2025 IEEE 8th International Conference on Industrial Cyber-Physical Systems (ICPS) | 979-8-3315-4299-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICPS65515.2025.11087872

Alignment of ADACOR Holonic Architecture with RAMI4.0 and Industry 5.0 Principles

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***Abstract*—The ADACOR holonic architecture introduced an adaptive reconfigurable manufacturing control approach that promotes a balance between centralized and decentralized control, reducing the reliance on a pure central node and enhancing the robustness, responsiveness and fault tolerance. In the digital transformation era, it is crucial to understand the alignment of ADACOR with Industry 4.0 and Industry 5.0 principles. In this context, the paper discusses the alignment of ADACOR with the RAMI4.0 model, as well as with the human-centric and sustainability dimensions defined by Industry 5.0. Finally, the research challenges to develop an ADACOR 4.0 architecture fully aligned with these principles were also discussed.**

***Index Terms*—ADACOR, Industry 4.0, RAMI4.0, Industry 5.0.**

I. INTRODUCTION

Industry 4.0 is changing the way machines and processes are operating based on the intensive use of data, combined with emergent digital technologies, e.g., Internet of Things (IoT) and Artificial Intelligence (AI), and supported by cyber-physical systems (CPS) [1], which act as the backbone to implement such systems. CPS are characterized by a network of cyber and physical entities connected to share data and apply simulation and AI-based data analytics aiming, e.g., monitoring, diagnosis, optimization prediction, and planning. The Industrie 4.0 platform established the Reference Architectural Model Industry 4.0 (RAMI4.0) [2] to serve as a reference for engineering Industry 4.0 systems, considering the use of industry standards along its three dimensions. RAMI4.0 also defines the Asset Administration Shell (AAS) [3] as the main component for digitalizing industrial assets, being defined as a digital representation of an asset in a standardized and semantically unambiguous form along its life cycle, transforming a passive asset into an Industry 4.0 component [4]. The AAS offers important functionalities, e.g., storing information of the asset and providing a standardized communication interface to connect the physical asset to the Industry 4.0 environment.

More recently, Industry 5.0 [5], introduced by the European Commission, extends the Industry 4.0 principles by prioritizing the human-centric and sustainability dimensions aligned with societal development goals, emphasizing the well-being of workers as a key aspect in the production process [6].

Twenty years ago, ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) holonic architecture [7] introduced an innovative reconfigurable manufacturing control approach that addresses the agile reaction to emergence and condition change, increasing the agility and flexibility, especially for manufacturing systems characterized by the frequent occurrence of disturbances. ADACOR combines holonic principles, Multi-agent Systems (MAS) and self-organization capabilities to achieve an adaptive mechanism that balances between a more centralized approach when the objective is the optimization and a more heterarchical approach in presence of unexpected condition changes. Some years later, ADACOR 2 [8] extended the original adaptive mechanism by pushing the self-organization capability to its limits through the introduction of a 2-dimensional approach that comprises the structural and behavioral components.

In the current digital transformation environment, a pertinent question is to which extent the ADACOR architecture is aligned with the Industry 4.0 related reference architectures, particularly with the RAMI4.0 model, and the Industry 5.0 principles. Having this in mind, this paper discusses the alignment of the ADACOR holonic manufacturing control architecture, and its evolution, with the RAMI4.0 model mainly mapping its principles according to the three axes defined by the model, as well as with the human-centric and sustainability dimensions defined in Industry 5.0. The research challenges that arise to develop an ADACOR 4.0 architecture fully compliant with RAMI4.0 and Industry 5.0 principles are also discussed.

The rest of the paper is organized as follows. Section II overviews the ADACOR holonic architecture and its extension ADACOR 2. Section III analyses the alignment of ADACOR with the RAMI 4.0 model, and Section IV with the Industry 5.0 principles. Section IV discusses the research challenges for extending ADACOR to fully comply with RAMI4.0 and Industry 5.0. Finally, Section VI rounds up the paper with the conclusions and points out some future work.

II. OVERVIEW OF ADACOR HOLONIC ARCHITECTURE

This section overviews the fundamentals of the ADACOR architecture and its evolution into ADACOR 2.

