Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 55-2 (2022) 193–198

Agent-Based Asset Administration Shell Approach for Digitizing Industrial Assets

Lucas Sakurada * **Paulo Leitao** * **Fernando De la Prieta** **

* *Research Centre in Digitalization and Intelligent Robotics (CeDRI), Polytechnic Institute of Bragança, Campus de Santa Apolónia, 5300-253, Bragança, Portugal (e-mail: {lsakurada, pleitao}@ipb.pt)*
** *BISITE Digital Innovation Hub, University of Salamanca, Edificio Multiusos I+D+i, 37007, Salamanca, Spain (e-mail: fer@usal.es)*

Abstract: Modern manufacturing systems are facing new challenges related to the fast-changing market conditions, increased global competition and rapid technological developments, imposing strong requirements in terms of flexibility, robustness and reconfigurability. In this context, the Industry 4.0 (I4.0) paradigm relies on digitizing industrial assets to fulfil these requirements. The implementation of this digitization process is being promoted by the so-called Asset Administration Shell (AAS), a digital representation of an asset that complies with standardization and interoperability strategies. At this moment, a significant part of the AAS developments is more focused on the information management of the asset along its lifecycle and not concerned with aspects of intelligence and collaboration, which are fundamental aspects to develop I4.0 compliant solutions. In this sense, this paper presents an agent-based AAS approach for enhancing the digitization process of assets, considering agents to embed distributed intelligence and collaborative functions, service orientation to support interoperability, and holonic principles to provide the system organization. The proposed agent-based AAS was implemented in an industrial automation system aiming to analyze its applicability.

Keywords: Asset Administration Shells, Industrial Cyber-Physical Systems, I4.0 components, Multi-agent Systems, Reference Architecture Model Industrie 4.0.

1. INTRODUCTION

During the past few years, the traditional paradigms adopted for industrial automation are becoming increasingly insufficient to meet the fast-changing market conditions, increased global competition and rapid technological developments (Leitão et al., 2016; Ye and Hong, 2019). The production systems need to be more flexible, adaptable, reconfigurable, scalable and intelligent to handle a high product variability at a reasonable cost and frequent changes to the system configuration with real-time reactivity (Leitão et al., 2016; Colombo et al., 2017; Ye and Hong, 2019). In this context, Industry 4.0 (I4.0) is promoting the digitization of traditional production systems towards the so-called smart factories to address these requirements. This revolution is associated with the implementation of Industrial Cyber-Physical Systems (ICPS) to equip industrial systems with intelligent, highly automated and rapidly adaptable capabilities (Colombo et al., 2017; Leitão et al., 2016).

Under this digitization perspective, a set of specifications towards the digitization of industrial systems is provided by the Reference Architecture Model Industrie 4.0 (RAMI4.0) (ZVEI and VDI/VDE, 2015). RAMI4.0 is a three-dimensional model that provides guidelines to develop I4.0 compliant solutions based on industrial standards. As the main specification of the RAMI4.0, the Asset Administration Shell (AAS) is a standardized digital representation of an asset that enables interoperability across different suppliers' solutions (Plattform Industrie 4.0 and ZVEI, 2020a). The AAS encapsulates the logic or physical asset, transforming it into an I4.0 component, a specific ICPS category, allowing the access and control of the asset information and functionalities, and providing an interoperable interface communication between I4.0 components (Ye and Hong, 2019; ZVEI and VDI/VDE, 2015; Plattform Industrie 4.0, 2019; Ye et al., 2020).

According to its role, the AAS can be classified as passive or active (Belyaev and Diedrich, 2019; Vogel-Heuser et al., 2020), where the main difference is regarding its degree of autonomy to make decisions. The passive AAS contains the asset information described in submodels and responds to external requests but does not have the capability to take initiatives and decisions. On the other hand, active AAS refers to decision-making entities that interact autonomously with other AASs to achieve their goals. At this stage, the AAS solutions reported in the state-of-the-art are still more conceptual, and the implementation practices are still restricted to passive AAS. However, some current research directions have been highlighting the use of Multi-agent Systems (MAS) (Wooldridge, 2002) as a key enabler to implement active AAS (Karnouskos et al., 2020; Vogel-Heuser et al., 2020; Sakurada and Leitão, 2020).

