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SURVEY

# Ten Years of Asset Administration Shell: Developments, Research Opportunities, and Adoption Challenges

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**ABSTRACT** Over the past decade, the Asset Administration Shell (AAS) has emerged as a cornerstone of digital transformation in Industry 4.0 (I4.0), providing a standardized approach to managing digital representations of industrial assets. With 2025 marking approximately ten years since its introduction, this article aims to provide a comprehensive analysis and discussion of AAS development over the past decade, potential research opportunities, and the challenges associated with its adoption. To this end, the study combines a literature survey with an examination of specifications from key organizations, such as the Plattform Industrie 4.0 and the Industrial Digital Twin Association (IDTA), which play a central role in the AAS standardization and development. A key insight from this survey is that AAS is progressing toward becoming a game-changer in realizing I4.0. Unlike a decade ago, AAS has now reached a level of maturity that enables its increasing adoption, supported by specifications and standards, dedicated development platforms for its implementation, and several examples in the literature showing a wide range of applications. Additionally, research opportunities for AAS align with emerging industrial trends and contribute to addressing them. However, several challenges must still be addressed to facilitate the widespread adoption of the AAS.

**INDEX TERMS** Asset administration shells, cyber-physical systems, industry 4.0, reference architecture model industrie 4.0.

## I. INTRODUCTION

Industry 4.0 (I4.0) emerges as a digitization paradigm, aiming to shift from traditional industrial systems toward industrial Cyber-physical Systems (CPS) [1]. In this context, the adoption of reference architectures, namely the Reference Architecture Model Industrie 4.0 (RAMI4.0) [2] and the Industrial Internet Reference Architecture (IIRA) [3], assume a critical role in facilitating this transition. In particular, RAMI4.0, a German initiative aligned with the ''Industrie 4.0'' strategy, has gained increasing recognition. RAMI4.0 introduces a three-dimensional model that formalizes all key aspects related to the digitization of assets, aiming to provide guidelines and a shared understanding for stakeholders in developing I4.0-compliant solutions based on industrial standards. At the core of RAMI4.0 lies the concept of the I4.0 component, which can be seen as a specific interpretation or specialization of the CPS concept, encompassing an asset and its digital counterpart, the Asset Administration Shell (AAS).

As shown in Figure 1, the AAS reflects the upper layers of the ''layers'' axis of the three-dimensional RAMI4.0 model.

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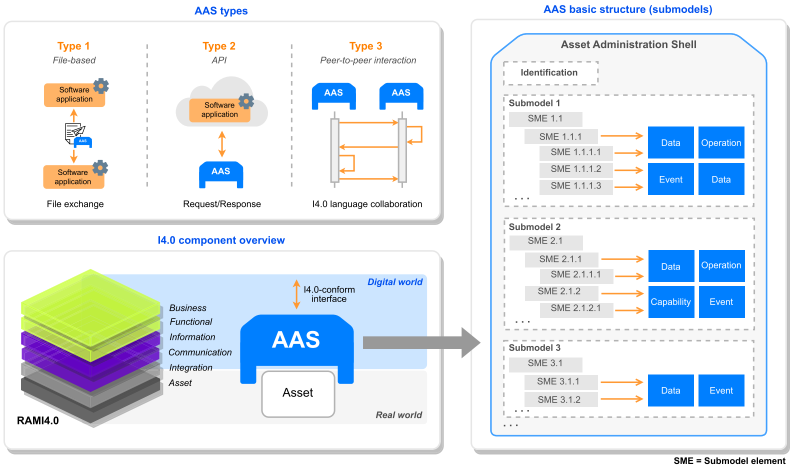


**FIGURE 1.** **I4.0 component overview (bottom), AAS types (top), and AAS basic structure (right) [4].**

According to [5], it serves as a "standardized digital representation of an asset", capturing all relevant aspects of the asset across its entire lifecycle. The AAS is designed for every logical or physical object with value for industry (i.e., an asset) that needs to be connected within the I4.0 network, enabling interoperability not only within but also across companies along the value-added network, particularly addressing the issue of data silos. By providing a standardized digital representation, the AAS allows assets to seamlessly exchange information and collaborate, overcoming the barriers posed by proprietary and legacy systems. This facilitates the flow of data across various stakeholders, ensuring more efficient and flexible industrial operations and advancing the realization of interconnected, intelligent, resilient, and self-organizing factories envisioned by I4.0.

Today, AAS is progressing toward becoming a game-changer in the realization of I4.0, serving as a crucial enabler of interoperability in industrial environments, where the seamless integration and communication between various systems, devices, and platforms are crucial. In this context, with 2025 marking approximately ten years since the introduction of AAS [6], [7], it is both timely and necessary to reflect on its journey, evaluate its current state, and explore its future trajectory. Having this in mind, this article aims to contribute by providing an analysis and discussion of how AAS has evolved over the past decade, the research opportunities, and the challenges related to its adoption. Although research opportunities may also pose challenges, this article distinguishes between the two to provide a clearer and more structured discussion. Specifically, adoption challenges are examined separately, as they directly contribute to the limited implementation of AAS-based solutions in industrial settings. On the other hand, research opportunities refer to promising directions and perspectives aligned with emerging industrial trends that could leverage the benefits offered by AAS to enhance interoperability and support the development of more intelligent, collaborative, and sustainable industrial systems.

The remainder of this article is organized as follows: Section II presents the review strategy adopted to conduct the study, including the methodology and research questions. Section III provides an overview of the AAS, particularly fundamental AAS-related concepts. Section IV explores the evolution of the AAS over the past decade, providing a characterization of the current research landscape, available specifications and standards, development platforms, and advances in AAS developments, applications, and R&D projects. Section V outlines research opportunities for AAS, while Section VI discusses the main challenges related to its adoption. Finally, Section VII concludes the article by summarizing the findings, addressing the research questions, and reflecting on the future role of the AAS.

## II. REVIEW STRATEGY

### A. METHODOLOGY AND RESEARCH QUESTIONS

This article adopted a review strategy to analyze and discuss how the AAS has evolved over the past decade, the research opportunities, and the challenges associated with its adoption. Although this review was inspired by systematic approaches such as PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses), it was designed to follow a more flexible selection protocol due to the broad and exploratory scope of the study, which approaches the AAS from a general perspective rather than focusing on a specific domain or application.

The review process was guided by the authors' expertise and prior experience in the topic, prioritizing representative and relevant studies that provide meaningful insights into key developments, practical applications, and theoretical perspectives across different domains. The review includes both original (primary) research papers and selected secondary sources, chosen for their relevance and ability to contextualize developments in the AAS domain. Additionally, the study is complemented by an examination of official documents, particularly specifications published by the Industrial Digital Twin Association (IDTA), a spin-off of Plattform Industrie 4.0, which plays a central role in the standardization and advancement of AAS. To guide the research, the following two research questions were defined:

- **RQ1:** How has the AAS evolved over the past decade in terms of adoption, standardization, and its proposed applications?
- **RQ2:** What are the key challenges and future research directions for the continued development and implementation of AAS?

### B. SEARCH STRATEGY AND STUDY SELECTION

The bibliographic search was conducted in the Scopus, Web of Science, and IEEE Xplore scientific databases on the topic "Asset Administration Shell", occurring in the title, abstract, or keywords. The search covered the period from 2015 to 2024, as the AAS concept was introduced in 2015. Moreover, the search was conducted based on the following criteria: papers written in English; conference paper, book chapter, and article documents; subject areas of engineering, computer science, and related fields; and duplicates were removed using the DOI or document title as a reference.

From the initial set of 485 documents obtained, a screening process was conducted by analyzing titles and abstracts to identify the most relevant papers. This step aimed to select studies that directly contribute to understanding the current applicability of AAS in the context of I4.0. Following this initial filtering, the full texts of the selected papers were thoroughly examined to extract detailed information on the evolution, applications, and research opportunities related to AAS. This approach enabled the identification of recurring themes and key insights that inform the discussion presented in this review. Finally, a subset of representative studies was chosen to illustrate and support the main points of analysis throughout the paper. While other contributions explored similar themes, the selected studies were identified as the most illustrative and relevant for capturing the core developments, challenges, and trends discussed in this review.

Regarding the official documents published by the IDTA, particularly the specification series, these were directly sourced from the IDTA's official website at https://industrialdigitaltwin.org/en/. Additionally, other relevant documents and related standards were identified throughout the review process and based on the authors' expertise and prior knowledge in the field.

Finally, it is important to acknowledge certain limitations inherent to the methodology. Due to the defined criteria, particularly the screening process and selection of representative studies, which depend on the authors' subjective judgment despite the impartial nature of the research, it is possible that some relevant publications may have been excluded from the study. Additionally, the exclusion of papers not written in English and those for which the full text was not available means that some potentially relevant publications may have been disregarded.

## III. ASSET ADMINISTRATION SHELL OVERVIEW

In the context of I4.0, assets are sourced from different vendors and often exhibit significant variations in their functional and communication capabilities. This diversity poses challenges when designing solutions that aim to enable the seamless integration and collaboration of such heterogeneous assets, which initially remain "unknown" within the system. In this regard, AAS plays a key role in addressing these challenges. Once an asset is equipped with its own AAS, it transforms into an I4.0 component, enabling it to be recognized, accessed, and managed in the information world through I4.0-conform interfaces. This transformation facilitates interoperability and new collaboration forms that were previously difficult or impossible to achieve. With AAS, collaboration extends beyond company boundaries, paving the way for a truly connected world.