A. *Original ADACOR Architecture*

ADACOR introduces a reconfigurable manufacturing control system based on holonic principles that considers four types of holons to represent the manufacturing assets: product, task, operational and supervisor [7]. The product holon (PH) represents a product model and contains the necessary information to produce that product, namely the CAD design files and the process plan. A task holon (TH) represents a production order launched to the shop floor to produce a product and is responsible for managing its production. Operational holons (OHs) represent the physical resources as part of the production process, e.g., robots, processing stations and operators, managing their behaviors according to their objectives, knowledge, and skills. Finally, the supervisor holon (SH), inspired by biological systems, introduces coordination and global optimization in such a decentralized system.

The main innovation introduced by ADACOR is the adaptive control approach that balances between two alternative states, as illustrated in Fig. 1: stationary state, where the system control uses the supervisor holon to achieve the global optimization of the production process, and the transient state, triggered with the occurrence of disturbances and presenting a heterarchical behavior in terms of agility and responsiveness. The adaptive mechanism is based on the stimergy concept and considers the holon's autonomy factor (representing the level of autonomy of the holon) and the spreading of pheromones (used to propagate the occurrence of disturbances and signaling the need to re-configure).

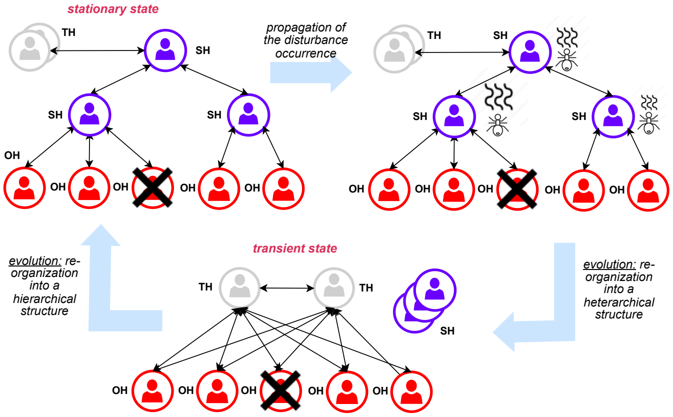

Figure 1. Adaptive control mechanism defined by ADACOR based on the use of the holon's autonomy factor and a pheromone-like mechanism [7].

In the stationary state, task and operational holons are organized in a federated structure, with supervisor holons interacting directly with task holons during the resource allocation process aiming the production of demanded products. Based on aggregated data and powerful algorithms, the supervisor holon calculates optimized schedule plans that are proposed to task and operational holons, that see them as advice, having enough autonomy to accept or reject the proposed schedule.

In case a condition change is detected, e.g., a machine breakdown or a delay in the execution of an operation, a pheromone is propagated to the neighbor holons using a gradient pattern, triggering the re-organization of the holons into a heterarchical control structure, typically during a short period of time. In this transient state, operational holons try to recover locally from the disturbance by interacting directly with the task holons and elaborating alternative schedule plans; the advice provided by supervisor holons is, at this stage, not considered by task and operational holons.

After recovering from the disturbance, operational and task holons return to the stationary state, following again the optimized schedule plans sent by the supervisor holons.

B. ADACOR 2 Architecture

ADACOR 2 [8] is an evolution of the original ADACOR by enhancing the self-organization mechanism with two components (Figure 2): behavioral and structural self-organization.

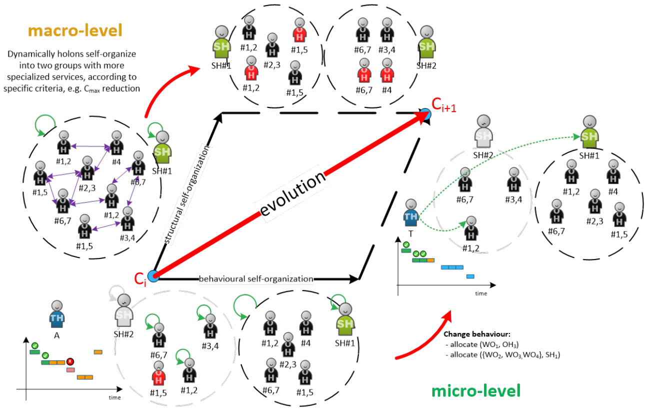

Figure 2. Structural and behavioral self-organization defined by ADACOR 2 architecture to support a truly reconfigurable system [8].