The MAS technology is being applied in several industrial applications in recent years, particularly the industrial

10.1016/j.ifacol.2022.04.192

agents oriented to address emerging industrial challenges (Leitão et al., 2016). Industrial agents take advantage of MAS inherent characteristics and are key enabling for realising ICPS, empowering them with several capabilities such as flexibility, on-the-fly reconfigurability, intelligence and robustness (Karnouskos et al., 2020). Moreover, the industrial agents are designed to cope with industrial requirements, namely hardware integration, reliability, fault-tolerance, scalability, industrial standard compliance, quality assurance, resilience, manageability and maintainability (Karnouskos and Leitão, 2017), which are requested characteristics for I4.0 components.

Having this in mind, this paper presents an agent-based AAS approach aiming to enhance the digitization process of industrial assets, particularly enabling the development of active, intelligent and collaborative AAS. For this purpose, the concept and internal structure of the agent-based AAS were presented that also combines service-oriented and holonic principles. The applicability of the proposed approach was preliminary demonstrated in an industrial automation system case study.

The rest of the paper is organized as follows. Section 2 overviews the AAS concept and the existing related works for its implementation. Section 3 presents the proposed agent-based AAS approach and its internal structure. Section 4 describes the digitization of industrial assets using the proposed agent-based AAS. Finally, Section 5 rounds up the paper with the conclusions and points out the future work.

2. RELATED WORK

The I4.0 component, as proposed by RAMI4.0, encompasses an asset and an AAS, that is a standardized digital representation of such asset that encapsulates its information and functionalities. The AAS is perceived as the cornerstone of interoperability, enabling interoperable communication among I4.0 components across the value-added network and offering means to implement and enable interoperability across the Digital Twins of different suppliers. The AAS presents a structure consisting of several submodels that hold the information and describe the functionalities of the asset, e.g., characteristics, properties, status, and capabilities (Industrial Internet Consortium and Plattform Industrie 4.0, 2020; Plattform Industrie 4.0, 2019). Moreover, the AAS can be provided in different forms, namely passive and active, according to its degree of autonomy regarding the decision-making and the capability to perform cooperative tasks.

Although AAS has received increasing attention in the last few years, a significant part of the AAS approaches in the state-of-the-art is more focused on the information management of the asset along its lifecycle, i.e. aligned with the passive AAS. These approaches are implemented mainly using Automation Markup Language (AutomationML) and Open Platform Communications Unified Architecture (OPC UA) to provide a means to model information and construct a communication interface compliant with the standards. For instance, the authors in (Ye and Hong, 2019) present the digitization of a manufacturing system employing AAS, describing the asset information using the AutomationML and promoting the exchange of information between the assets (e.g., robots, sensors and conveyors) through OPC UA. Based on the same approach, in (Ye et al., 2020), the authors implement an AAS solution focused on the plug-and-produce strategy. Moreover, the standard web-based technologies, e.g., the Representational State Transfer (REST), is also explored for enabling the access to the asset information via Application Programming Interfaces (API) as suggested in (Plattform Industrie 4.0 and ZVEI, 2020b) and used in (di Orio et al., 2019).

