. We believe that Cyber Physical System (CPS) and Industrial Internet of Things (IIoT) will have a major role in the emerging I4.0. In this context, researchers and experts from major factories are exploring these technologies in order to keep up with this digital transformation, developing IIoT systems and CPS architectures capable of connecting network devices from different information and communications technologies (ICT) systems, virtualizing the companies' assets and integrating them with other manufacturing sectors and companies. This article performs a survey covering the main CPS architecture models available in the industrial environment, emphasizing their key characteristics and technologies, as well as the correlations among them, pointing objectives, advantages and contribution for the IIoT introduction in I4.0. It also provides a literature review covering projects from CPSs and IIoT point-of-view, identifying main technologies employed in current state-of-the-art and how they can meet the I4.0 key features of vertical and horizontal industrial integration. Finally, the article points requirements for current and future challenges, limitations, gaps and necessary changes in the CPS architectures in order to improve and introduce them in the I4.0 scenario.

1. Introduction

The growing need for the increase of the production, efficiency and quality on industrial products led the humans to jointly develop new technologies capable of keeping up with the exponential technology evolution we are experiencing today in production processes [1]. During the eighteenth and nineteenth centuries, the First Industrial Revolution has occurred, mechanizing the production of water and steam energy. Already in the twentieth century, the Second Industrial Revolution introduced electricity into factories, combined with mass production, while the Third Industrial Revolution was marked by the emergence of Computer Numeric Control (CNC) machines, robots, industrial and electronic automation and information technology [2,3].

In the 21st century, we are driven the Fourth Industrial Revolution, also known as Industry 4.0 [4–6], which is an initiative that started in Germany to automate production systems efficiently. A connected and smart world has become a reality through the presence of the Internet in all key areas, allowing the emergence of the Internet of Things and

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Services, capable of networking information, objects, people and resources. For example, in the energy supply sectors, there is the emergence of Smart Grids and in the healthcare one can observe solutions for Smart Health. In the manufacturing perspective, this technological evolution can be described as Industry 4.0.

I4.0 deployment is leveraged by its key features, namely: horizontal integration through value networks, converging information technology systems at different stages of a manufacturing and business planning processes involving data exchange both within a company and between several companies; end-to-end digital integration of engineering across the entire value chain; and vertical integration and networked manufacturing, converging information technology systems at different hierarchical levels for delivering an end-to-end solution. These aspects foster the so called Smart Factory paradigm [7–9], integrating physical and digital worlds through creation of smart products and processes capable of transforming the conventional value chains, forming the Cyber-Physical Systems [10].

As a consequence, merging Internet of Things and Services [11,12] and Cyber Physical Systems in I4.0 [13–15] will impact on industrial processes through the IT-OT convergence in order to promote connected factories [16,17]. In this context, a challenge is to elaborate a reference architecture model to provide technical description and standards for these technologies integration and implementation. In addition, it is frequently discussed how the CPS proposal and other emerging technologies can be deployed in the I4.0 environment to guarantee vertical and horizontal integration, as well as how to enable interoperability among different companies and sectors of the industry [10].

1.1. Motivation

Faced with this reference architecture challenge, many studies have been carried out from the CPS perspective in the scope of I4.0, standardizing ideal frameworks for its use in the industry. As can be seen in Table 1, there are several literature reviews about CPSs on Smart Manufacturing context, focusing on a variety of topics. In [18–20], entities communication is approached by introducing Unmanned Aerial Vehicles (UAV) networks, wireless connectivity, Ethernet, Time-Sensitive Networking (TSN) and 5G mobile networks; in [21–24], a discussion involving security and privacy on CPS systems is performed, also analyzing security vulnerabilities on blockchain; in [25,26], emerging technologies on CPSs have been analyzed, including cloud computing, mobile robots, wireless sensors and Software Defined Networking (SDN); finally, the CPS approaches in general are reviewed in [27–29], introducing surveys related to CPS origin and concepts, in addition to CPS technology standards and characteristics on future Smart Factories.

1.2. Proposal

As can be seen in Table 1, the related works are focused on specific issues and topics in the CPS context, but do not bring their impact on the I4.0 perspective, nor discuss how they can embrace its key features. In contrast to previous surveys, this article provides a novel overview about the entire CPS architecture in the scope of I4.0, highlighting current CPS works in the industrial environment and how they can reach the I4.0 key features, such as vertical and horizontal integration [30–32]. To the best of our knowledge, this paper provides a unique perspective not yet explored in literature. In this context, the article main contributions are:

(i) A review of the main CPS reference architectures models in I4.0, highlighting their main goals, existing industrial technologies, standards and protocols focusing on Open Platform Communications United Architecture (OPC UA), as well as interoperability and correlation among them. It includes 5C Architecture [33], Reference Architectural Model Industrie 4.0 (RAMI 4.0) [34] and Industrial Internet Reference Architecture (IIRA) [35], which will be detailed in Section 3.
(ii) A comprehensive literature review on current CPS solutions developed for factories and a detailed analysis and discussion about how these works correlate to the reference architecture models and how they can reach the I4.0 key features, such as the vertical and horizontal integration.
(iii) A discussion pointing limitations and open issues for the current CPS projects, pointing out possible suggestions to be implemented in order to ensure the improvement of this technology in the industrial scenario and to meet the I4.0 key features in practice.

1.3. Text organization

The remaining of this article is organized as follows. Section 2 provides a brief presentation on Industry 4.0 and IIoT, listing their key concepts and technologies, emphasizing the CPS one, which is the focus of this paper. Section 3 approaches a review of the main CPS reference architecture models for I4.0 (5C Architecture, RAMI 4.0 and IIRA). It is also performed a discussion about the correlation and interoperability among these architectures, in addition to common emerging and legacy technologies, protocols and standards. Section 4 performs a literature review about CPS based on technologies and concepts capable of impacting on I4.0 vertical and horizontal integration. Section 5 presents an analysis about the CPS works, correlating them to the reference architectures described in Section 3 and discussing how they can better meet the key I4.0 features, pointing limitations, open issues and suggestions. Finally, Section 6 concludes this literature review, showing the reader future works and possible improvements in the CPS architectures

Table 1
CPS surveys, their main topics and technologies covered.

Ref.	Topics covered				Overview
	Communication	Security	Emerging technologies	CPS general	
[18]	x				UAV networks for CPSs applications.
[19]	x				Wireless Connectivity for CPSs in Smart Manufacturing.
[20]	x				Ethernet, TSN and 5G telecommunication networks in automation for CPSs.
[21]		x			State-of-art survey on security and privacy for CPSs.
[22]		x			Literature review about security and privacy for CPSs.
[23]		x			Decentralized consensus mechanisms for CPSs using blockchain algorithms.
[24]		x			Smart Contracts security vulnerabilities in the blockchain network.
[25]			x		CPSs with Cloud Computing for mobile robots, wireless sensors and vehicular networks.
[26]			x		SDN approaches and software defined Cyber-Physical Systems.
[27]				x	CPSs in general: Origin, concepts and application.
[28]				x	Review of CPSs technologies standards for advanced manufacturing.
[29]				x	Review of CPSs characteristics for future Smart Factories.

for their application in Industry 4.0.

2. Background

This section covers the necessary concepts for the reader's better understanding about the proposed review. It will be approached a brief presentation of the pillars and concepts of Industry 4.0 and IIoT, and an introduction about the CPS technology, which is the focus of this paper.

2.1. Industry 4.0 and IIoT

Adopted as part of the High-Tech Strategy 2020 Action Plan in 2011, Industry 4.0 is a strategic initiative of the German government developed to revolutionize the manufacturing process [36–47], by bringing together a set of pillars that enable the fusion of the physical, digital, human and biological worlds, fostering new technologies in the industrial environment, as illustrated in Fig. 1. Among these pillars, the introduction of the Internet of Things and Services in the factory environment [48] (also known as IIoT, Industrial Internet, Internet of Everything and Internet 4.0 [49]), can be highlighted for the emergence of the fourth industrial revolution.

IIoT contributes for the industrial scenario through its concepts and technologies to develop a network of industrial devices [50–54], which are composed by sensors and complex industrial robots and actuators, connected to communication technologies that make possible the systems to monitor, analyze, deliver, collect and change data quickly and easily [55]. Consequently, the Industrial Internet allows Industry 4.0 to reach its key features, which includes: horizontal integration through value networks for supporting companies business strategies; end-to-end engineering by integrating the digital and real worlds across the entire value chain; and vertical integration by networking manufacturing systems.

As a consequence, IIoT combined to I4.0 can generate a lot of benefits to the industrial environments, such as the Information Technologies-Operational Technologies (IT-OT) convergence. The IT and OT domains are converging, integrating the manufacturing control systems and data storage, computing and communication. While OT includes hardware and software systems to control shop floor processes, they were usually not integrated into a network or a larger computerized system. Nowadays, the IT-OT convergence allows OT components to communicate directly with other machines, as well as centralized servers, exchanging information through an IT network [56].

In addition, it can also be noted the reduction in quantity of required operations; better performance and use of assets; minimization of the asset's cycle-cost; faster decision making; purchase and sale of products as services, expanding business opportunities and making possible the emergence of new business models for manufacturing [57]. Therefore, the requirements to the emergence of factories that establish global networks incorporating assets, storage systems and productions processes in the shape of Cyber-Physical Systems are the key topics of this survey [58,59].

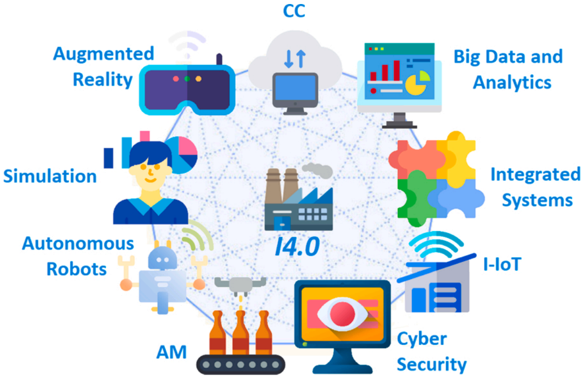


Fig. 1. The pillars of the Industry 4.0.