Formally, the AAS is defined as a "standardized digital representation of an asset" [5], capturing all relevant information (ranging from design, operational, and business-related aspects to end-of-life) about the asset throughout its lifecycle and organizing it in a standardized structure. This standardization helps address the silo problem, where asset-related information is fragmented across systems and departments, hindering integration and reuse. By offering a common data model, the AAS enables consistent communication, seamless data exchange, and informed decision-making across the entire value chain, benefiting various stakeholders (e.g., manufacturers, operators, service providers, and regulatory bodies) with accessible and valuable information.

As illustrated in Figure 1 (right), the AAS structure comprises an identification (globally unique identifier) and a collection of submodels following the architectural principle "separation of concerns" [5]. In this context, each submodel can be viewed as a modular building block that encapsulates specific information about the asset, such as identification, capabilities, technical data, and operational data. Moreover, each submodel contains a set of submodel elements (include data properties, operations, events, and other elements), which can be organized hierarchically to represent information across varying levels of granularity in a clear and structured manner. For a more technical perspective of the AAS, submodel, and submodel elements structure, see [5].

Submodels can also be standardized through the use of submodel templates, which promote interoperability and guide the creation of submodels based on predefined structures. As an example, "Asset Interfaces Description" [8] submodel template specifies an information model and a common representation for describing the interface(s) of an asset service or asset-related service. Currently, the IDTA provides standardized submodel templates to support AAS implementation.

Additionally, as illustrated in Figure 1 (top), the AAS can be implemented in different types, categorized according to their interaction pattern to exchange information and degree

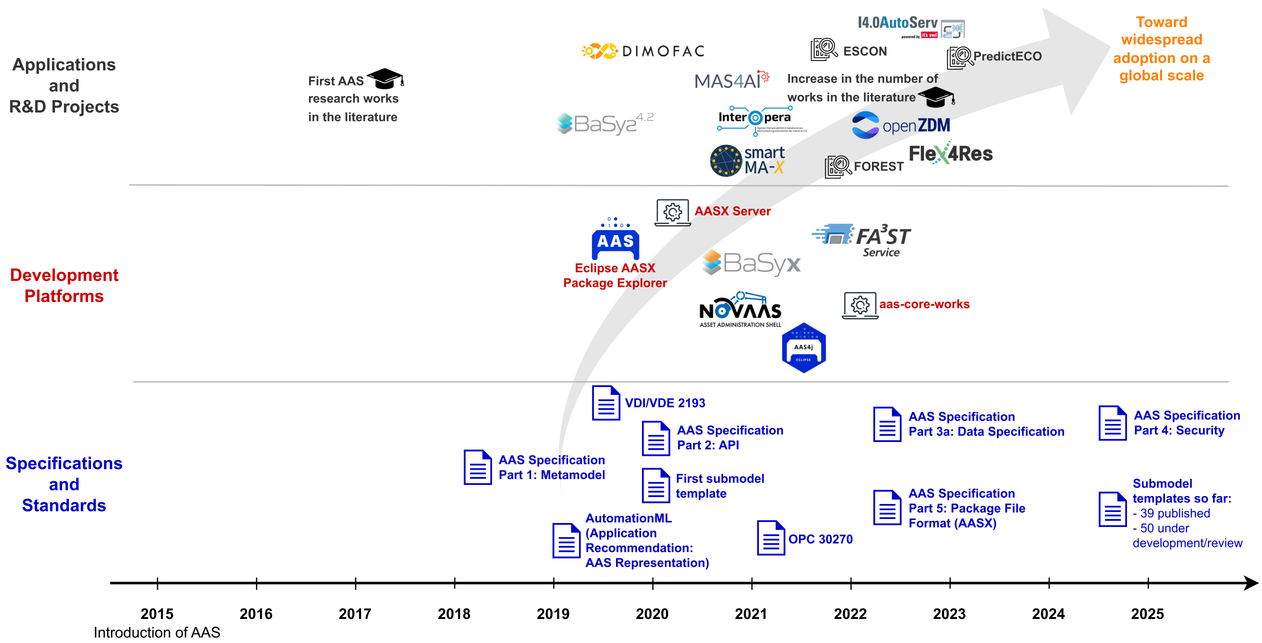


**FIGURE 2.** Timeline of AAS evolution over the last decade: specifications and standards, development platforms and applications (each milestone is centered on the time axis to represent the corresponding reference date, e.g., the milestone "AAS Specification Part 1: Metamodel" corresponds to its release in Nov. 2018. Dates of the milestones are approximate, based on evidence from the literature, official IDTA documents, and public repositories).

of autonomy to make decisions, namely passive (Type 1), reactive (Type 2), and proactive (Type 3) [4], [9].

- Type 1: represents a file-based AAS that stores the asset information throughout its lifecycle and can be exchanged as a whole in the form of a machine- and human-readable file, e.g., XML, JSON, and AASX.
- Type 2: functions as an API that responds to external requests, enabling online access to asset information, but lacks the capability to initiate actions or make decisions.
- Type 3: represents a more advanced and extended form of AAS, functioning as a decision-making entity capable of autonomously interacting with other AASs to exchange information and collaborate.

In summary, the three types of AAS reflect increasing levels of digital maturity, progressing from a passive information model to an active and intelligent component. Type 1 provides a static, structured digital representation of the asset, primarily supporting documentation and identification. Type 2 extends this by introducing basic behavior and interaction capabilities, enabling the response to external requests through predefined functions, but it cannot act autonomously. Type 3, the most advanced form, incorporates autonomous decision-making and execution, allowing the asset to operate independently, collaborate with other AASs, and support decentralized and dynamic industrial scenarios. It is important to note that the AAS type does not necessarily imply that Type 3 is better than Types 1 or 2. The appropriate type should be selected based on the specific requirements of the intended solution. For instance, an AAS Type 1 might be sufficient and more suitable for certain applications, whereas Types 2 or 3 may be more appropriate for others.

## IV. THE EVOLUTION OF ASSET ADMINISTRATION SHELL: TEN YEARS OF PROGRESS AND ADOPTION

Over the past decade, the AAS has evolved significantly, with refinements in its specifications and standards, the emergence of platforms for its implementation, and an expanding range of applications. In this context, this section explores these advancements, as shown in Figure 2, which illustrates the timeline of AAS evolution over the past decade. The milestones shown in the figure serve as reference points for key developments related to the AAS. However, they may not represent the exact dates of each advancement but approximations, as they were based on available dates in the literature, official documents, and public repositories (e.g., GitHub). For specifications and development platforms, the dates reflect when they were first released since they are continually updated over the years to incorporate new features and improvements. In the case of R&D projects, the dates correspond to their start, with some projects already completed and others still ongoing.

### A. OVERVIEW

Despite being a relatively new topic with around a decade of development, Figure 3 illustrates a rise in AAS-related publications, especially from 2022 onward, following the release of the initial AAS specifications and development platforms (cp. Figure 2). Furthermore, there were no publications prior to 2017, as the AAS concept was introduced in 2015, and it took some time for its ideas to be disseminated and for research in this field to begin.

It is important to note that this survey primarily focuses on the AAS from an academic perspective. However, many companies within the industry are already integrating AAS into their solutions. For instance, at Hannover Messe fair 2023, Siemens, Bausch+Ströbel, Bosch Rexroth, CADENAS, Festo, HARTING, SICK, Phoenix Contact, and WAGO jointly demonstrated how the AAS can be implemented in practice [10]. More recently, at the Hannover Messe fair 2025, a total of 51 practice-proven AAS solutions from various companies were exhibited [11]. Moreover, as highlighted in [12], several companies are developing AAS solutions at an industry-ready maturity level, reinforcing its practical applicability and growing relevance in industrial digitization.

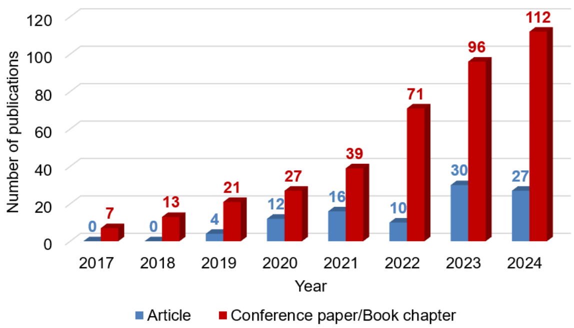


**FIGURE 3. Number of AAS-related publications in recent years.**

Figure 4 highlights the geographical distribution of AAS-related publications based on the authors' affiliations obtained from the bibliographic search. As AAS is a German initiative aligned with RAMI4.0, Germany naturally leads by a significant margin in scientific contributions to the field, influencing other European countries, e.g., the Czech Republic, Spain, Austria, Italy, Portugal, Greece, and France, which are also contributing to this field. However, it is possible to notice that this topic is not limited to Europe, as other countries such as China, South Korea, and the USA are also contributing to the AAS research.

