Positioning Cyber-Physical Systems and Digital Twins in Industry 4.0

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***Abstract*—Industry 4.0 has brought innovative concepts and technologies that have greatly improved the development of more intelligent, flexible and reconfigurable systems. Two of these concepts, Cyber-Physical Systems (CPSs) and Digital Twins (DTs), have gained significant attention from various stakeholders, e.g., researchers, industry practitioners, and governmental organizations. Both are vital to support the digitalisation of products, machines, and systems, and they focus on the integration of physical and cyber processes, where one affects the other through feedback loops. Having this in mind, this paper aims to better understand how CPS and DT are correlated, particularly exploring their similarities and differences, their positioning within the Industry 4.0 paradigm, and their convergence to develop Industry 4.0 solutions. Some research challenges to develop Industry 4.0 solutions by integrating these concepts are also discussed.**

***Index Terms*—Cyber-Physical Systems, Digital Twin, RAMI4.0.**

I. Introduction

THE emergence of the Industry 4.0 brought to light several new concepts and technologies that strongly contribute to the development of more intelligent, responsive and reconfigurable systems, taking advantage of the connectivity and the value of data. Some of these new concepts seem to be a new reshaping of older concepts from which they got inspiration, and others seem to overlap, representing different technological perspectives for the same functionality/approach.

Cyber-Physical Systems (CPSs) and Digital Twins (DTs) are two of these emergent concepts that have gained significant attention from researchers and practitioners in industry, as well as governmental organizations, which strongly contribute to the implementation of Industry 4.0 solutions, acting as backbone infrastructures for the digitalisation of products, machines and processes. These paradigms share the same foundation principles focusing on the cyber–physical integration. The physical part is related to physical systems (e.g., a machine's mechanical and electrical components) or the physical world in which the system interacts (e.g., factory, materials and operators). The cyber part is related to higher-level computing capabilities, data management and data analytics for decision-making [1]. This integration allows the establishment of feedback loops in which the physical part affects the cyber parts and vice-versa, i.e., the physical part senses and collects data and executes decisions from the cyber part, while the digital part analyses and processes the collected data to support decision-making [2].

Although there are already some works comparing the two technologies and researching within the scope of smart manufacturing, few works point out clearly the position of the two technologies within Industry 4.0, particularly within the Reference Architectural Model Industrie 4.0 (RAMI4.0) [3], established by the Plattform Industrie 4.0. Having this in mind, this paper contributes to fulfilling this gap by clarifying the similarities and complementary aspects between these concepts, as well as discussing their positioning in Industry 4.0 and RAMI4.0 model. This work also analyses the convergence aspects of DT and CPS, and the associated research challenges that should be addressed for developing Industry 4.0-compliant solutions, based on these two technological concepts.

The paper is organized as follows: Section II discusses the commonalities and complementary aspects of CPS and DT concepts, and Section III presents their alignment with the RAMI4.0 model. Section IV analyses the convergence perspectives between CPS and DT, and Section V discusses some research challenges to develop Industry 4.0 solutions by integrating these concepts. Finally, Section VI rounds up the paper with the conclusions and points out future work.

II. CHARACTERIZATION OF CPS AND DTs

A. Overview of Cyber-Physical Systems and Digital Twin

CPS aims to integrate computational capabilities with physical processes, being defined by US National Science Foundation (NSF) as *"engineered systems that are built from and depend upon the seamless integration of computational algorithms and physical components"* [4]. The real-time cyber-physical integration allows for establishing a bidirectional connection between the physical and cyber parts and the integration of computing, communication, and control to support the monitoring and control of physical assets in a reliable, safe, collaborative, robust, and efficient way [5]. CPS was included as an innovation trigger in the Gartner Hype Cycle for Manufacturing Operations Strategy in 2019 [6].

An example of a generic CPS is illustrated in Fig. 1, where it is possible to verify the integration of cyber and physical counterparts and the connectivity among a network of cyber-physical components. The distributed components may present some level of autonomy and ability to communicate to share data and realise collaboration models aiming to achieve a common objective, with the overall system behaviour emerging from their interaction.

