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MULTI-AGENT SYSTEMS TO REALIZE INTELLIGENT ASSET ADMINISTRATION SHELLS

SISTEMAS MULTIAGENTES PARA UNA ADMINISTRACIÓN INTELIGENTE DE ACTIVOS

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ABSTRACT: The digital transformation driven by the fourth industrial revolution is promoting the transition of traditional manufacturing systems towards flexible, reconfigurable and intelligent factories based on Cyber-Physical Systems (CPS), bringing new opportunities and innovative solutions for modern manufacturing systems. However, this condition imposes complex planning across the production chain and lifecycle of the industry. In this context, the Reference Architecture Model Industrie 4.0 (RAMI4.0) provides guidelines to develop Industry 4.0 (I4.0) compliant solutions based on industrial standards. As the main specification of RAMI4.0, the Asset Administration Shell (AAS) is a standardized digital representation of an asset that represents an object of value for the industry. This paper discusses how Multi-Agent Systems (MAS) technology can be used to realize the AAS, mapping their inherits characteristics into AAS functionalities and also extending them, introducing intelligence and data analytics capabilities.

Moreover, it explores the necessity to develop a light and industrial oriented MAS framework to attend the industry requirements, showing the gaps in existing frameworks and some ideas of how to fulfil these requirements.

KEYWORDS: multi-agent systems; cyber-physical systems; asset administration shell.

RESUMEN: La transformación digital impulsada por la cuarta revolución industrial está promoviendo la transición de los sistemas de fabricación tradicionales hacia fábricas flexibles, reconfigurables e inteligentes basadas en sistemas sistemas físicos (CPS), lo que aporta nuevas oportunidades y soluciones innovadoras para los sistemas de fabricación modernos. Sin embargo, esta condición impone una planificación compleja en toda la cadena de producción y el ciclo de vida de la industria. En este contexto, el Modelo de Arquitectura de Referencia de la Industria 4.0 (RAMI4.0) proporciona directrices para desarrollar soluciones conformes con la Industria 4.0 (I4.0) basadas en estándares industriales. Como especificación principal de RAMI4.0, AAS es una representación digital estandarizada de un activo que representa un objeto de valor para la industria. En este documento se analiza cómo puede utilizarse la tecnología de los sistemas multiagentes (MAS) para realizar el AAS mapeando sus características heredadas en funcionalidades AAS y también ampliándolas, introduciendo capacidades de inteligencia y análisis de datos. Además, explora la necesidad de desarrollar un marco de trabajo más ligero y orientado a la industria para atender los requisitos de la misma.

PALABRAS CLAVE: sistemas multiagente; sistemas ciber-físicos; administración de activos.

1 Introduction

The digital transformation driven by the fourth industrial revolution is promoting the transition of traditional manufacturing systems towards flexible, reconfigurable and intelligent factories based on Cyber-Physical Systems (CPS) [22]. As a backbone of the Industry 4.0 (I4.0), CPS creates digital ecosystems through the combination and coordination between the cyber and physical counterparts, supported by the information communication technologies (ICT) to develop complex large-scale and intelligent systems [3]. However, the development of these I4.0 systems is not a straightforward task, requiring the adoption of new production system architectures as a key enabler to reduce complexity and achieve interoperability in the industry [11].

A set of specifications for proceeding digitalizing industrial system is offered by the Reference Architecture Model Industrie 4.0 (RAMI4.0) [23]. 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 RAMI4.0, the Asset Administration Shell (AAS) is a standardized digital representation of an asset that represents an object of value for the industry. The AAS encapsulates the logic/physical asset, transforming it into an I4.0 component, allowing the access and control of the asset information, and provides an interface communication with other I4.0 components based on the Service-Oriented Architecture (SOA) [16, 22, 23].

In this context, Multi-Agent System (MAS) [21] is a suitable approach to realize CPS and particularly AAS, providing means to implement the key functionalities of AAS, such as providing a digital representation of the asset, collecting data and enabling I4.0 components interactions [11], as well as embed and decentralize the intelligence over the system. MAS comprises a society of autonomous, proactive and cooperatives entities, called agents, that represents physical/logical objects in the system. The agents are endowed with communication and self-x capabilities in order to exchange information and make decisions according to the conditions changes.