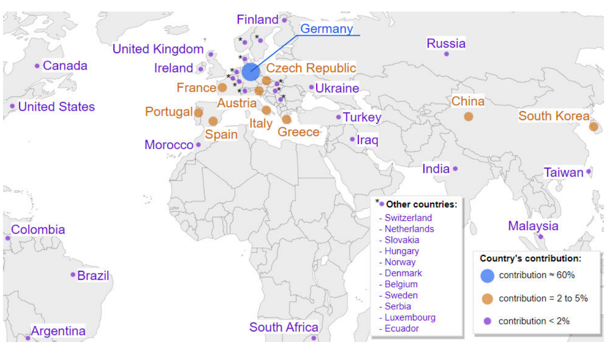


**FIGURE 4. Geographical distribution of AAS-related publications.**

The comparatively lower publication volume from these countries relative to Germany can partly be attributed to the existence of alternative strategic initiatives tailored to their specific economic and industrial strengths, namely "Industrial Internet Consortium" in USA, "Industria 4.0" in Italy, "Produktion 2030" in Sweden, and "Made in China 2025" in China, to name a few [13], [14]. Although these initiatives pursue different digitization strategies, many also incorporate similar and complementary elements. For instance, as discussed in [15], the RAMI4.0 and IIRA reference architectures, developed by German and USA initiatives respectively, are not conflicting but rather complementary, each offering unique perspectives that enable the advancement of industrial digitization. However, further coordinated efforts will be necessary to pave the way toward a global standard, in which the AAS could play a pivotal role by promoting interoperability and harmonization across diverse industrial ecosystems. In this context, and given the current disparity in scientific contributions, this paper will later discuss the challenges related to AAS adoption to help address these barriers.

Recurring to the VOSviewer tool (https://www.vosviewer.com/), a software designed for creating and visualizing bibliometric networks, the retrieved publications were analyzed to identify the general research topics in this field based on the author's keywords obtained from the bibliographic search. Figure 5 depicts the most common terms obtained from this analysis, representing the concepts, technologies, approaches, and application domains in the context of AAS. In this type of network, the size of the nodes indicates the frequency of the keywords, while lines between nodes represent links between the keywords.

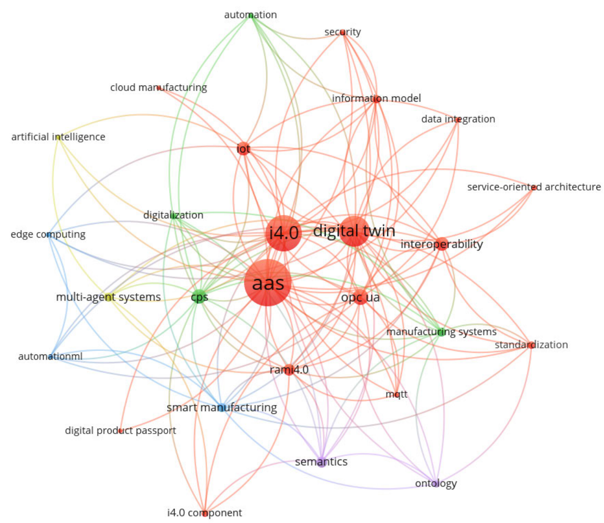


**FIGURE 5. Co-occurrence network with the most common terms found in scientific publications in the AAS topic.**

As shown in Figure 5, the term AAS ("aas") represents the searched term, which explains its size, given that it appears as a keyword in most documents. This term is connected to related terms such as "rami4.0", "i4.0", "i4.0 component", and "cps". This connection is expected as the AAS reflects the asset in the digital world in the upper five layers (layers axis) of RAMI4.0, a reference architecture model for developing I4.0-compliant solutions. Furthermore, the AAS and its asset form an I4.0 component, a specific CPS category.

Along the term "aas", it is also possible to see the main applications domains ("manufacturing systems" and "automation") and some terms related to its roles/functions, namely "digitalization", "standardization", "data integration", "information model", and "interoperability". In addition, supporting technologies including "opc ua", "artificial intelligence", "multi-agent systems", "iot", "automation ml", "mqtt", "edge computing", and "cloud manufacturing" are related, along with essential concepts like "semantics", "ontology", "security", and "service-oriented architecture" relevant to the implementation of AAS solutions.

The term "aas" is also closely associated with "digital twin", which is currently a widely discussed topic in the context of asset digitization. Moreover, related terms such as digital thread, digital shadow, and other "digital *" concepts frequently appear in the literature, often leading to confusion due to overlapping definitions and interpretations. A recurring question within the community concerns the relationship between AAS and Digital Twin (DT), as both are described as digital representations of assets. In this context, due to the increased popularity and adoption of these "digital *" concepts, several research works have explored their relationships and distinctions, namely [16], [17], [18], [19], [20].

Based on these research works, the relationship between AAS and DT is complex and has been interpreted in different ways in the literature. While some sources consider AAS as a synonym or a way to implement DT, others view it as a fundamental information model that supports the creation and interoperability of DTs. Furthermore, there is ongoing discussion about how well an AAS represents a DT, with its suitability suggested to increase from Type 1 to Type 3. The relationship of AAS Type 3 with DT is considered the strongest, with the potential to be a near-complete implementation technology for DT [20]. However, a clear understanding of these relationships remain an area of ongoing research and should be revisited in the future, especially since AAS Type 3 is still in its early stages of development.

It is important to emphasize that this work does not aim to engage in broader conceptual debates or to classify and systematize the various interpretations of these concepts. Instead, it focuses on reviewing advancements in AAS over the past decade, as well as identifying research opportunities and challenges related to its adoption. In this sense, studies that refer to the AAS as a synonym of DT, a way to implement it or support its implementation, were also considered for review. However, those studies that discuss DT without a direct link to AAS or are only loosely associated with it were not included.

Finally, special attention should be given to the terms "multi-agent systems" and "digital product passport", as they represent emerging trends in the current literature. Multi-agent Systems (MAS) have been considered a key enabler for realizing AAS Type 3, particularly by providing the autonomy, intelligence, and collaborative capabilities envisioned for this most advanced AAS type. On the other hand, the AAS has been used as a foundational technology for implementing the Digital Product Passport (DPP), offering a standardized and interoperable structure for storing and sharing essential product data throughout its lifecycle. A more detailed discussion of MAS-based AAS Type 3 solutions and AAS-based DPP implementations will be presented in later sections.

### B. SPECIFICATIONS AND STANDARDS

The AAS relies on well-defined specifications and standards to ensure interoperability, scalability, and seamless integration into I4.0 environments. Various organizations contribute to its development, with the IDTA playing a key role by providing essential specifications and standardized submodel templates to support the digitization of industrial environments. In this context, this section presents an overview of these specifications and other relevant standards that contribute to the development of AAS-based solutions, as summarized in Figure 6.

*Part 1: Metamodel – IDTA Number: 01001-3-0-1* [5] describes the AAS structure to facilitate the exchange of asset information between partners in I4.0, particularly focusing on how such information needs to be processed and structured to ensure seamless interoperability, consistency, and efficient data exchange within industrial ecosystems. At the core of this specification is the technology-neutral AAS information metamodel, which presents the main classes and their relationships to develop AASs. These AASs can be represented using various data formats for exchanging, such as XML, JSON, RDF, AutomationML (IEC 62714), and OPC UA information model (IEC 62541-5). For a detailed representation of the metamodel, refer to Figure 10 in [5].

*Part 2: Application Programming Interfaces – IDTA Number: 01002-3-0-3* [21] defines APIs for enabling the access to the information provided by an AAS, which includes the interfaces for a single AAS and its submodels, and a repository of AASs. These interfaces are specified in a technology-neutral manner, and in this version of the document, an HTTP/REST API is provided. Future versions of this specification plan to define APIs using other technologies, e.g., gRPC and MQTT.

*Part 3a: Data Specification – IEC 61360 – IDTA Number: 01003-a-3-0-2* [22] complements the Part 1 (Metamodel specification) by defining a data specification template that enables the inclusion of additional attributes in an element instance, which are not part of the standard AAS metamodel. These additional attributes follow the IEC 61360 standard, which describes how to define the semantics of properties in a data dictionary, e.g., ECLASS [23] and IEC CDD [24].