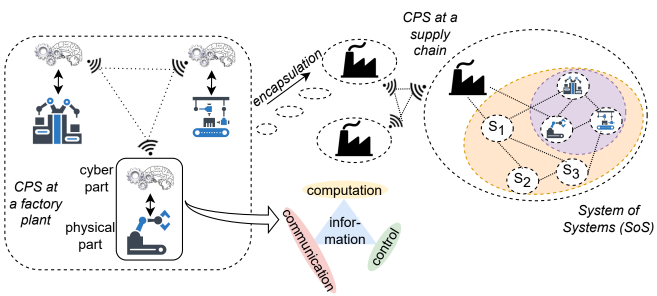

Fig. 1: Overview of a CPS and its organisation.

CPS recalls the holonic principles to represent cyber-physical integration. In fact, holonic manufacturing systems already define that a holon comprises an information processing part (similar to the cyber part) and a physical part. Similarly, this representation structure can also be seen in an industrial agent, where the cyber part is a software agent [7]. Also illustrated in Fig. 1, a CPS can be seen as a System of Systems (SoS), where an individual CPS can be part of a larger CPS, allowing the creation of more complex systems that offer more functionalities and properties than the simple sum of the individual parts. This also recalls the recursivity characteristic associated with holonic systems, where a holon is simultaneously the whole and the part, which strongly contributes to simplifying the design of complex systems [8].

On the other hand, the DT term, considered one of the top ten strategic technology trends in 2019 [9], evolved from the original idea behind the product life-cycle management, based on real and virtual spaces and the link for data flow between them, boosted with the emergence of Industry 4.0 technologies, e.g., Internet of Things (IoT), Artificial Intelligence (AI), Big data and Cloud computing. Despite the diversity of definitions that can be found in the literature, according to the Digital Twin Consortium, *"a digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity"* (digitaltwinconsortium.org), which is also reinforced by the ISO 23247 standard [10]. This means that the DT, as CPS, relies on the digital-physical interaction, creating a digital copy of a physical asset (digital model), which is simulated in the background and in an accelerated timescale to evaluate different scenarios and possibilities using real-time and historical data and provide feedback to the physical asset, e.g., adaptation and optimization of the asset control operation through the prediction of future states and behaviours [11].

The DT encompasses several related concepts, such as digital copy, model and shadow. The distinction between these concepts can be made according to the data integration levels [12], namely the data flow direction, i.e., unidirectional or bidirectional, and the type of interaction, i.e., manual or automatic. Briefly, a *Digital Copy* is a virtual model of the physical asset without any data flow between the physical and virtual spaces. A simulation model is an example of a copy of a physical system, considering the unidirectional use of data from the physical system to test different configurations and predict its performance without constraining the physical asset. The *Digital Model* comprehends the existence of a digital copy of the physical object but does not integrate any automated data exchange between the virtual and physical spaces. In this case, the changes that happen on the physical level are only reflected on the virtual level, and vice versa, by performing manual data exchange. The *Digital Shadow* considers an automatic flow of data from the physical to the virtual space and a manual data flow from the virtual to the physical space. Lastly, the third level of integration is represented by the *Digital Twin*, being fully integrated for automatic data exchange in both directions.

B. Synthesis of Differences

Despite sharing similar foundation principles of integrating cyber and physical worlds, CPS and DT exhibit different features, summarised in Table I.

Regarding the concept, CPSs are network structures formed by integrating the trinity of the physical asset (equipment), computational platform (computer or controller), and the cyber representation of this whole that introduces control, autonomy and decision-making. In contrast, DT is related to synchronizing two similar entities, one operating in the physical space (equipment and environment where it is placed) and another operating in the virtual space, the digital replica of the first. Shortly, the cyber-physical component is an object, and a DT is a digital replica of the object.

The scope of CPS is to actuate in the physical environment in (soft-hard) real-time, controlling the operation of physical assets and focusing on the interconnection between physical assets and their autonomous and collective control behaviour. In the DT case, the physical asset controls the environment, and the DT exercises the virtual model with the collected and

TABLE I: Differences between CPS and DT.