Individually, behavioral self-organization occurs at the micro-level, allowing individual holons to dynamically adapt their behavior in response to local disturbances. This ensures smooth and efficient operation under varying conditions. Therefore, when facing local disturbances or by the identification of potential for evolution, the holon adapt its behavior, e.g., by improving its local knowledge or by adjusting its decision method. Collectively, the structural self-organization operates at the macro level, enabling the system to reconfigure its structure in response to significant changes or disruptions. This involves reassigning roles, responsibilities and relationships among holons to optimize the overall system performance. Therefore, when facing disturbances or opportunities to evolve that involve higher complexity, e.g., by impacting a multitude of holons, the system promotes a reorganization of its structure.

III. ALIGNMENT WITH THE RAMI4.0 MODEL

RAMI4.0 defines a model structured in 3 axes [2]: Hierarchy levels, Life-cycle & Value stream, and Layers. As illustrated in Fig. 3, the model defines a 2-tuple associated with an asset placed in an industrial system, according to the hierarchy levels and considering the life-cycle & value stream phases. The digitalization process of each one of the 28 cells (defined according to the hierarchy level and life-cycle phase) considers a bottom-up approach following the layers dimension.

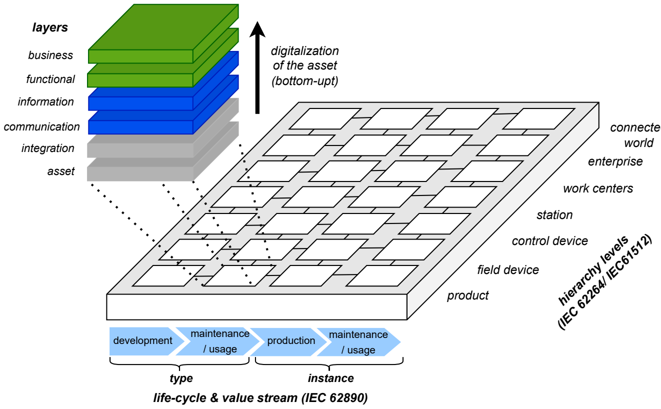

Figure 3. Digitalization process following the 3D RAMI 4.0 model.

A. Hierarchical Levels Dimension

The hierarchy levels dimension covers the roles and functionalities exhibited by hardware/software assets placed in industrial automation systems, following the levels specified by IEC 62264 and IEC 61512 standards (also known as ISA-95 [9]). CPS act as the backbone infrastructure to implement Industry 4.0 compliant solutions, and different cyber-physical components mapping the control functions defined in ISA-95, e.g., a robot, or a MES (Manufacturing Execution System), are integrated to form a connected and dynamic control approach.

As previously referred, ADACOR focuses on manufacturing control, which, according to ISA-95, is included as one function of a MES that is responsible for managing manufacturing operations in factories. As illustrated in Fig. 4, the overall function provided by the distributed ADACOR holons, including the adaptive control mechanism, is placed in layer 3 of ISA95, but the physical assets they represent are placed in lower levels: products at the bottom of the hierarchy levels and resources at level 1 and 2, depending of their granularity, e.g., sensors and actuators in level 1 and Programmable Logic Controllers (PLCs) at level 2. Additionally, ADACOR holons comprise an information processing entity, in this case, an agent, and a physical asset, recalling the cyber and physical counterparts defined by CPS. In this holonic structure, task and supervisor holons do not have physical representation.

In hierarchy levels, the RAMI4.0 model introduces two innovative characteristics: i) the control functions are not anymore organized in a fixed and rigid hierarchical structure, but instead, they are decentralized through the use of intelligence and connectivity features, and ii) the product is now an intelligent entity that takes part of the decision-making process. In fact, ADACOR had already broken the rigidity and hierarchy defined in ISA95 by introducing a distributed set of holons that exhibit autonomy, intelligence, and connectivity. Product, task and operational holons are already intelligent and connected entities involved in collaborative models with the other system actors. The product holon is an active part on the decision-making process, different from ISA95 where the focus is the process and not the product.