As aforementioned, these approaches respond to external requests and commands but do not consider aspects of intelligence in decision-making, and coordination and collaboration strategies to perform the designated tasks. In this context, MAS and holonic paradigms may be suitable candidates to implement active AAS since their features enable the development of more intelligent and collaborative AAS. In the literature, some works are aligned with this research direction. The authors in (Vogel-Heuser et al., 2020) demonstrate how the I4.0 emerging challenges can be fulfilled with the support of agents, particularly addressing that the agents can implement an AAS and an agent-based platform can realize their interactions. In (Sakurada and Leitão, 2020), a mapping between agents characteristics and AAS functionalities is presented, indicating the possibility to use agents to extend the AAS functionalities, supporting the collaboration and embedding AI algorithms. Lastly, in (López et al., 2021), it is proposed a pattern for the implementation of AAS based on industrial agents.

Despite gaining more relevance in the last few years, the agent-based approaches and the holonic paradigms are still underexplored to implement active AAS. However, several European R&D projects have been demonstrated the benefits of introducing agents and holons in manufacturing systems. For instance, the GO0D MAN project proposes a MAS-based approach that focuses on zero-defect manufacturing, allowing the early detection of defects and the implementation of self-adjustments through the distribution of intelligence by agents (Queiroz et al., 2021). On the other hand, the GRACE project proposes a MAS-based approach that focuses on integrating the process and quality control (Leitão et al., 2015), resorting to the holonic principles of ADACOR architecture (Leitão and Restivo, 2006).

3. AGENT-BASED AAS APPROACH

Considering the development of an AAS approach that can exhibit intelligence and collaboration in decision-making, as well as self-reorganization to adapt its behaviour to the condition changes, an agent-based AAS approach is proposed to enhance the digitization process of industrial assets. As shown in Fig. 1, the proposed approach takes advantage of the agents' capabilities, service orientation and holonic principles to implement more active, intelligent and collaborative AAS.

3.1 Agents to Embed Distributed Intelligence

As previously mentioned, the inclusion of intelligence and collaboration strategies to perform tasks are gaps in the

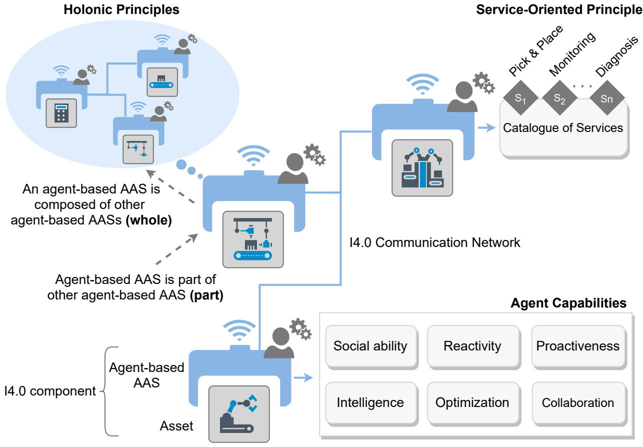

Fig. 1. Overview of the proposed agent-based AAS.

current AAS state-of-the-art. These requirements should be considered to provide flexible, highly dynamic and intelligent networking of machines and processes aiming to enhance the digitization process of manufacturing systems. In this sense, the concept of agents, particularly their inherent capabilities, are key enablers to achieve these requirements. In fact, the agents are suitable for implementing an AAS as suggested in (Karnouskos et al., 2019), being recently used to implement the cyber counterpart of ICPS, particularly to perform the interface with assets through the so-called industrial agents that are complied with industrial requirements.

For these reasons, the agent-based AAS is developed based on the main capabilities of the agents' paradigm, namely social ability, reactivity and proactiveness. According to (Wooldridge, 2002), the reactivity is defined as the capacity to *"(...) perceive their environment, and respond in a timely fashion to change that occur in it in order to satisfy their design objectives"*. On the other hand, the proactiveness is defined as the capacity to *"(...) taking the initiative in order to satisfy their design objectives"*. Lastly, the social ability is defined as the capacity to *"(...) interacting with other agents (and possibly humans) in order to satisfy their design objectives"*.