Feature	CPS	DT
Concept	Network of interacting physical assets, e.g., equipment or processes, and their cyber representation.	Digital copy of the equipment or process and the environment where it is placed.
Scope	Cyber-physical entity that controls (actuates) the environment.	Real physical entity controls the environment while the DT provides relevant instructions for optimizing operation.
Design	Focus on the interconnection between physical assets and their autonomous and collective control behaviour and the interconnection with other cyber-physical components.	Focus on the virtual model, the real-time interconnection between the real and virtual spaces, and the use of simulation and/or AI to provide improvements in the physical asset.
Tangibility	Asset should exist and be tangible, e.g., a robot or MES system.	Asset can exist, e.g., a robot or an assembly line, or can not yet exist, e.g., during the design phase of a process or equipment.
Correspondence	Cyber-physical entities interact in a distributed manner to achieve their individual objectives (one-to-many), i.e. one cyber part can connect several physical parts.	Usually focus on a single process, which is the virtual model, but several DT can also be associated with the same asset, e.g., covering different phases of life-cycle (many-to-one).
Responsiveness	(Soft - hard) real-time control and adaptation of physical assets.	Run in parallel (background) to derive optimized configurations for the operational parameters of the physical asset.
Intelligence	Distributed by different networked cyber-physical components focusing on supervising and controlling the physical part.	Centered on one component (virtual model) focusing on monitoring, diagnosing and optimizing the real asset.
Technologies	Supporting the cyber-physical and cyber-cyber connectivity and the execution of computational tasks associated with the cyber part.	Supporting the virtual-physical connectivity, the execution of computational tasks associated with the virtual model, and the execution of the human interaction.

historical data to optimize its operation. In this case, the focus is on the virtual model, the real-time interconnection between the real and virtual spaces, and the use of simulation and/or AI to extract improvements in the physical equipment/process.

Focusing on tangibility, the physical part of the CPS should exist and can be an HW or SW asset, e.g., a robot or an ERP (Enterprise Resource Planning) system. However, during the design phase, the asset may not exist in a DT, e.g., a machine or a plant, which also supports the virtual commissioning capability. Regarding the cyber-physical correspondence, there is one-to-many connectivity in CPS, where the cyber part can affect more than one physical asset. In a DT, there is usually a one-to-one correspondence, with a virtual model including structure, behaviour and functional properties corresponding to a physical asset, which, however, can be composed of different machines involving a complex model. However, several DTs can be associated with the same asset, e.g., covering the life-cycle phases. Another difference is related to intelligence, being distributed by the networked components in CPS and centred in one component (virtual model) in the DT.

Finally, similar technologies are used to implement both concepts, but in CPS, they are centred on the cyber-physical connectivity (e.g., OPC-UA), the cyber-cyber connectivity (e.g., REST, MQTT), and the execution of computational tasks associated with the cyber part (e.g., AI, Big data analytics, Edge/Cloud computing). For the DT, the technologies are centred on the virtual-physical connectivity (e.g., OPC-UA), the execution of computational tasks of the virtual model (e.g., simulation, AI, cloud computing), and the execution of the human iteration (e.g., virtual and augmented reality).

III. Alignment with the RAMI4.0 Model

Governmental and private organisations worldwide have been working to define standards and architectures to regulate the fourth industrial revolution. RAMI 4.0 [3], proposed by the German Plattform Industrie 4.0, defines a three-dimensional architecture to guide the engineering of Industry 4.0 systems, being structured according to the Hierarchy Levels, Layers and Life-Cycle & Value Stream axes. The Hierarchy levels dimension covers the hierarchy of industrial infrastructure and represents the roles and functionalities of their HW/SW assets, following the levels specified by IEC 62264 and IEC 61512 standards. The Layers dimension represents the IT perspectives for the digitalisation of assets. Finally, the Life-cycle & Value Stream dimension represents the life-cycle of plants and products based on the IEC 62890 standard.

The alignment of CPS and DT with the RAMI4.0 is crucial to understand their compliance with standards to promote their industrial adoption. The industrial CPS acts as the backbone infrastructure to implement the Industry 4.0 compliant solutions and is mapped in the RAMI4.0 model in the hierarchy levels dimension. Different cyber-physical components map several control functions provided by HW and SW devices defined in ISA-95. In such structure, automation systems, e.g., a sensor, a robot or an ERP, are integrated and interconnected to form a highly connected and dynamic control architecture.

