

Towards the Digitization using Asset Administration Shells

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Abstract—Industry 4.0 (I4.0) is promoting the digitization of traditional manufacturing systems towards flexible, reconfigurable and intelligent factories based on Cyber-Physical Systems (CPS). In this context, the Reference Architecture Model Industrie 4.0 (RAMI4.0) provides guidelines to develop I4.0 compliant solutions based on industrial standards. As the main RAMI4.0 specification, the Asset Administration Shell (AAS) is a standard digital representation of an industrial asset that plays a pivotal role in enabling interoperable communication among I4.0 components across the value chain. This paper provides an analysis of the current state-of-the-art of implementing AAS, discussing, amongst others, the key enabling technologies used to implement the AAS and the alignment of the research works found in the literature with the I4.0 components criteria.

where the asset’s information and functionalities are described, e.g., characteristics, properties, status, and capabilities [6], [7].

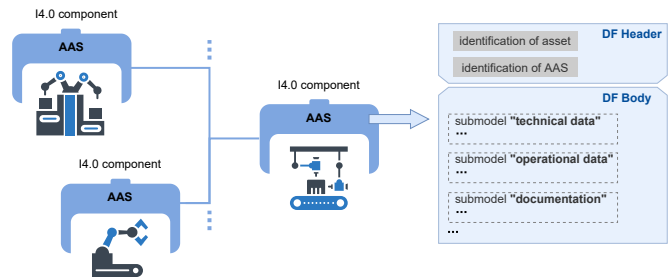


Figure 1. Overview of the AAS structure and functionalities.

I. 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) [1]. As the backbone of Industry 4.0 (I4.0), CPS creates digital ecosystems through the combination and coordination between the cyber and physical counterparts, supported by the information and communication technologies (ICT) to develop robust and intelligent large-scale systems [2]. 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 [3].

A set of specifications for digitizing industrial systems, based on industrial standards, is offered by the Reference Architecture Model Industrie 4.0 (RAMI4.0) [4]. As the main specification of RAMI4.0, the Asset Administration Shell (AAS) is the standardized digital representation of an asset representing an object with value for the process. As illustrated in Figure 1, the AAS encapsulates a logical or physical asset, transforming it into an I4.0 component, allowing to integrate the asset into a network of I4.0 components, access the asset information, establish a standardized and secure communication interface based on the Service-Oriented Architecture (SOA), and manage the entire asset lifecycle [1], [4], [5]. Regarding its structure, the AAS consists of several submodels

Although the AAS is a recent topic [6], and its specification are still ongoing [7], the AAS is seen as a key enabler to create interoperable communication among all entities participating in the I4.0 network [7]. Several academic research strives to contribute and design AAS-based solutions to cope with the greater diversity of industrial devices and frequent changes provoked by the fast-changing market conditions. In this sense, two important questions arise:

- How is the AAS, together with its respective asset, fulfilling the requirements of the I4.0 components?
- What are the core technologies to implement the AAS?

Having this in mind, this paper analyses the current status of implementing AAS in Industry 4.0, aiming to identify the core technologies to implement the AAS and the alignment of the existing research works with the I4.0 components criteria [8]. For this purpose, a literature survey in scientific publications was carried out to investigate these questions, being possible to verify that the majority of criteria are addressed, and the key enabling technologies are mainly the Automation Markup Language (AutomationML) and Open Platform Communications Unified Architecture (OPC UA).

The rest of the paper is organized as follows. Section II describes the applied methodology to conduct the literature survey and Section III presents a characterization of the

current research on AAS, mainly focusing a demographics analysis. Section IV summarizes how the AAS, with its asset, is aligned with the I4.0 components requirements, and Section V discusses the key enabling technologies for implementing the AAS. Finally, Section VI rounds up the paper with the conclusions and points out the future work.

II. METHODOLOGY

The adopted methodology to carry out the literature survey of AAS related publications is divided into the selection of most relevant papers and further individual analysis of each of them according to the previously defined questions. For this purpose, the selection of papers followed the four phases proposed by Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) methodology, namely *Identification*, *Screening*, *Eligibility* and *Included*, as illustrated in Figure 2.