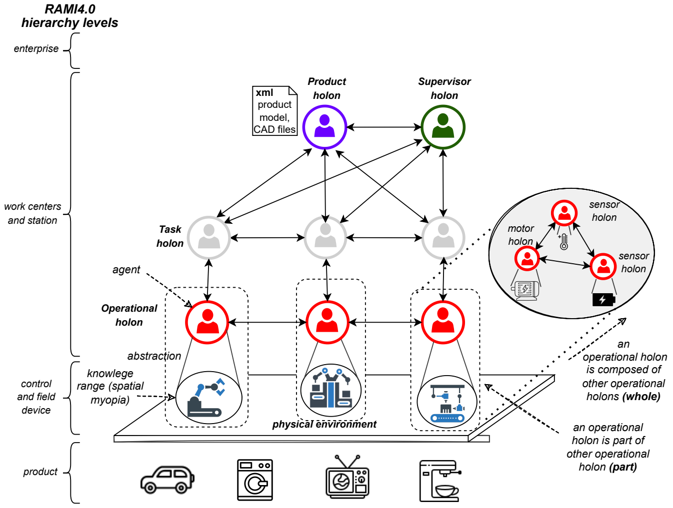

Figure 4. Mapping ADACOR according to RAMI4.0 hierarchy levels.

In this way, ADACOR is fully aligned with the hierarchy levels dimension, exhibiting a reconfigurable CPS structure based on holonics principles. Using the recursivity capability inherited by holonics, ADACOR can be structured as a System of Systems (SoS), e.g., with an operational holon embedding other holons, namely an assembly line comprising several robots and processing machines.

B. Life-Cycle & Value Stream Dimension

The life-cycle & value stream dimension represents the life-cycle of products and production plants based on the IEC 62890 standard, making a distinction between a *"type"* and an *"instance"*: a *"type"* becomes an *"instance"* when the development and prototype production is completed and the product is produced.

Being centered on manufacturing control, ADACOR does not cover the entire life-cycle of an asset. However, as illustrated in Fig. 5, the life-cycle dimension is covered by the ADACOR holons. In fact, the product holon represents the product during its design and prototype production phase, covering the *"Type"* stage. The task holon represents the production order to produce one product, managing its proper execution and being the *"Instance"* of such *"Type"* (product). These two types of holons, representing the product in different phases of its life-cycle, interact with each other using forward and backward loops, to provide respectively, production process plans, and feedback for adjusting the process plans.

The operational holon represents a resource that is placed on the shop floor, contributing to the production of new products, which means that it is a product placed in the *"Instance* phase that before was a product being produced and represented by a task holon (in certain situations, produced products are used as resources in the shop floor, e.g., robots, which are represented by operational holons). Finally, the supervisor holon does not have representation along the life cycle, and its operation is focused on the production stage.

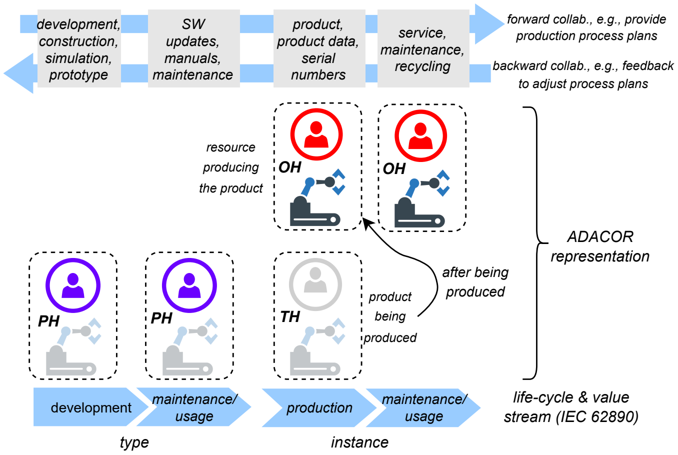

Figure 5. Mapping ADACOR according to the RAMI4.0 life-cycle & value stream dimension.