The DT is mapped with the Layers dimension that represents the digitalisation of the assets. The RAMI4.0 model defines the AAS [13] as a digital representation of an asset in a standardised and semantically unambiguous form along its life-cycle, transforming it into an Industry 4.0 component [14], and providing functionalities, e.g., storing information, creating a standardised communication interface to connect the physical asset to the Industry 4.0 environment and enabling the integration of passive assets. In this sense, each physical asset must have its administration shell to enable its integration into the Industry 4.0 ecosystem, where the AAS forms the digital part of the physical asset. AAS is a specific component within the RAMI4.0, facilitating the interoperability and the digitalisation of assets in Industry 4.0 environments. Recently, it has been observed that the concepts of DT and AAS are evolving in the same direction, with the AAS being perceived as an enabler in developing DTs for industrial applications [14], providing the required structure and composition, namely sub-models based on the digitised data and information associated with different structural and functional specifications of the asset [14], [15]. Therefore, the layers specified by the RAMI4.0 model are implemented, with AAS focusing mainly on the integration, communication and information layers and the DT extending to include the functional and business layers.

IV. Convergence of CPS and DT

The analysis of the literature allows to conclude on the existence of three perspectives on how CPS and DT can be correlated. The first perspective considers CPS and DT as distinct technologies, diverging e.g., in engineering practices, cyber-physical mapping, and core elements, but they share similar features and essential concepts, e.g., cyber-physical connection, real-time interaction, integration and in-depth collaboration (see e.g., [16], [17]). The second group of references (see e.g., [18]–[22]) already point out some differences that allow their complementary use, mainly using the DT as the cyber part of the CPS as a way to improve the CPS operation and implement the CPS functions. In this case, DT is seen as a synonym for the cyber part of CPS, i.e., is the digital representation of a physical system, acting as the digital controller for the real system. A third perspective (see e.g., [23]–[27]) sustain the use of CPS as the asset digitalised by the DT, which is used to enhance digital services for improving the CPS operation, e.g., through simulation, monitoring, diagnosis, prediction, and optimization.

Considering the previous insights, Fig. 2 illustrates a way to combine CPS and DT taking the best of the two worlds. In such approach, CPS controls and operates a smart system, taking advantage of the real-time decision-making and connectivity among cyber-physical components. As sustained by several works, the cyber part of a CPS can be a DT that provides monitoring and control features (see the left side of Fig. 2). The overall CPS control operation can be optimized by using DT that considers the exercise of the virtual model to diagnose, predict and optimize the operation of the CPS (see the right side of Fig. 2). The DT can also be used during the design phase for the design and virtual commissioning or even during the training of complex processes.

The simulation and AI-based data-driven analytics of virtual models can be used to enrich the implementation of CPS, particularly aiming to provide optimisation to monitoring and control functions, supporting the continuous improvement along the assets' life-cycle. MAS [7] can also play an important role in the convergence of CPS and DT since they can act as a pivotal technology to implement both concepts. Firstly, MAS provide the adequate infrastructure to distribute the intelligence and data analysis capabilities among the different components in a CPS. Secondly, MAS can be used to extend the AAS functionalities with their inherent capabilities to provide intelligence and collaboration models [28], supporting the implementation of the DT concept.

These two perspectives to combine CPS and DT are illustrated in Fig. 3 by a case study that considers a transfer system comprising modular Fischetechnik conveyors, each one

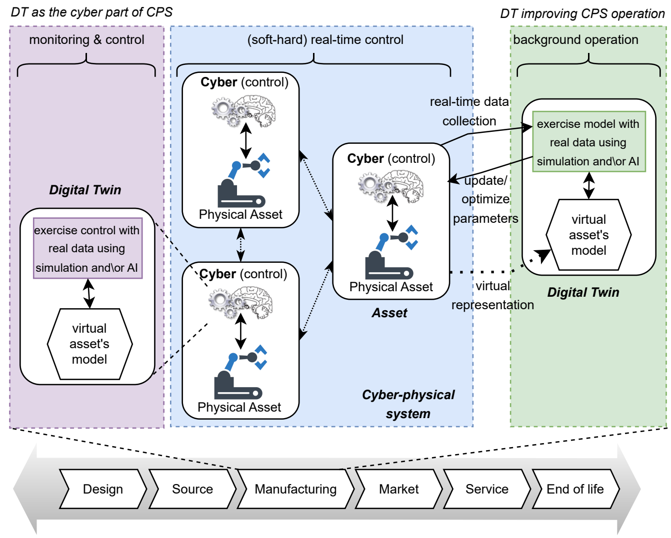

Fig. 2: Convergence of CPS and DT for the life-cycle.