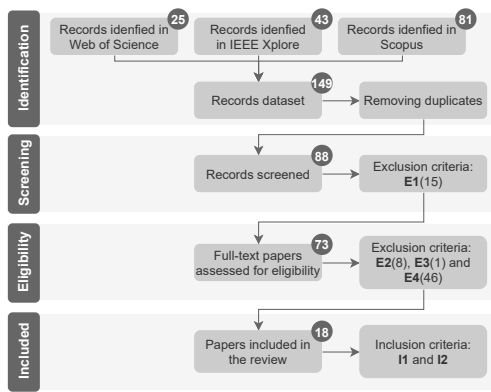


Figure 2. Procedure for selection of scientific publications related to AAS.

The *Identification* phase aims to collect a comprehensive set of scientific publications. For this purpose, the search was conducted by using three scientific papers repositories, namely Scopus, IEEE Xplore and Web of Science. In each repository, the search string was performed using proper queries, considering the combination of the operator “OR” between the terms “*Asset Administration Shell*” and “*Administration Shell*”. Furthermore, the search was performed in the abstract, title and keywords of the paper, which should contain the Digital object identifier (DOI). The result was a dataset containing the papers information (e.g., title, authors, abstract, keywords, DOI, etc.) from the three repositories, where the duplicates were removed using the DOI as reference.

In the *Screening* phase, some papers were excluded based on the exclusion criteria presented in Table I. This process was performed by reading the titles and abstracts to identify the relationships with the study field (E1). The unrelated papers were disregarded, as well as the papers that present their abstracts poorly organized and with unclear objectives. The *Eligibility* phase was related to analyze the remaining papers (73) in more detail. In the first iteration, papers that the full text is not available (E2) or are not written in English (E3) were excluded. In the second iteration, another criterion was applied to verify if the AAS is really the main focus of the paper

(E4). Finally, in the *Inclusion* phase, the selected papers were extensively analyzed with the support of the Nvivo software and classified according to the inclusion criteria (see Table I). Nvivo simplifies the deep analysis by efficiently storing and organising the information, and analysing data with advanced management, query, and visualisation tools.

Table I
EXCLUSION AND INCLUSION CRITERIA FOR SCIENTIFIC PUBLICATIONS.

E/I	Criteria
Exclusion	<ul style="list-style-type: none"> - E1: Filtering by title and abstract. - E2: Paper full text not available. - E3: Paper full text not in the English language. - E4: The AAS is not the main focus of the paper (i.e., AAS is only used as an example, as a part of its future research direction or as a cited expression).
Inclusion	<ul style="list-style-type: none"> - I1: The paper clearly addresses the technologies involved with AAS. - I2: The paper is aligned with some I4.0 components criteria addressed in [8].

In parallel, an automatic analysis was conducted based on Natural Language Processing (NLP), aiming to obtain preliminary insights regarding the current state-of-the-art of AAS. For this purpose, the NLTK library [9], codified in Python, was adopted to perform the n-grams analysis in the dataset (abstract, title and keywords) obtained in the *Eligibility* phase, since the previous datasets versions could have records out of this study’s scope. The initial procedure consists of a preprocessing to clean and structure the data, i.e., removing symbols (e.g., comma, punctuation, etc.) and stop words (e.g., “the”, “a”, “in”, etc.), and the lemmatisation, a technique to grouping the different inflected form of a word. With the structured data, the last procedure consists of forming a list of n-grams, i.e., a combination of one, two or more words, aiming to provide possible relevant terms associated with AAS.

The described methodology has some limitations that should be highlighted. The search keywords used in this work are specified to find AAS-related papers, but not ensure that all records in this research field were found from the electronic databases. Thus, some papers may not have been included in this study. Also, the exclusion of papers not written in English and full text not available naturally implies disregarding some publications that could be relevant.

III. CHARACTERISATION OF AAS CURRENT RESEARCH

The Plattform Industrie 4.0 consortium relies on AAS to enable the implementation of the “Industrie 4.0” initiative, supporting the transition of traditional manufacturing systems towards the so-called smart factories. This naturally reflects the Germany’s predominant contribution in scientific publications in the AAS field, as illustrated in Figure 3. Note that the determination of each country’s contribution considers a composite score coming out from all authors listed in the publication, with linearly decreasing weights (where the first author weighs more than the second, and so on).