C. *Layers Dimension*

The layers dimension represents the different Information Technologies (IT) layers for the digitalization of assets. The structure of each ADACOR holon is aligned with this digitalization process, as illustrated in Fig. 6. The *integration layer* is related to the connection between the physical and digital worlds, which is mapped in ADACOR by using the virtual resource (VR), inspired by the Virtual Machine Device (VMD) concept from the Manufacturing Message Specification (MMS) protocol [10]. VR acts as a virtual server that represents the functionality of the real asset and its local controller and supplies primitives to be invoked remotely by the client part [7]. The agent acts as the client part accessing the physical asset by invoking the primitives provided by VR.

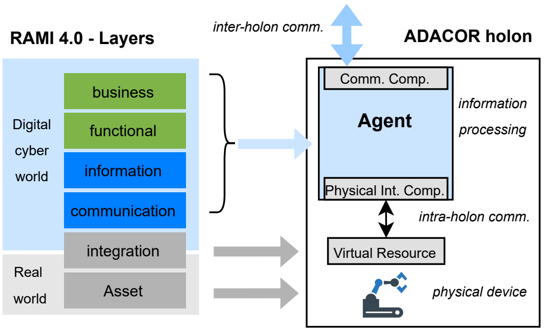

Figure 6. Mapping ADACOR according to the RAMI4.0 digital layers.

The *communication layer* provides a standardized communication to transmit and receive data. In ADACOR holons, this layer is implemented by following the IEEE2660.1-2020 standard [11] that establishes the recommended interface practices to interconnect software agents and automation devices (in this case, the interconnection between the agent as cyber part and the VR representing the physical device). The agents, representing the information processing part of ADACOR holons, implement the functions associated to *storage and functional layers*, which are responsible, respectively, for storing the product and process data using an internal database, and implementing a set of functionalities to pursuit the execution of their objectives, e.g., resource allocation, dispatching, monitoring and failure recovery. Finally, the *business layer* comprises the business strategy, environment and goals, supporting the interaction with other entities. In ADACOR, the interaction among agents follows the FIPA-ACL (Agent Communication Language) [12], but its conceptual design is technology agnostic and can also be implemented using Services-oriented Architecture (SoA) technology to address interoperability.

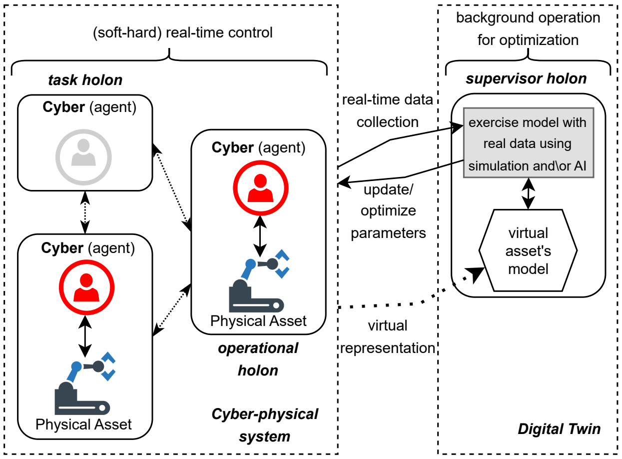

Figure 7. Supervisior holon acting as the Digital Twin of the ADACOR CPS to optimize its operation.

ADACOR already explores the convergence between CPS and digital twins since the supervisor holon can be seen as the digital twin of the CPS system represented by ADACOR, aiming to optimize its operation, as illustrated in Fig. 7. The supervisor holon has the virtual model of the production system, which digital model can be exercised in background using the aggregated historical and real-time data, and powerful AI algorithms. Supervisor holons perform optimization of the scheduling plans in a timely manner or when requested by lower-level holons, i.e., operational and task holons, and provide new schedule plans when optimization is reached.

IV. ALIGNMENT WITH INDUSTRY 5.0 PRINCIPLES

European Commission introduced the Industry 5.0 vision that complements the Industry 4.0 approach by considering a transition to a sustainable, human-centric, and resilient European industry. This vision places the well-being of operators at the center of the production process and considers emergent digital technologies to provide sustainability while respecting the production resources available in the planet [13].

A. *Human-centric Dimension*

The ADACOR architecture does not primarily focus on the human aspects, with operational holons representing the shop floor resources, e.g., robots and processing machines. However, they can also represent operators placed in production plants, recognizing their importance in such industrial systems.

This position is similar to RAMI4.0, which, at the moment, misses the definition of proper guidelines for its integration or considers a fully integrated human-centric design.