with a logic control running on a Raspberry Pi, with the overall behaviour emerging from the interaction between the individual components. Considering the first approach (see the left side of Fig. 3), the cyber part is implemented by a DT that contains the model of the physical conveyor behaviour and executes the monitoring and control of the physical conveyor, using an agent that embeds the control mechanisms.

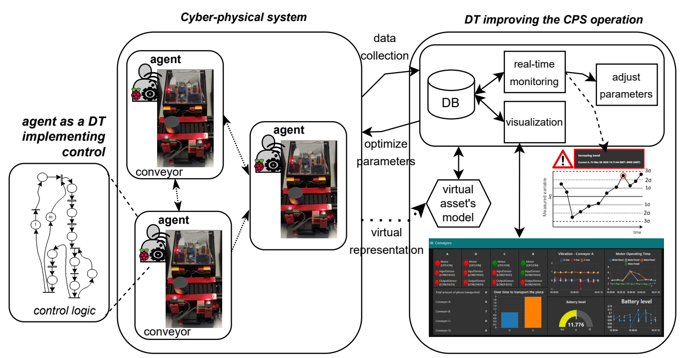

Fig. 3: Analysis of the convergence of DT and CPS concepts.

On the other hand, considering the second approach (see the right side in Fig. 3), the DT can be the representation of the CPS that constitutes the physical asset, contributing to improve its performance through the analysis of the system's health condition and the prediction of failures based on the collected real-time data. The virtualisation and real-time monitoring of the system under study can be seen at [29].

V. Research Challenges

In spite of the discussed benefits, the engineering of Industry 4.0 solutions that combine CPS and DT are facing several research challenges and open issues, summarised in Table II.

The engineering of SoS can bring several benefits in the design, deployment and maintenance, but also brings research

TABLE II: Challenges for developing CPS and DT solutions.

Key Research Challenge	Coverage
Engineering SoS	Ensure the synchronisation and management of distributed models/processes, particularly the data analysis at global and local levels, and the adoption of proper deployment methodologies.
Integration and connectivity	Cyber-physical integration to ensure interoperability and cyber-cyber connectivity to ensure the distribution of features.
Semantic data models	Use standard semantic data models and ontologies, at operational and business levels, to ensure data/system integration and information/knowledge sharing.
Data security and integrity	Ensure secure communication, data integrity and privacy, along with all the networked components, including those with resource constraints, and consider ML algorithms for the detection of cyber threads.
Self-organization	Manage and control emergent behaviour(s), myopia and nervousness in self-organised systems.
Embedding AI and simulation	Select the proper AI algorithms for data analysis, as well as explainable AI techniques, properly combine data analytics with simulation, and consider ethical aspects, e.g., involving multi-disciplinary teams.
Life-cycle coverage	Manage and integrate the asset along its entire life-cycle, particularly design, production, operation and maintenance.
Human integration	Augment the human capabilities and enhance the human interaction in the automation loop, either at the operational or strategical levels and enhance human trustworthy decision-making recommendations.
Standards compliance	Adoption of industrial standards to ensure the systems' interoperability and scalability, e.g., along RAMI4.0 layers.

challenges, namely related to managing the evolution, aggregation, granularity and synchronisation of such systems, with CPS and DT being developed in a recursive manner following the principles exhibited by holonic systems. In particular, methodologies to guide the definition of the granularity of the digital models assumes crucial importance.

In the CPS and DT essence, there is the need to integrate the cyber/digital and physical counterparts, requiring the usage of standard communication technologies. Since several alternatives exist to implement this interface, the recently established IEEE 2660.1 standard [30] provides recommendations on the best interface practices to implement this interconnection, e.g., the communication layer of the RAMI4.0 model, according to the application scenario requirements. Also important is to focus on cyber-cyber connectivity, namely the establishment of proper collaboration models that reflect the desirable functions provided by CPS and DT.