However, this topic is not restricted geographically and other countries are also being encouraged by national government strategies towards the digitization of the industry, e.g., Italy and Spain with the “Piano Industria 4.0” and “Industria

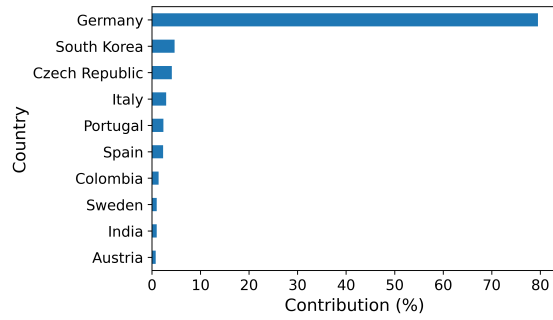


Figure 3. Geographical distribution of AAS related publications.

Conectada 4.0” initiatives, respectively. Surprisingly, US and China do not appear in this list, which may be justified by the use of different terminology to represent similar concepts.

The AAS concept was introduced in 2015 [6], and despite being a recent topic, the increasing of AAS-related publications shows a growing interest, as illustrated in Figure 4. Since the initial specifications, aiming to provide implementation guidelines, were only published in 2018 [7], [10], it is expected, for the next years, a better understanding and wide adoption by the research community and industry stakeholders.

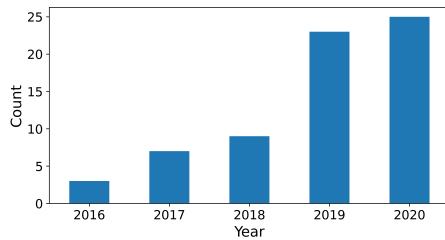


Figure 4. Evolution of AAS related publications over the time.

The collaboration between the Plattform Industrie 4.0 and the Industrial Internet Consortium (IIC) [10], which proposes the Industrial Internet Reference Architecture (IIRA) [11], may also contribute to widespread the AAS concept since both are looking for solutions to ensure interoperability. The alignment between them can contribute to develop more robust systems based on AAS, taking advantages from both architectures.

IV. INDUSTRY 4.0 COMPONENTS REQUIREMENTS

As aforementioned, the AAS encapsulates the information and functionalities of a given asset, transforming it into an I4.0 component. However, a common understanding between customers and developers is needed on how to label products as I4.0 components. In this sense, an AAS must satisfy a list of technical criteria [8], namely identification, communication, semantics, virtual description, services and states, standard functions and security (see Table II).

According to [8], a list of minimum product characteristics is necessary to satisfy each criterion, which takes into account a detailed description of a product with a focus on the market. However, this degree of detail is often not reported in scientific

Table II
CRITERIA FOR I4.0 COMPONENTS (ADAPTED FROM [8]).

Criteria	Description
Identification	All entities (assets, AASs, data, etc.) participating in the I4.0 network needs to have a globally unique identifier.
Communication	I4.0 components need to be able to communicate with each other, exchanging and accessing information.
Semantics	I4.0 components need to have a common language regardless of the manufacturer.
Virtual description	Digital description of the product, e.g., technical features, datasheets, security features, information regarding product support, etc.
Services and States	Interfaces to provide I4.0 components services and report states in a way accessible to all.
Standards functions	Standard functions executed regardless the manufacturer, which are described/implemented in AASs submodels.
Security	Features to provide privacy, resilience and reliability for I4.0 components.

papers. In this context, this work investigates how the criteria defined in Table II are addressed in scientific publications (summarized in Table III).

The identification criterion plays a pivotal role in assigning a unique identifier for all entities participating in the I4.0, which facilitates the distinguish and search for specific assets, AASs, submodels, and properties within the smart manufacturing domain. According to the identifiers recommendations defined in [6], [29], some papers highlight the use of identifiers as indicated in Table III. As example, the Uniform Resource Identifier (URI) according to RFC 3986 [16], [19], [25], the ISO 29002-5 identifier that is used in the ecl@ss and IEC Common Data Dictionary (CDD) [18], the Internationalized Resource Identifier (IRI) according to RFC 3987 [26], and the URI and globally unique identifiers (GUIDs) [1].