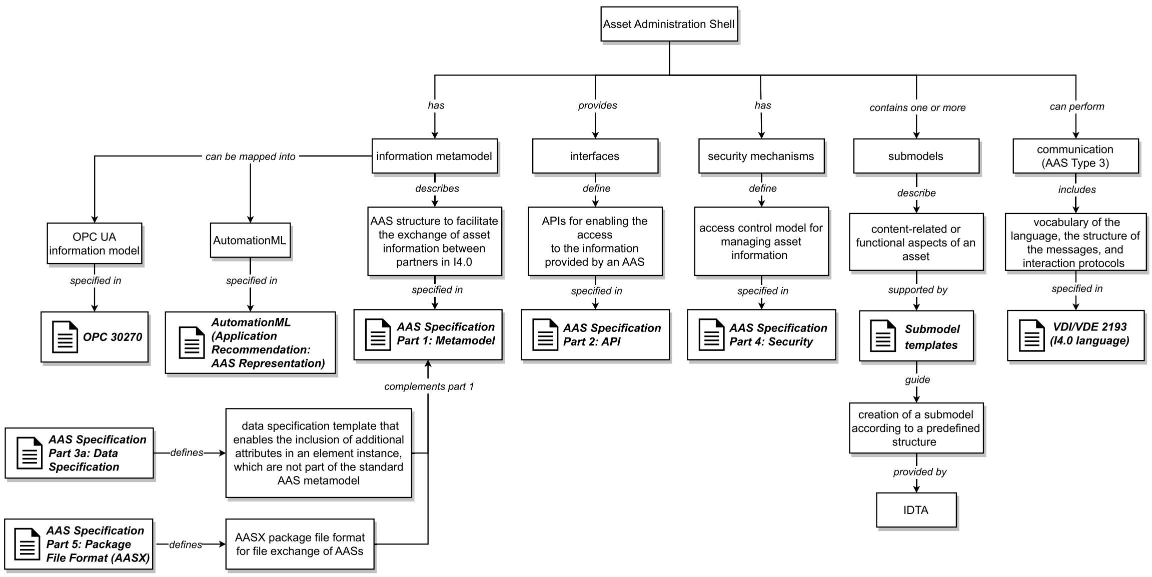


**FIGURE 6.** **Available specifications and standards for AAS development.**

*Part 4: Security – IDTA Number: 01004-3-0* [25] defines the security mechanisms for the AAS and its submodels. This part introduces an access control model that enables targeted and fine-grained control over access rights to asset information. Finally, *Part 5: Package File Format (AASX) – IDTA Number: 01005-3-0-1* [26] defines the AASX package file format for file exchange of AASs.

*OPC 30270: Industry 4.0 Asset Administration Shell* [27] provides guidelines for mapping the AAS metamodel to the OPC UA information model to represent AAS and their submodels in the address space of an OPC UA server, which enables OPC UA clients to request the submodels information from the server. Similarly, *AR_004E – Asset Administration Shell Representation* [28] defines rules for mapping the AAS information model to the AutomationML information model. However, it is important to note that both documents [27], [28] are based on an earlier version of the AAS information metamodel. Consequently, some adaptation may be required to align with the current version of the metamodel.

The previous specifications and documents enable the development of AAS Type 1 and Type 2 solutions. Although there is no formal specification for AAS Type 3, it is suggested that the communication between AASs Type 3 should be based on the I4.0 language, as defined by VDI/VDE 2193 standards, which includes the vocabulary of the language and the structure of the messages (VDI/VDE 2193-1) [29], as well as interaction protocols (VDI/VDE 2193-2) [30].

Another crucial contribution of IDTA is the standardization of submodel templates, which provide predefined structures for representing specific aspects of assets in a consistent and interoperable manner. See some examples in [31].

### C. DEVELOPMENT PLATFORMS

The adoption and implementation of the AAS rely on various development platforms that provide the requirements for modeling, managing, and deploying AAS-based solutions. Through the survey, several open-source development platforms were identified, supporting different aspects of the AAS implementation, ranging from the creation and visualization of AAS to the deployment of AAS infrastructures. This section does not aim to provide a detailed review and compare the performance of such platforms but rather overviews their features and the distinctions between the types of AAS they implement. For more information, please refer to the repositories of these platforms.

Eclipse AASX Package Explorer [32], Eclipse AAS4J [33], and aas-core-works [34] enable the development of AAS Type 1 in accordance with the AAS information metamodel [5]. According to the survey, Eclipse AASX Package Explorer is the most widely adopted tool for AAS implementation, being a must-have tool for developing AAS solutions. It offers a user-friendly graphical interface that allows non-programmer users to easily create, edit, and view AAS files. Moreover, this tool enables the export of the developed AAS in various file-exchange formats, e.g., XML, JSON, and AASX. On the other hand, Eclipse AASX Server [35], BaSyx [36], FA$^3$ST [37], and NOVAAS [38] support the implementation of AAS Type 2. In general, these platforms have their own specific features, but all provide the necessary requirements to implement AAS Type 2 at different levels of fulfillment. However, variations exist in their support for key functionalities, e.g., communication protocols, data format compatibility, security mechanisms, and synchronization with physical assets. Despite the benefits offered, the research works [39], [40] have analyzed some of these platforms and highlighted the need for further improvements and full compliance with AAS specifications.

It is important to note that these platforms have been receiving continuous updates to align with the latest AAS specifications, as well as the inclusion of new features. Moreover, based on the survey and the authors' knowledge, there is currently no dedicated platform for implementing AAS Type 3, particularly its collaborative capabilities. However, existing platforms can be leveraged to support AAS Type 3, but they need to be integrated with other non-AAS-dedicated software solutions, e.g., the Java Agent DEvelopment (JADE) framework, to implement agent-based AAS solutions that realize AAS Type 3.

### D. DEVELOPMENTS, APPLICATIONS, AND R&D PROJECTS

This section provides an overview of AAS developments, applications, and R&D projects over the past decade. The goal is not to categorize or conduct an in-depth comparative analysis of existing research but to summarize the key objectives and progress in AAS research during this time frame. To this end, a selection of representative papers has been included to highlight and illustrate significant developments.

As illustrated in Figure 2, the years around 2017 are marked by the earliest AAS research works identified in the literature. These initial studies (e.g., [16], [41], [42], to name a few) played a crucial role in introducing and disseminating the AAS concept through theoretical discussions, examples, and preliminary implementation efforts. Since no formal specifications were available at the time, these works were based on the AAS initial ideas and general structure outlined during that period. Overall, these early research efforts helped to establish the concept of AAS and highlighted its potential benefits, laying the groundwork for future advancements in the field.

With the release of the first version of the specification (Part 1: Metamodel) at the end of 2018, the research began exploring how to map the proposed AAS information metamodel into various data formats to share I4.0-compliant information, e.g., RDF [43], AutomationML [44], [45], and the OPC UA information model [46]. Despite these advancements in AAS research, the introduction of the first development platforms significantly facilitated the process of creating AAS solutions, addressing the time-consuming and error-prone nature of early AAS development and making the process easier and more efficient. For instance, a comparison between the research work [47] and its preceding study [45] highlights how the Eclipse AASX Package Explorer tool simplifies AAS modeling compared to the earlier method, which relied on AutomationML.

From around 2020 onward, new specifications and additional development platforms emerged, resulting in a wide range of AAS-based solutions, particularly in the manufacturing sector. For instance, some research works present solutions to enable interoperable DTs by leveraging AAS to ensure efficient information management [48], and to facilitate standardized data exchange between the DT layer and various system components (e.g., robots, execution planning systems, and monitoring systems) within reconfigurable production environments [49], as well as between DTs of different companies [50]. In the context of predictive maintenance, [51] proposes a model based on AAS, aiming to improve the performance and reliability of industrial systems. In another application of I4.0, [45] presents an approach that uses AAS to enable the Plug-and-Produce strategy, enabling more flexible and agile integration of new components into production environments.

AAS implementation is also explored across different architectural layers for manufacturing systems. For example, [47] suggests a solution based on a three-layer architecture that distributes the solution along Edge AAS deployment and Cloud AAS management. Moreover, [52] proposes an AAS solution to represent IEC 61131-3 programs and the relevant relationships with PLCs and each device of the controlled plant. On the other hand, [53] explores the mapping of the AAS metamodel and IEC 61499 to establish a complete model containing both information access and process control. Finally, [54] introduces a methodology that provides guidelines for integrating physical assets in I4.0 using AAS.

Beyond the typical applications of AAS in manufacturing systems, other research efforts are exploring and demonstrating its potential in diverse domains. For instance, [55] proposes a methodological approach based on AAS for a water supply system. In intralogistics, [56] presents a solution by integrating AAS with Autonomous Mobile Robots (AMR) and other logistics systems to enhance efficiency, safety, and adaptability. In the construction industry, [57] explores how AAS can be used for precast concrete elements. In the energy domain, [58] demonstrates the role of the AAS in facilitating a cross-organizational plant engineering process. In the agri-food sector, [59] proposes an AAS-based DPP solution for the dairy supply chain. Additionally, AAS is investigated in sustainability-related initiatives [60], [61], [62], [63], and for supporting data integration throughout the Product Lifecycle Management (PLM) process, a widely adopted approach across various sectors [64].

Furthermore, some research (e.g., [65], [66], [67], [68], [69], [70], to name a few) align with the capability- and skill-based engineering domain, formally specified in the Capability-Skill-Service (CSS) model [71]. Designing industrial systems based on these concepts is crucial for developing more flexible and reconfigurable systems. In such systems, assets should contain a machine-readable self-description of their functions (capabilities). By exposing these capabilities as services (based on service-oriented principles), assets can be automatically integrated into the system (enables Plug-and-Produce) and orchestrated to execute a desired process through the execution of specific capabilities (skills). In this sense, the AAS is a key enabler in describing capabilities in a standardized manner, exposing them as services, and defining how to execute (or even execute, if implemented to this end) the skills.

Typically, AAS solutions in the literature are designed for physical assets, such as machines, robots, and products. However, some research are exploring AAS-based solutions for other types of assets. For instance, [72] presents a method for implementing AAS for software assets, such as Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems. Similarly, [73], [74], [75], [76] propose the use of AAS for human entities, while [77] explores the use of AAS for AI assets, e.g., models, learning algorithms, and datasets. Additionally, [78] investigates AAS as a means to describe software agents [79]. In summary, these studies illustrate the versatility of AAS as a standardized approach capable of representing not only physical assets but also digital and human entities.