Despite all the benefits and advantages by implementing IIoT and Industry 4.0, the proposal is quite complex, since the great amount of digitization and networking of companies involved increases the number of architectures created by different authors and, consequently, possible problems related to communication networking and systems interoperability [60].

2.2. Cyber-physical systems

As one of the main technologies of I4.0, CPS is proposed by the American scientist Hellen Gil in 2006 in the National Science Foundation [61]. CPS addresses several concepts also present in IIoT. It is responsible for the link between virtual spaces and physical reality, through the integration of networking, computing and storage, making possible an interactive industrial environment, creating Smart Factories. In this perspective, there is the emergence of smart products uniquely identifiable that can be located in real-time [10].

CPSs are automated distributed systems that integrate physical reality with communication networks and computing infrastructures [62,63]. Unlike traditional embedded systems, their main focus is on networking various devices for I4.0 [64]. Therefore, it consists in a control unit able to handle sensors and actuators, which interact with the physical world, processing obtained data and exchanging them with other systems and/or Cloud services through a communication interface. In other words, the CPSs can be seen as systems able to send and receive data from devices through a network.

An important characteristic of a CPS is its ability to obtain information and services in real-time, independently from its location [65], by implementing Internet access in the manufacturing machines [66]. In addition to real-time communication, it is necessary to ensure its stability, reliability, efficiency and security in operations [67]. For this aim, one of the goals of the I4.0 is to provide a high level security support in all layers of the CPS architecture, protecting confidential information, while providing data anonymity [68].

In the I4.0 scenario, CPSs cover not only machines and products, but also clients, service providers and stocks, ensuring an appropriate interaction on all the areas being executed autonomously [69].

CPSs are applied to several areas. Among them, it can be cited Manufacturing [70], Healthy [71], Renewable Energy [72], Smart Building [73], Transport [74], Agriculture areas [75], and Computers' Network [76,77]. In the Manufacturing area, it is used for the auto-monitoring, production control and information sharing in real-time. In the Health area, it can be used in the real-time remote monitoring of patients physical conditions. In the Renewable Energy sector, sensors allow the network monitoring and control, ensuring reliability and efficiency in the energy consumption. In the Smart Building area, the interaction between CPS and smart devices can reduce the energy consumption and increase the protection, safety and comfort for the residents. In the Transport area, this technology allows the communication between vehicles and the infrastructure, sharing information such as traffic intensity, congestion location and accidents to prevent further accidents or congestion. In the Agriculture sector, information about the weather and several resources, such as irrigation and humidity data, can be collected, increasing the precision in the agricultural management systems. Finally, in the Computers' Networks, this concept is applied to the better understanding of the systems and users behaviors in virtual environments.

Among the existing architecture proposals for CPS, the 5C Architecture can be highlighted since it is a well-known reference model with widespread usage while developing cyber-physical systems. With the fourth industrial revolution and the increase in data and industrial devices, other reference architectures were created with proposals related to CPSs, such as RAMI 4.0 in the manufacturing sector for device virtualization in the value chain, and IIRA for integration and cooperation among industries with a focus on IIoT.

3. Review of the CPS reference architecture models

As described in previous sections, I4.0 and IIoT implementations suffer from some limitations, such as security support, connectivity, standardization and interoperability among devices [78–80]. To address these gaps, some CPS architecture reference models have been standardized. In this section, the main CPS reference architecture will be approached. The methodology used for the selection of these architectures was based on a literature review focused on keywords related to the CPS architectures widespread in the scenario and a deep research about the main I4.0 and IIoT initiatives around the world. As the main initiatives, it can be cited the Platform Industry 4.0, which has the collaboration of companies as partners in order to promote the digital transformation of manufacturing in Germany [81]; and the Industrial Internet Consortium (IIC), which has a collaborative council of senior executives from industry in order to promote the technologies necessary to accelerate the growth of the industrial internet [82]. Based on the methodology adopted, in this section, the 5C Architecture, RAMI 4.0 and IIRA models will be presented, making a brief description of their operations, highlighting implementation issues behind CPS concepts in each architecture. In addition, it will be discussed the correlation among these reference architecture models, as well as existing standards and protocols implemented to ensure the correct operation of them, detailing emerging and legacy technologies, their key enablers and the security perspective.

3.1. Overview of 5C

The 5C Architecture is a proposal implemented by [83] based on automation processes models, and it is centered in a data acquisition model for industrial devices. This architecture consists of 5 levels for the system operation, as shown in Fig. 2.

The 5C Architecture Levels are defined in Table 2. Although 5C model provides an implementation guide for CPS ecosystems, containing good guidelines, some basic characteristics were not taking into account for its application in the I4.0 scenario [84]. First, it is necessary to consider the information flow not only in the vertical direction, but also horizontally between products and machines, in which they can be processed according to the client specifications.

Furthermore, it is important to predict a model able to perform the connectivity among clients and service providers in the industry, in other words, among distinct industries, since I4.0 services must be connected to the Internet along with the controllers, machines, products and other objects. These services include stock management, request of load transport and purchase. With factories' virtualization, these processes and services can be automated, making possible the so called Internet of Services (IoS), that is one of the main pillars of the I4.0 [85].

Table 2
Overview of the 5C architecture levels.

5C level	Description
Smart Connection	Integration of the physical devices connected in a communication network.
Data-to-Information Conversion	Conversion from monitored device data to information, in order to understand them and apply to the physical world.
Cybernetic	Use of information for the device virtualization. It is also the level responsible for the communication among assets.
Cognition	Functions of monitoring and prognostics for failure prediction and maintenance optimization.
Configuration	Transmission from the virtual to the physical world, making the machines self-adjusting and self-adaptive.

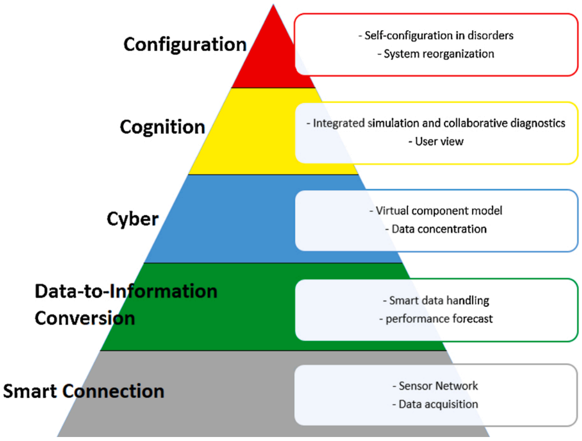


Fig. 2. 5C Architecture of CPS. Adapted from [83].

Since existence of I4.0 architectures are not complete in the context of Smart Factories [86], other reference models were created to meet the needs of the current scenario and to provide a I4.0 standardization [87], such as RAMI 4.0 and IIRA. On these architectures, CPS concepts are covered and their functionalities will be highlighted on the next subsections.

3.2. Overview of RAMI 4.0

RAMI 4.0 is an Architecture Reference Model for the Industry 4.0, created by Platform Industrie 4.0 effort to define communication structures and a common language within the factory with its own vocabulary, semantics and syntax. Such language enables integration of IoT and services in the I4.0 context, connecting them to the rest of the world [88]. It is a Service Oriented Architecture (SOA) that combines IT components to promote the main aspects of I4.0, such as the horizontal integration among factory networks and plants; and the vertical integration within a factory, with products at one end and the Cloud at another.

This architecture is represented by a three-dimensional map composed of 3 axes, termed as Hierarchy Levels, Product Life-cycle and Architecture Layers, which addresses Industry 4.0 issues in a structured manner, ensuring that all participants involved in the factory can understand each other and connecting the entire manufacturing process. Fig. 3 shows the three-dimensional model of the RAMI 4.0.

The Axis 1, responsible for the Hierarchy Levels, intends to change the proposed idea of the Industry 3.0, in which the infrastructure was based in specialized hardware, limiting its functions; the communication

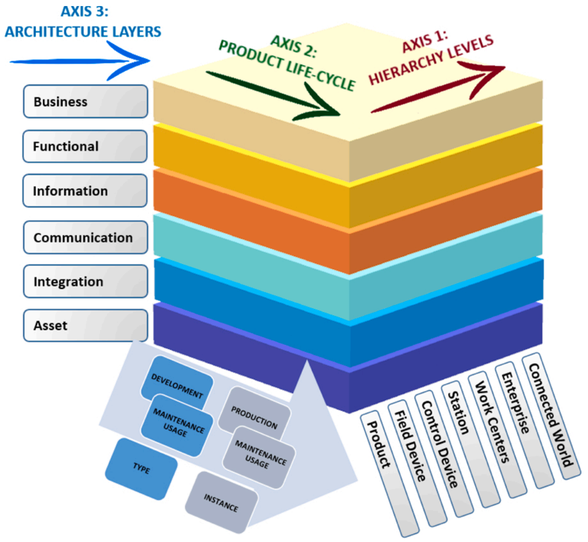


Fig. 3. Three-dimensional model of the RAMI 4.0. Adapted from [89].

model based on hierarchy; and the products isolated one another. In the I4.0, the objective is to disseminate the idea of flexible machine and systems, distributed functions over the network ensuring the interaction and communication among all the involved participants, and products being seen as part of the architecture.

The Axis 2, responsible for the Product Life-cycle, describes assets in the value chain from its idea, development and maintenance of an asset type up to its production, usage and maintenance. Assets are objects that have a value for an organization, such as a device or equipment [90].

The Axis 3 is in charge of the development of the CPS proposal, which is the focus of this article, and it will be detailed below. It encompasses the Architecture Layers of the RAMI 4.0, which is defined in Table 3 [90].