In terms of communication criteria, most of the papers use the OPC UA to provide a machine-to-machine (M2M) communication mechanism between heterogeneous industrial devices. However, the use of standard web-based technologies, e.g., the Representational State Transfer (REST), is also recommended to cover other domains since OPC UA is still restricted in the industrial domain [30]. Moreover, the agents’ communication capabilities are explored to support I4.0 interactions [22], [23].

The semantic criterion is contained in the RAMI4.0 information layer, being fundamental to ensure the interpretability and avoid the ambiguity of exchanged information between two or more I4.0 components. At this stage, ecl@ss and IEC CDD are recommended candidates, as suggest in [8] and explored in [13], [18], [24]. Other authors, namely [25], [26], propose the Resource Description Framework (RDF) towards a common semantic model for I4.0.

The virtual description criterion plays a fundamental role in providing valuable information regarding the asset, that is used across the asset lifecycle, e.g., technical data, schematics, configuration parameter values and communication information [1], [12], [15]–[20], [24], [25], as well as information about the maintenance, guiding the operator on how to perform this process for each asset [13]. In this context, AutomationML may be used for describing and storing information wrapped in AAS submodels [1], [12], [15], [17], [28].

Table III
OVERVIEW OF THE CURRENT STATUS OF ASSET ADMINISTRATION SHELLS IN THE SCIENTIFIC PUBLICATIONS.

Ref.	Contribution	Criteria for Industry 4.0 components							Supporting Technologies
		ID	CM	SM	VD	SS	SF	SC	
[1]	Presents an implementation example in a manufacturing system, showing guidelines to deploying AASs.	✓	✓	✓	✓	✓	✓		OPC UA and AutomationML.
[12]	Presents an implementation of an AAS-enabled plug-and-produce solution.	✓	✓	✓	✓	✓	✓		OPC UA, AutomationML and HTTP.
[13]	Proposes the use of AAS aiming to support humans during the maintenance process, in particular by maintenance submodel.	✓	✓	✓	✓	✓	✓	✓	OPC UA.
[14]	Proposes the implementation of AAS submodels responsible for secure identity, auto-configuration and managing Blockchain.	✓					✓	✓	-
[15]	Proposes an implementation of AAS exploring standard web-based technologies and a microservice-based architecture.	✓	✓	✓	✓				REST and AutomationML.
[16]	Presents a flexible and lightweight framework for implementing the AAS.	✓	✓	✓	✓	✓	✓		REST and MQTT.
[17]	Analyzes a mechanism, which enables PLCs accessing content of its AAS during run-time.				✓				AutomationML.
[18]	Addresses an information model for condition monitoring included in an AAS, which is implemented in a PLC of a work cell.	✓	✓	✓		✓			OPC UA.
[19]	Presents a case study on the application of the AAS in an industrial context, integrating a machine tooling with a robotic arm.	✓	✓	✓	✓	✓	✓		OPC UA.
[20]	Shows how users can translate OPC UA information model into the AAS submodels.			✓	✓				OPC UA.
[21]	Proposes an AAS able to represent IEC 61131-3 programs and the relationships with PLCs and other assets.		✓	✓		✓	✓		OPC UA and REST.
[22]	Shows how emerging challenges in some I4.0 scenarios can be met with the help of MAS.		✓	✓		✓			MAS.
[23]	Explores the use of MAS to implement the AAS functionalities.		✓	✓		✓	✓		MAS.
[24]	Explores the AAS to enable interoperable Digital Twins, translating their proprietary information models into the AAS format.	✓	✓	✓	✓	✓	✓	✓	REST.
[25], [26]	Present an RDF-based approach for semantically representing the asset information through the AAS.	✓		✓					-
[27]	Presents insights regarding the modelling techniques to define the OPC UA Information Model exposing the AAS information.	✓	✓	✓					OPC UA.
[28]	This paper focus on AutomationML-based AAS to support the collection of engineering dataset and the serialization of AAS.			✓	✓				AutomationML.