Moreover, [80] highlights the importance of incorporating knowledge representation formalisms, e.g., RDF and Web Ontology Language (OWL), to enhance AAS (known as a semantic AAS), enabling machines and systems to understand better the meaning of the data being exchanged. This understanding facilitates interoperability and supports the autonomous decision-making in industrial environments.

Other innovative research efforts, namely AAS Type 3, human-centered approaches, industrial AI, DPP, and Small and Medium-sized Enterprises (SMEs), were also identified in the literature. However, due to their innovative nature and alignment with emerging industrial trends, these topics will be further discussed later as research opportunities for AAS. Additionally, other critical aspects, namely submodels standardization, integration with legacy/existing, and security concerns for AAS solutions, will be addressed later in the context of challenges to AAS adoption.

In addition to the research found in the literature, several R&D projects were also identified through the survey. For instance, the openZDM project [81], [82] focuses on developing an AAS-enabled open platform for implementing I4.0-compliant Zero Defect Manufacturing (ZDM) strategies in production systems. The DIMOFAC project [83] aims to enhance the digitization of manufacturing environments by integrating Plug-and-Produce modules (a description of 18 developed production modules utilizing AAS, covering various manufacturing processes, is presented in [84]). The MAS4AI project [74], [78], [85] focuses on developing a distributed and interoperable AI architecture based on MAS technology and AAS.

The FOREST project [86], [87] focuses on developing a framework for an AAS-based DT for the paper production process that tracks energy and material flows, as well as carbon flows and footprints. The I4.0AutoServ project [88], [89] aims to automate the collection and processing of industrial data, enabling companies to develop data-driven services, where the AAS plays a central role by structuring the data of assets in a standardized manner. The BaSys 4.2 project [90] focuses on developing an open-source platform for facilitating the implementation of AAS, which is now available as the Eclipse BaSyx platform, as previously mentioned.

The Flex4Res project [91], [92] aims to establish an open platform for reconfiguring production networks for a resilient production value chain, relying on the principles of Gaia-X [93], International Data Spaces (IDS) [94] connectors, and AAS. The InterOpera project [95] aims to develop 50 interoperable AAS submodels applicable to different business areas. Moreover, under the scope of smartMA-X project [96], the research works [68], [97], [98] combine Gaia-X, I4.0 language, and AAS concepts to enable the shared production scenario. Other AAS-related projects, namely AASHub, ESCOM, and PredictECO, are reported in [99].

In summary, many of these research works and R&D projects have been validated through laboratory prototypes and real-world case studies, demonstrating relevant and promising outcomes. The reported implementation outcomes include enhanced standardized communication and interoperability among heterogeneous systems, support for Plug-and-Produce capabilities that reduce setup times and increase system flexibility, scalability, and reconfigurability, improved asset traceability, and more effective lifecycle management. Moreover, since the AAS provides a standardized structure to describe asset information, it facilitates integration with a range of solutions, e.g., data analytics, condition monitoring, predictive maintenance, and supply chain management. These findings illustrate that the AAS is a viable and adaptable concept for enabling I4.0-compliant digitization across diverse industrial scenarios, while also enhancing the value and applicability of digitized assets.

## V. PROMISING RESEARCH OPPORTUNITIES

Through the survey, several research opportunities for AAS have been identified, with some studies already aligning with these opportunities. These opportunities represent promising directions and perspectives aligned with emerging industrial trends, where AAS can play a critical role in enhancing interoperability and enabling the development of more intelligent, collaborative, and sustainable industrial systems. In this context, this section discusses these research opportunities, namely AAS Type 3, human-centered approaches, industrial AI, DPP, and SMEs, as illustrated in Figure 7.

### A. AAS TYPE 3

Despite its potential, AAS Type 3 remains an emerging and underexplored topic in the literature. While traditional AAS implementations (i.e., Types 1 and 2) have been widely studied and adopted, research on AAS Type 3 is still in its early stages. Compared to other types, AAS Type 3 goes a step further. It not only serves as a key enabler of interoperability in I4.0 environments but also introduces a higher degree of autonomy, intelligence, and collaborative

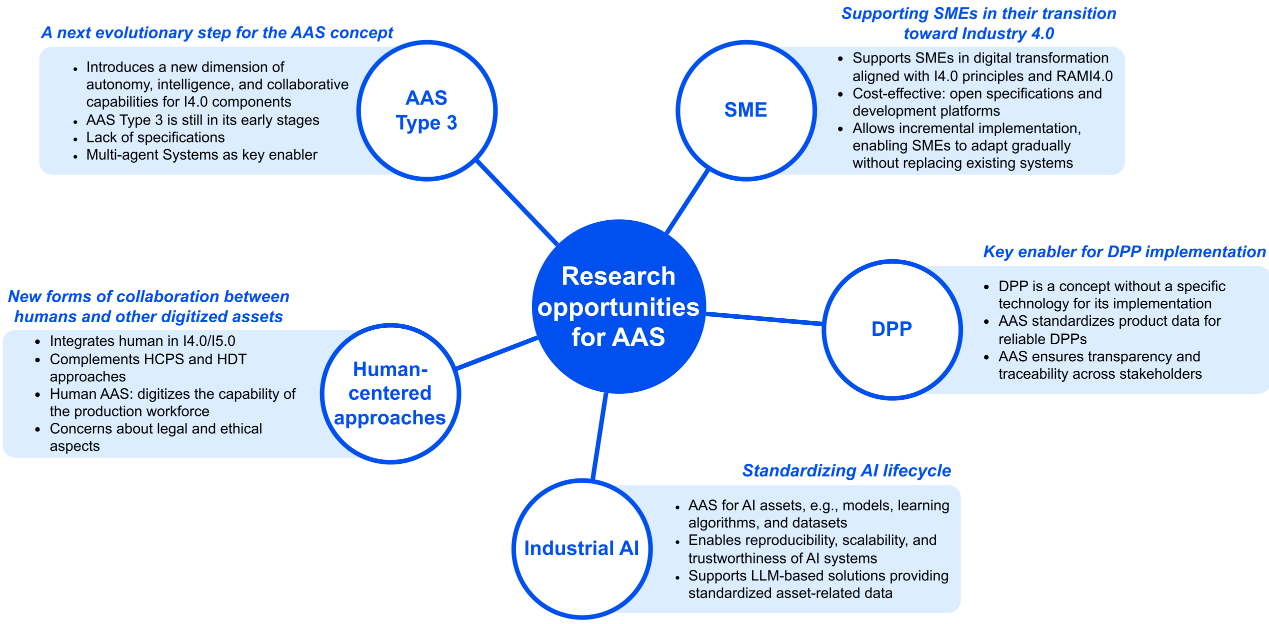


**FIGURE 7.** Overview of research opportunities for AAS.

capabilities. These advanced features are indispensable for I4.0 components and play a critical role in realizing the complete vision of I4.0 of fully connected, intelligent, resilient, and adaptive industrial ecosystems.

The AAS Type 3 concept recalls the MAS [79], [100] derived from the Distributed AI (DAI) area, which comprises a society of intelligent, autonomous, and cooperative entities called agents. In fact, a system composed of AASs Type 3 can be conceptualized as a MAS, where each AAS is an autonomous and intelligent entity representing a specific asset. These AASs not only manage the lifecycle information of their respective assets but also engage in interaction strategies, e.g., collaboration and negotiation, to achieve the system goals and adapt to the condition changes. In this regard, to support this initial hypothesis, [101] investigates the feasibility of applying the MAS to address the challenges of the I4.0 scenarios, discussing that agent-based communication capabilities could fulfill the needs of AAS Type 3. Moreover, [4], [102] discuss that agents could be used to implement the AAS (Type 3) or support it by providing functionalities, e.g., data gathering, communication, intelligence, and autonomous decision-support.

Given this similarity, it is no surprise that most research works related to AAS Type 3 leverages MAS as a key enabling technology. For instance, [103] proposes a pattern for implementing AASs based on industrial agents, and [104] presents an agent-based approach to enable the development of intelligent and collaborative AASs. On the other hand, [105] discusses that the asset information described in the AAS may be used as a standardized agent's knowledge representation, i.e., the agents get all the relevant information to make decisions from the AAS submodels. Following a similar strategy, [106] concentrates on modeling AAS submodels for resource and product agents to use in dynamic replanning applications, and [107] introduces a MAS architecture designed to enable shared production grounded in holonic principles. In this approach, AAS serves as the self-description mechanism for the holons, providing the necessary information for their operation, interaction, and integration.

Beyond MAS, other research efforts align with the AAS Type 3 concept. Reference [108] introduces possibilities for transitioning from AAS Type 2 to AAS Type 3, along with modules/applications designed to support this transition, particularly to enable message exchange between AASs using MQTT, while ensuring alignment with the I4.0 language. On the other hand, [109] presents an architecture for implementing AAS Type 3. The solution employs a Business Process Model Engine (BPME) capable of interpreting and executing behavior descriptions modeled as Business Process Model Notation (BPMN) workflows.

AAS Type 3 represents the most ambitious vision for the future, introducing a new level of intelligence, autonomy, and collaboration among industrial assets. While the literature has already identified MAS as a key enabling technology for AAS Type 3, its implementation remains in its early stages due to the lack of clear specifications and standardized guidelines. As observed with previous AAS developments, the adoption and understanding of AAS solutions (Type 1 and 2) became more widespread once specifications and dedicated development platforms were established (see the correlation in Figure 2). Similarly, for AAS Type 3, coordinated efforts from the scientific community, industry stakeholders, and standardization bodies will be essential to define its structure, capabilities, and practical applications.