Having this in mind, this work discusses how MAS can be used to realize the AAS, mapping their inherits characteristics into AAS functionalities and also providing new functionalities. Moreover, it explores the necessity to develop a light and industrial oriented MAS framework to attend the industry requirements, showing the gaps in existing frameworks and some ideas of how to fulfil these requirements.

The rest of this paper is organized as follows. Section 2 overviews the related work related to the development of emergent industrial CPS, namely regarding Industry 4.0 compliant solutions. For this purpose, the RAMI4.0 architecture is re-visited, as well as its main specification, i.e. the Asset Administration Shell (AAS). Section 3 discusses how MAS can be used to realize AAS by mapping their inherent functionalities and extending with new functionalities, e.g., decision-making capabilities. Section 4 describes the need to develop a light and industrial oriented MAS framework that can support a wider adoption of agentbased AAS solutions. Finally, Section 5 rounds up the paper with the conclusions and points out future work.

2 Related Work

2.1 RAMI4.0

RAMI4.0 is a three-dimensional layer model that provides a flexible serviceoriented framework, combining services and data to facilitate and address different aspects of the I4.0 systems. RAMI4.0 classifies existing standards along three dimensions, namely, Lifecycle and Value Stream, Hierarchy Levels, and Layers [23].

The *Layers* represents various properties of an I4.0 component through six layers, namely, asset, integration, communication, information, functional and business. The *asset* reflects the physical world such as physical and non-physical objects (e.g., machines, services or documents), managed by the upper layers, which are in the digital world. The *integration* represents the transition from the real to the digital world, providing the assets information in a form which can be processed by a computer. The *communication* provides a standard communication, using uniform data format to the *information* level, and services to the *integration* level. The *information* describes the information that is used and exchanged between functionalities, services and components, using a common semantic definition. The *functional* describes the functionalities of an asset according to its role in the I4.0 system. The *business* includes information regarding the business-related features of the assets under the legal and regulatory constraints [4, 18, 23].

The *Lifecycle and Value Stream* follow the IEC 62890 standard and describes the asset lifecycle throughout the supply chain, since an asset can perform different functions and different data can be collected during its lifecycle. This recorded information may be used to make corrections and improvements during the asset lifecycle. The *Hierarchy Levels* follows the IEC 62264 and IEC 61512 standards, and describes the different functionalities within factories or facilities, namely product, field device, control device, station, work center, enterprise and connected word, based on the so-called automation pyramid [23].

As a reference model, the descriptions of RAMI4.0 are implemented through the I4.0 components, a specific case of CPS [22]. The I4.0 components combine the assets with their digital representation, called Asset Administration Shell (AAS), the main specification of RAMI4.0. The asset is a physical or nonphysical component with value for a company, which needs to be connected to create I4.0 compliant solutions. In this context, the AAS provides means to integrate the asset into I4.0 environment, allow the access to the asset information, provides a standardized and secure communication interface, and covers the asset lifecycle. Furthermore, the AAS structure illustrated in Figure 1, consists of a number of submodels in which all the information and functionalities of the asset, including the manifest, i.e., a list of properties, are described and managed by the component manager [16, 22, 24].

The Industrial Internet Reference Architecture (IIRA) [8] is another reference standards-based open architecture for Industrial IoT systems, which may be used to complement missing aspects in RAMI4.0. Unlike RAMI4.0, which develops a solid base of service-oriented interoperability, focusing on the digitization of manufacturing, through the I4.0 component, in particular the AAS. The IIRA focuses on industrial analytics, highlighting the collection and analysis of machine data, applying analytical insights in decision making, which would be beneficial for building intelligent I4.0 systems [9].