These capabilities make possible to create a distributed network of agent-based AAS across the edge and cloud levels, introducing intelligence in decision-making through rule-based mechanisms or Artificial Intelligence (AI) algorithms. This distributed system of agent-based AAS come from the need to achieve more flexible, adaptive and reconfigurable solutions, addressing the dynamic industrial environments. For this purpose, the processes' optimization and adaption may be achieved by resorting to the bio-inspired MAS techniques. Moreover, the social ability of agents may be extended to perform collaborative and coordinating functions, e.g., negotiations and following the holonic organizational structures to provide a high-level of (self-)organized agent-based AAS system.

3.2 Service-Oriented Principles Towards Interoperability

The agent-based AAS consider service-oriented principles aiming to achieve a more interoperable, flexible, reconfigurable and scalable I4.0 communication network between distributed and heterogeneous industrial assets, creating a service-oriented ecosystem. For this purpose, the agent-based AAS encapsulates its asset's functionalities and exposes them as services, which are technology independent. These services are available to be consumed and can be reached using discovery services mechanisms by other entities, e.g., other agent-based AASs or external users. Moreover, based on the business needs, the agent-based AAS system will perform the orchestration of the services exposed in the ecosystem by sequencing and synchronizing the execution of services and allow to compose several atomic services and provide the resulting aggregation as a composed service.

In this context, the agent-based AAS structure follows a microservices-based architecture, taking advantage of its benefits, namely scalability, maintainability, reusability, and resilience. As shown in Fig. 2, in this structure, all the functionalities of the agent-based AAS are codified as microservices, where each one may be independently deployed, and new microservices can be easily added, removed, or changed on the fly. Moreover, the distributed event streaming platform acts as a message broker to facilitate asynchronous communication between the microservices.

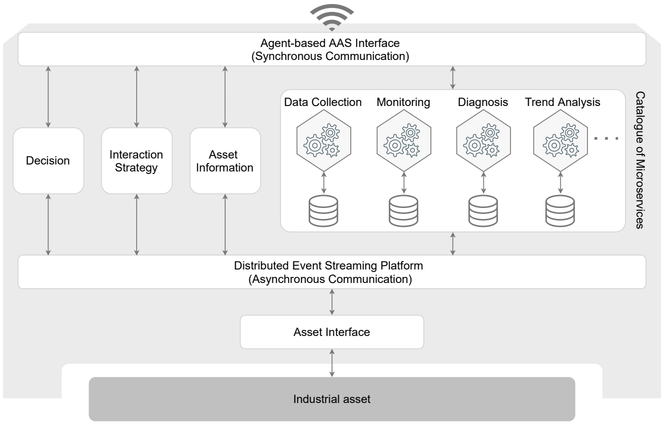

Fig. 2. Agent-based AAS internal structure.

In this structure, some microservices are mandatory, namely the *Agent-based AAS Interface*, *Asset Interface* and *Asset Information*. The *Agent-based AAS Interface* is responsible for interacting with other agent-based AAS or external users, making the data exchange transparent. The *Asset Interface* is responsible for performing the connectivity with the asset to collect information and transmit the instructions to perform its control. Finally, the *Asset Information* stores the static asset information following the structure of the submodels as specified in (Plattform Industrie 4.0 and ZVEI, 2020a). Furthermore, some specific microservices are required to implement the agents' main capabilities, namely reactivity, proactiveness and social ability. The reactivity and proactiveness are implemented through a *Decision Microservice* that is responsible for the decision-making and the optimization of the process according to the obtained data during the asset lifecycle. For this purpose, different degrees of intelligence and autonomy may be considered to support this process, e.g., using stimulus-response mechanisms based on rules or more complex and sophisticated AI algorithms. Lastly, the social ability is implemented through an *Interaction Strategy Microservice* that is responsible to manage the collaboration and coordination strategies to perform tasks in a cooperative manner between agent-based AASs.

In addition, additional functionalities based on data analysis and AI techniques may be codified into decoupled microservices and be included in the *Catalogue of Microservices* offered by the agent-based AAS, e.g., providing monitoring, diagnosis, optimization and trend analysis capabilities, particularly to support the *Decision Microservice* of the agent-based AAS.

