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A conceptual framework for smart production planning and control in Industry 4.0

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ABSTRACT

This article aims to introduce the challenge (i.e., integration of new collaborative models and tools) posed by the automation and collaboration of industrial processes in Industry 4.0 (I4.0) smart factories. Small- and medium-sized enterprises (SMEs) are particularly confronted with new technological and organisational changes, but a conceptual framework for production planning and control (PPC) systems in the I4.0 context is lacking. The main contributions of this article are to: (i) identify the functions making up traditional PPC and smart production planning and control in I4.0 (SPPC 4.0); (ii) analyse the impact of I4.0 technologies on PPC systems; (iii) propose a conceptual framework that provides the systematic structuring of how a PPC system operates in the I4.0 context, dubbed SPPC 4.0. Thus SPPC 4.0 is proposed by adopting the axes of the RAMI 4.0 reference architecture model, which compiles and contains the main concepts of PPC systems and I4.0. It also provides the technical description, organisation and understanding of each aspect, which can provide a guide for academic research and industrial practitioners to transform PPC systems towards I4.0 implementations. Finally, theoretical implications and research gaps are provided.

1. Introduction

Industry 4.0 (I4.0) is a term that emerged in 2011 in research towards the initiative of strengthening industrial production in Germany (Kagermann et al., 2011). The I4.0 term has been studied in the literature and usually refers to the fourth industrial revolution; i.e., the inclusion of the Internet of Things (IoT) or Services (IoS) and cyberphysical systems (CPS) in manufacturing processes (Kagermann et al., 2011; Brettel et al., 2014; Cañas and Mula, 2020). Studies have been exhaustively conducted to define I4.0. In doing so, Nosalska et al. (2019) studied different definitions in the literature during the 2012–2017 period. These authors proposed a reference framework for defining I4.0. This framework lies in I4.0 pursuing the optimisation of production costs, while balancing the trend towards mass product customisation as a consequence of individual changes in customer needs. Within the I4.0 framework, they categorised this term according to its enablers or drivers and two integral factors: technological factors and organisational factors. They put forward a definition of I4.0 as follows: "I4.0 is a concept of technological and organisational changes along integrated value chains and the development of new business models that are driven by customer needs and the requirements of mass customisation and enabled by new technologies, connectivity and the integration of information technology (IT)" (Nosalska et al., 2019). Of technological factors, they identified that smart factories play the most important role because they are based on the fact that CPSs can autonomously make decisions and communicate with one another in real-time, and the IoT is seen as an enabler (Hermann et al., 2016). With the organisational factor, they identified the changes that value chains would undergo as a result of communication and data sharing. Cañas et al. (2021) reviewed the literature on I4.0 principles, and proposed a category based on the I4.0 design principles of Hermann et al. (2016): (i) interconnection, which refers to the enabling technologies for connecting machines, devices, sensors and people; (ii) information transparency, when all the data from the physical/virtual worlds can be accessed by all stakeholders; (iii) decentralised decision making, which is enabled by CPS where decisions are autonomously made; (iv) technical assistance, which refers to the need of humans to be supported by assistance systems or any kind of human–machine collaboration.

Production planning and control (PPC) systems are information systems (IS) designed to assist managers in decision making. These tools

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support all the activities that define what, how much and when to efficiently produce, buy and deliver to meet customer needs (Bonney, 2000). Recently, efforts have been made to transform PPC systems towards I4.0 in line with our work. In line with this, Bueno et al. (2020) developed a literature review to propose an analytical framework that explains how PPC is influenced in the I4.0 context by the smart capabilities of five digital technologies: IoT, CPS, big data and analytics/ artificial intelligence and additive manufacturing; Wang et al. (2021) focused on a framework and deploying a cloud-based advanced production and scheduling system (APS). Rahmani et al. (2022) provided a tool to assess the need for smart PPC based on analysing the characteristics of the planning environment. Nevertheless, no work has established a PPC system framework in the I4.0 context to guide academic research and industrial implementations. To bridge this gap in research, the following research questions are posed: (RQ1) what are the main functions involved in a traditional PPC?; (RQ2) what impact will I4.0 technologies have on PPC systems?; (RQ3) what conceptual framework could be suitable for transforming a traditional PPC system into an SPPC 4.0?

In order to answer the above research questions, a literature review is conducted to analyse the current state of research and technology regarding PPC systems. To this end, the different definitions, concepts, manufacturing strategies, management methodologies, techniques, functions, technologies, and reference models identified in the literature, and related to PPC systems, are presented in a structured chronological manner, along with the smart PPC concepts identified in the I4.0 literature. A detailed comparative review of the different automation pyramids and I4.0 reference architecture models identified in the literature is provided: ANSI/ISA-95, 5C, 8C, IBM Industry 4.0, RAMI4.0 and IIRA. RAMI 4.0 has been identified as being most suitable for framing our conceptual proposal because it provides a generic standard-based architectural model for designing a smart manufacturing system by providing vertical, horizontal and end-to-end integration across the entire product cycle and at all the hierarchical levels. No evidence has been found for approaching a conceptual framework of PPC systems and RAMI4.0.

The rest of the article is arranged as follows. Section 2 presents the definitions, concepts, manufacturing strategies, methodologies and techniques addressed in the literature about traditional PPC and SPPC 4.0 systems. Section 3 discusses the analysis of different I4.0 reference architectures and models. Section 4 proposes a conceptual framework that integrates SPPC 4.0 features. Section 5 includes the main results and identifies research gaps and recommendations to further research. Section 6 comprises the conclusions.

2. Literature review

The research methodology consists of selecting databases for the initial search, in this case Scopus and Web of Science (WoS). The selection criteria comprised the inclusion and abstract filtering of peer-reviewed scientific articles, reviews, conference papers and book chapters that were related to the research questions. The search for information consisted of the combination of the following keywords: "*production planning and control*", "*production control*", "*architecture*", "*production planning*", "*industry 4.0*″ and "*system*".

Traditional PPC encompasses all the repetitive value-creating management activities in a company's processes (Bendul and Blunck, 2019). Its main objective is to produce what the market demands in the expected time and with the expected quality at a minimum cost. It is capable of adjusting to disruptions whenever necessary (Oluyisola et al., 2020).

The design of a PPC system is influenced by several factors, such as the volume and variety of expected output. These factors are usually related to customers' influence on the design of a product or service to be delivered through a company's business processes. This degree of influence forms part of four basic manufacturing strategies (Chapman, 2006): make to stock (MTS), assembly to order (ATO), make to order (MTO) and engineer to order (ETO).

A general PPC outline consists of three abstraction levels according to the decision-making process: i.e., strategical, tactical and operational decision levels. Decision making in PPC is classified into different planning time horizons: i.e., long, medium and short terms. The basic PPC functions are master production schedule (MPS), material requirements planning (MRP), demand management, capacity requirements planning (CRP) and job scheduling and sequencing. These functions aim to reduce the work in process (WIP), minimise time and costs, and improve responses to changes in demand (Stevenson et al., 2005).

On PPC methodologies, Stevenson et al. (2005) reviewed their applicability in MTO manufacturing systems. They identified different methodologies, such as Kanban/JIT (just-in-time), MRP, MRPII, TOC (theory of constraints), workload control, constant WIP (CONWIP) and paired cell overlapping loops of cards with authorisation (POLCA). POLCA forms part of the QRM (quick response manufacturing) strategy (Suri, 1999) and ERP (enterprise resource planning), Internet-based supply chain management (SCM) or e-SCM. Different research gaps were also identified: collaboration, the applicability of the aforementioned PPC methodologies, their implementation, and the inclusion of sustainability and technological innovation.