The vertical axis of the Architectures' Layers has the purpose of describing the physical entities of the industrial network being modeled, such as devices, equipment and machines, and mapping them to their respective virtual representations as Industry 4.0 Components (I4.0C), which describes in detail the properties of a CPS.

I4.0C are objects globally and uniquely identifiable with communication capacity [88], and it is represented by an asset and an Administration Shell (AS), which contains relevant information for the management of the asset. It also includes assets' technical functionalities, storing all data and information about them. AS is the standardized interface for communication networks, capable to connect the physical things to the Industry 4.0. The I4.0C can be related to an equipment, machine or product in the Asset Layer and the AS in the Information, Functional and Business Layers. For example, an asset, such as a machine, represents the physical part and the AS represents its digital part. Furthermore, all Administration Shells (i.e. digital twins) in the system are managed by a Superior System Administration Shell (SAS), capable of combining the intercommunication of them [91].

3.3. Overview of IIRA

IIRA is an open architecture developed by IIC based on IIoT standards, emphasizing the interoperability among industries [90]. This model is organized in four Viewpoints to identify and classify the common preoccupations of an IIoT architecture. Thus, the concerns about IIoT systems are systematically analyzed and addressed, and then, their results are documented as models and other information in the respective Views associated to the Viewpoints [82].

The four Viewpoints are: (i) Business Viewpoint, (ii) Usage Viewpoint, (iii) Implementation Viewpoint and (iv) Functional Viewpoint. A brief description about Business, Usage and Implementation Viewpoints is presented below; and then it will be highlighted the Functional Viewpoint with a more detailed description, due to the fact that it encompasses the CPS proposal, which is the key objective of this literature review.

The Business Viewpoint identifies participants and their business views, values and objectives in IIoT systems. The Usage Viewpoint describes the IIoT system's expectation to provide the intended business objectives. The Implementation Viewpoint identifies the technologies required to implement the functional components, their communication schemes and their life-cycle procedures, such as topology, structure and technical distribution and description of components.

Finally, the Functional Viewpoint focuses in the functional components and the inter-relation and interaction among them and with the external elements in the environment. Fig. 4 shows the Functional Viewpoint architecture, their Crosscutting Functions and Systems Characteristics.

As can be seen in Fig. 4, the Functional Viewpoint is divided into five domains, which are described in Table 4 [82], i.e. control, operation, information, application, and business. In addition to these Functional Domains, which are responsible for describing the main system functions, there are the Crosscutting Functions aimed at enabling them; as well as the System Characteristics, which are properties or emergent behaviors of the integrating parts of an IIRA system [90]. Among the Crosscutting Functions, the Connectivity function is responsible for the connection of the system functions one another, ensuring the interaction among them for their completely functionality.

Table 3
Overview of the Architecture Layer of the RAMI 4.0.

Architecture Layers	Description
Asset	Representation of physical things in the real world. These things can be components, hardware, documents and human workers.
Integration	Transition from the physical to the virtual world. It represents the visible assets and their digital capacities, consequently providing control via computers, making it possible to generate events for themselves.
Communication	Standardized communication from services and events or data to the Information Layer, and from services and control commands to the Integration Layer. It focuses on transmission mechanisms, networks discovery and the connection among them.
Information	Description of services and data that can be offered, used, generated or modified by the technical functionality of the asset.
Functional	Description of the logical functions of an asset, such as its technical functionality, in the context of I4.0.
Business	Organization of the services to create business processes and links among different ones, supporting business models under legal and regulatory constraints.

3.4. Correlation among 5C Architecture, RAMI 4.0 and IIRA

This subsection consists of analyzing the correlation among the architecture reference models previously described, highlighting their main goals and the interoperability among them.

First, it is necessary to emphasize that, although the mentioned architectures have CPS concepts, their proposals are target in different ways. The following topics summarize the main goals and the ideal development scenario for each architecture:

(i) The 5C Architecture is focused on assets data acquisition and processing, commonly used in embedded systems and small

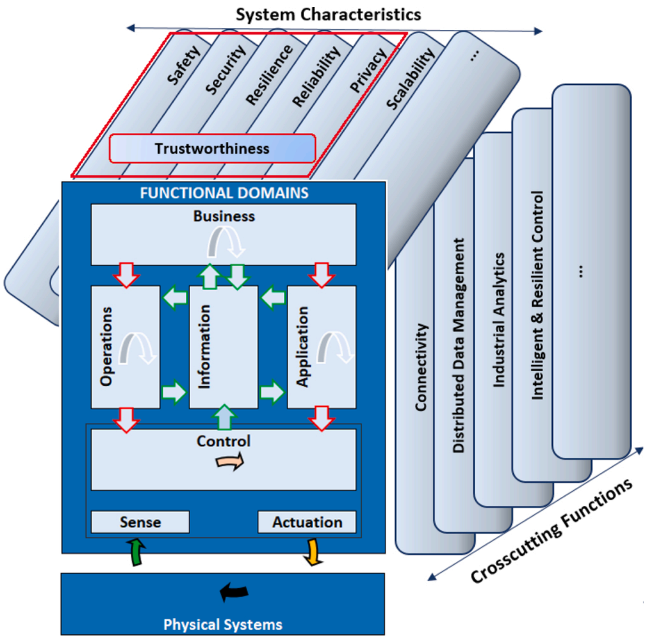


Fig. 4. IIRA functional domains, crosscutting functions and system characteristics. Adapted from [82].

Table 4
Overview of the domains of the IIRA.

IIRA domains	Description
Control	Functions for industrial control systems, such as: the sensor data reading and writing; communication among sensors, actuators, controllers, gateways and other devices; abstraction of the devices through the representation of a virtual entity; interpretation of data collected by sensors and other devices; operation management of control systems, such as configuration and firmware/software updates; and the execution of control logic for the understanding of the states, conditions and system's behavior.
Operation	Functions for prognostics, management, optimization and monitoring of the systems in the Control Domain, such as: configuring, recording and tracking assets; management commands transmission; detection and prediction of problem occurrences through real-time monitoring of assets; predictive analysis of IIoT systems based on historical data operating and performance; reduction of the energy consumption for the system optimization.
Information	Functions for domain's data collection, and then the data transformation, modeling and analyzing to acquire high-level system-awareness. It includes a set of functions responsible for data collection of operation and sensor states in all domains; and a set of functions for data modeling and analytics.
Application	Functions capable of implementing application logic while performing specific business functionalities. This domain applies: a set of rules with specific functionalities required in considered use cases; and a set of functions whose application can expose their functionalities to other applications that consume them; or user interfaces for human interactions.
Business	End-to-end operation of IIoT systems, integrating them with specific business functions of traditional or new system types.

industrial environments. It is one of the first CPS architectures disseminated in the literature;

(ii) Based on the Smart Grid Architecture Model (SGAM), RAMI 4.0 was created to adapt the CPS architecture in the I4.0 scenario. It defines how a manufacturing plant can operate, and it is centered in the manufacturing sector deeply through the product life-cycle, integrating the value chain of the company;

(iii) With IIoT proposal as a highlight, IIRA is based on the ISO/IEC/IEEE 42010 and it defines how an IIoT system can be developed, centered in IIoT systems concerns in all sectors, such as products' operation and maintenance, business and mainly in the interoperability among industries.

The Functional Mapping among 5C Architecture, IIRA and RAMI 4.0 is illustrated in Fig. 5. As can be seen in this figure, there are similarities among the architectures, whose domains from IIRA implements similar functions with the respective levels from the 5C Architecture and layers from the RAMI 4.0. In addition, there are correlation and interoperability among the reference models.

However, RAMI 4.0 and IIRA are been more discussed in the industrial community, due to the fact that these architectures are mainly focused on the I4.0 proposals, developing application, services and business ideas for the integration among industries and for the entire manufacturing sector.

Then, according to [90], in order to ensure the interoperability between RAMI 4.0 and IIRA specifically, there are some required concepts, such as standardized functions and semantics, and unique identifiers by property and assets. Therefore, identification, networking, semantics and functional mapping are fundamental concepts for the interoperability between IIoT and Industry 4.0 systems. For example, services of operation and maintenance under IIoT systems (IIRA) requires technical data about the materials, components and the entire manufacturing process of a product that, on the other hand, are available from their manufacturers (RAMI 4.0). For the correct interoperability among these systems, the standardization of the parameters cited above allows the recognition of the same product and its respective data for both RAMI 4.0 and IIRA architectures.