3.3 Holonic Principles for the System Organization

As illustrated in Fig. 1, the proposed agent-based AAS approach also resorts to the holonic principles, which are characterized by holarchies of holons that may represent industrial assets. A holon is an identifiable part of a system and is made up of sub-ordinate parts and, in turn, is part of a larger whole, being the autonomy and cooperation their main capabilities. On the other hand, a holarchy is defined as a hierarchical system of holons with fixed rules and directives, where a holon can dynamically belong to multiple holarchies and preserve their autonomy and individuality at the same time (Koestler, 1969).

These holonic principles can be used to implement organizational structures that combine the advantages of hierarchical and heterarchical approaches. This combination enables to development of agile and adaptive systems, which move between centralized configurations when the focus is to optimize the system and decentralized configurations when the objective is dynamic and adaptive control. Based on that, the holonic principles are introduced to create holarchies of agent-based AAS, taking advantage of the features provided by the holons, namely the recursivity properties, organizational structures, and cooperative functions. In particular, the use of the recursivity property associated to holons allows to simplify the design of an ICPS based on I4.0 components, where an agent-based AAS is composed of several other agent-based AASs, and at the same time, is a part of the agent-based AAS system.

4. DIGITIZATION EXAMPLE USING THE AGENT-BASED AAS

The proposed agent-based AAS approach was implemented in an industrial automation system, aiming to analyze its applicability, particularly for digitizing industrial assets and including novel functionalities to the industrial asset that are encapsulated as services.

4.1 Description of the Testing Scenario

The implemented agent-based AAS was applied and tested in an industrial automation system developed using the Factory I/O (https://factoryio.com/) and CODESYS (https://www.codesys.com/) software. The Factory I/O was used to design and simulate the industrial assets and the CODESYS to control each asset through a virtual programmable logic controller (PLC) according to the IEC 61131-3 standard. The virtual industrial automation system was adopted since it facilitates the fast prototyping and testing of various industrial scenarios that can be implemented using the same logic as real applications but without concerning with the real hardware.

Fig. 3. Layout of the industrial automation system.

The industrial automation system, illustrated in Fig. 3, comprises a set of individual industrial assets, namely conveyor belts responsible for transporting the products, two robots for performing pick-and-place and assembly tasks, two machining centers to manufacture lids and bases from raw materials, and sensors to detect the products during the process. In this paper, this set of assets was considered as a unique asset, namely the factory station asset, which considers all the processes performed by these individual assets throughout the station, i.e., to produce lids and bases products from raw materials and assemble these parts to develop the final product.

4.2 Development of the Agent-based AAS

The implementation of the agent-based AAS followed the proposed structure described in Section 3.2 and is illustrated in Fig. 4, considering the Docker containers (https://www.docker.com/) to host the microservices of the agent-based AAS since that provides a lightweight runtime environment. In terms of communication mechanisms, the agent-based AAS provides asynchronous and synchronous communication, supporting different applications and requirements. The asynchronous communication is used mainly to exchange messages between microservices following a publish-subscribe schema to decouple services aiming to increase the performance and scalability. On the other hand, the synchronous communication is adopted for the request-response schema, mainly for cooperative tasks among agent-based AASs.

In this case, the interface with the asset was performed using the OPC UA protocol, and the collected data was forwarded to the services using the Apache Kafka (https://kafka.apache.org/) distributed event streaming platform for asynchronous communication and to create an adapter to standardization of exchange data since different protocols can be used according to the asset, e.g., Modbus and EtherNet/IP. In this way, the microservices only need to subscribe to a topic in the Apache Kafka's broker to receive the desired data. For this purpose, a cluster of three brokers was created, ensuring more fault-tolerance to the system since if one broker fails, the others can assume its tasks. Moreover, the Apache Kafka platform can persist the data, allowing a service to obtain the data in the period when it was unavailable for some reason, e.g., update or maintenance of the service code and the network failure.