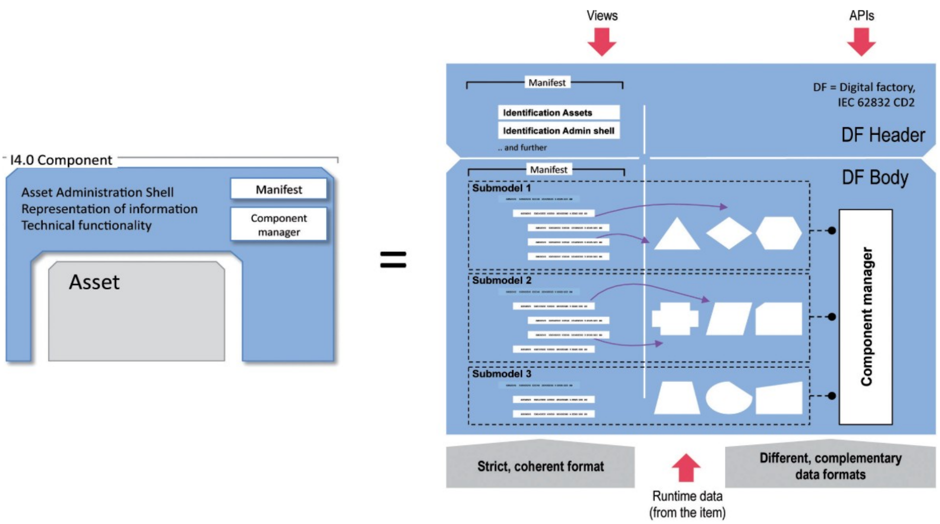

Fig. 1. Asset Administration Shell structure [24].

2.2 Multi-Agent Systems

Derived from the area of distributed AI, MAS comprises a society of autonomous and intelligent entities, named agents, which represent physical or logical objects in the system [21]. The global functioning of these systems emerges from the interaction between the different agents, whose autonomy, cooperativeness and proactivity play a fundamental role in the agents behaviour, promoting modularity, reconfigurability and flexibility to the system.

MAS are a suitable technology for decentralized architecture in industrial environments, as well as embedding intelligence in the system. The agents are distributed over the environment, interacting with each other and the environment, in order to reach a particular or a common goal, exchanging information, making decisions and adapting their behaviour according to condition changes [2,21]. Furthermore, MAS and more specifically industrial agents can be used for realizing industrial CPS. The industrial agents expand the potential application domains of MAS, having the inherits characteristics of traditional agents and the capability to interface low-level control of industrial automation systems, addressing industry requirements [10].

3 MAS to Realize AAS

Due to their characteristics, MAS are a promising technology to realize AAS. The agents can encapsulate the AAS structure, access the asset information, and enable I4.0 interactions with other AAS. Some of the MAS characteristics, such as encapsulation, reusability, reactivity, social ability, learning ability, proactivity, cooperation, autonomy and service-orientation, can be mapping to implement the AAS functionalities associated with the RAMI4.0 layers as illustrated in Table 1.

The encapsulation allows the agent knows the properties and functions of the asset, which is solely accessible by the agent itself, since not all information of asset must be visible and changed from outside [20]. As a software component, some generic structures and functionalities of agents can be reused to encapsulate the assets, making only adaptations to meet the specifics of the asset when necessary. The reactivity of agents allows establishing a bridge with the digital world, perceiving the real-world by sensors and low-level control devices, and acting to achieve their goals. These interfaces can be assisted by the IEEE 2660.1 standard [7], which provides recommended practices to interconnect software agents with low-level automation functions.

Table 1. Mapping MAS into AAS functionalities [17]

RAMI4.0 Layers	AAS Functionalities	MAS Characteristics	MAS Support Functionalities
Asset	Provide a digital representation of the asset	Encapsulation Reusability	JADE framework to develop the MAS-based solution compliant with FIPA
Integration	Establish a connection between the asset and its digital representation	Reactivity	Recommended practices by IEEE 2660.1. standard of how to interconnect software agents with low-level automation functions
Communication	Access the asset information and establish the communication with the other assets	Socialability	Communication by FIPA-ACL messages Client-Server or Publish-Subscribe schema Lightweight IoT protocols, e.g., MQTT
Information	Provide data in a structured and integrated manner	Learningability	Combine MAS with data models, such as AutomationML, to support the exchange of data in a structured and integrated manner
Functional	Provide functions based on the collected information	Proactivity Cooperation	Combine MAS with ML algorithms, IoT technologies, data analytics, computational processing layer (edge, fog and cloud) and Intelligent Products
Business	Provide services based on the AAS functions	Autonomy Service-orientation	Combine MAS with Service-Oriented Architecture The Directory Facilitator from the agent platform allows the registration and discovery services

Agents are also endowed with social abilities, which enable the interaction with other agents. These interactions are based on a semantic definition and ontologies, following a client-server or publish-subscribe schema. In this sense, the communication between AAS may be perfectly realized by agents following the standardized FIPA-ACL communication language or using lightweight IoT communication protocols, e.g., Message Queuing Telemetry Transport (MQTT). Furthermore, from the learning abilities of agents, their knowledge can be provided in a structured and integrated manner to other

I4.0 components, recurring the adoption of standard approaches for data exchange, e.g., AutomationML.