Olhager (2013) reviewed PPC evolution from production to supply chain planning from 1960 to 2010. He identified that advances in information systems (IS) and information and communication technologies (ICT) facilitate and improve the planning and control of operations. JIT and TOC paradigms were categorised as alternative methodologies to MRP, which was one reason for discussion about which methodology was better. As a result, Berry and Hill (1992) modelled the relations between market and product characteristics and different strategies to design PPC systems, which correspond to the MPS level. In the 1980 s, noteworthily companies were interested in the available-to-promise (ATP) concept in MPS, which enabled them to know how many products were available for immediate delivery at a certain time point. The 1990 s corresponded to sales and operations planning (S&OP), in which the term ERP was introduced by the Gartner Group (Wylie, 1990). However, with the inclusion of S&OP, PPC can be viewed as a four-level structure consisting of S&OP, MPS, MRP and shop floor control. The S&OP level involves two planning strategies i.e., chase for low-volume and highly customised products; level for high-volume and standardised products.

Between 2000 and 2010, the interest shown in supply chain planning began when competitive strategies shifted from intercompany to intersupply chain competition (Christopher, 1998; Christopher, 2017). In PPC systems terms for supply chains, the ERP system was considered essential in all the manufacturing systems in which ERP had different applications, such as collaborative planning, forecast and replenishment (CPFR) and vendor-managed inventory (VMI). ERP systems were also extended with software tools, such as e-SCM, customer relationship management (CRM) systems, which build up the ERP II concept (Olson et al., 2018) and APS, the last of which incorporates models and solution algorithms related to operations research (Stadtler, 2005). Fig. 1 summarises the main aspects of traditional PPC systems adapted from previously analysed works.

Since the introduction of I4.0 in 2011, very few works have focused on how this paradigm will transform PPC management and its software tools. Moeuf et al. (2018) reviewed the literature in an attempt to analyse I4.0 empirical cases related to transform traditional PPCs in small- and medium-sized enterprises (SMEs). The authors identified a major change in the way that PPC systems are integrated, and they did not expect the methodologies developed for large organisations to match SMEs' needs and constraints. They concluded that despite the growing number of new I4.0-related tools and technologies, most were not fully exploited and were ignored by SMEs. Of all these tools and technologies, cloud computing, simulation and RFID technologies were the most

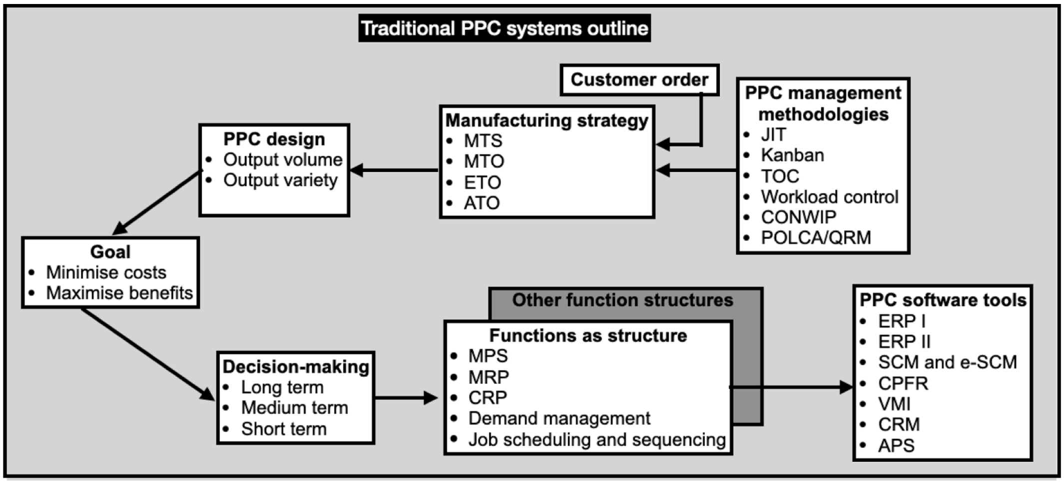

Fig. 1. Traditional PPC systems outline. Adapted from (Wang et al., 2021; Rahmani et al., 2022; Bendul and Blunck, 2019; Chapman, 2006; Christopher, 1998).

exploited. Bendul and Blunck (2019) reviewed the literature on production systems design, holistic PPC, distributed control systems, and their relations to current trends in I4.0 control systems. They proposed a framework to classify decision making into different distributed PPC approaches, e.g., Kanban systems, CONWIP control, product-resource-staff architecture (PROSA) and adaptive holonic control architectures. Bueno et al. (2020) reviewed the PPC systems literature in the I4.0 context and included the term smart in PPC with the idea that smart manufacturing was the core concept of I4.0. They developed a framework to explain how PPC would be influenced by five key I4.0 technologies, including IoT, CPS, big data, artificial intelligence and additive manufacturing. They identified the digital capabilities that can create new opportunities for traditional PPC, which they called "smart capabilities". They compared the smart capabilities of I4.0 to all the following traditional PPC functions: demand forecasting, capacity planning and control, inventory planning and control, S&OP/aggregate planning, MPS, MRP, production scheduling/shop floor control and holistic PPC. They also identified that PPC could be transformed by using digital technologies, and by the vertical and horizontal integration of physical and digital production systems, i.e., CPS, digital twins (DT), ERP integration, manufacturing execution systems (MES), and machine-to-machine (M2M) approaches in order management systems.

Herrmann et al. (2021) conducted a literature review about PPC and I4.0 based on the Aachen PPC structure (Schuh and Stich, 2012), which consists of five different tasks: production requirements planning, order management, in-house PPC, controlling and data management. They proposed a PPC system architecture that comprises the following layers: a terminal (human–machine interaction), cloud application, PPC (MES and ERP data), network and physical resources. They concluded that most reviewed articles at that time had focused on production control and its improvement had been achieved via real-time capability.

Usuga Cadavid et al. (2020) reviewed the literature on applying machine learning (ML) to PPC functions and the smart manufacturing of I4.0. They identified the current trends of ML modelling techniques, tools, data sources, use cases, and their targeted characteristics for smart manufacturing. They showed that resources self-organisation was the most addressed characteristic in ML-PPC applications which, according to Tao et al. (2018), refers to the capability to create a smart production plan based on the internal and external data from different manufacturing sites to form the optimal configuration. Thus ML-PPC models can enable manufacturing systems to adapt to unexpected events and predict future production problems. ML techniques are also useful for generating knowledge from PPC data and improving know-how in organisations.

Cañas et al. (2021) presented a holistic literature review on I4.0 principles and addressed PPC in the I4.0 context by classifying the different conceptual frameworks, technologies, architectures and models related to production planning and I4.0.

Although PPC and I4.0 research has been addressed, sustainability and supply chains mainly lie beyond its scope. Cañas et al. (2020) identified I4.0 sustainable supply chains as an extension of the I4.0 definition to incorporate embedding value creation into the business processes concept.