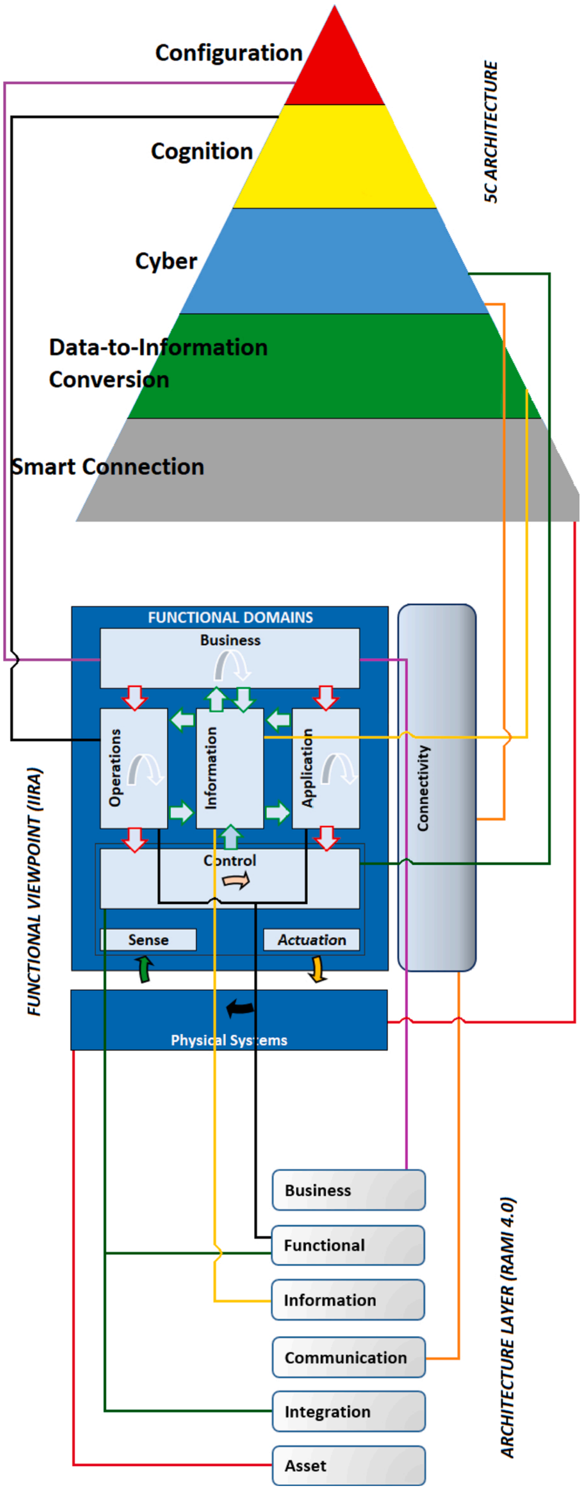


Fig. 5. Functional mapping among 5C Architecture, IIRA and RAMI 4.0.

3.5. Standards/protocols for CPS architectures

This subsection performs an overview of industrial standards/protocols used in CPS architectures to ensure that they meet the I4.0 needs, in addition to a discussion related to how to enable new technologies on legacy systems, also covering system's security. Table 5 illustrates the standards/protocols commonly used in the CPS architecture based on reference models structure [28,90,92–95].

Regarding to the physical device, it can be highlighted ISO/TS

Table 5
Architecture reference models and related standards/protocols.

Function description	Architecture reference models	Standards and protocols
Physical Industrial Asset	RAMI 4.0 Asset Layer IIRA Physical System5 C Smart Connection Level	ISO/TS 14649-201, IEC 61360
Virtual representation of assets and functions for industrial control systems	RAMI 4.0 Integration and Functional Layers IIRA Control Domain5 C Cybernetic Level	ModBus, ISO 15926, ISO 15746
Standardized communication for data, assets and services	RAMI 4.0 Communication Layer IIRA Connectivity Crosscutting Function 5C Cybernetic Level	RFC 2616 (HTTP), IEC 61784, IEC 29182-1, RFC 7540 (HTTP2), TCP, UDP, IP, 6LoWPAN, CoAP, MQTT, DDS, IEC 62541 (OPC UA), Web Services, oneM2M, TSN, 5G
Data processing for collecting, transformation, modeling and analyzing	RAMI 4.0 Information Layer IIRA Information Domain 5C Data-to-Information Conversion Level	IEC 62714, IEC 24760, ISO 19629 **Semantics:** SPARQL, RDF(S), OWL, RIF/SRWL
Runtime environment for applications, assets technical functionality, in addition to management and maintenance functions	RAMI 4.0 Functional Layer IIRA Application and Operation Domains 5C Cognition Level	IEC 62337, ISO 19629
Business functions and support to business models	RAMI 4.0 Business Layer IIRA Business Domain5 C Configuration Level	ISO 19439, B2MML, ISO 22400, ISO 13374, ISO 15704

14649-201 and IEC 61360, responsible for, respectively, specifying machine description data elements and providing a basis for the clear definition of characteristic properties of all industrial components.

In order to help in the asset virtual representation, ISO 15926 specifies an ontology for its planning at process plants. Functions for industrial control systems can be performed through the serial ModBus protocol employed in Programmable Logic Controllers (PLCs) and ISO 15746. They are responsible for the integration of advanced process control for manufacturing systems [92].

The set of standards for data processing and conversion from industrial data to information includes: IEC 24760 that defines terms for identity management applied on information systems; ISO 19629 to structure semantic concepts that capture and exchange manufacturing process information; and IEC 62714, which is a solution for industrial data exchange in the Automation Markup Language (AML) format. Besides, the most used semantics on CPS systems for I4.0 are Resource Description Framework (RDF), Ontology Web Language (OWL), SPARQL Protocol and RDF Query Language (SPARQL) and Rule Interchange Format/ Semantic Web Rule Language (RIF/SRWL) [93]. For describing the assets technical functionality, the ISO 19629 previously described is also recommended, in addition to IEC 62337, responsible for the commissioning of electrical, instrumentation and control systems in the process industry.

In addition, standards for business functions and support to business models can be addressed by: ISO 19439, providing unified conceptual basis for model-based enterprise engineering. It ensures convergence among various modeling methodologies; ISO 22400 related to Key Performance Indicators (KPIs) for manufacturing operations management; ISO 13374 for condition monitoring and diagnostics of machines; ISO 15704 to identify requirements for enterprise-reference architectures and methodologies; and Business To Manufacturing Markup Language (B2MML), which is an Extensible Markup Language (XML) implementation defined as a common data to link Enterprise Resource Planning (ERP) and supply chain management systems with manufacturing systems [94].

Regarding to communication functions, there are several standards that can be divided according to the ISO/OSI model. For 5–7 OSI layers, application-level protocols including Hypertext Transfer Protocol (HTTP), HTTP 2, Constrained Application Protocol (CoAP) and Message Queue Telemetry Transport (MQTT) can be highlighted. Finally, the transport network is composed by Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), while the Internet Protocol (IP) is the common protocol for the network one. In addition, it can be cited 6LoWPAN as an acronym of IPv6 over Low power Wireless Personal Area Networks, which is widely used on IIoT systems; and Time Sensitive Networking (TSN) and 5G as emerging technologies [90]. Finally, IEC 61784 and IEC 29182-1 standards are also used for, respectively, discussing about Ethernet-real-time-enabled Industrial communication networks and sensor networks characteristics.

In order to ensure the complete interoperability among the function descriptions and protocols described in Table 5, the IIC defined The Data Distribution Service (DDS), Web Services, oneM2M and OPC UA as potential IIoT connectivity core standards [96]. DDS is referred as a data-centric middleware standard to connect industrial components (devices or gateways or applications) to another ones. Used in the application domain, Web Services are devised for human user interaction interfaces, but it is not efficient for device-to-device communication and real-time communication. The oneM2M standard include applications hosted on connected machines and devices, enterprise systems and mobile devices and their efficient and secure intercommunication. Finally, OPC UA will be focused on following Subsection, since it is considered a core standard for both RAMI 4.0 and IIRA architectures and essential for CPSs on I4.0 context.

3.5.1. OPC UA

OPC UA is a SOA-based communication protocol responsible for exchanging data among industrial control systems and the enterprise levels [97], making possible the interoperability of components as described in Table 5. For the architecture reference models previously described, OPC UA is designed to RAMI 4.0 Communication Layer, IIRA Connectivity Crosscutting Function and 5C Cybernetic Level, being a key technology for ensuring the industrial vertical integration and interconnecting the entire CPS architecture.

In this platform-independent standard, the communication among various systems and devices can be performed by using Client/Server or Publish/Subscribe communication models. In the OPC UA Client/Server, OPC UA Binary is employed, together with OPC UA XML and JavaScript Programming Language (JSON) data encoding standards to describe how to construct these request/response messages. They are sent through OPC UA Connection Protocol (UACP), OPC UA TCP, Simple Object Access Protocol (SOAP) over HTTP, OPC UA HTTPS and Web Sockets transport protocols according to the application. On the other hand, the OPC UA Publish/Subscribe (Pub/Sub) uses Message Mappings to specifies the network messages structure and encoding. These Message Mappings include UADP and JSON, representing the payloads in the Transport Protocol Mappings for publishing messages, which are OPC UA UDP, OPC UA Ethernet, Advanced Message Queuing Protocol (AMQP) and Message Queuing Telemetry Transport (MQTT) [98].

For PLC level application, OPC UA can be combined with AML. Based on XML, AutomationML describes which data and information is exchanged and stored, while OPC UA determines how data and information exchange takes place. AML also combines existing established XML data formats, such as: (i) CAEX (IEC 62424) for object topologies including hierarchies, properties and relations of objects; (ii) PLC Open XML (IEC 61131) for discrete behavior of objects; and (iii) COLLADA (ISO/PAS 17506) for geometries and kinematics of objects [99]. The integration of these technologies is performed through the standard DIN SPEC 16592, responsible for combining AML engineering data with OPC UA online information.

On the other hand, in a one-to-many scenario there is an issue related to the huge volume of resource allocation on devices. For this, a solution is the OPC UA Publish/Subscribe (Pub/Sub) specification [100]. In this case, the data exchange between publisher and subscriber can be implemented by using broker and broker-less concepts, as illustrated in Fig. 6. In the first one, the broker is a middleware between publisher and subscriber to provide data exchange. The sender publishes the message to the broker using AMQP or MQTT protocols and the receiver notifies its interest, finally receiving the message. In the second case, the network infrastructure is used to message delivering by sending it to a UDP multicast group, ensuring lower latencies [101].

In order to ensure the interoperability among different systems, standards and protocols, there is the implementation of gateways as a forwarding component, enabling various networks to be connected. The gateway is typically divided into: core gateway to connect via core connectivity standards (a.k.a. DDS, Web Services, oneM2M, OPC UA); and non-core gateways to connect a specific technology used in the architecture layers to a core connectivity standard.