### B. HUMAN-CENTERED APPROACHES

Although AAS has been predominantly applied to physical assets (e.g., machines), its application to human entities remains in the early stages. Using AAS in this context could enhance human integration in I4.0/I5.0, facilitating new forms of collaboration between humans and other digitized assets that were previously not possible. According to [110], the integration of humans in I4.0 environments is not new [111], but how it can be realized is still a challenging undertaking [112], [113]. In this regard, AAS can serve as a complementary approach by providing a standardized and I4.0/I5.0-compliant digital representation of human entities, which is intended to empower humans rather than replace them [114], [115]. For instance, some few works, e.g., [73], [74], [75], [76], address the concept of Human AAS (HAAS), a specific type of AAS that digitizes the capability of the production workforce. Reference [76] proposes a HAAS approach for managing the cognitive load, integrating real-time data from wearable sensors (physiological metrics), user characteristics, task specifics, and environmental conditions (e.g., temperature, noise levels, and humidity) to assess whether a worker is in an optimal state to perform a given task, aiming to maximize productivity while maintaining a comfortable work environment. Similarly, [75] develops HAAS for worker fatigue estimation and task assignment in collaborative robotics, and [73] for optimizing the allocation of workers to workstations.

Besides the research discussed before, using the AAS for human entities may offer additional benefits. For instance, by storing operator data, namely skills, certifications, experience, and historical performance, an AI-driven AAS-based tool could analyze this information to recommend personalized training programs and perform skill gap analyses, ensuring operators are continuously upskilled to meet evolving industrial demands. Additionally, the AAS allows workers to access vital information about assets, e.g., [116] proposes the utilization of AAS to support humans during the maintenance process by providing information on the required tools, step-by-step instructions, safety protocols, and regulatory requirements, minimizing workplace hazards, and enhancing safety and efficiency. In summary, AAS could support better decision-making and personalized task allocation, contributing to operator well-being while maintaining operational efficiency.

One last but crucial point concerns the legal and ethical aspects of AAS for digitizing human entities. Its implementation must comply with data protection regulations, ensuring transparency, security, and respect for workers' privacy while preventing excessive monitoring or misuse of personal data. AAS should enhance worker well-being, safety, and skills development, promoting a human-centric and legally compliant industrial environment.

### C. INDUSTRIAL AI

Industrial AI [117] plays a crucial role in enhancing automation, efficiency, and decision-making across industrial systems. Historically, AI was perceived as a "black-box" technology, often mistrusted due to its complex nature and the unpredictability of its outcomes in real-world scenarios. On the other hand, industrial AI follows a more systematic and structured approach, with a focus on ensuring that solutions are repeatable, scalable, and sustainable over the long term. The aim is to produce predictable and reliable results that are applicable in industrial environments, particularly CPS applications, addressing the shortcomings of traditional AI.

To fully leverage its potential, it is essential to standardize the AI lifecycle, ensuring that every stage, from dataset preparation to model deployment, is systematically documented. Such standardization improves the accessibility, reproducibility, and reusability of AI models, allowing industries to scale intelligent solutions more effectively. For instance, "model cards" [118], [119] proposed by Google is one initiative aiming to standardize AI to encourage such transparent model reporting. Inspired by the concept of "model cards", the AAS could adapt and extend this idea to enhance transparency and trustworthiness in AI-driven decision-making processes while ensuring compliance with I4.0 standards and enabling broader applications in domains such as manufacturing. In this sense, AAS could provide a structured and I4.0-compliant approach to documenting AI assets, enabling stakeholders to gain clear insights into how AI models are trained, deployed, and utilized, as well as other relevant information. The literature already presents some research aligned with this AI standardization effort. For instance, [77] proposes use AAS for AI assets, e.g., models, learning algorithms, and datasets (AAS for datasets recall the "datasheet for dataset" [120] concept proposed by Microsoft), in order to integrate the AI lifecycle in the I4.0, and [121] proposes AI-specific submodels templates, namely *AI Dataset*, *AI ModelNameplate*, and *AI Deployment*, to represent AI lifecycle.

Other related approaches are also reported in the literature, showing how AAS has been used to support AI applications, namely [122], [123]. In summary, a key insight gained is the advantage of combining AAS with standardized, machine-readable interchange formats for AI models, such as Predictive Model Markup Language (PMML) [124], Portable Format for Analytics (PFA) [125], and Open Neural Network Exchange (ONNX) [126]. These formats may bring several benefits, such as representing AI models in a standardized manner, enhancing interoperability, facilitating seamless integration across diverse systems, and reducing the time required to make a model production-ready [122]. Moreover, recent advancements in Large Language Models (LLMs) offer promising capabilities that further complement Industrial AI [127]. As presented in [123], AAS can support LLM-based solutions by providing a structured and standardized representation of asset-related data. This integration facilitates insight generation and enhances decision-making and control processes in industrial automation systems.

Overall, the AAS plays a key role by standardizing the representation of the AI lifecycle, helping to build trust and demonstrate that AI solutions are reliable, scalable, and aligned with business objectives. Moreover, a promising enhancement could be the integration of Explainable AI (XAI), which would allow documenting model decisions and their underlying rationale directly within the AAS, increasing transparency and stakeholder confidence.

### D. DIGITAL PRODUCT PASSPORT

Currently, product information is often scattered across labels, instruction manuals, and other sources that are difficult to access. The DPP serves as a digital identity card for products, consolidating all relevant details into a single, easily accessible source, thus establishing a new standard for transparency. The DPP is gaining traction within the EU and global industries in the context of digital traceability, regulatory compliance, and sustainability. Its relevance is expected to grow in the coming years, particularly with the Ecodesign for Sustainable Products Regulation (ESPR), which aims to leverage DPPs to enhance circularity, energy efficiency, and overall environmental sustainability for products sold in the EU [128]. Given the structured and standardized nature, the AAS emerges as a key enabler for the DPP implementation, providing a framework to store and manage valuable data on a product's sustainability performance, recyclability, and environmental impact, as well as other relevant information on the product throughout its lifecycle.

Some research works are already discussing the applicability of AAS in implementing DPP. For instance, [129] discusses that the AAS could be a potential technology to implement the Digital Battery Passport (DBP), a specific DPP to the battery industry. On the other hand, [130] provides an example of how AAS can be used to address the recycling aspect of the DBP. These research works align with the EU Battery Regulation 2023/1542, which will mandate a DBP for all light means of transport batteries, industrial batteries above 2 kWh, and electric vehicle batteries placed on the EU market starting in February 2027 [131]. Additionally, to support the adoption of AAS, a submodel template is under development by IDTA (number: 02035) that could be used for DBPs in the future.

Another important contribution of the DPP is aligned with the EU Green Deal, which aims to ensure zero emissions by 2050, making Europe the first climate-neutral continent in the world [132]. In this regard, monitoring the Product Carbon Footprint (PCF) can help to regulate this measure. This is exemplified by the ZVEI showcase PCF@Control Cabinet [60], [133], which demonstrates an AAS-based DPP in action. Each product (from the participating companies) used to assemble the cabinet has its own DPP, implemented using AAS. Among other details, it includes information on the PCF. Based on that, the system integrator can automatically retrieve the PCF value of a product and use this data to calculate the total PCF of the entire cabinet. Moreover, other research works [61], [62], [63] are also aligned with this initiative and developing AAS-based DPP solutions that can contribute to the PCF context.

Besides the aforementioned AAS-based DPP solutions, another notable application example is provided by [59], which uses AAS for implementing the DPP for the dairy supply chain. In this approach, all assets involved in producing the dairy product, namely the farm, the cow, the milk, the equipment, and the transport, are digitized using AAS. After, these components are combined to create the DPP, enabling traceability of the product. Moreover, [134], [135], [136] presents an AAS-based DPP solution that focuses on the later lifecycle phases of the product (e.g., sorting and recycling of electrical/electronic equipment), which can be used by multiple stakeholders (e.g., manufacturers, customers, maintainers, recyclers, and designers) while incorporating privacy-preserving mechanisms to ensure appropriate information access rights.

The role and impact of DPP in the coming years are undeniable, being a future requirement for every product in the market. The scope of DPP will open new opportunities in digitization, expanding to encompass areas such as manufacturing, agriculture, healthcare, logistics, and beyond. Given its structured and standardized approach, the AAS is a strong candidate for facilitating the implementation of DPP. Furthermore, Gaia-X can support this process by ensuring secure and trustworthy data exchange and collaboration across the entire value chain, as highlighted in [137].

### E. DIGITIZING SMALL AND MEDIUM-SIZED ENTERPRISES

SMEs play an important role in the economy, representing 99% of all businesses within the EU [138] and contributing 43.5% of the entire USA Gross Domestic Product (GDP) [139], to name a few examples. Despite their economic significance, many SMEs face challenges in adopting the digital transformation based on I4.0 principles due to high costs and complex implementation requirements. Therefore, it is essential to develop effective strategies to facilitate the digital transformation of SMEs, ensuring they remain competitive in the market.