On the creation of sustainable value in the I4.0 context, in Kagermann et al. (2011) the IIoT (Industrial Internet of Things) referred to the integration of IoT technologies into an industrial production system to, thus, establish a digitalised connection of industrial value creation or I4.0. It is important to highlight that the sustainability concept in the scientific literature has been approached from three dimensions, namely economic, social and environmental, which make up the so-called triple bottom line (Cañas et al., 2020; Elkington, 1998; Norman and MacDonald, 2004). Sustainability within the I4.0 framework is considered most important, and the purpose of this section is to highlight the challenges and benefits for its inclusion in PPC systems and I4.0. The work of Kiel et al. (2017) is stressed because they investigated sustainable value creation in the IIoT context of I4.0 by identifying the challenges and benefits of implementing I4.0 into the sustainability context. Thus sustainable industrial value creation requires extending three more dimensions that cannot be integrated into the triple bottom line i.e., technical integration, data/information/security, the public context. These authors highlighted that implementing modern IT and standardised data interfaces, and communication protocols that enable vertical and horizontal integration across value chains and hierarchies, is a fundamental prerequisite to achieve the IIoT concept.

As identified, sustainability within the I4.0 framework must be considered throughout the value chain of a product or business process. Hence this section takes its incorporation into a PPC system as being relevant, i.e., including sustainability in a product's life-cycle management (PLM) system across all an organisation's business processes.

Regarding technical integration, the work of Wang et al. (2016) has been identified because these authors highlighted that the I4.0 objective is to integrate business processes and process engineering and IoT/IoS in a flexible resource-efficient way to adapt to customer demand, which is environment-friendly, offers high quality and is low-cost. Lucke et al. (2008) proposed that smart factories would be vertically, horizontally and end-to-end integrated. In the same context, Cañas and Mula (2020) classified these three integration types in I4.0 interoperability, which integrates things, services, data and people. It should be noted in the PPC and I4.0 contexts that different systems integration types are considered relevant.

Recent approaches in the literature are related to the digital twin (DT) term and manufacturing, in which all PPC functions are linked by integrating all the data (Agostino et al., 2020). Ivanov and Dolgui (2019) classify DTs as a new generation of models that, through simulation, optimisation and data analytics, will extend current decision-making systems. The first known definition to date of the DT in the literature was given by the NASA (National Aeronautics and Space Administration) as the probabilistic simulation of a multiphysics multiscale integrated system or vehicle that uses the best available physical models, sensor updates, spacecraft history, etc., to mirror the life of its twin (Shafto et al., 2012). The DT is the realisation of a CPS, also included in the 5C-level architecture for implementing a CPS developed by Lee et al. (2015). The 3C level specifically acts as a bridge between the physical and virtual worlds in the form of a central information hub, where data analytics can be used to provide insights into individual machines, to be compared to other machines or to predict future behaviours. According to Boschert and Rosen (2016), the DT connects different value chains, e. g. a DT of a product that can be used as equipment in a production system, and carries important information in the form of data or executable models to stakeholders, which makes systems integration easier.

Qi and Tao (2018) compared the DT and I4.0 big data by specifically comparing their definitions and functions. In terms of functions, they indicated that big data focus on data processing, in which qualities or patterns are identified and helpful for decision makers. Big data functions are also based on useful predictions or optimisations for training the dataset and for making comparisons to historical data, whereas DT functions are based on the simulation and evolution of digital models. Both technologies contain similar features, e.g., predicting and diagnosing problems, real-time monitoring, optimisation and improvement in manufacturing processes. In terms of technologies, the authors identified that big data focus more on technologies like cloud computing, data cleaning, data mining and ML, whereas a DT centres on technologies to integrate CPSs, such as simulation, virtual reality (VR) and augmented reality (AR). The authors concluded that the DT provides data from different aspects of a product's life cycle and innovation in product design and quality traceability. They also argued that the DT promotes efficient synergies between each product life-cycle stage by achieving iterative optimisation. They identified DT benefits as: minimising the product development cycle, improving manufacturing efficiency and ensuring certainty, stability, and quality. These authors argued that the DT and big data complement one another, and the combination of both enables agile and predictive smart manufacturing, which are characteristic of I4.0. Schroeder et al. (2020) proposed a methodology for designing and implementing DTs into I4.0. In parallel, they developed a component-based DT reference architecture to enable basic identification, storage, communication, security, data management, human–machine (HMI) interface and simulation functionalities. These authors stated that the DT concept is unclear because of its methodology, but is the most appropriate architecture for implementation purposes. Kritzinger et al. (2018) reviewed the literature and categorised DTs according to data integration levels, the approach in which they were studied, and the technology used to develop them. They subdivided the DT concept into three categories: digital model, digital shadow and the DT. A digital model represents a virtual model in which no data are exchanged with a physical object; the digital shadow is the extension of the digital model with unidirectional automated data exchange with a physical object; the DT is the extension of the digital shadow with bidirectional and automated data exchange with a physical object. The authors mentioned that a DT in manufacturing offers the opportunity to simulate and optimise a production system. Of the technologies followed to develop DTs, they identified simulation methods (discrete, continuous, etc.), communication protocols and I4.0 technologies, and the main research focus related to DTs and manufacturing is data integration with which all PPC functions are linked (Agostino et al., 2020). Gürdür and Asplund (2018) reviewed the literature about interoperability, tool integration and CPSs. They identified how tool integration focuses on software development and is intrinsically related to interoperability. Ruppert and Abonyi (2020) addressed the integration of a real-time location system based on DTs. Jiang et al. (2021) indicated that a unified DT architecture that maps and synchronises behaviour between the physical and digital spaces is lacking. Luo et al. (2021) proposed a conceptual DT-driven MRP software framework, including a domain model, a simulation module, a production planner and a scheduler. The domain model integrates data from heterogeneous sources (MES, ERP, IoT), and acts as the bridge between physical and visual systems. The production planner comprises an ML tool, a generic mathematical model and an algorithm for stochastic optimisation. Uysal and Mergen (2021) posited that information integration is a relevant issue for I4.0 smart manufacturing and one discipline that addresses major aspects in relation to integration is Industrial Information Integration Engineering (IIIE).

3. Reference architectures for Industry 4.0

This section addresses the definitions of architecture, reference architecture and reference architecture models for automation in an I4.0 environment. According to ISO15704, architecture is defined as a description of the basic arrangement and connectivity of system parts (either physical or conceptual object or entity). Reference architectures describe the main concepts to be used in enterprise engineering. They distinguish among human-oriented concepts, process-oriented concepts, and technology-oriented concepts, and define the life cycle and life history concepts. Reference architectures are the building blocks or constructs to be used in the creation of a particular enterprise model (Kosanke et al., 1999). Reference architecture models represent a common structure and language to describe specific system architectures and are, therefore, beneficial for promoting common understanding and systems interoperability (Fraile and Poler, 2019).

Specifically, the architectures, reference architectures and reference architecture models identified in the literature are analysed: ANSI/ISA-95, 5C, 8C, IBM I4.0, IIRA and RAMI 4.0.

Efforts have been made to define the structural and architectural aspects of manufacturing and control systems. In 2010, one of the most popular one was the ANSI/ISA-95 reference architecture proposed by the International Society of Automation (ISA), also known as the IEC/ISO 62264 standards for Enterprise-Control System Integration (Colombo et al., 2014). This standard with models contains five hierarchical automation levels. Level 0 comprises the physical processes of a production system. Level 1 contains the sensor layer, i.e., the manipulation of the process by sensors and actuators. Level 2 is for the monitoring, supervisory control and automated control of the production process. Supervisory control and data acquisition systems (SCADA), distributed control systems (DCS) and programmable logic controllers (PLC) are also considered at level 2. Level 3 consists of the workflow and activities needed to produce the desired products. At this level, we find MESs, production information management systems, warehouse management systems and computerised maintenance management systems. At level 4, business-to-manufacturing transactions appear, in addition to business planning, logistics, production scheduling and operational management. The commonest systems at level 4 comprise different IS, including ERP, PLM, human resource management (HRM), and CRM and SCM systems.