The core gateway supports communication among various systems that can employ different core standards on their respective architectures. In the OPC UA perspective, some solutions can be implemented. For the interoperability between OPC UA and DDS, the Open Management Group (OMG) and OPC jointly develop the OPC UA/DDS Gateway to create a bi-directional bridge among them, mapping DDS to the client/server and lightweight OPC UA UDP Pub/Sub models [102]. Furthermore, according to the oneM2M Organization, the interaction between OPC UA and oneM2M can be performed based on Interworking Proxy Application Entity (IPE), supporting OPC UA interface and mapping OPC UA data models to oneM2M resources [103]. In addition, OPC UA clients can connect to OPC UA servers via HTTP. On the other hand, in the non-core gateway perspective, there are commercially-available gateways between OPC UA and many industrial protocols, such as ModBus, Profibus, Foundation Fieldbus, among others [96].

In addition to commercial solutions provided by different companies and organizations, the literature points several researches related to OPC UA gateways, such as: OPC UA based universal edge gateway for legacy equipment [104]; interoperability through Smart OPC UA/DDS gateway [105]; OPC UA/ModBus gateway applied to an energy recovery system identification [106]; power and cost-reduced OPC UA Gateway for IIoT Platforms [107]; OPC UA-based gateway for supporting different fieldbus protocols [108]; OPC UA Gateway Solution for the Automotive Industry through a scalable service Oriented middleware over IP [109]; and OPC UA server as a gateway for sharing CAN network data [110].

Although benefits related to interoperability among different standards/protocols and systems combined with the huge data volume of industrial devices connected to the Internet, the security becomes an essential topic for discussion by I4.0 research community [111]. To deal this issue, the Transport Layer Security (TLS) is being widely used in the industrial environment, ensuring private connection through symmetric cryptography of the data transmitted; authentication using public-key cryptography; and reliability through message integrity check preventing undetected loss or data alteration during transmission.

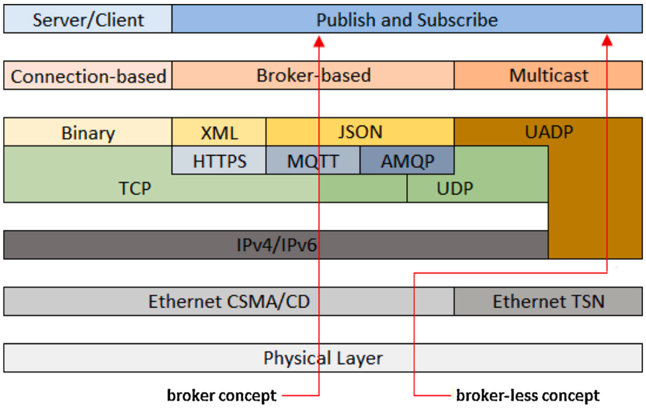


Fig. 6. Broker and broker-less concepts for OPC UA Pub/Sub.

Besides being implemented in new technologies such as OPC UA, the TLC cryptographic protocol can also be used on legacy ones, such as ModBus TCP. ModBus protocol does not include a communication validation mechanism between master and slave devices. Therefore, TLS inclusion mitigates this lack by preventing an attacker from issuing arbitrary commands, being a robust security solution [112].

4. Literature review of CPSs projects for Industry 4.0

Based on reference architecture models for Industry 4.0 and IIoT presented in Section 3 [83,88,82], some projects emerged to develop CPS projects in the factory environment. A comprehensive analysis of the current industrial CPS works have been performed in order to point their gaps, solutions and suggestions for ensuring I4.0 key features.

For the selection of CPS works state-of-the-art, we have performed a detailed literature review from different publishers that contribute through scientific articles related to CPS in the I4.0 context. These publishers include IEEE Xplore, Elsevier Journals, Horizon 2020 Projects, Brazilian Symposium on Intelligent Automation, Hindawi Publishing Corporation, Springer Verlag, Engineering and Applied Research Journal, Science and Technology Publications (SciTePress) and Brazilian Digital Library of Theses and Dissertations.

Based on these literature sources, we adopted as an exclusion criteria the selection of CPS manuscripts from 2011 to the present day, focusing on recent ones. This time range was designed due to the fact that the first CPS reference architecture widespread on industrial environments was created in 2013 (5C Architecture) and it could make possible to keep up with the evolution of CPS architectures before and after the emergence of these reference models for I4.0.

Finally, to aim our survey on CPS works in the I4.0 context and discuss how they can reach the industrial vertical and horizontal integration, the keywords adopted have been defined as the aforementioned D1-D8 Dimensions, which are ingredients that enable these works to meet I4.0 key features. These D1-D8 Dimensions have been divided into: D1 (IIoT), D2 (Cloud Computing) and D3 (Big Data) as I4.0 Base technologies Dimensions; D4 (Semantics), D5 (ID/Loc) and D6 (Digital Twins) as Dimensions for the emergence of the I4.0 vertical integration; and D7 (SOA) and D8 (Connectivity) as Dimensions for I4.0 horizontal integration.

The I4.0 Base technologies' Dimensions are defined as technologies capable of supporting the Smart Factories in the industrial scenario, which are essential for the introduction of CPSs in the I4.0 context [113]. On the other hand, the Dimensions for I4.0 vertical integration include a set of technologies and concepts that enable the integration of industrial hierarchical levels, such as: the factory floor, operation, production, control and business planning levels. Finally, the Dimensions for I4.0 horizontal integration consist of a set of technologies and solutions for the digitization of the entire supply and value chain, integrating different companies and clients. In this context, it is necessary to evaluate concepts from the perspective of data exchange and collaboration across corporate borders, improving the existing IT link between supplier and customer, which is an important factor for the digital information sharing and horizontal integration [114]. Table 6 describes the D1-D8 Dimensions keywords employed in the literature review.

Firstly, in Table 7, it will be illustrated an overview about the surveyed works involving CPS projects and their respective I4.0 key features approached, which are the vertical and horizontal integration previously discussed. Therefore, these projects will be detailed for future

Table 6
The set of keywords employed for articles selection in this literature review are the D1-D8 Dimensions on CPSs for meeting the I4.0 key features.

CPS concepts on I4.0	Dimension	Technology	Description
I4.0 Base Technologies	D1	IIoT [115–117]	IIoT is the infrastructure that allows CPSs to be networked, being an industrial network of unique identifiers assets connected via Internet for exchanging data in real time.
	D2	Cloud Computing [118–121,32]	Cloud Computing is used in the I4.0 context for data storage and computing capacity, supporting a more robust industrial system.
	D3	Big Data [122–125]	Given the emergence of IIoT and a huge volume of networked devices, Big Data is the technology for analysis and interpretation of large volume of data of great variety.
I4.0 Vertical Integration	D4	Semantics [126–128]	Semantic models offers the access to information in the context of the real world in a consistent way.
	D5	ID/Loc [129–131]	ID/Loc is a proposal adopted in the IIoT scenario, and consists in how to uniquely identify and locate the assets connected in the network.
	D6	Digital Twins [132–134]	Digital Twins is a digital abstraction of a physical entity to virtualize assets, working as a detailed simulation of them and allowing to users device acting in the real world through the virtual one.
I4.0 Horizontal Integration	D7	SOA [135–137, 30,31]	SOA allows the extension of industrial services concept to clients and servers, and it can be applied for integrating different companies through development of services and applications as cloud services.
	D8	Connectivity [138,139]	Due to the multitude of IT systems that hamper collaborative efforts and information sharing among companies [114], Connectivity refers to communication concepts, standards and protocols for reaching the horizontal integration.

analysis in the following Sections.

In [140], it has been proposed a SOA-based Manufacturing Resources Virtualization Model (MRVM) and manufacturing resources service composition. As a result, the project comprises the I4.0 features of manufacturing digitization and details of the implementation process.

Karakostas et al. [141] developed a Domain Name System (DNS) architecture able to translate unique identifiers (IDs) of physical objects to addresses of objects in the network, providing name resolution to support ID/Locator decoupling, being considered in modern mobility-friendly architectures, such as MobilityFirst [160] and Nova-Genesis [161].

In [142], the authors developed in Stuttgart a CPS extension in an embedded system using the Cerebot 23MX7 edge microcontroller as a gateway, connecting to cloud via HTTP and with a coffee machine via Controller Area Network (CAN) communication. An Android application and a website for CPS operation have been created for data exchange with the machine by accessing the cloud via smartphone, making possible to identify defective or depleted products.

Table 7
Overview of the selected CPS works and their relations to I4.0 key features.

Ref.	Short description	Vertical integration	Horizontal integration
[140]	Dynamic Manufacturing Resource Architecture (MRA).	x	x
[141]	DNS-based architecture to translate unique IDs of physical objects to object addresses.	x	
[142]	CPS application for an industrial coffee machine.	x	x
[143]	Architecture based on OPC.NET for industrial and smart building sectors.		x
[144]	CPS Architecture for power equipment detection based on Industry 4.0.	x	x
[145]	Semantic representation of I4.0 devices with RDF-based Administration Shell (AS).	x	
[146]	Cloud Collaborative Manufacturing Networks (C2NET): optimization of asset processes.	x	x
[147]	Improved 5C Architecture for I4.0.		x
[148]	Adapted 5C Architecture for I4.0.		x
[149]	A novel architecture for large-scale digital twins (uDiT).	x	
[150]	SOA on smart manufacturing utilities for identification, data access and control.	x	x
[151]	NodeI4.0: added 5C Architecture Smart Connection Layer to legacy systems.	x	
[152]	Cyber-Physical Manufacturing Cloud (CPMC) integrating cloud, CPSs and manufacturing.	x	x
[153]	Cloud-Based Rapid Elastic Manufacturing (CREMA) for agile and scalable manufacturing.	x	x
[154]	Multi-level, point-of-view engineering method for CPS.	x	
[155]	5C Architecture for the industrial environment.	x	
[156]	Architecture for equipment discovery in manufacturing processes for I4.0.	x	x
[157]	Resource virtualization: A core technology for developing CPSs on production.	x	
[158]	A cloud-based CPS for adaptive shop-floor scheduling and condition-based maintenance.	x	
[159]	A Cyber-Physical Machine Tools Platform using OPC UA and MTConnect.	x	x

Ungurean et al. [143] have proposed an architecture based on OPC. Net specifications, allowing the client to participate in the industrial processes. In addition, a data server module was created for sending and receiving data from sensor network via Zigbee and fieldbus in smart buildings and CANopen and Modbus in industrial environments. In addition, a Human Machine Interface (HMI) application enables customers to read sensor information and send commands. As a benefit, the integration of new fieldbuses into the OPC.Net server did not require an upgrade or recompilation of the entire application.