Since the exchange of data assumes crucial importance in such systems, the use of standard data models is a challenge that should be addressed, particularly the development of semantic data models covering different application domains and merging business and operational data. In this context, AutomationML is gaining significant importance in industrial environments, particularly addressing operational levels. However, it is still missing the integration with other standards addressing, e.g., business levels. Addressing interoperability aspects, cloud middleware platforms to connect applications or devices with other applications, databases, or even clients and servers, providing benefits in terms of scalability, modularity, interoperability and robustness. As an example, the FIWARE (www.fiware.org/) platform can be used to handle these demands by defining standards for the data gathered from various sources, solving issues related to the diversity of protocols and languages that can be used, and translating the collected data into a common language. In the same manner, implementing security and privacy mechanisms is crucial to ensure a secure exchange of data, which can be empowered with AI algorithms in applications running on computationally constrained resources (i.e., edge AI).

Being CPS a distributed system, and DT going in the same direction with the models' distribution, emergence and self-organization are desirable features to achieve on-the-fly reconfiguration. However, some challenges will appear, e.g., the management of emergence, i.e. only allowing the emergence of "desired" behaviours and preventing the occurrence of "undesired" behaviours, and the control of nervousness, i.e., balancing between being too calm and too nervous.

Embedding AI and simulation in such systems are crucial to extract knowledge and perform monitoring, control and optimization. Particularly combining simulation and data analytics in a symbiotic manner is a promising research perspective to be explored. It is also important to address the non-deterministic nature of some AI algorithms, e.g., by adopting explainable AI techniques, and to consider ethics aspects to verify and certify such algorithms for their adoption and application in real environments, e.g., ensuring that the actions of such systems do not cause any harm or endanger operators. At this level, it is challenging to involve multi-disciplinary research teams that include researchers from the ethics and law fields.

Another important aspect to be considered by both concepts is related to managing and integrating the asset along its entire life-cycle, particularly in the design, production, operation and maintenance phases. In this context, the deployment of forward and backward collaborative models are required to support the interaction among the different CPS and DT components representing the same asset at different phases of its life-cycle.

The user interaction is also a crucial challenge to be considered aiming for the development of sustainable solutions aligned with Industry 5.0, being required solutions that can augment human capabilities and enhance human interaction in the automation loop, either at the operational or strategic levels, as well as mechanisms that can extract the knowledge from the human's experience. Additionally, the decision-making recommendation systems associated with the DT concept should consider the human trustworthiness.

Finally, a crucial challenge is the adoption of industry standards and technologies to ensure the scalability and interoperability of the systems, following the layers in the RAMI4.0 model. At this level, standard frameworks and toolsets are required to simplify the development of these industry-oriented systems, being the ISO 23247 [10] is an example of a comprehensive framework to develop DTs.

VI. Conclusion

The increasing interest in CPS and DT technologies has raised fundamental questions about their similarity, differences and complementarity. It is clear that CPS and DT are different concepts that share similar principles regarding the digitization of assets towards the development of the new generation of smart automation systems, mainly being based on the digital/cyber representation of processes, equipment and products. However, they present some differences, e.g., DT emphasizes more in the simulation of the virtual model using real-time and historical data to provide monitoring, adaptation and optimization of the physical asset, and CPS is more related to the integration and control of physical assets. Their differences are complementary, being desirable to combine the concepts in the engineering of Industry 4.0 systems. In this sense, the DT can be used as the cyber part of a CPS or the digital representation of the CPS as an asset to improve its operation. A case study was presented to illustrate this convergence, one considering them as dependent concepts.

These concepts are aligned with the RAMI4.0 model, where the CPS is mapped in the hierarchy levels dimension, assuming different roles and functionalities according to the control functions provided by the cyber-physical components, and the DT is mapped in the Layers dimension, representing the digitisation of the assets. Some research challenges to develop Industry 4.0 solutions by integrating the DT and CPS concepts were also discussed, clustered in engineering SoS, integration and connectivity, semantic data models, data security and integrity, self-organisation, embedding AI and simulation, life-cycle coverage, human integration and standards compliance.

Future work will be devoted to further addressing some identified research challenges for combining CPS and DT, aiming to develop Industry 4.0 solutions that are more efficient, resilient, intelligent and industrially adopted.

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