The ANSI/ISA-95 allows an ERP to be considered a solution for transformation into I4.0. Although it is an indispensable requirement, it is taken as only a steppingstone towards such a transformation. An SME should have at least one IS at this level if it pursues I4.0 in the future, and previous levels are implemented at this level.

In 2015, Lee et al. (2015) proposed the 5C automation architecture towards a CPS system in manufacturing in the I4.0 context. The architecture consists mainly of two components: firstly; the connectivity required to establish real-time data acquisition from the physical world, and feedback information from the physical and virtual world; secondly, data management of the analytical and computational capability required by the virtual world. This architecture defines the conceptual workflow for building a CPS from the initial data acquisition and data analytics to the final value creation. Fig. 2 graphically depicts each 5C architecture level.

The 5C architecture contains five automation levels. The first level, 1C, corresponds to the smart connection layer where data are acquired through sensors, controllers or MES, ERP, SCM and CRM systems. At this level, protocols to manage various types of data and tether-free methods, such as MTConnect (Vijayaraghavan et al., 2008), AutomationML (Schleipen and Drath, 2009) or OPC-UA (Mahnke et al., 2009), are needed. Level 2C corresponds to the conversion of data into information. The authors mentioned that prognostic and health management algorithms are found at this level because they provide machines with self-awareness. Level 3C corresponds to the cyber level, which acts as a central information hub. Information from each machine connected to the hub forms a network of machines. These collected big data can be analysed to collect further information to gain insights into the individual machine's status. At this level, the authors mentioned that such analytics provides machines with the self-comparison attribute against other machines, where individual machines' performance and historical information can be used to predict future behaviours. Cognition appears at level 4C which, thorough knowledge of the monitored system, and the proper presentation of the acquired knowledge, can be used for expert users' decision making; for example, prioritisation of tasks for maintenance optimisation based on a comparative information and an individual machine's status. Level 5C corresponds to configuration, i.e., feedback from the virtual to the physical world, which acts as a supervisory control to make machines self-configuring and self-adapting. The authors mentioned that this level acts as a resilient control system at which the corrective and preventive decisions that were previously made at level 4C can be applied. It should be noted that the 1C level in the 5C architecture is similar to the level 1 of the ANSI-/ISA-95 automation architecture. However, at 1C, data acquisition can be retrieved from the MES, ERP, SCM, and CRM systems, while data acquisition in ANSI/ISA-95 can only be done between two adjacent layers; e.g. a controller can only communicate from/to sensors and actuators. If a request is made from MES, this message needs to be transmitted via the SCADA system to a PLC, but this limits information exchange efficiency, especially with considerable data sampling (Dai et al., 2019). From the 5C architecture, the following I4.0 attributes can be highlighted: self-aware, self-predictive, self-comparative, self-configuring, self-maintaining, self-organising.

In 2018, the work of Jiang (2018) proposed an 8C architecture as an extension of the architecture 5C proposed in Lee et al. (2015); and added three more levels to it. Level 6C corresponds to the coalition; i.e., the integration of both the value and production chains between different stakeholders in production process terms. At this level, these distinct stakeholders in a supply chain can collaborate in scheduling production lines in the form of a production chain so that production is met on time. Level 7C corresponds to the customer. At this level, a factory can accept different production orders with small quantities from a variety of customers, and can meet orders on time. Customers can be involved in product design, and even in its modification during the production process. Level 8C corresponds to content, and is about extracting, storing and inquiring product traceability. In short, it is about managing all the information about a product, from raw material to supply and procurement, production processes, plant temperature, humidity, vibration, etc. The 8C architecture corresponds to vertical, horizontal and end-to-end integration to, thus, represent the I4.0 interoperability attributes identified in Cañas and Mula (2020).

In 2018, Moghaddam et al. (2018) reviewed a previous version of the IBM 4.0 reference architecture, which had been updated, but no records of its updated versions are found. IBM 4.0 is a service-oriented architecture (SOA) consisting of two layers that describe the functional architecture of a smart manufacturing system, including a platform or hybrid cloud layer, and an equipment or device layer. At the two layers, three perspectives are included: edge, plant, enterprise. These perspectives are based on ANSI/ISA-95 levels, where the edge perspective corresponds to levels 0–2, plant to level 3 and enterprise to level 4. IBM's 4.0 includes these technologies: blockchain, cloud manufacturing, the IIoT, artificial intelligence and software-defined networks (SND) (IBM, 2021). It also describes the relation among users, machines, applications, supply chain integration and technologies.

In 2015, the IIRA (Industrial Internet Reference Architecture) was initially released and has been the subject of different reviews and updates until its version 1.7, which was presented in 2019. IIRA describes four industrial Internet viewpoints or layers: business, usage, functional, implementation. The business layer contains the vision, values goals/objectives expected to be met with the IIoT system. The usage layer comprises concerns about how an IIoT system realises the capabilities identified at the business layer, and describes how the system is used. The usage layer acts as a base for the design, implementation, deployment, operations and evolution of the IIoT system. The functional layer contains five ISO/IEC 42010:2011-based functional domains in an industrial system, along with their interrelations, structure and interactions (Industrial Internet Consortium, 2019; Scanzio et al., 2021).

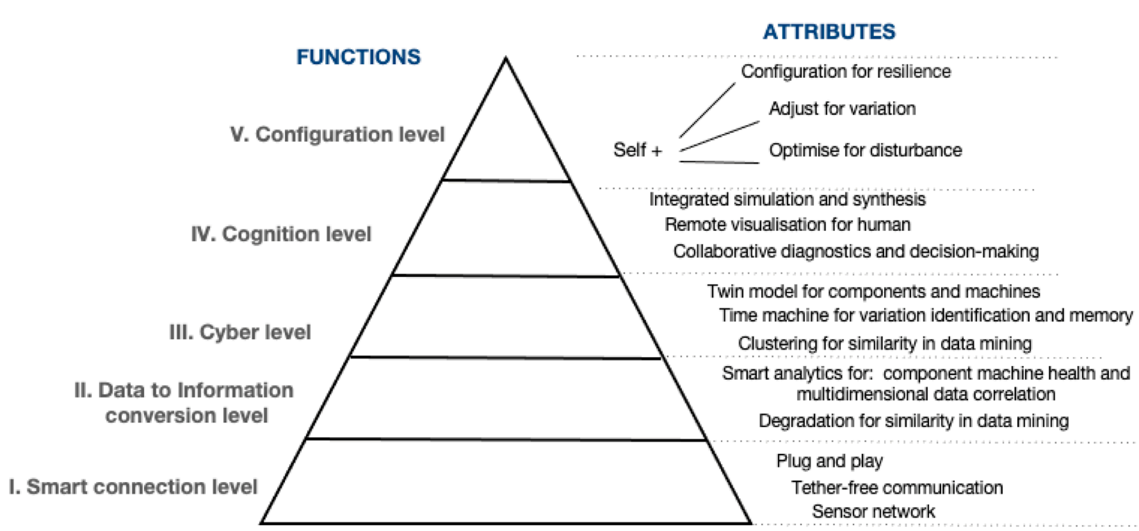

Fig. 2. 5C architecture. Source: adapted from (Lee et al., 2015).