The proactivity and cooperation enable agents starts their tasks itself in order to reach the asset objectives, cooperating or not with other agents. For this purpose, the agents can extend the AAS functionalities, acting as intelligent products to cover the asset lifecycle, and vessels for ML algorithms and data analytics capabilities to support monitoring, diagnosis, prediction and optimization. Moreover, the agent may enable the distributed intelligence process on the cloud, fog and edge. Lastly, the autonomy and service-orientation allow agents formulate strategies based on the business-related features and provided the asset functionalities as a service, implementing the concept of directory facilitator (DF) for registration and discovery services, following FIPA specifications, and combining MAS with SOA.

The mapping of MAS characteristics into AAS functionalities provides an overview of how MAS technology fulfils the requirements to realize AAS. However, other aspects also need to be considering, such as the concepts involved, the technologies to complement MAS, the methodology to digitizing assets, and the MAS-based framework to implement the AAS. Figure 2 illustrates a conceptual map with all these aspects.

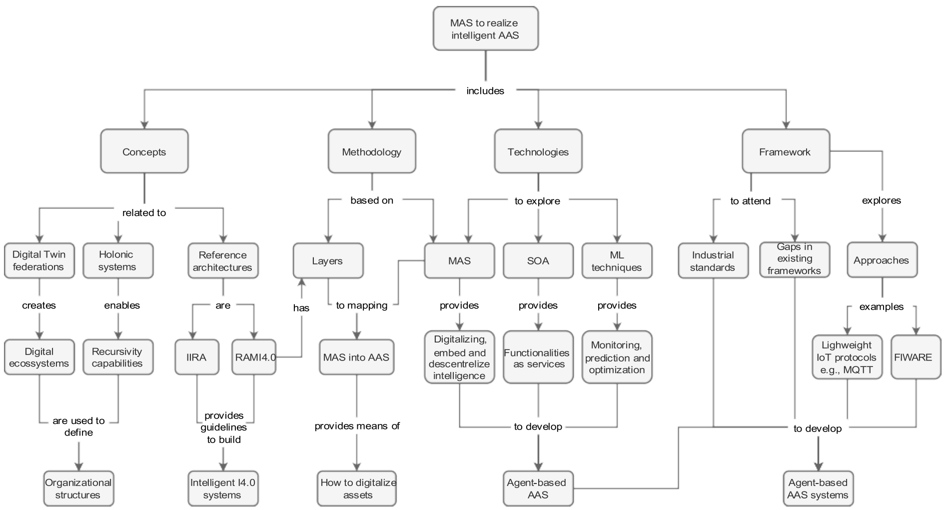

Fig. 2. Conceptual map with the aspects to consider to realize the AAS using MAS.

The first aspect to consider is the concepts included, which will provide the basis for realising the agent-based AAS. In this context, references architectures like RAMI4.0 and IIRA may support compliance with I4.0 solutions, providing guidelines based on industry standards to develop intelligent I4.0 systems. The RAMI4.0 focusing on the AAS specification to develop an interoperable network between I4.0 components and systems. In the other hand, the IIRA focusing on industrial analytics, processing and analysing data from assets to build intelligent components. Furthermore, the holonic principles and Digital Twin federations are another important concepts to develop organisational structures, taking the advantages of recursivity capabilities, e.g., in cases that one asset is composed by other assets, or even a factory can represent an asset and have its AAS, but also each asset within the factory can have its own AAS.

Besides MAS, the main technology used to realizing the AAS, other technologies need to be considered to support the implementation and extend the AAS functionalities. For instance, ML techniques may be used to support the analysis of collected data aiming monitoring, diagnosis, prediction and optimization, which combined with SOA enables to offer these functionalities in the form of services accessible for all I4.0 components. Moreover, the development of a methodology to digitalize assets is required to guide the stakeholders about the prerequisites and analysis to determine why, what and how to digitalize the assets, since this process has to bring added value to the industry. In this context, the mapping of MAS characteristics into AAS functionalities based on RAMI4.0 layers may assist in answering how digitalizing the assets. In the other hand, to answer what and why, the business-related features based on the industry strategies and the customer demands need to be deeply analyzed.