ID - Identification; CM - Communication; SM - Semantics; VD - Virtual description; SS - Services and States; SF - Standard functions; SC - Security.

As specified in [29], the AAS structure comprises several submodels in which the asset's information and functionalities are described and implemented. In this context, it is fundamental to define standard functions in the format of submodels regardless of the manufacturer to facilitate cross-company-interoperability. In the content analysis in the included papers for review, some initiatives are identified and may be standardized in the future. For instance, generic submodels applicable regardless of the asset [1], [12], [15], functions to support humans during the maintenance process [13], to support condition monitoring [19], to represent IEC 61131-3 configurations [21], to provide security features [14], as well as the possibility to use Multi-agent Systems (MAS) to support Artificial Intelligence (AI) methods [23].

I4.0 components must provide their functionalities in the form of services and states to other partners in the value-added network. For instance, in [12] the robot AAS may provide the functionality of pick-and-place as a service, which can be invoked according to the plug-and-produce strategy, showing the current robot state in a web user interface. Moreover, as suggest in [22], [23], MAS may enable the registration and discovery services mechanisms using yellow pages services.

In addition to providing reliability for I4.0 components, the

security criterion is responsible for defining restrictions and permissions regarding the accessibility of the services and states. In [13], the authors propose an access control mechanism to determine the user's role and access rights, mainly using attribute-based access control (ABAC) to access the elements of the AAS submodels as specified in [29]. Also, [14] proposes an AAS submodel responsible for the secure identity, automatic configuration, and Blockchain management.

V. KEY ENABLING TECHNOLOGIES

According to the n-grams analysis, illustrated in Figure 5, and the content analysis, summarized in Table III, some frequent principles and technologies related to the AAS implementation were identified.

As shown in Figure 5, interoperability, service orientation and real-time are the main design principles related to AAS. These results reflect the current research directions aiming to enable interoperability between industrial systems, providing their functionalities in the form of services throughout the entire I4.0 network, and execute its tasks with time constraints.

In terms of technologies, some clearly stand out focusing the interoperability principles, e.g., AutomationML and OPC UA, by providing a means to model information and construct

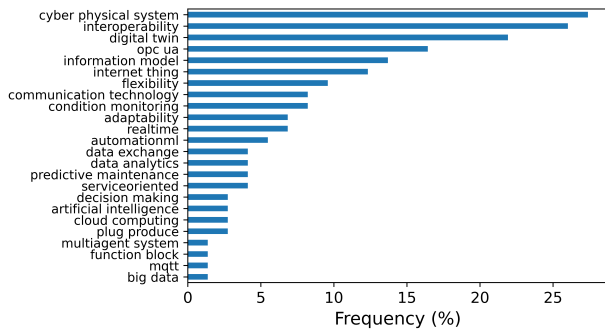


Figure 5. Technologies and concepts in AAS related publications.

a communication interface in compliance with the standards and RAMI4.0 specifications.

AutomationML is an open and XML-based data exchange format that enables exchanging data between heterogeneous engineering tools. Concerning the AAS, the AutomationML describes the asset information, considering its different life-cycle phases. For instance, the authors in [1], [12] use AutomationML to describe the asset information in a structured manner, considering the AAS structure comprised by the header and the individual submodels in the body.

OPC UA supports the vertical and horizontal connectivity between industrial assets by providing information and communication models, in particular acting as an AAS communication interface. The authors in [1], [12] combine AutomationML with OPC UA, mapping the AutomationML model that contains the AAS information into OPC UA nodes in a standardized manner. In this way, the information can be accessed and exchanged among OPC UA clients embedded in other AASs. Other approaches, like [13], [19], [21], implement the AAS through the mapping of the asset information (e.g., in JSON and XML formats) into the OPC UA information model. On the other hand, [20] presents a method for mapping descriptions of plants, machines, or individual components based on existing OPC UA information models, particularly OPC UA Part 100, into submodels of the AAS.