Functional domains include business, operations, information, application and control. Here the business domain enables an industrial system's end-to-end operations, including production planning, PLM, CRM, MES, HRM, assets management, service life-cycle management, billing and payment, scheduling and ERP systems. The functional domain is given by the Industrial Internet Consortium (2019). The business layer enables an industrial system's end-to-end operations, including production planning, PLM, scheduling and ERP. One of the particularities of the IIRA is that it covers different sectors; e.g. energy generation, healthcare, manufacturing and transportation industries. Moghaddam et al. (2018) compared the functional layer of the IIRA to RAMI 4.0 and identified similarities: both architectures are based on the ANSI/ISA-95 reference model; i.e., the previously discussed automation pyramid. The implementation layer contains the technologies needed to implement the function layer components, e.g., communication, life-cycle procedures. The elements in this layer are coordinated by the activities at the usage layer and are supported by the system capabilities identified at the business layer. Fig. 3 depicts the layers and functional domains of the IIRA.

In 2015, RAMI 4.0 (Reference Architecture Model for I4.0) was presented in a technical report. It development was based on the Smart Grid Architecture Model (SGAM) (ZVEI, 2015). RAMI 4.0 is a reference architecture model that comprises entities "I4.0 components". According to the I4.0 Platform glossary, an I4.0 component is a globally and uniquely identifiable participant with communication capability that consists in an administration shell and an asset (ZVEI, 2015).

Fig. 4 shows the RAMI4.0 reference architecture model and the I4.0 components.

The RAMI 4.0 reference model consists of a three-dimensional model to represent the I4.0 system concept, while the layers dimension represents the perspectives of data maps, functional descriptions, communication behaviours, hardware/assets or business processes. The layer dimension defines the structure of the IT representation of the I4.0 components (ZVEI, 2015). The layers dimension includes the business, functional, information, communication, integration and asset perspectives. The hierarchical levels dimension is based on standards IEC 62264/61512, and comprises the enterprise level, work centres, station and control devices (bottom-up). The levels that support a smart factory are field devices, products or workpieces and the connected world (ZVEI, 2015). The life-cycle and value stream dimension is, according to standard IEC 62890, a guideline for the PLM of entities, products, factories or workpieces. This dimension consists of two phases: type and instance. Type refers to the phase in which an idea is generated or a product prototype is created, while instance denotes the phases production to the end of products' life cycles (Mourtzis et al., 2019).

Apart from the above-explained dimensions in RAMI 4.0, it describes the I4.0 components (ZVEI, 2015) which, according to Bangemann et al. (2016), indicate CPS properties. Furthermore, an I4.0 component is an IoT-enabled smart CPS in manufacturing, which is communicated via standard protocols like OPC UA (Mahnke et al., 2009) and contains an administration shell. An I4.0 component can be a production system, a single machine, an assembly line, an object or a "thing", and must possess passive communication ability, and be surrounded by one administration shell or many (ZVEI, 2015).

An administration shell acts as the digital representation of an asset and contains technical functionalities. RAMI 4.0 specifies how the I4.0 components interact with one another in communication terms. Its latest version of specifications provides its content, technology, serialisation formats and security aspects. The control and management of interactions are performed by using "submodels", which provide a separation of concern and employ application programming interfaces (APIs) (Bader et al., 2022).

Wagner et al. (2017) compared the definitions of the DT and administration shells by highlighting that both terms converge against one another. However, the DT is a fully enriched version, while the administration shell is the digitised data of a real "thing" i.e., the virtual representation of an I4.0 component.

After having identified the relations among ANSI/ISA-95 reference model and 5C, 8C, IIRA and RAMI4.0, common characteristics can be used as a reference to properly compare and determine which architecture, reference architecture or reference architecture model is the most suitable one for framing our conceptual proposal. Table 1 presents a comparison of the architectures, reference architectures and reference architectures models related to I4.0. It is noteworthy that the adopted criteria are based on the five levels of the ANSI/ISA-95 reference model (business, operational, process and field/device levels); value chain integration, which is found on the RAMI 4.0 axis and "coalition" in the 8C architecture; customer level, which is found in the 8C architecture and the RAMI 4.0 life cycle and value stream axis; life-cycle management, which is represented in the RAMI 4.0 life cycle and value stream axis, and also in the 8C architecture as "content". Readers are referred to (Fraile and Poler, 2019; Moghaddam et al., 2018; Li et al., 2018; Nakagawa et al., 2021; Resman et al., 2019) for more comparisons of I4.0 reference architectures and reference architecture models. However, only RAMI 4.0 and the IIRA have been standardised. RAMI 4.0 has been chosen to act as the basis of a conceptual framework because it provides a generic standard-based architecture to design a smart manufacturing system by providing vertical, horizontal and end-to-end

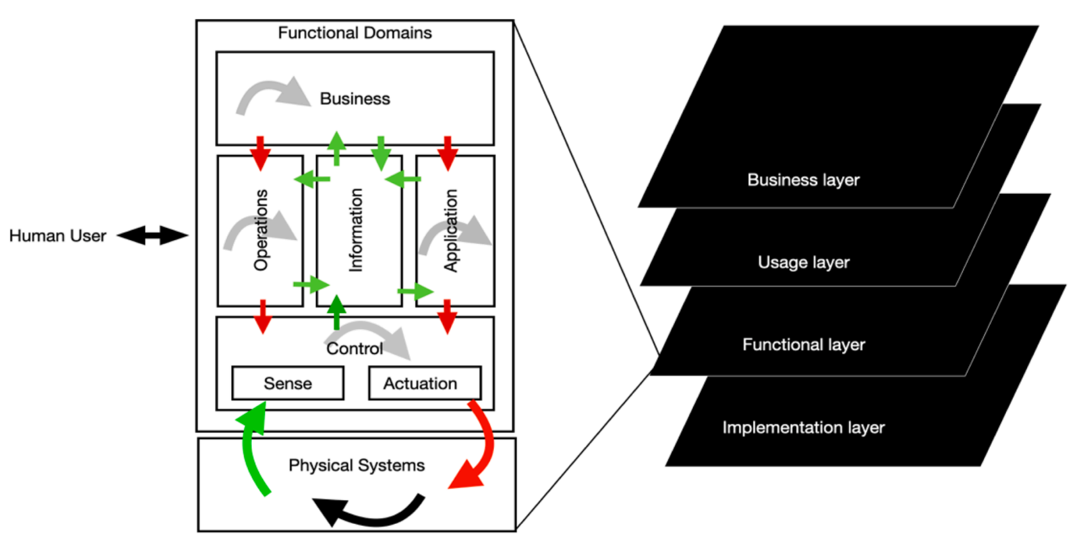

Fig. 3. The IIRA reference architecture's layers and functional domains. Source: adapted from (Industrial Internet Consortium, 2019).