Yu et al. [144] proposed a network architecture so that autonomous vehicles could transport electrical devices identifiable via QR Codes to stations named as testing areas. The network architecture was divided into: Main Control Network Layer for device monitoring based on TCP/IP and UDP and a Zigbee wireless network; Intermediate Interaction Layer for data communication and multimedia equipment; and Station Network Layer or accessing the subnets of the various stations to connect to the Intermediate Layer. The network, based on SOA and Java 2 Enterprise Edition (J2EE) showed an improvement in electrical equipment detection efficiency of 300%.

In [145], an approach has been proposed to semantically represent Industry 4.0 device information with an RDF-based Administration Shell using a Uniform Resource Identifier/Internationalized Resource Identifier (URI/IRI) identification scheme. Unified access to information has been done through SPARQL. A semantic AS from a servo motor controller was generated and the authors intend to expand AS vocabulary to a wider range of devices.

In [146], a European project aimed at optimizing and manufacturing asset processes called Cloud Collaborative Manufacturing Networks (C2NET) was proposed for building cloud-enabled tools to optimize the supply chain of small and medium-sized manufacturing and logistics assets based on collaborative demand, delivery, and production plans. The C2NET is a layered architecture with cloud infrastructure, based on concepts of Everything as a Service (XaaS), Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). The project has been tested in the automotive, metallurgical, dermo-cosmetic, and Original Equipment Manufacturer (OEM) sectors, proving its efficiency.

Pishing et al. [147] have proposed a CPS architecture proposal based on the 5C model has been created, been tested on a workbench divided into 5 stations with parts production modules: distribution, testing, handling, processing and classification of parts. Each module consisted of sensors and actuators, a PLC, a local computer for reading data through the Festo Inc. OPC server (Codesys V2.3) and a library of the OPC client for C# available from the OPC Foundation website. Local computers also communicates to the central computer responsible to create the system virtual model of the system, developed in C# object-oriented language to analyze the conditions of the smart objects, such as actuation failure, usage time and informing users about maintenance needs.

Based on the 5C Architecture, in [148], the authors expanded the knowledge model to an 8C Architecture by adding Alliance, Client, and Content guidelines. Alliance is responsible for integrating the value chain and production chain among different parts of production processes; Client is focused on its participation in the production process, giving rise to Quality of Service (QoS) improvement services; and Content allows the extraction, storage and traceability of the product. The project is beneficial for the development of Smart Factories.

In [149], authors developed a novel architecture of large-scale digital twin platform named uDiT (universal Digital Twin) platform with flexible data-centric communication based on OMG DDS and co-simulation functions based on Functional Mockup Interface (FMI). The platform has the proposal to abstract devices through the representation of its virtual entity. It also supports data sharing by the entities in any formats, interworking functions for a large number of digital twins and physical systems.

Ayatollahi et al. [150] have developed an SOA in smart manufacturing products for a tool turret. Some services have been developed by OPC UA server, such as discovery, reading, stakeholder link and subscription creation, using a trial version of a C++ Software Development Kit (SDK). An OPC UA information modeling for customers to data reading and writing has been implemented through the MTConnect standard. The project has been compiled on a Linux-based platform and transferred to a Raspberry Pi for sensor and actuator control. The developed OPC UA server application has been tested by a client, noting factory devices capacity to describe themselves, their status and offer their functionalities.

Paulo et al. [151] have developed the NodeI4.0 project, which consists of an embedded prototype capable of adding the 5C Architecture Smart Connection level to any legacy system. The hardware has analog inputs and digital outputs circuits, as well as an ESP8266-01 module for Internet connection and a PIC18F2550 microcontroller for the transmission of I/O variables from serial communication. A configuration page is generated for activating read and write commands, making possible to send data to the server via request HTTP protocol. The prototype resulted in efficiency for systems whose response requirement is above 50ms.

Liu et al. [152] have proposed a scalable SOA called Cyber-Physical Manufacturing Cloud has been developed, in which every manufacturer in an industry owns machines monitored by controllers that communicate with their own local server via TCP/IP and MTConnect protocols. The controllers can also send data to the cloud via HTTP protocol, responsible for communication between the cloud and consumers. The architecture provides cloud services in a pub/sub model, virtualization through web-accessible Representative State Transfer (RESTful) web services and applications management for customers to perform cross-platform internet manufacturing operations. Tests with a large-scale operational prototype demonstrated viability to monitor and execute cloud operations and manufacturing processes over the Internet.

In [153], a European project called Cloud-Based Rapid Elastic Manufacturing (CREMA) has been approached. Its main principles are manufacturing virtualization, interoperability, optimization and collaboration of cloud manufacturing processes, ensuring the integration of the stakeholders. CREMA incorporate CPS technologies, including support for RDFS and OWL 2 semantics, assets and services abstraction and virtualization, Cloud Computing and Big Data. The results have been targeted so that manufacturing orchestrations among organizations and integration of distributed resources were allowed, making manufacturing processes more efficient.

Kannengiesser et al. [154] have authors have proposed SITCHEN 4.0, which is a multi-level, point-of-view engineering method for CPS modeling based on RAMI 4.0 standardization and network semantics. The project describes abstraction levels for CPS embodied in physical and virtual worlds; CPS types represented through Views; Viewpoints for specifying notations, languages, and model types for constructing a view type; and definition of RDF and OWL network semantic standards to build and represent Viewpoints. Models can be transformed into CPS instances and be used as the main application that generates dynamically or on-demand executable code (e.g. in PLCs) with Industry 4.0 standard interfaces, such as OPC UA, MQTT, AMQP, and PLCopen XML.

In [155], the authors proposed a CPS architecture based on 5C reference, consisting of 5 modules: Configuration, Intelligence; Cybernetics, Conversion and Communication. The architecture uses OPC UA protocol via XML and for system information management. Tests were implemented in a Smart PD3 industrial teaching plant with a PLC transmitting its data via ModBus TCP/IP and a Raspberry Pi 3 connected to the PLC's Ethernet network. In addition, an HTTP standard page was created to publish data containing events such as samples and conditions of equipment running in the plant. The results showed data accuracy.

In [156], a SOA architecture for equipment discovery in manufacturing processes has been designed based on the RAMI 4.0 reference model, including AS and unique IDs on devices. It is capable of providing components to enable communication among products and equipment. A web service capable of providing a mechanism similar to the DNS for locating equipment to process is also offered. Based on the RAMI 4.0 model, the architecture was developed using the Production Flow Schema (PFS)/Petri Net (PN) technique and applied in a modular production system, showing its efficiency.

Lu et al. [157] have proposed a test-driven resource virtualization framework for smart factories that create digital twins to easily represent their manufacturing assets. The proposed framework specifies the digital twin hierarchy, the information to be modeled and the modeling methodology. A case study was performed in an international company to create digital twins for all their manufacturing resources. Obtained results showed that the proposed resource virtualization framework is efficient to virtualize complex factory setups in the cyberspace.

In [158], authors presented a cloud-based CPS for adaptive shop-floor scheduling and condition-based maintenance. The proposed CPS consists of different modules (monitoring, adaptive scheduling, condition-based maintenance), which have been developed in a cloud environment supported by different I4.0 and IoT paradigms. It can be highlighted the cost-effective monitoring; reliable real-time data collection, processing, analysis from the shop floor; and an adaptive decision making system. A real-case study from a high-precision mold-making industry was performed in order to validate the work, proving its efficiency, and future works include energy consumption estimation and predictive maintenance planning.

Liu et al. [159] have proposed a Cyber-Physical Machine Tools (CPMT) Platform based on OPC UA and MTConnect for efficient data communication among machine tools and software applications. The method used was based on a generic OPC UA information model for CNC machine tools and the interoperability between OPC UA and MTConnect was reached through an interface capable of transforming MTConnect information model and its data to their OPC UA counterparts. Different application were developed, such as a conceptual framework for CPMT powered cloud manufacturing environment, and results showed that CPMT Platform can improve the production efficiency and effectiveness in the manufacturing.