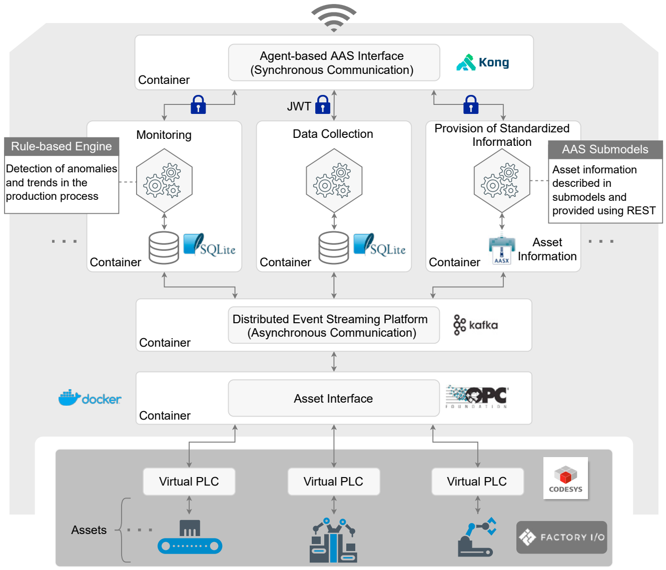

Fig. 4. Experimental deployment of the agent-based AAS.

Besides the asynchronous communication between the microservices, another communication based on REST was adopted for specific cases, such as receiving requests from external entities. In this case, the Kong API Gateway (https://konghq.com/kong) was adopted, acting as a single entry point for API-enabled applications. The Kong API gateway is responsible for routing all received requests from other entities to the appropriated services and offering monitoring and alerts capabilities. In addition, an authentication mechanism using JSON Web Token (JWT) has been added to each endpoint to ensure more security.

Regarding the offered *Catalogue of Microservices*, the implemented agent-based AAS contains three microservices. The first one was implemented with the support of the AASX Package Explorer (https://github.com/admin-shell-io/aasx-package-explorer) to describe the asset information in submodels and provide this information using REST. The second one stores the assets' data in an SQLite database, providing a historical record of the operational data. Lastly, the last microservice analyses the asset's operational data aiming to monitor the health condition of the industrial automation system. For this purpose, a process control method was adopted by following the Nelson Rules that consider the means value and the standard deviation (σ) to determine if a measured variable is under control or not (Nelson, 1984). For instance, the first implemented rule detects an outlier in the measured variable evolution over time, being triggered when a value is greater than 3σ, and the third implemented rule identifies a trend in the measured variable, i.e., six or more consecutive ascending or descending values.

4.3 Discussion

The developed agent-based AAS allowed the preliminary observation that the proposed approach is suitable for enhancing the digitization process of industrial assets, particularly providing new functionalities as services.

Despite being based on simple rules, the implemented microservice to monitor the industrial automation system allow verifying the system's condition during the production process. Aiming to test the monitoring service, system failures were injected to cause delays in the production of the products. The achieved results (see Fig. 5) showed that the rule-based process control method is suitable for detecting trends and abnormal situations during the process, particularly monitoring the cycle time parameter.

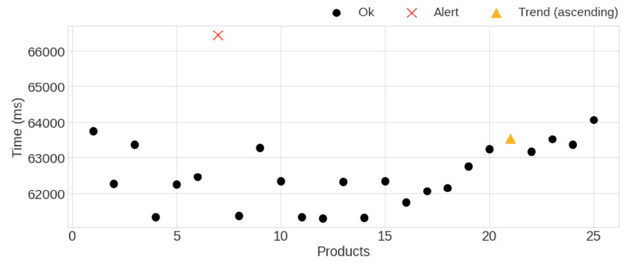

Fig. 5. Condition monitoring of the industrial automation system during a production process.