As previously referred, the intra-communication within the holon is performed by using interface practices that interconnect agents and industrial assets following the IEEE 2660.1-2020 standard [11]. However, the agent-human interaction is not covered by ADACOR and the IEEE 2660.1-2020 standard.

B. Sustainability Dimension

Based on its structure and capability to dynamically adapt to condition changes, ADACOR contributes to achieve sustainable automation solutions by reducing the resource idle time, the processing and transport times, and the re-work, waste, and lack of quality of products, e.g., aligned with Zero Defects Manufacturing (ZDM) strategies.

As example, ADACOR principles were applied to develop MAS solutions for the real-time integration of quality and process control following a ZDM strategy for washing machines (Whirlpool) and automotive assembly (Volkswagen AutoEuropa) lines, bringing several relevant benefits. In particular, for the last case, it was noticed a reduction of 10% of the number of produced cars with defects, 10% of the number of cars needed to be aligned, 15% of production costs due to unnecessary alignment operations, and 50% of the inspection time [14].

V. DISCUSSION

As summarized in Table I, it is clear that ADACOR is generally well aligned with the RAMI4.0 model axes but further efforts are required to address the Industry 5.0 dimensions.

As previously referred, the primary focus of the ADACOR architecture is the manufacturing control, but its principles can be extended for other applications, as illustrated in automotive assembly lines. Product, task and operational holons already contribute to implement manufacturing control functions, i.e., planning, scheduling, and plan execution, and supervisor holons are digital twins that can represent shop floor processes. Aiming to cover a wider spectrum of manufacturing functions, it will be necessary to consider additional holons, depending on the requirements of the target application. However, the potential benefits of ADACOR, based on its unique on-the-fly reconfiguration mechanisms, should be considered when deciding which applications should be accommodated. ADACOR 2 is an important step in accomplishing this objective since it already conceptually abstracts the type of holons used in the designed self-organization mechanism.

Regarding the hierarchy levels dimension, ADACOR is already well aligned since it presents a decentralized holonic control approach with holons exhibiting intelligence, autonomy, and connectivity capabilities. The main challenge is related to extend the specification of the holons behavior and collaboration models to address its application to other manufacturing functions besides the manufacturing control.

ADACOR 4.0 should cover the life-cycle in a more effective manner by establishing adequate forward and feedback loops to support the interaction among the different types of holons representing the product life-cycle, namely product, task, and operational holons. At the moment, ADACOR already specifies the interaction patterns between product and task holons, but they are focused on the forward loops (with product holons providing production process plans to task holons) and not on feedback loops (with task holons providing feedback to adjust the process plans). Additionally, currently, there is no specification for the interaction between operational and product holons (representing the same product), being crucial to specify the feedback loops that will allow the optimization and adjustment of process and production models, at the design phase, based on the real-time feedback operation.

ADACOR holons are already aligned with the layers' dimension, following the bottom-up digitalization process. In fact, they consider agents technology to implement the upper levels (information and functional layers), and the IEEE 2660.1 standard and the VR concept to implement the lower levels (integration and communication layers), allowing the integration of the asset (asset layer). The use of agents to implement the cyber part of the holons can enhance the development of AASs Type 3, characterized by its capability to participate in collaborative schemes. This idea is being explored, as documented e.g., in [15], but requires a deeper adoption in industrial environments. Aiming to address interoperability of such Industry 4.0 compliant solutions, SoA technologies can be combined with agents by encapsulating the provided functionalities as services. Also in this dimension, the role of the supervisor holon as a digital twin needs to be deeply explored, not only for optimizing the scheduling plans but also for optimizing individual and collective behaviors of the industrial CPS.

The human-centric dimension is not primarily focused by ADACOR, but operational holons represent the manufacturing resources disposed along the production plant, including operators. However, besides considering human-centric design approaches in the development of such solutions, a research challenge is related to integrate humans in a symbiotic manner and particularly implementing proper agent-human interfaces that consider humans placed at operational or strategical levels, and enrolled in different decision-making tasks (detection, determining, development and description). This challenge relies also on developing Human Digital Twins by exploring the digitalization of human assets.