5. Analysis and discussion

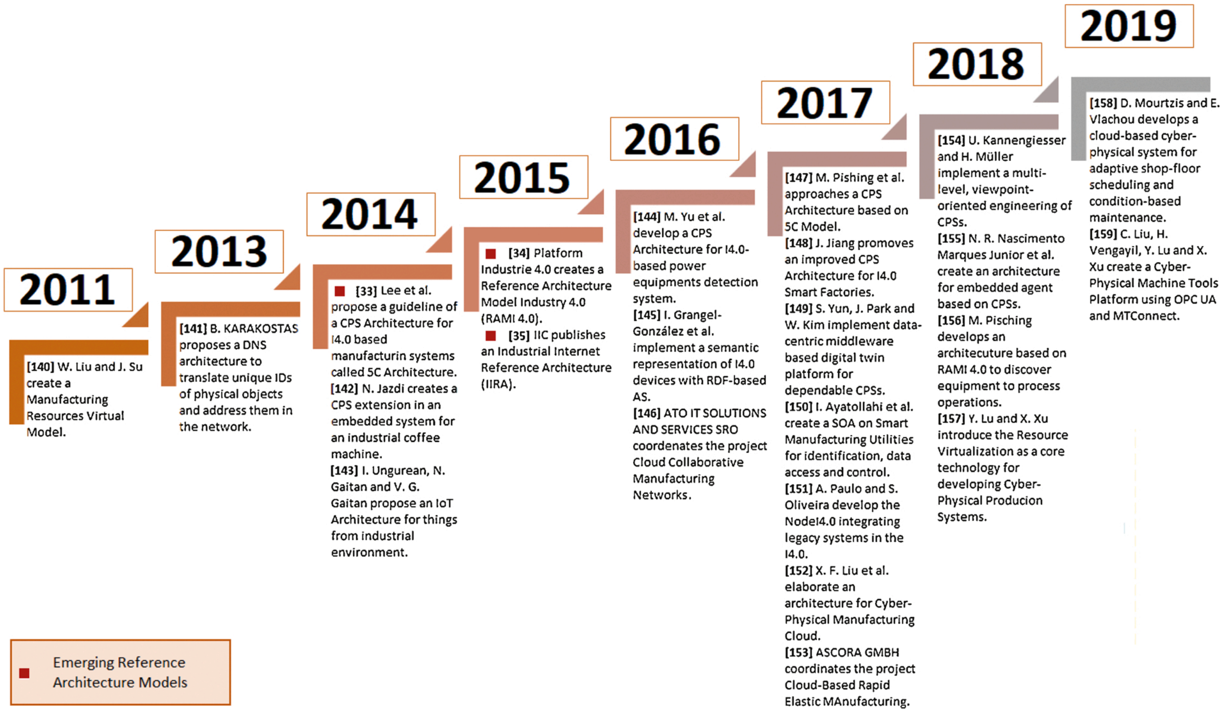
Fig. 7 illustrates an evolutionary line of the surveyed projects, as well as the reference architecture models studied. As can be seen, there were already some proposals related to manufacturing virtualization and unique identification for the I4.0 context before the emergence of the CPS reference architecture models. However, these projects also contain ideas and similarities with the proposals disseminated by the reference architectures. In other words, key proposals for architectural reference models have been employed in the industrial environment for a long time, but as can be seen in the evolutionary line, the emergence of these models has resulted in a significant increase in CPS proposals, proving their effectiveness and importance in the I4.0 scenario.

In this context, this Section performs a detailed analysis and discussion about the surveyed projects, accordingly to the next 3 subsections: Correlation of the surveyed projects with the reference architecture models, namely: 5C, RAMI 4.0 and IIRA; analysis of dimensions D1-D8 as adopted in CPS reviewed projects and their impacts on I4.0, pointing limitations, contributions and suggestions for ensuring a CPS proposal that meets the I4.0 key features, such as industrial vertical and horizontal integration; and finally, the open issues for the improvement of CPS in the context of I4.0.

5.1. *Correlation with the reference architecture models*

Table 8 correlates the surveyed papers to the reference architecture presented in Section 3, in order to point the most used reference architecture concepts (5C Levels, RAMI Layers and IIRA Domains) and analyze concepts that could be more explored on these works. According to Table 8 it can be noted:

(i) Regarding to the 5C Architecture, the Smart Connection, Data-to-Information Conversion and Cybernetic Layers were more explored than the Cognition and Configuration ones. Prognostics for failure prevention, Simulation tools and self-characteristics for the CPSs could be more applied to complement this architecture.
(ii) Regarding to the RAMI 4.0, Functional, Integration and Information layers were the focus of the surveyed projects. The Business Layer could be more applied with the introduction of SOA. Furthermore, the CPSs were commonly applied in one specific sector of the product life-cycle. Since one of the characteristics of RAMI 4.0 is to integrate the entire manufacturing sector, it is necessary to expand this structure to all stages of the life-cycle products. It can be performed by collecting data assets from these stages via IIoT and CC, enabling greater integration and collaboration among them.
(iii) Regarding to the IIRA, the Control and Information Domains were more popular in the state-of-art papers. Application and Business Domains could be developed more authentically, such as end-to-end operation of IIoT systems; exposition of available services and functionalities for application to other ones that consume them. Since one of the main goals of the IIRA is the integration among industries, the IIoT and Cloud Computing dimensions could be employed in the projects in order to obtain data and information sharing.



[140] W. Liu and J. Su create a Manufacturing Resources Virtual Model.

[141] B. KARAKOSTAS proposes a DNS architecture to translate unique IDs of physical objects and address them in the network.

■ **[33]** Lee et al. propose a guideline of a CPS Architecture for I4.0 based manufacturin systems called 5C Architecture.
[142] N. Jazdi creates a CPS extension in an embedded system for an industrial coffee machine.
[143] I. Ungurean, N. Gaitan and V. G. Gaitan propose an IoT Architecture for things from industrial environment.

■ **[34]** Platform Industrie 4.0 creates a Reference Architecture Model Industry 4.0 (RAMI 4.0).
■ **[35]** IIC publishes an Industrial Internet Reference Architecture (IIRA).

[144] M. Yu et al. develop a CPS Architecture for I4.0-based power equipments detection system.
[145] I. Grangel-González et al. implement a semantic representation of I4.0 devices with RDF-based AS.
[146] ATO IT SOLUTIONS AND SERVICES SRO coordenates the project Cloud Collaborative Manufacturing Networks.

[147] M. Pishing et al. approaches a CPS Architecture based on 5C Model.
[148] J. Jiang promoves an improved CPS Architecture for I4.0 Smart Factories.
[149] S. Yun, J. Park and W. Kim implement data-centric middleware based digital twin platform for dependable CPSs.
[150] I. Ayatollahi et al. create a SOA on Smart Manufacturing Utilities for identification, data access and control.
[151] A. Paulo and S. Oliveira develop the NodeI4.0 integrating legacy systems in the I4.0.
[152] X. F. Liu et al. elaborate an architecture for Cyber-Physical Manufacturing Cloud.
[153] ASCORA GMBH coordinates the project Cloud-Based Rapid Elastic MAnufacturing.

[154] U. Kannengiesser and H. Müller implement a multi-level, viewpoint-oriented engineering of CPSs.
[155] N. R. Nascimento Marques Junior et al. create an architecture for embedded agent based on CPSs.
[156] M. Pisching develops an architecuture based on RAMI 4.0 to discover equipment to process operations.
[157] Y. Lu and X. Xu introduce the Resource Virtualization as a core technology for developing Cyber-Physical Producion Systems.

[158] D. Mourtzis and E. Vlachou develops a cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance.
[159] C. Liu, H. Vengayil, Y. Lu and X. Xu create a Cyber-Physical Machine Tools Platform using OPC UA and MTConnect.

■ Emerging Reference Architecture Models

Fig. 7. Evolutionary line of the projects and reference architecture models.

Table 8
Correlation among CPS projects and the reference architectures models for I4.0.

Ref.	Relation to 5C	Relation to RAMI 4.0	Relation to IIRA
[140]	Virtual component model and resource data concentration, similar to the Cybernetic Layer.	Integration Layer via virtual proxies; Met digitization requirements in the product life cycle.	The Control Domain is explored through the resources' digitization;
[141]	Data acquisition and concentration; virtual component model encompassing Smart Connection and Cybernetic Layers.	Integration and Communication Layers: ID/Loc splitting as required by Administration Shell and I4.0C in RAMI 4.0.	Control Domain: abstraction of devices and the Connectivity Function in the Location perspective.
[142]	Smart Connection, Data-to-Info Conversion and Cyber Layers.	Deals with the Functional, Integration and Information Layers.	The CPS application covers the Control and Information Domains.
[143]	Focus on devices data acquisition and contextualization, used in the Smart Connection and Data-to-Information Conversion Layers.	Information Layer via data contextualization; A communication method that can be used to integrate different industry sectors.	Information Domain: data collection, transformation and analysis for awareness. Customers' participation in industrial processes.
[144]	Data acq. from test stations and data processing (Smart Connection and Data-to-Info Layers).	Data contextualization at Info. Layer; Manuf. integration, connecting processes (equipment to control/test stations).	The project encompasses data acquisition and processing of assets described in the Control Domain.
[145]	Smart Connection and Cybernetic Layers: Data acquisition and virtual component models.	Integration and Functional Layers: AS representation; semantic-based device IDs and virtual entity.	The abstraction of devices and description of their functionalities are perspectives included in the Control Domain.
[146]	Data Collection Framework (DFC) module covers the main 5C Architecture premises.	C2NET modules covers the main RAMI 4.0 Layers premises and integrates the entire manufacturing.	C2NET modules covers the main IIRA Layers premises and collaborative activities in manufacturing networks.
[147]	Adapted 5C Layers in order to contribute for use in the Smart Factories.	Smart objects communicates with all factory sectors (stations).	Discussion on inclusion of IoS for the communication among distinct industries.
[148]	Adapted 5C Layers in order to contribute for use in the Smart Factories.	Value and production chains integration among production processes.	Inclusion of the costumers and other industries in the production processes.
[149]	uDiT approached the Cybernetic Layer with the digital twins.	Integration Layer: digital twin concept.	Control Domain due to the use of digital twin technology.
[150]	Smart Connect, Data-to-Info, Cyber and Cognition Layers: data acquisition, smart data handling, concentration, acting according to asset functional data.	RAMI 4.0 Integration, Comm. and Functional Layers: Devices describe themselves, their status and functionalities; collected data can be contextualized to info.	IIRA Control and Information Domains: assets describe themselves, offer their functionalities; data transformation, modeling and analysis.
[151]	Added Smart Connection Layer to legacy systems.	Information and Communication Layers: Data collection from machines and devices.	The assets' data collection is a perspective of the Information Domain.
[152]	CPMC supports 5C Arch. Layers: data collection and analysis and virtualization of the manufacturer resources.	All Layers: data collection, virtualization, cloud comp., data contextualization, operations for each asset and application services.	All Domains: similar to RAMI 4.0; App services from different customers' and integration among industries, which is the main goal of this model.
[153]	The project contains all the relevant premises included in the 5C Architecture Layers.	The project contains all the relevant premises included in the RAMI 4.0 Layers.	The project contains all the relevant premises included in the IIRA Layers.
[154]	The project focuses on the virtual model systems for CPS, proposed in the Cybernetic Layer.	SITCHEN 4.0 explores the Integration Layer, representing the physical assets in the virtual world.	SITCHEN 4.0 covers the Virtual Representation of the assets, important for Control Domain.
[155]	Improvement of 5C Arch. for operation in industry.	Integration, Functional and Information Layers: asset data acquisition, processing and functions description.	Control and Information Domains: assets' virtualization and functional description, data contextualization.
[156]	Data-to-Info. Conversion, Cybernetic, Cognition and Configuration Levels: Focus on functions for data monitoring, collecting and processing, based maintenance and adaptive decision making.	Integration, Information, and Functional Layers: asset data acquisition and processing.	Control, Operation and Information Domains: System optimization, management and monitoring.
[157]	The project has characteristics defined in the 6 layers of the 5C Architecture.	Focus in manufacturing sector; all the layers of the reference model were introduced.	The concepts included in the RAMI model are also introduced in the IIRA.
[158]	Resource and assets virtualization, and information modeling, proposed on Smart Connection, Data-to-Info. Conversion and Cybernetic Levels.	Focus on Integration, Information and Functional Layers to virtualize complex factory setups.	Control and Information Domains, focusing on assets virtualization.
[159]	Smart Connection, Cybernetic and Configuration Levels: Focus on communication among machines.	Communication, Information and Business Levels: Focus on application development and data communication among assets.	Information, Application and Business Domains: interoperability among different machines and software applications.