This additional information may offer a greater understanding of the current system conditions to support more accurate decision-making. Based on that, the collaboration and coordination of tasks between agent-based AAS can be initiated in order to optimize or solve disturbances in the system. Furthermore, the stored data history of the industrial automation system may be used to support further data analysis based on AI techniques to enable, e.g., system optimization and identification of patterns. Lastly, the asset information was structured by following the submodels templates and make available by using REST, according to the guidelines defined in (Plattform Industrie 4.0 and ZVEI, 2020a,b), showing that the agent-based AAS complies with the AAS specification series towards more interoperability to exchange data.

As a final remark, it is important to highlight some limitations of the proposed approach. Despite the agent-based AAS offering an authentication mechanism using JWT, the approach does not address more advanced security-related aspects, particularly techniques that allow the agent-based AASs to find, trust and interact with each other following security protocols. Additionally, although the AAS metamodel has contributed to describing the asset information in a standardized way, the required submodels, particularly related to collaborative tasks, were still not specified, which may be a challenge to design the agent-based AAS. From this viewpoint, a methodology to guide the stakeholders to develop active AAS based on the proposed approach may be explored in further works.

5. CONCLUSIONS AND FUTURE WORK

The I4.0 is promoting the digitization of traditional manufacturing systems towards flexible, reconfigurable and intelligent factories based on ICPS. Currently, this digitization process is being facilitated by the AAS, which encapsulates the asset information and functionalities along its lifecycle and enables interoperable communication between I4.0 components across the value-added network. However, the current AAS approaches are still not fulfilling all emerging industrial challenges, and some fundamental aspects required for I4.0 systems are few or even unexplored, namely intelligence in decision-making and coordinating and collaborative mechanisms to perform tasks.

This paper presented an agent-based AAS approach aiming to enhance the digitization process of industrial assets, considering agents to embed distributed intelligence and collaborative functions, service-oriented principles to support interoperability, and holonic principles to provide system organization. The feasibility of the proposed approach has been illustrated by digitizing an industrial automation system case study using the agent-based AAS. This preliminary implementation demonstrated the potentialities and modularity of the agent-based AAS, particularly simplifying the inclusion of novel functionalities as services, e.g., the real-time monitoring and access to the historical stored data, to support decision-making and collaborative tasks. Moreover, the proposed approach considers holonic principles, in particular, to aggregate several related agent-based AAS to form a unique agent-based AAS with its own identity, knowledge and capabilities.

Future work will be devoted to develop collaborative tasks between agent-based AASs following the MAS and holonic principles, mainly to perform the self-organization of industrial assets due to condition changes in the system. Furthermore, other services based on AI algorithms will be designed and implemented, particularly related to diagnosis, prediction and optimization, to support the intelligent decision-making of the agent-based AAS.

ACKNOWLEDGEMENTS

This work has been supported by FCT - Fundação para a Ciência e Tecnologia within the Project Scope: UIDB/05757/2020. The author Lucas Sakurada thanks the FCT - Fundação para a Ciência e Tecnologia, Portugal, for the PhD Grant DFA/BD/9234/2020.

REFERENCES

Belyaev, A. and Diedrich, C. (2019). Specification "demonstrator i4.0-language" v3.0.

Colombo, A.W., Karnouskos, S., Kaynak, O., Shi, Y., and Yin, S. (2017). Industrial Cyberphysical Systems: A Backbone of the Fourth Industrial Revolution. *IEEE Industrial Electronics Magazine*, 11(1), 6–16.

di Orio, G., Maló, P., and Barata, J. (2019). NOVAAS: A Reference Implementation of Industrie4.0 Asset Administration Shell with best-of-breed practices from IT engineering. In *Proc. of the 45th Annual Conf. of the IEEE Ind. Electronics Society (IECON'19)*, 5505–5512.