Finally, ADACOR holons can be enriched with more powerful AI algorithms to implement additional functionalities, e.g., aligned with ZDM strategies and energy efficiency policies, contributing to achieve more sustainable solutions. For this purpose, advanced data analytics will allow the correlation of data at individual and/or multi-stage production stages aiming for the earlier detection of defects (thus reducing waste, re-work, and resources' inactivity) or the optimization of operation variables (thus increasing productivity and efficiency). Large Language Models (LLMs) will play an important role in implementing several tasks, namely health condition and diagnosis, but the presence of the human will be crucial to

Table I

CHALLENGES TO FULLY ALIGN THE ADACOR HOLONIC ARCHITECTURE WITH RAMI4.0 AND INDUSTRY 5.0.

Issue	**Alignment**	**Challenge**
Scope	ADACOR focuses on the manufacturing control positioned in layer 3 of ISA95, with their physical representations placed in layers 1 (sensors and actuators) and 2 (controllers).	Extend types of holons already defined to address other manufacturing functions, e.g., focusing on maintenance and logistics, as well as addressing functions at layer 4 of ISA95.
Hierarchy levels	ADACOR provides a decentralized holonic control approach with holons embedding intelligence and connectivity capabilities, and considering the product in the control loop.	Extend holons behavior and collaboration models to achieve other manufacturing functions besides the manufacturing control.
Life-cycle & value stream	Primarily focusing on the production phase of products but the designed holons cover the life-cycle of the product, namely with product holons focused on the design phase (*Type*), task holons being *Instances* representing products being produced, which later are operational holons (*Instances*) representing the products that are placed at shop floor as part of the production process.	Consider a more effective correlation among the different types of holons representing different life cycle stages, by using forward and feedback loops, mainly between product-task-operational holons for the same product instance.
Layers	ADACOR holons already follow the bottom-up digitalization engineering approach, considering agent technology to implement the upper levels and following the IEEE 2660.1 standard and the VR concept for integrating the physical asset. The supervisor holon acts as a Digital Twin.	Consider using agents technology to develop AAS type 3 and microservices technology to address interoperability, and explore more the supervisor holon as a digital twin, not only for optimizing the scheduling plans but also for optimizing individual and collective behaviors of the industrial CPS.
Human-centric	Operational holons represent manufacturing resources in the production plant, but they can also represent operators placed on the shop floor and included in production.	Extend the specification of operational holons to represent humans by integrating humans and implementing agent-human interfaces that consider humans placed at operational or strategical levels, and enrolled in different decision-making tasks.
Sustainability	Reconfigurable and self-organization mechanisms allow to reduce waste and device inactivity, contributing to achieving more sustainable solutions.	Enrich holons' functionalities with more powerful AI algorithms to implement additional functionalities, such as those aligned with ZDM strategies and energy efficiency policies, contributing to achieve more sustainable solutions.

validate the proposed decision-making, being necessary to design guidelines to support the interaction and integration.

VI. CONCLUSION

ADACOR holonic architecture introduced an innovative reconfigurable manufacturing control approach that addresses the agile reaction to condition changes, increasing agility and flexibility of such systems. In the digital transformation era, Industry 4.0 and Industry 5.0 are reshaping the way machines and processes operate based on the intensive use of data, combined with digital technologies. This paper analyzes the alignment of ADACOR with RAMI4.0 and Industry 5.0 principles, particularly the human and sustainability dimensions.

ADACOR is generally very well aligned with the 3 dimensions of the RAMI4.0 model and the sustainability dimension, and presents some gaps in the alignment with the human-centric dimension. The challenges for a complete alignment were discussed, mainly focusing on its extension to address other types of applications, a more effective correlation along life-cycle phases, the use of agents to enhance the development of AAS Type 3, and consider human-centric design and interface practices for the agent-human interconnection.

Future work will address the identified challenges and develop the ADACOR 4.0 architecture that fully aligns with the RAMI4.0 model and Industry 5.0 principles.

ACKNOWLEDGMENTS

This work was supported by national funds through FCT/MCTES (PIDDAC): CeDRI, UIDB/05757/2020 (DOI: 10.54499/UIDB/05757/2020) and UIDP/05757/2020 (DOI: 10.54499/UIDP/05757/2020); and SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020).

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