Another aspect to taking account is the development of a light framework for agent-based AAS systems, since the currently MAS-based frameworks do not support the development of I4.0 compliant solutions, which restrict the wide adoption of MAS solutions in these scenarios. Section 4 will deeply address this topic, showing the gaps in existing frameworks and some ideas of how to fulfil these requirements.

4 Need for a Light and Industrial Oriented MAS Framework

The development of a MAS-based system should follow existing standards in this field. The Foundation for Intelligent Physical Agents (FIPA) [1] provides a set of specifications for the development of heterogeneous agent-oriented systems. FIPA specifications represent a collection of standards that are grouped in different categories (see Figure 3) [1, 14]:

- Applications: refer to the application areas where FIPA agents can be deployed, representing ontology and service descriptions specifications for a particular domain.
- Abstract architecture: provides entities which are required to build agent services and agent environments.
- Agent communication: deals with Agent Communication Language (ACL) messages, interaction protocols, speech act theory-based communicative acts and content language representations, to support the exchange of messages between agents.
- Agent management: specifies a reference model for the creation, registration, location, communication, migration and retirement of agents.
- Agent message transport: deals with the transport and representation of messages across different network transport protocols.

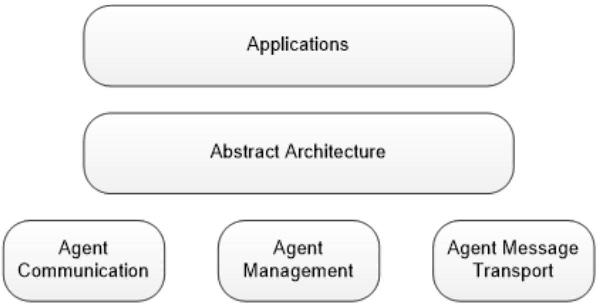

Fig. 3. Categories of the FIPA specifications [1].

Due to the high popularity of the FIPA-compliant Java Agent DEvelopment (JADE) framework [2], FIPA is usually adopted by the agent developers community. JADE aims to simplify the development of MAS by providing a set of services and agents in compliance with the FIPA specifications, e.g. naming service and yellow-page service, message transport and parsing service, and a library of FIPA interaction protocols ready to be used [2, 13]. JADE is a Java-based architecture that uses the Java Remote Method Invocation (RMI) to support the creation of distributed Java technology-based applications. Each agent is implemented with Java «threads» and associated with a container, using the concept of behaviours to model concurrent tasks in agent programming [2]. Aiming to simplify the debug of developed applications, JADE provides a set of useful tools, e.g., Dummy, Sniffer and Introspector.

Industrial applications, and particularly the industrial CPS environments, impose strong requirements that may affect the adequacy of the existing MAS frameworks, and particularly the JADE framework, for the adoption of the agent technology. Examples of these requirements are the integration with hardware devices, industrial standard compliance, reliability, fault-tolerance, scalability, quality assurance, resilience, manageability and maintainability [6, 12, 19].

In particular, the JADE framework presents the following limitations [14]:

– Need for real-time interaction protocols for industrial and large-scale systems, ensuring scalability and latency.
– Need to adopt IoT technologies for the interconnection among the agents, and particularly a publish-subscribe schema that ensures loosely coupled integration.
– Need for distributed yellow pages service and discovery mechanism to improve the system robustness.
– Need to combine agents and services to support interoperability, allowing to agents to encapsulate their functionalities as services that are offered, discovered and consumed by other agents (acting as service consumers).
– Need to integrate agents and low-level automation functions, as well as legacy systems, using standard interfaces, e.g., the recent established IEEE 2660.12020 standard.
– Need to simplify the debug and maintenance of agent-based applications (note that in the essence, the agents developed using the JADE platform are Java Threads, which makes the debugging of multi-threading very difficult).

In this context, the development of a light and industrial oriented MAS framework is fundamental to attend the industrial requirements, considering the communication between I4.0 components, the structure to interconnect all the modules and the integration with hardware devices. Figure 4 illustrates some aspects to consider in this framework, mainly the MQTT protocol, FIWARE [5] and service-orientation. For communication, the use of lightweight IoT protocols, e.g., MQTT that is based on the publish-subscribe paradigm, is a suitable alternative to provide highly scalable solutions. Instead of client-server protocols which demand communication directly, the publish-subscribe does not rely on a direct connection between the data producers and the data consumers, having a message broker to deliver the messages. Furthermore, MQTT provides small message headers to optimize network bandwidth, reliable message delivery and security aspects [15].