Industrial Internet Consortium and Plattform Industrie 4.0 (2020). Digital Twin and Asset Administration Shell Concepts and Application in the Industrial Internet and Industrie 4.0 - An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper.

Karnouskos, S. and Leitão, P. (2017). Key Contributing Factors to the Acceptance of Agents in Industrial Environments. *IEEE Transactions on Industrial Informatics*, 13(2), 696–703.

Karnouskos, S., Leitao, P., Ribeiro, L., and Colombo, A.W. (2020). Industrial Agents as a Key Enabler for Realizing Industrial Cyber-Physical Systems: Multiagent Systems Entering Industry 4.0. *IEEE Industrial Electronics Magazine*, 14(3), 18–32.

Karnouskos, S., Ribeiro, L., Leitão, P., Lüder, A., and Vogel-Heuser, B. (2019). Key Directions for Industrial Agent Based Cyber-Physical Production Systems. In *Proc. of the IEEE Int'l Conf. on ICPS*, 17–22.

Koestler, A. (1969). *The Ghost in the Machine.* Arkana Books.

Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., and Colombo, A.W. (2016). Smart Agents in Industrial Cyber–Physical Systems. *Proceedings of the IEEE*, 104(5), 1086–1101.

Leitão, P., Colombo, A.W., and Karnouskos, S. (2016). Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges. *Computers in Industry*, 81, 11–25.

Leitão, P. and Restivo, F. (2006). ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in Industry*, 57(2), 121–130.

Leitão, P., Rodrigues, N., Turrin, C., and Pagani, A. (2015). Multiagent System Integrating Process and Quality Control in a Factory Producing Laundry Washing Machines. *IEEE Transactions on Industrial Informatics*, 11(4), 879–886.

López, A., Casquero, O., and Marcos, M. (2021). Design patterns for the implementation of Industrial Agent-based AASs. In *Proc. of the 4th IEEE Int'l Conf. on ICPS*, 213–218.

Nelson, L.S. (1984). The Shewhart Control Chart - Tests for Special Causes. *Journal of Quality Technology*, 16(4), 237–239.

Plattform Industrie 4.0 (2019). Details of the Asset Administration Shell - from idea to implementation.

Plattform Industrie 4.0 and ZVEI (2020a). Details of the Asset Administration Shell - Part 1 - The exchange of information between partners in the value chain of Industrie 4.0 (Version 3.0RC01).

Plattform Industrie 4.0 and ZVEI (2020b). Details of the Asset Administration Shell - Part 2 - Interoperability at Runtime - Exchanging Information via Application Programming Interfaces (Version 1.0RC01).

Queiroz, J., Leitao, P., Barbosa, J., Oliveira, E., and Garcia, G. (2021). Agent-based Distributed Data Analysis in Industrial Cyber-Physical Systems. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics.*

Sakurada, L. and Leitão, P. (2020). Multi-Agent Systems to Implement Industry 4.0 Components. In *Proc. of the IEEE Conf. on ICPS*, 21–26.

Vogel-Heuser, B., Seitz, M., Salazar, L.A.C., Gehlhoff, F., Dogan, A., and Fay, A. (2020). Multi-agent Systems to Enable Industry 4.0. *at - Automatisierungstechnik*, 68(6), 445–458.

Wooldridge, M. (2002). *An Introduction to MultiAgent Systems.* John Wiley and Sons.

Ye, X. and Hong, S.H. (2019). Toward Industry 4.0 Components: Insights Into and Implementation of Asset Administration Shells. *IEEE Industrial Electronics Magazine*, 13(1), 13–25.

Ye, X., Jiang, J., Lee, C., Kim, N., Yu, M., and Hong, S.H. (2020). Toward the Plug-and-Produce Capability for Industry 4.0: An Asset Administration Shell Approach. *IEEE Industrial Electronics Magazine*, 14(4), 146–157.

ZVEI and VDI/VDE (2015). Reference Architecture Model Industrie 4.0 (RAMI4.0).