Although OPC UA is the leading technology to provide the communication interface in the industry domain, some research approaches rely on web technologies, mainly the REST and JSON standards. The authors in [15] follow the RAMI4.0 specifications but also propose the use of REST for the request-response exchange and an architecture based on microservices instead of the SOA approach. Besides, a RESTful API is used to obtain AAS in standardized exchange formats, e.g., XML, JSON and AASX (package file format for the AAS) via Hypertext Transfer Protocol (HTTP) endpoints [16], [24]. A module for communication via Message Queuing Telemetry Transport (MQTT) is also supported to read and write property values on AAS [16]. These approaches are aligned with the current AAS specification [31], which specifies exchanging information via API and considers REST, MQTT and OPC UA to be supported in the future.

Derived from distributed AI, MAS are also a promising

technology for implementing AAS, being their capabilities suitable to implement the AAS's functionalities, e.g., object encapsulation, data gathering, communication, negotiation, reconfiguration, and particularly supporting the collaboration and embedding intelligence for the decision-making functions [3], [22], [23], [32]. Agents are also enabled to make the information and capabilities of its asset or AAS available to other agents in the form of services. For this purpose, the FIPA standard defines how agents can publish or search a specific service through the concept of directory facilitator (DF) for registration and discovery services [33]. Furthermore, agents can extend the AAS functionalities, acting as intelligent products [34], supporting the collaboration and embedding AI algorithms to support monitoring, diagnosis, prediction, and optimization [23].

Other emergent technologies are also identified, e.g., Internet of Things (IoT), AI, Cloud Computing and Big Data, assuming a crucial role in implementing I4.0 solutions, in particular supporting the AAS functionalities. Also noticed, the terms "Cyber-Physical System" and "Digital Twin" appear directly associated with AAS, highlighting the strong relationship between them. In fact, Digital Twins and AASs are often considered synonymous, as both act as digital representations of assets and can correspond to the cyber part of CPSs. Nevertheless, the AAS has its basis tightly linked with the standardized digitization of assets, offering means to implement and enable interoperability across proprietary Digital Twins.

VI. CONCLUSIONS

AAS plays a pivotal role in enabling interoperable communication among I4.0 components across the value-added network. However, achieving the cross-company-interoperability is a complex task that involves academic research and working groups' efforts to develop innovative solutions based on standard specifications and recommended practices.

This paper analyzed the current status of deploying AAS, particularly the alignment with the I4.0 components criteria and the key enabling technologies for its implementation. Firstly, the geographical distribution of the relevant AAS's papers, and their evolution over the time, was analysed, allowing to observe that, as expected, Germany is the predominant contributor in research topic, with strong interest by many other countries. Secondly, relevant information was extracted by deeper analysing the selected papers for review. This allowed to identify that at this stage most of the research publications concentrate their focus on implementing passive AAS, i.e., without decision-making and autonomous capabilities, interacting by file exchange, API-based access and OPC UA. The implementation of active AAS (i.e., intelligent decision-making entities that interact autonomously with other AASs to achieve their goals) is still a gap in the AAS state-of-the-art. However, the current research directions using MAS as a key enabler to implement the AAS itself or support its functionalities could be further explored in the future, mainly

to enable the peer-to-peer interaction pattern among intelligent and active AASs.

Regarding the first question “How is the AAS, together with its respective asset, fulfilling the requirements of the I4.0 components?”, the survey shows that the research addresses most of the I4.0 components criteria, except for the security criterion that is much less explored when compared with the others. The ABAC concept recommended in [29] to cope with security aspects is a starting point towards incorporating more robust security mechanisms based on AI techniques for the next generation of AASs.

Lastly, to address the second question “What are the core technologies to implement the AAS?”, OPC UA and AutomationML are identified as core technologies to deploy the AAS, covering the communication and information layers of RAMI4.0. However, other approaches based on REST and MAS are also promising and may be combined with OPC UA and AutomationML to develop more intelligent, robust and powerful AAS-based systems.

Future work will be devoted to discuss the challenges of implementing the AAS and explore the MAS technology to enhance the industrial assets’ digitization process by introducing collaboration, intelligence in decision-making and interface with industrial assets.

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