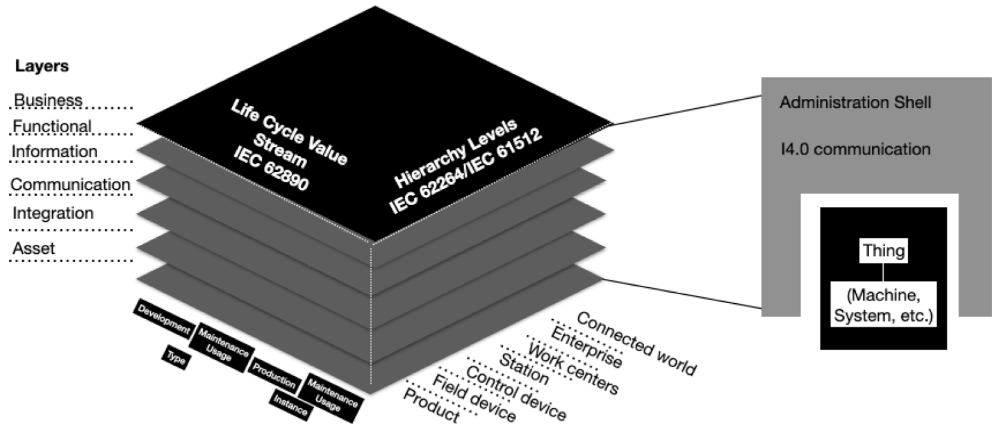

Fig. 4. The RAMI 4.0 reference architecture model and an I4.0 component. Source: adapted from (ZVEI, 2015).

Table 1
Comparison of the architecture, reference architecture and reference architecture models.

Content	5C	8C	IBM I4.0	IIRA	RAMI 4.0
Business level	X	X	X	X	X
Operational level	X	X	X	X	X
Process level	X	X	X	X	X
Control level	X	X	X	X	X
Field or device level	X	X	X	X	X
Value chain integration		X	X	X	X
Customer level		X	X	X	X
Life-cycle management		X	X	X	X
Standards				X	X
Documentation				X	X
Multisector			X	Generic	Generic

integrations across the entire product cycle, and also at all the hierarchical levels. As previously identified, the I4.0 component is suitable for the realisation of an I4.0 system or a "thing", and the administration shell is the digital or virtual representation of a "thing".

4. Conceptual proposal

The main contribution of this proposal is to provide the systematic structuring of how a PPC system operates in the I4.0 context.

A conceptual framework compiles and contains the main concepts under study, and allows the identification, description, organisation and understanding of these aspects (Alarcón et al., 2009).

Here the aspects were adapted to an I4.0 context by utilising RAMI 4.0 axes. Fig. 5 shows the relational matrix aligned with RAMI 4.0 layers and hierarchy levels and the life cycle and value stream is represented in each cell, where the upper part represents development and the lower part represents production. Given the vast information and specifications contained on each axis, we consider only the relevant information to present the relation among the layers, hierarchy levels, and life cycle and value stream in the PPC and the I4.0 context. Such relations are described as follows.

Product.

- Business
  - o Development: it contains the product design with a unique identification. A customer has influenced the design of a product. The rules or specifications to develop a product, a set of products or services, i.e., product structure (BOM), volume and variety. Planning models could be used in the development phase which are a value/added generated by engineer's experience and make possible for complex systems to be built. Simulations models could be used also in the phase of product prototype, these models could describe existing systems to acquire knowledge about the system through the model (Kagermann et al., 2011). This section will be crucial by selecting the enterprise manufacturing strategy.
  - o Production: at this level, the product has already the specifications of its production plan, allocation, and location of where it will be produced (strategic decisions), and the scheduling plans (operational decisions) by which machine, station, and work centre. For a service, the guidelines and roles of each service are specified.
- Functional
  - o Development: it contains the functional capabilities of the rules or specifications that apply at the previous business layer. A digital model can lie at this level, where a user or customer has remote access to a product's catalogue and specifications, a customer could be involved in the product design.
  - o Production: it refers to a production process and its value-added activities which are common in its life cycle i.e., painting, assembly, etc. Production of an instance of the manufacturing or all services of a type of product. A product is modified by a customer during the production process.
- Information
  - o Development: information flows regarding the structure of the network (strategic decisions).
  - o Production: it is a product's historical data about its production state, location, temperature, energy and resource usage, faults, and its product use by customers. The history of the entire product's life cycle should be collected via sensors and actuators towards the virtual and physical worlds' integration layer that enables I4.0 performance.
- Communication
  - o Development: communication capabilities regarding the product design and previous specifications in the upper layers (business-functional-information). It contains the communication protocols for performing the specifications of the business, functional and information layers.
  - o Production: Products can communicate during production i.e., RFID or wireless technologies. The collected information can be useful for monitoring, controlling, predicting future events, etc.
- Integration
  - o Development: a product DT can be approached in this level.
  - o Production: it is the transition from the physical world to the information layer (virtual world).
- Asset
  - o Development: the physical product contains all the activities related to business/development.
  - o Production: it is the physical product materialised with the specifications applied at the previous business, functional and information layers. The physical asset layer contains all the activities

Layers/Hierarchy levels	Product	Field device	Control device	Station	Work centre	Enterprise	Connected world
Business	Product design, structure, volume and variety.	Quantity, type of field device, location and allocation.	Models, simulation methods, control architecture selection.	Station design, influenced by the production process.	Work centre design, influenced by the production process.	Business strategy, business goals, production planning, manufacturing strategy, PPC methodology.	Collaborative strategies, agreements, rules.
	Who, how, when it will be produced.	Field device specifications.	Role as decision maker.	Machine specifications.	Production line specifications.	Departments involved in transforming goods and satisfy customers.	Production department or factory in a network of factories that can share resources.
Functional	Product specifications, visualisation and products catalogue.	Functional capabilities.	Quantity, type of field device, location and allocation.	Functional capabilities.	Functional capabilities.	PPC software tools, data analysis tools, remote access functionalities, vertical, horizontal, integration, blockchain security.	Functional capabilities. Collaborative planning tools.
	A product is modified by a customer during production.	HMI, real-time visualisation, information visualisation, VR and AR technology.	Controller functionalities.	HMI, real-time visualisation, information visualisation, VR and AR technology.	HMI, real-time visualisation, information visualisation, VR and AR technology.	Enterprise departments are integrated by software tools. Collaboration with stakeholders.	Production as part of a network of factories that can share resources.
Information	Information flows.	Information flows.	Information flows.	Information flows.	Information flows.	S&OP, MPS, MRP, MRP II, SCM and maintenance plans supported by software solutions.	Information flows.
	Historical production information, product usage.	Temperature, humidity, location, process state, energy/resource usage, faults.	Controller indications.	Machine indications, temperature, machine state, energy/resource usage, machine faults.	Production line, process indications, temperature, machine state, energy/resource usage, faults.	Production department information, performance indicators, demand forecasting.	Collaborative production plans.
Communication	Communication capabilities.	OPC-UA, AutomationML, MTConnect, blockchain security.	OPC-UA, AutomationML, MTConnect, blockchain security.	OPC-UA, AutomationML, MTConnect, blockchain security	OPC-UA, AutomationML, MTConnect, blockchain security	Design of the IT plant infrastructure.	Design of the partners IT infrastructure.
	RFID or wireless.	Uses a protocol to communicate.	Uses a protocol to communicate.	Uses a protocol to communicate.	Uses a protocol to communicate.	Uses a protocol to communicate.	Uses a protocol to communicate.
Integration	Product DT.	Interoperability, heterogeneous data and software integration.	Interoperability, heterogeneous data and software integration.	Interoperability, heterogeneous data and software integration.	Interoperability, heterogeneous data and software integration.	Interoperability, heterogeneous data and software integration.	Interoperability, heterogeneous data and software integration.
	Physical world to information layer transition.	Physical world to information layer transition.	Physical world to information layer transition.	Physical world to information layer transition.	Physical world to information layer transition.	Physical world to information layer transition.	Physical world to information layer transition.
Asset	Historical data related to its development.	Historical data related to its development.	Historical data related to its development.	Historical data related to its development.	Historical data related to its development.	Historical data related to its development.	Design of the physical facilities (suppliers, factories, distributors and customers).
	Smart product.	Sensors and actuators.	Controller component, PLC or physical production controller.	Station component, production physical machine.	Work centre component, production physical line, production process.	Field devices, control devices, station, work centre, products, documents.	Partner assets.