5.2. *Analysis of the D1–D8 dimensions for I4.0 key features: limitations and suggestions*

This subsection discusses the impact of the D1-D8 Dimensions previously defined in Table 6 on CPS projects while meeting I4.0 key features, including vertical and horizontal integration. Based on Table 9 and in the Fig. 8, it can be noted that, although most of the works address D1 as a base technology for I4.0 (85%), D2 and D3 were not implemented (30% and 10%, respectively). For this, it is necessary to approach these architectures for greater data storage capacity, since in the I4.0 context the volume of industrial assets, applications, services and data flows with IIoT are very large, and Cloud Computing combined with Big Data can solve these issues for better system orchestration, operation, management, and storage.

Regarding I4.0 key features, only 40% of the surveyed CPS works cover both I4.0 vertical and horizontal integration, pointing the need of the focus on both: (i) assets digitization in the entire manufacturing; and (ii) integration among companies and clients. Analyzing these I4.0 key features individually, 85% of these works cover at least one of the Dimensions related to I4.0 vertical integration. D4 and D6 have been discussed on 45% of the surveyed projects, and RDF and OWL have been the most popular standards as semantics for data exchange. Digital

Table 9
Coverage of dimensions D1-D8 when applied for CPS and their impacts on I4.0 key features.

Ref.	I4.0 base technologies				I4.0 integration						
					Vertical				Horizontal		
	None	D1 – IIoT	D2 – Cloud Comp.	D3 – Big Data	None	D4 – Semantics	D5 – ID/Loc	D6 – D. Twins	None	D7 – SOA	D8 – Connectivity
[140]	x									x	
[141]		x							x		
[142]			x					x			
[143]		x			x						x
[144]	x						x			x	
[145]		x				x	x		x		
[146]		x	x	x		x	x	x		x	x
[147]		x			x						x
[148]		x			x						x
[149]		x						x	x		
[150]		x				x				x	x
[151]		x					x		x		
[152]		x	x				x	x		x	x
[153]		x	x	x		x	x	x		x	x
[154]		x				x		x	x		
[155]		x				x			x		
[156]		x	x			x	x	x		x	x
[157]		x						x	x		
[158]		x	x			x			x		
[159]		x				x					x

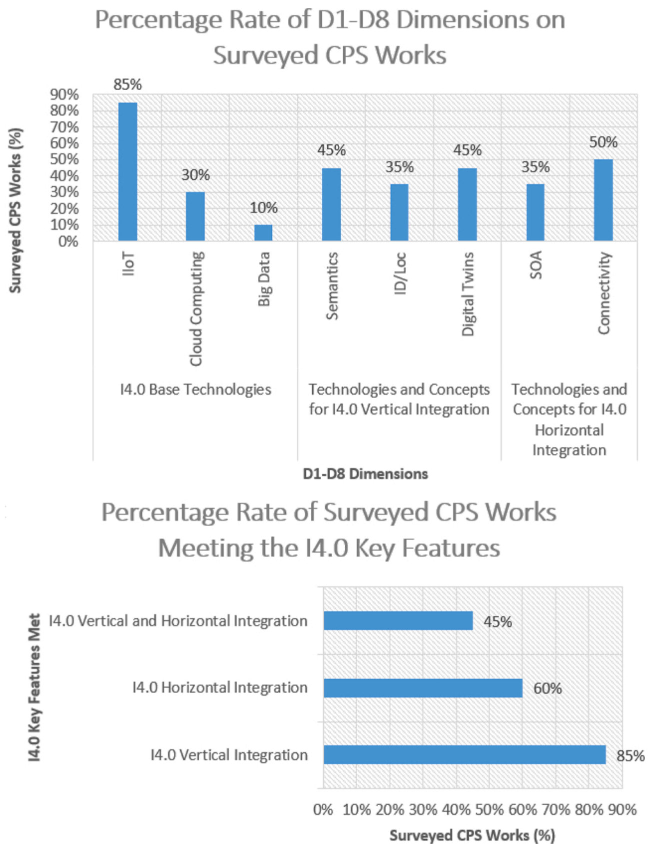


Fig. 8. Graph for percentage rate analysis on CPS works meeting the I4.0 key features.

Twins could be addressed more consistently to enable assets representation and digitization. On the other hand, D5 was addressed in only 35% of the surveyed works, commonly using name resolution based on DNS to resolve things identifiers to locators. However, further work is required, since devices and services identification are still dependent on the dual semantics of IP addresses [162]. For this, ID/Loc Splitting is an interesting concept that should be introduced in CPS to ensure assets unique identifiers.

In addition, 60% of the CPS works cover technologies and proposals related to I4.0 horizontal integration. While 35% of the surveyed manuscripts introduced D7 on their works, D8 was implemented by only 50% of them. In fact, D7 should be more widespread on CPS for I4.0, adopting SOA while developing applications and services for different clients and integrating companies. Regarding common communication protocols and standards applied on surveyed CPS (D8), it can be summarized: Ethernet is preferred for link layer; IP in the network layer, TCP and UDP in the transport layer; and HTTP in the application layer. It can also be highlighted that the OPC UA protocol is a core standard for I4.0, being discussed in 6 of the 20 papers analyzed. [143,147,150,154,155,159]. Finally, 5G, SDN and WSN technologies are candidates for I4.0 environment, as well.

5.3. *Open issues*

This subsection is intended to identify open research topics based on the analysis of the surveyed papers, giving possible suggestions to improve CPS works that meet the I4.0 key features. These open issues are listed below:

(i) Self-characteristics, despite being an idea proposed in the reference architectures, is not a popular topic in the context of Smart CPSs. For this aim, Artificial Intelligence (AI) technologies could be integrated for CPSs.
(ii) Given the emergence of Future Internet (FI) proposals, CPSs should be applied on architectures which support this research field, in order to keep pace with conceptual and technological development.
(iii) Softwarization, servitization and software-control are still in the early stages of development. The full adoption of these ideas will truly revolutionize industry. Also, comprehensively mirroring physical and virtual realities is another very important step in digital transformation.
(iv) The inclusion of digital ledger technologies (DLTes) will enable novel and dynamic industrial economies, which could provide immutable information (through nodes consensus) and computing (via smart contracts). However, much remains to be done until digitization through production chain “tokenization” takes place using DLTes.

6. Conclusion and future works

Given the diversity of CPS architecture proposals developed for Industry 4.0 and their divergences while ensuring interoperability among Cyber-Physical Systems, this survey performed a detailed review of CPS architecture reference models, their standards/protocols and the correlation among them, using IIoT as the main pillar in the scenario. Furthermore, this article proposed a literature review of experimental CPS architecture projects and an analysis of the architectural dimensions employed in CPS design while meeting the I4.0 key features. The manuscript pointed gaps and limitations for improving the architectures. Possible suggestions for vertical and horizontal integration of CPS works have also been done. Due to the importance of industry in the economy, these ideas can contribute to the development of countries with growing economies, adding to society improvements in processes, products and value generation.

As a highlight, it can be noted the need to implement Cloud Computing and Big Data more broadly, while addressing the I4.0 requirements for huge data flows generated by swarms of IIoT devices. It is also necessary the introduction of technologies and concepts for both I4.0 vertical and industrial integration, such as semantic rich orchestration (SOA) and contextualization, ID/Loc Splitting and Digital Twins for data modeling and device representation based on unique identifiers. This enables co-creation and co-development of applications and services for companies ecosystems. Finally, the cyber-security is a challenge to ensure users' and industrial data privacy.

For future works, other trending technologies must be included in the I4.0 reference architecture design and CPS works, such as WSN, 5G, Blockchain and Future Internet, so that industrial CPSs keep up with technological developments. In addition, it must be explored a clearer and unified standardization solution capable of ensuring interoperability among different industrial systems.

Declaration of Competing Interest

The authors report no declarations of interest.

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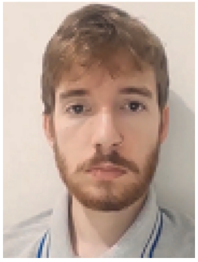

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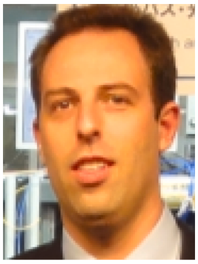

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