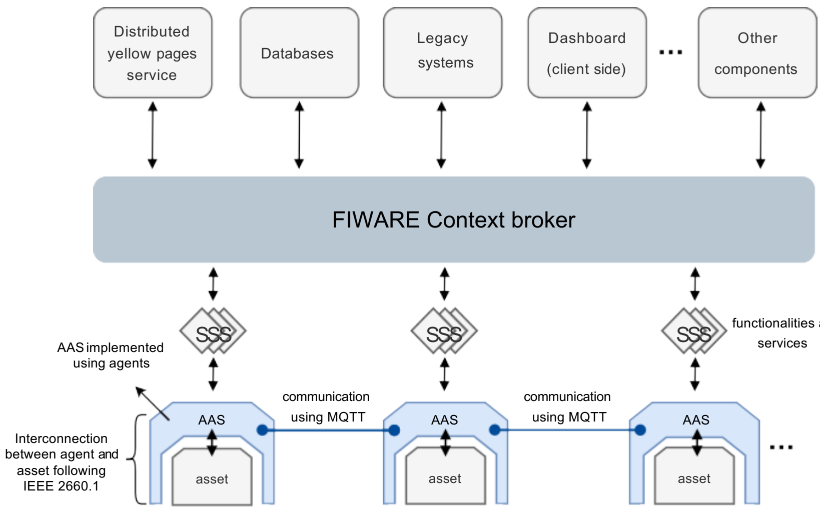

Fig. 4. Aspects to consider in the framework for agent-based AAS systems.

Another pertinent issue is related to create an interoperable network of I4.0 components. For this purpose, FIWARE [5] is an open-source platform that enables the integration of components (including legacy systems) and provides the conditions for the development of smart solutions. FIWARE has the context broker as the core component, which enables the interfacing with

IoT devices, robots and third-party systems, and also the processing, analysis, and manage of context information in a highly decentralized manner. These interfaces are realized by entities, called IoT Agents, that facilitates the interface with devices using protocols like HTTP, MQTT and OPC UA. In this sense, the recommended practices from IEEE 2660.1 standard may also assist and complement these interfaces realized by the IoT Agents from FIWARE.

Additionally, other aspects can be considered, for instance, the adoption of SOA to provide the AAS functionalities as services, as well as the ML techniques, where each I4.0 component can require these services from a distributed yellow pages service and discovery mechanisms. Also, the strategies to distribute the intelligence among edge, fog and cloud computing layers, since each layer presents differences in terms of functional, data analysis, technological and implementation aspects.

5 Conclusions and Future Work

The digitalization associated with Industry 4.0 brings several benefits and opportunities for innovative solutions based on Cyber-Physical Systems, but also new challenges for modern manufacturing systems. RAMI4.0 is a reference architecture that provides guidelines to develop I4.0 compliant solutions based on industrial standards, aiming to reduce the complexity and achieve interoperability in these systems. As a reference model, the I4.0 components implement this model in practice, combining the asset with its digital representation, the AAS. In this context, MAS is a suitable approach to implement the key functionalities of AAS, as well as to embed intelligence in the system.

This paper discusses how MAS technology can be used to realize the AAS, mapping their characteristics into AAS functionalities and also extending them, introducing intelligence and data analytics capabilities. Additionally, also considered other aspects involved, as the fundamental concepts to support the development of an agent-based AAS, namely the references architectures compliant with I4.0 solutions like RAMI4.0 and IIRA, and Holonic principles and Digital Twin federations to build organizational structures. Furthermore, the paper discussed the needs of developing a methodology to digitalize assets aiming to provide guidelines for stakeholders of why, what and how to digitalize. Lastly, the gaps in existing frameworks to attend the industrial requirements were analyzed, showing some ideas of how to fulfil these requirements using the MQTT protocol, FIWARE and industrial standards.

Future work will be devoted to developing a methodology to digitize assets based on the mapping of MAS characteristics into AAS functionalities, as well as the development of a light framework for agent-based AAS systems.

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