Fig. 5. The SPPC 4.0 conceptual framework.

related to manufacturing, product use, resource and maintenance, among others.

Field device.

– Business
  o Development: it contains strategic decisions, related to the quantity/type of sensors and actuators to place i.e., supplier selection, layout planning, location, and allocation decisions. It also contains the requirements of the information to be collected.
  o Production: it contains sensors and actuators, rules, or specifications, the information to collect, quantity, etc.
– Functional
  o Development: it contains the functional capabilities that were established by the manufacturer.
  o Production: it contains the functional capabilities established or planned at the previous business layer, with capabilities like HMI, real-time asset visualisation, captured data visualisation using different technologies, i.e., VR and AR.
– Information
  o Development: information flows in accordance with the structure of the network (strategic decision).
  o Production: it collects production information, such as temperature, humidity, location, energy, resource, etc.
– Communication
  o Development: it contains the communication capabilities that were set by the manufacturer, protocols like OPC-UA, AutomationML, MTConnect and blockchain security in communications.
  o Production: during production, field devices can communicate using a protocol, the collected information can be useful to establish performance indicators, predict future events, etc.
– Integration
  o Development: ensuring interoperability, heterogenous data and software integration.
  o Production: it refers to the transition from the physical sensor and actuators' information to upper layers (digital world).
– Asset
  o Development: the physical asset contains all the activities related to its development (supplier).

o Production: it is the physical asset that contains sensors and actuators.

Control device.

– Business
  o Development: it incorporates the modelling characteristics that are to be selected, the simulation techniques to be used, and the control methods established by an agreement based on blockchain technology smart contracts throughout the value chain, which will be based on the parameters collected from the physical layer. Production control methods and intelligence features will create an information loop in the system. It should be noted that more artificial intelligence can have both a negative and positive effect, i.e., a negative effect could arise because a higher level of artificial intelligence would mean more automation in operations and, consequently, human decision-making interventions would be less needed, with possible employment losses: a positive effect could imply that bigger yields and more improvements could be made in certain elements along the value chain. Control architecture selection can take place in this level (hierarchical, heterarchical or semi-heterarchical architecture).
  o Production: during production, the control device takes the role of a decision-maker.
– Functional
  o Development: it contains strategical decisions, related to the quantity/type controllers to place i.e., layout planning, location, and allocation decisions. HMI functionalities.
  o Production: it contains the functionalities of the controller established at the business layer.
– Information
  o Development: designing the information flows between sensors and actuators.
  o Production: it comprises information about the controlled processes and indications for every state of the production process
– Communication
  o Development: it contains the communication protocols that are considered by the control device supplier.
  o Production: the different communication protocols, i.e., OPC-UA, AutomationML, MTConnect, and blockchain protocols, which can take place at this level.
– Integration
  o Development: ensuring interoperability, heterogeneous data, and software integration.
  o Production: the transition from the physical layers of the production physical controller information to upper layers (digital world).
– Asset
  o Development: the physical asset contains all the activities related to its development (supplier).
  o Production: the physical production controller.

Station/Work centre.

– Business
  o Development: it contains the station/work centre design with a unique identification. The design of a station/work centre is influenced by the production process, products volume, variety, and the manufacturing strategy adopted. The rules or specifications to develop a product, batch of products and individual products. Decisions related to location, allocation, capacity planning, production planning, scheduling, maintenance planning can take place.
  o Production: a set of production machines, production line/process specifications.
– Functional
  o Development: it contains the functional capabilities to perform the rules or specifications that took place at the previous business layer. Capabilities include HMI, real-time asset visualisation, captured data visualisation using different technologies, i.e., VR and AR.
  o Production: A digital model can be found at this level where an operator or decision maker has remote access to a product's machine or workstation, and also to its specifications.
– Information
  o Development: information flows in accordance with the structure of the network (strategic decision).
  o Production: information in terms of indications to the machine, workstation, etc. It is a station/work centre historical data about the production process state, setups, downtimes, machines faults, maintenance, resources usage.

Communication.

o Development: it contains the communication capabilities that were set by the manufacturer.
o Production: different communication protocols i.e., OPC-UA, AutomationML, MTConnect, and blockchain protocols, can take place at this level.
  – Integration
o Development: ensuring interoperability, heterogenous data and software integration.
o Production: the transition from the physical layer from the production physical controller information to upper layers (digital world).
  – Asset
o Development: the physical asset contains all the activities related to its development (supplier).
o Production: different physical machines, physical production lines, physical production process, etc.

Enterprise.

– Business
  o Development: it contains business strategies, the business goals specified by stakeholders, sustainability, business processes, production planning, and the selection of the manufacturing strategy and the PPC methodology to design the manufacturing system. We take it as the most important one because every decision that takes place at this level affects other components. Strategical planning can take place in this section, such plant location, technology selection, allocation of capacity, network design, layout, investment, etc.
  o Production: the enterprise has different departments working together to transform the goods and satisfy customers.
– Functional
  o Development: it contains the enterprise's specifications that were established at the previous business layer with the functionalities of PPC software tools, data analysis tools, remote access to functionalities, blockchain security, vertical/horizontal integration, and end-to-end integration.
  o Production: enterprise departments i.e., accounting, purchasing, production, sales, warehouse are integrated by software functionalities allowing vertical information integration and collaboration between different stakeholders.
– Information
  o Development: different information from the business level in the form of PPC plans is contained at this level, such as S&OP, MPS, MRP, MRP II, SCM and maintenance plans supported by software solutions.
  o Production: information related to the production department, the collected information can be useful to establish performance indicators, business process reengineering, demand forecasting, etc.

- Communication
  - o Development: the design of a global IT plant infrastructure.
  - o Production: different communication protocols are required at this level. However, the need for a global IT plant infrastructure is highlighted.
- Integration
  - o Development: ensuring interoperability, heterogeneous data, and software integration in the design of the enterprise.
  - o Production: interoperability, heterogeneous data and software integration between different business processes and physical resources.
- Asset
  - o Development: the physical asset contains all the activities related to its development (supplier).
  - o Production: it contains physical entities, i.e., field devices, control devices, stations, work centres, products, people, documents, etc.

Connected world.

- Business
  - o Development: it contains collaborative business strategies, agreements, rules, collaborative production planning, every activity that is external to the enterprise, but the enterprise is not excluded.
  - o Production: production department or the factory is part of a network of factories.
- Functional
  - o Development: the functional capabilities established at the business layer. The functionalities of collaborative planning software tools take place at this level.
  - o Production: production as part of a network of factories can share resources.
- Information
  - o Development: design of the information flows according to a network design.
  - o Production: the collaborative production plans that will be delivered to the partner/s and received by partners.
- Communication
  - o Development: design of the IT infrastructure.
  - o Production: the protocols needed to establish communication between the plant IT and partner's IT infrastructure.
- Integration
  - o Development: ensuring interoperability, heterogeneous data, and software integration in the design of IT infrastructure.
  - o Production: the interoperability, heterogeneous data and software integration between different companies and physical resources.
- Asset
  - o Development: design of the physical facilities comprised of suppliers, factories, distributors and customers.
  - o Production: the partner's physical resources.