In this context, AAS plays a key role in this transition, as it enables the digitization of industrial environments in alignment with RAMI4.0 and I4.0 principles. By providing a standardized and structured approach to managing the asset information, AAS can support SMEs in integrating into the digital ecosystem more effectively. The AAS benefits from open specifications, standards, and open-source development platforms, as previously discussed, making it a cost-effective option for SMEs. Moreover, AAS can be designed to integrate with existing systems rather than requiring a complete replacement, which allows companies to implement AAS incrementally, adapting to their budget and specific requirements.

Some research has already focused on developing AAS-based solutions for SMEs, showing their benefits through practical use cases. For instance, [140] presents an approach to support the digitization process of SMEs based on RAMI4.0 and AAS, demonstrating its applicability in three SMEs from the brewing, dairy, and wine industries. On the other hand, [141] proposes an integrated tool based on AAS to help SME service providers achieve a balanced order situation to optimize resource utilization. Moreover, [142] presents a solution for energy optimization in the electronics industry, and [143] introduces an approach that decreases the time required to set up a new testing process while reducing the need for expert intervention in controlling operations in an industrial dry-air leak testing system. These studies highlight how AAS serves as a key enabler of digital transformation, helping SMEs improve operations efficiently without requiring complex infrastructure while remaining cost-effective.

From another perspective, some research works explore the cost minimization by implementing AAS using low-cost technologies. For instance, [144] presents a methodology for AAS implementation into an embedded system based on the STM32 board, aiming to simplify and accelerate the digitization process. Additionally, [145] implements an AAS service collector solution using single-board computers (e.g., ESP32 and Raspberry Pi), demonstrating the feasibility of deploying AAS with affordable hardware solutions.

Due to its interoperability, modularity, and flexibility, the AAS enables SMEs to gradually adopt this solution without having to replace their existing systems, which allows companies to transition toward I4.0, aligning their business with modern industrial standards. As a result, AAS adoption is expected to accelerate in the coming years, and SMEs, in particular, should consider adopting AAS to secure their place in the future of the smart industry.

## VI. CHALLENGES FOR ADOPTION

After analyzing the evolution of AAS over the past decade and introducing potential research opportunities, this section discusses the challenges related to AAS adoption.

Based on survey findings and the authors' perspective, AAS has now reached sufficient maturity to be increasingly adopted. At this stage, the following years will be crucial for its widespread adoption and integration across industries, requiring further efforts to overcome remaining barriers. Over ten years, the AAS has progressed from its initial conceptual stages to a more mature and standardized version, supported by the appearance of development platforms, specifications, and standards designed to facilitate the adoption of AAS solutions. In addition, the literature now includes a wide range of application examples demonstrating its practical value. In this context, the challenges associated with adopting AAS (here the discussion is limited to AAS Type 1 and 2 solutions) are no longer primarily focused on technical implementation, as was the case in the initial stages when tools and community support were limited. Instead, current adopting challenges are increasingly related to the limited global visibility, the need for workforce upskilling, the expansion of standards, integration with legacy/existing systems, and security concerns, as summarized in Table 1. While some of these challenges are already being addressed, their persistent and complex nature makes it essential to discuss them in detail to raise awareness and encourage coordinated solutions from both academic and industry communities.

As mentioned earlier, AAS is predominantly confined to Germany and certain other European countries (see Figure 4), at least from an academic perspective. This highlights the need to expand the adoption and research of AAS beyond these regions to foster the broader global engagement and application. International cooperation, following the examples between IDTA with Digital Twin Consortium (USA), Korea Smart Manufacturing Office (KOSMO), Alliance Industrie du Futur (France), and FEDERTEC (Italy), to name a few, could play a crucial role in making this possible, facilitating the cross-border collaboration and knowledge sharing in implementing AAS solutions. Moreover, the dissemination of materials adapted to different cultural contexts and the presentation of region-specific case studies that illustrate the role and benefits of AAS could encourage adoption, particularly in less developed regions.

Another strategy to promote the widespread adoption of AAS is through workshops, conferences, and participation in demonstrative events, which facilitate knowledge sharing, industry collaboration, and hands-on experience with AAS implementations. Some initiatives are already being carried out but should be further expanded to reach a broader audience. For instance, in 2024, during the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), the 3rd Workshop on Implementing Asset Administration Shells (ImplAAS) was held to discuss practical experiences related to the AAS implementation. Moreover, the IDTA has been consistently present at the Hannover Messe fair in Germany, presenting AAS demonstrations to further drive visibility and industry engagement.

Since AAS introduces a new digitization paradigm, workforce upskilling is fundamental for the successful adoption and integration of AAS in industrial settings, where both managers and employees must acquire the required skills to effectively implement and manage these new solutions. Without the proper training, companies may face challenges in leveraging AAS to its full potential. In this sense, upskilling initiatives, namely specialized training programs, can empower professionals to work with AAS solutions. For example, IDTA and University4Industry (https://www.university4industry.com/en/digital-twin/) offer training programs focused on a foundational understanding of AAS. By investing in workforce education, industries can drive innovation, ensure alignment with I4.0 standards, and facilitate the seamless integration of AAS across industries. Furthermore, integrating emerging trends, namely CPS, I4.0 reference architectures (e.g., RAMI4.0), and digitization concepts (e.g., AAS and DT) into university curricula can

**TABLE 1. Overview of key challenges for AAS adoption.**

| Challenge | Aspects | Possible actions to overcome | Ongoing initiatives |
|---|---|---|---|
| Global visibility | – AAS development and usage are concentrated in EU, especially Germany<br>– Without visibility and industry engagement, AAS risks becoming a regional concept, hindering its potential to drive global interoperability and collaboration across industries | – Encourage international collaboration and industry partnerships<br>– Create educational materials, e.g., tutorials and best practice guides<br>– Organize international conferences, online presentations, hands-on workshops, and MOOCs<br>– Create promotional materials adapted to different cultural contexts and explain the role of AAS through regional case studies | – International cooperation, e.g., between IDTA with other organizations from USA, Korea, Italy, France, to name a few<br>– Realization of workshops, e.g., Workshop on Implementing AAS (ImplAAS)<br>– Participation in industry events, e.g., Hannover Messe fair |
| Workforce upskilling | – AAS represents a significant shift in the digitization of industries<br>– Industry professionals lack the knowledge and skills to design, develop and apply AAS-based solution effectively in practice | – Develop specialized training and certification programs<br>– Encourage industry-academic collaboration to develop real-world projects that demonstrate the application of AAS in operational settings | – Training programs, e.g., offered by IDTA and University4Industry<br>– R&D projects (this work identified 12 projects that are already completed or in progress) |
| Standardization | – Standardization is key for AAS adoption in industrial settings<br>– To cover the diverse spectrum of industrial asset-related information, more standardized submodels templates are necessary | – A greater engagement from both the industrial and academic communities in proposing submodel templates<br>– Develop recommendation tools that can guide users to the most relevant submodel templates based on specific use cases and asset types | – Development of specifications and official submodel templates<br>– Research works proposing submodels for specific applications |
| Integration with legacy/existing systems | – Existing industrial systems have accumulated years of asset-related data stored in heterogeneous and proprietary formats, and physical documents<br>– Converting unstructured or legacy data into AAS-compliant formats is difficult, error-prone and time-consuming | – Use AI-powered tools to automate data extraction, mapping, and transformation into AAS models<br>– Create APIs to facilitate communication between legacy systems and AAS | – Research works developing automated data extraction tools (with some limitations yet, e.g., need for further development to enhance the robustness and precision of these automated processes) |
| Security | – AAS stores all asset information<br>– The distributed nature of AAS and its role in data exchange (not only inside but across companies) increases the risk of unauthorized access | – Define and implement robust security mechanisms for AAS data exchange<br>– Develop guidelines for authentication, authorization, and encryption in multi-stakeholder AAS environments | – Research works exploring security for AAS-based solutions<br>– Development of a specific specification for AAS security (Part 4: Security) |

ensure that future professionals are well-prepared for the next generation of smart factories.

Standardization plays a critical role in ensuring interoperability, consistency, and scalability in real-world industrial applications. Currently, IDTA is working to expand and refine AAS-related standards, specifications, and submodel templates to guide AAS implementation, reduce integration complexity, and promote broader adoption across different industries. Despite these efforts indicating that AAS standardization efforts are moving in the right direction, a greater number of official submodel templates (beyond the 39 published to date, with others still under development or review) are needed to cover the diverse spectrum of industrial asset-related information.

The development of a submodel template involves proposing an information model that defines its intended purpose and structure (see the official procedures in [146] and a methodology example for modeling submodels in [147]). For instance, the research work [121] proposed three submodel templates to represent the AI lifecycle, which today are available as official submodel templates under the IDTA numbers 02058, 02059, and 02060 (see these submodel templates in [31]). Other research works are also developing submodels (varying in their level of formality) for specific applications, e.g., quality inspection processes supported by Augmented Reality [148], user interface [149], 5G network [150], Time-Sensitive Networking (TSN) [151], robot applications [152], [153], production scheduling models [154], and the topology and layout of production sites [155], among others. Following these examples, a greater engagement from both the industry and academic communities in proposing submodel templates is essential to address this gap. Moreover, as the number of submodel templates is expected to grow significantly, the development of recommendation tools that can guide users to the most relevant submodel templates based on specific use cases and asset types becomes increasingly important.