Value stream.

- Contains collaborative capabilities with the different value chain stakeholders i.e., suppliers, factories, distributors and customers, all the information can be accessed from product design to its delivery, the historic of the versions that products design has been through.

An implementation approach of the SPPC 4.0 conceptual framework can firstly focus on the enterprise/business level. As previously identified, every decision made at this level horizontally and vertically affects the whole system. However, it should be noted that multidisciplinary engineering is necessary for developing SPPC 4.0 systems. Here vertical information integration (internal data from business processes) should be the first type of integration that SMEs should obtain with the help of IS, followed by enabling horizontal (integration from external data) and end-to-end systems scalability in the future. It has been explained how I4.0 components enable information integration.

5. Results remarks

Here we address the main theoretical implications by highlighting the answers to the research questions and research gaps that result from the study and proposal of a conceptual framework of a smart PPC in an I4.0 environment. The main results can be summarised as follows:

- **The main functions making up traditional PPC and SPPC 4.0**

The functions making up PPC systems have evolved at the same pace as ICT/IS developments, while companies have moved from managing one function in a vertically integrated PPC to managing supply chains, i. e., horizontal integration. The core functions of a traditional PPC are MPS, MRPI, MRPII (CRP), S&OP, SCM, scheduling and job sequencing. Other PPC function structures have been identified, such as the Aachen PPC model based on production requirements planning, order management, in-house PPC, controlling and data management. Concerning SPPC 4.0 functions, most literature reviews are based on traditional PPC functions, which act as a research framework. However, very few works have dealt with future functions in SPPC 4.0, namely data analytics or ML in this case. In addition, management methodologies like KANBAN, JIT, TOC, CONWIP, OPT, POLCA, workload control, drum-buffer-rope and QRM have been identified to complement or replace basic PPC functions.

- **Impact of I4.0 technologies on SPPC 4.0**

With the inclusion of the Internet, information digitisation and ICTs have enabled the evolution of operations management, during which competition has shifted from between companies to competition between supply chains (Christopher, 1998; Christopher, 2017). Hence ERP systems are considered essential for supply chains' PPCs because they have applications like CPFR and VMI. Here a traditional PPC system outline is depicted in Fig. 1 and indicates how the PPC design is influenced by PPC management methodologies, customer order trending to mass customisation/individualisation, and the selection of a manufacturing strategy. The goals proposed by an organisation to meet demand determine which kind of SPPC 4.0 functions and structures are needed in the organisation and its software tools. However, a standardised and widely known PPC function structure adopted by many organisations is required. Regarding technologies, we identify the inclusion of modelling, CPS, AAS, DTs, communication protocols (OPC-UA, AutomationML, MTConnect) and software tools (ERP, MES, PLM, VMI, SCM, CRM, HRM, SCADA, DCS and APS). ERP systems are at the highest decision-making level of the ANSI/ISA-95 automation architecture. The ANSI/ISA-95 architecture enables an ERP to be taken as a solution for transformation into I4.0. Although it is an indispensable requirement, it is considered only a steppingstone towards such transformation, and SMEs should have at least one IS at this level if they are to transform towards I4.0 in the future, with previous levels also implemented at this level. In a smart PPC, I4.0 enablers would be linked in a traditional PPC system. DTs arise as a key technology for real-time bidirectional data integration. Indeed interoperability, tool integration and CPS require studies about software development for PPC systems.

- **Modelling a conceptual SPPC 4.0 system**

All current I4.0 architectures are based on ANSI/ISA-95. RAMI 4.0 and IIRA are standard-based and are richer in content than others. RAMI 4.0 provides clear guidelines about how to model a smart manufacturing system by providing vertical, horizontal and end-to-end integration across the entire product life cycle and hierarchical levels. To advance with theories, modelling approaches and applications on the topic, a conceptual framework of a smart PPC, dubbed SPPC4.0, is proposed. It is based on RAMI 4.0 axes and presents the main aspects of PPC, while I4.0. SPPC 4.0 provides the systematic structuring of how a PPC system operates in the I4.0 context.

This conceptual framework provides answers to the research questions herein posed and in terms of research gaps and further research identification, and by also considering the reviewed articles. Thus we identified the following main research gaps in the literature which require further research to: (i) incorporate data analytics and ML into SPPC 4.0 to solve complex problems automatically and autonomously; (ii) combine management methodologies like JIT, OPT and/or QRM, and their specific tools and techniques, with I4.0 technologies, such as the IIoT and the DT, to design more sustainable resilient PPC systems; (iii) unify the DT architectures capable of both mapping the smart PPC system and synchronising behaviour between physical and digital spaces; (iv) define the functional characteristics of the software tools and devices required to implement SPPC 4.0; (v) identify, test and select specific software tools and devices to implement SPPC 4.0; (vi) develop new optimisation, simulation and artificial intelligence models and algorithms to allow resilience to support PPC systems; (viii) validate and apply SPPC 4.0 to different real world manufacturing environments.

6. Conclusions

In this paper, the main functions making up a PPC system were identified: MPS, MRP, CRP, S&OP, SCM, scheduling, and job and sequencing. It also identified that PPC functions have been approached with different structures and served as a basis for many research frameworks related to PPC systems. It was determined that I4.0 will transform the way that PPC functions will be integrated. Indeed, improvements can be expected with the inclusion of I4.0 technologies; i.e., data analytics or ML into PPC functions. PPC in the I4.0 context was identified as being affected by not only technologies, but also by management methodologies and current mass customisation/individualisation trends. One need was identified: to address different definitions and concepts, such as the DT, the IIoT, sustainability, sustainable value creation and the automation pyramid.

After comparing ANSI/ISA-95, 5C, 8C, IBM I4.0, IIRA and RAMI 4.0, the results showed that they were all based on the ANS/ISA/95 automation pyramid. Furthermore, the first 5C architecture started level from ANSI/ISA-95 architecture level 4, where a production system should already have a management system in place for the vertical integration of its business models. Based on this result, and in terms of applying SMEs' digital technologies and organisational changes, it was determined that digital transformation should have an IS, e.g., ERP, along with different technologies established at the sensor layer, monitoring and automated control levels of the ANSI/ISA-95 architecture's production process, workflow, as well as production activities.

RAMI 4.0 was determined as the most suitable to design a smart PPC system because it provides a generic standard-base reference architecture model to deploy I4.0 systems. Here the main contribution of this paper is the first proposal of a conceptual framework, based on the RAMI 4.0 reference architecture model, of smart PPC in an I4.0 environment to serve as a guide for researchers and practitioners to transform PPC systems towards I4.0. Managerial implications are oriented to deploy the proposed conceptual framework in terms of seven layers (product, field device, control device, decision, work centre, enterprise and connected world) and seven hierarchical levels (product, field device, control device, decision, work centre, enterprise and connected world), plus the value stream and the life cycle.

The main challenge of this proposal is its verification and validation in different industrial companies to compare several real-world SPPC 4.0 implementations, which is a forthcoming work. Additionally, there is still plenty of margin to propose different models and algorithms of the functions involved in a smart PPC system in the I4.0 context. Thus another forthcoming work will extend the SPPC 4.0 conceptual framework to research and propose new tools to deploy the conceptual framework, and to include the mapping of all the models and algorithms related to I4.0 and framed within a taxonomy for smart PPC. Additionally, human-centred design and human factor aspects will be studied and later incorporated into the proposed SPPC 4.0 conceptual framework to further the Industry 5.0 research agenda.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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