The ability for anyone to develop their own submodel presents both advantages and drawbacks. On one hand, this flexibility allows the development of tailored submodels that meet specific application needs. On the other hand, it can lead to the proliferation of submodels with overlapping purposes but without a commonly understood structure, potentially hindering seamless interoperability and creating integration challenges. In this context, it is crucial to develop mechanisms that facilitate the transformation of proprietary submodel templates used internally by companies into standardized submodel templates for data exchange between organizations. Moreover, as submodel templates are updated over time, it is essential to ensure that legacy submodels remain compatible with newer versions of the submodels. In this sense, a transformation engine could enable automatic updates to these legacy submodels, ensuring their continued compatibility with the latest versions of standardized templates [156].

Integration with legacy/existing systems is another crucial challenge that can prevent the AAS adoption in the short term. Many existing industrial environments have accumulated years of asset-related data stored in heterogeneous and proprietary formats, namely databases, Excel sheets, custom-built software, or even physical documents, making it difficult to aggregate and transform the information into a structured AAS-compliant format. To address this challenge, developing automated data extraction tools (which can be based on AI techniques) is necessary. These tools should automate the identification, mapping, and transformation of existing nonstructural data into AAS submodels, reducing the manual effort and accelerating the AAS adoption. For instance, [157] proposes a semi-automatic approach to extract engineering information from documents (PDF, STP, XML, XML/AML, URDF data types) and create AASs based on these engineering documents. On the other hand, [158] proposes a LLM-based solution to automate the generation of AAS from data extracted from datasheets describing assets, and [159] uses LLM to perform semantic searches to improve semantic interoperability and ensure a common understanding of individual properties, i.e., properties defined in submodels are linked to existing vocabularies and definitions in external standardized repositories (e.g., ECLASS). While these studies contribute with valuable advancements, the preliminary nature of this research highlights the need for further development to enhance the robustness and precision of these automated processes.

Since AAS stores all asset information through its lifecycle, it is essential to ensure data integrity, confidentiality, and protection against cyber threats. Furthermore, the distributed nature of AAS and its role in data exchange increases the risk of unauthorized access, which can compromise industrial operations. To address this challenge, security mechanisms should be implemented, e.g., encryption, authentication protocols, access control policies, and continuous monitoring. Additionally, the adoption of Decentralized Identifiers (DIDs) and Distributed Ledger Technology (DLT) can provide a crucial layer of security for decentralized communication between AASs (e.g., based on the I4.0 language) [160], as well as the alignment with Gaia-X principles [93] and the adoption of IDS connectors [161], [162] to ensure data security and sovereignty. Finally, the insights on AAS security presented in [163] and the recent specification (*Part 4: Security*) [25] offer valuable guidelines for implementing security mechanisms in AAS-based solutions.

## VII. CONCLUSION

This paper provided a comprehensive analysis of the evolution of AAS over the past decade, exploring research opportunities and the challenges associated with its adoption. To this end, a review of research works indexed in the Scopus, Web of Science, and IEEE Xplore databases was conducted, complemented by an analysis of official documents, particularly specifications published by the IDTA, which plays a central role in the standardization and development of AAS. In this context, this section aims to summarize the findings and address the two research questions initially defined to guide the study. Additionally, it offers a brief outlook on the future role of the AAS in I4.0 based on the insights gained throughout this work and the authors' perspective.

### *A. RQ1: HOW HAS THE AAS EVOLVED OVER THE PAST DECADE IN TERMS OF ADOPTION, STANDARDIZATION, AND ITS PROPOSED APPLICATIONS?*

Over ten years, the AAS has progressed from its initial conceptual stages to a more mature and standardized version. It could be said that AAS has outgrown its "formative phase", progressing from early ideas and prototypes to a robust I4.0 solution supported by formal specifications, active development platforms, and several examples in the literature showing a wide range of applications.

The number of AAS-related research publications has been growing in recent years, particularly from 2022 onward, following the release of initial AAS specifications and development platforms. Beyond academia, there is also growing evidence of AAS adoption in industrial contexts, indicating that the technology is reaching an industry-ready level of maturity. However, its adoption remains largely geographically concentrated, with Germany and a few other European countries leading the way, while global adoption is still in its early stages.

Regarding the development of AAS solutions in both the literature and R&D projects, it is evident that the availability of specifications, standards, and development platforms has had a significant impact. These elements have contributed to a clearer understanding of the AAS concept and how to design such solutions, while facilitating their development and implementation. Currently, based on the survey and the authors' knowledge as of the In addition, a growing number of submodel templates are currently available (39 published and 50 under development/review so far).

Beyond the common applications of AAS in the manufacturing domain, other research efforts are exploring and demonstrating its potential across diverse domains, as well as developing AAS for a variety of physical and non-physical assets. Through the survey, at least 12 R&D projects (completed or in progress so far) were identified, demonstrating the testing, validation, and application of AAS in industrial scenarios. These projects play a crucial role in supporting the transition from state-of-the-art research to state-of-practice implementations, facilitating the adoption of AAS in diverse industries and applications. Moreover, the majority of identified AAS solutions are of Type 1 and 2.

### B. RQ2: WHAT ARE THE KEY CHALLENGES AND FUTURE RESEARCH DIRECTIONS FOR THE CONTINUED DEVELOPMENT AND IMPLEMENTATION OF AAS?

From the current research on AAS, some research opportunities have been identified, namely AAS Type 3, human-centered approaches, industrial AI, DPP, and SMEs, with some studies already aligning with these opportunities.

So far, most of the AAS solutions are of Type 1 and 2, while research on AAS Type 3 remains an emerging and underexplored topic in the literature. AAS Type 3 introduces a new level of intelligence, autonomy, and collaboration among industrial assets, which are capabilities that are often beyond the scope of traditional AAS solutions. While the literature has already identified MAS as a key enabling technology for AAS Type 3, its implementation remains in its early stages due to the lack of clear specifications and standardized guidelines.

Beyond the common applications of AAS for physical assets, particularly in manufacturing contexts, AAS also plays a critical role in supporting human-centered approaches and enabling Industrial AI. The AAS can enhance the human integration within I4.0/I5.0 environments by facilitating new forms of collaboration between humans and other digitized assets that were previously not possible. Furthermore, by offering a standardized approach to represent the AI lifecycle, AAS can contribute to building trust and demonstrating to stakeholders that AI solutions are reliable, scalable, and aligned with long-term business objectives.

The DPP represents a promising development for the future and is expected to become a mandatory requirement for all products on the market. Initially driven by an EU initiative with a strong focus on sustainability, the scope of the DPP is set to expand across various sectors. In this context, given its structured and standardized approach, the AAS is a strong candidate for facilitating the implementation of DPP. Furthermore, the AAS can play a pivotal role in supporting SMEs in their transition toward I4.0, offering a modular and interoperable solution that can be tailored to their budgets and specific requirements.

Regarding the challenges to its adoption, based on the wide range of application examples found in the literature, as well as the availability of development platforms, specifications, and standards, the main barriers to the adoption of AAS are no longer predominantly technical, as was the case in the initial stages when tools and community support were limited. Instead, current adopting challenges are increasingly related to the limited global visibility, the need for workforce upskilling, the expansion of standards, integration with legacy/existing systems, and security concerns.

### C. CONCEPTUAL REFLECTIONS ON THE FUTURE OF AAS

Based on the answers to the two research questions, a conclusion can be drawn that reflects the current state of the AAS. In contrast to its early years, when it was considered a promising yet uncertain concept, AAS has gained increasing recognition and is progressing toward becoming a key enabler of I4.0. AAS has reached a level of maturity that enables its increasing adoption, supported by development platforms, specifications, standards, and several examples in the literature and R&D projects showing a wide range of applications.

In the future, it is expected a growing presence and relevance of the AAS across a wide range of industrial applications, making the commonly used slogan "AAS is everywhere" a potential reality. Figure 8 presents a conceptual vision of the AAS scenario in a hypothetical near future, emphasizing its potential to become a cornerstone for the consolidation of I4.0. In particular, it is expected to play a multifaceted role in enabling/supporting the implementation of DPP, DT, CPS, and System-of-Systems (SoS) solutions.

As previously mentioned, the AAS is designed to represent an asset throughout its entire lifecycle in the digital world, which precisely aligns with the objective of the DPP. However, the DPP is a conceptual framework requiring a concrete means for implementation. In this sense, the AAS, which can be viewed today as a concept, a standard, and a technology, represents a suitable approach for implementing the DPP by providing a standardized structure for storing and managing relevant information from the design phase through to the end-of-life of a product.

Specifically, during the usage (operational phase), i.e., when a product (e.g., machine) is deployed in an industrial environment to perform its intended functions and becomes a resource, a DT may be required to perform data analytics, process optimization, and adaptive control based on real-time feedback. In this context, the AAS can support the implementation of interoperable DTs. In fact, there is a growing trend to refer to AAS as a standardized form of DT based on the general discourse in the field and observations made during this survey. However, in practice, AAS Types 1 and 2 do not fully meet the requirements for a complete DT, as evidenced by a comparison between their capabilities and the requirements outlined in the *ISO 23247 (Digital twin framework for manufacturing)* [164], [165], as well as the *Digital Twin Capabilities Periodic Table* [166] proposed by the Digital Twin Consortium. Nonetheless, they can still

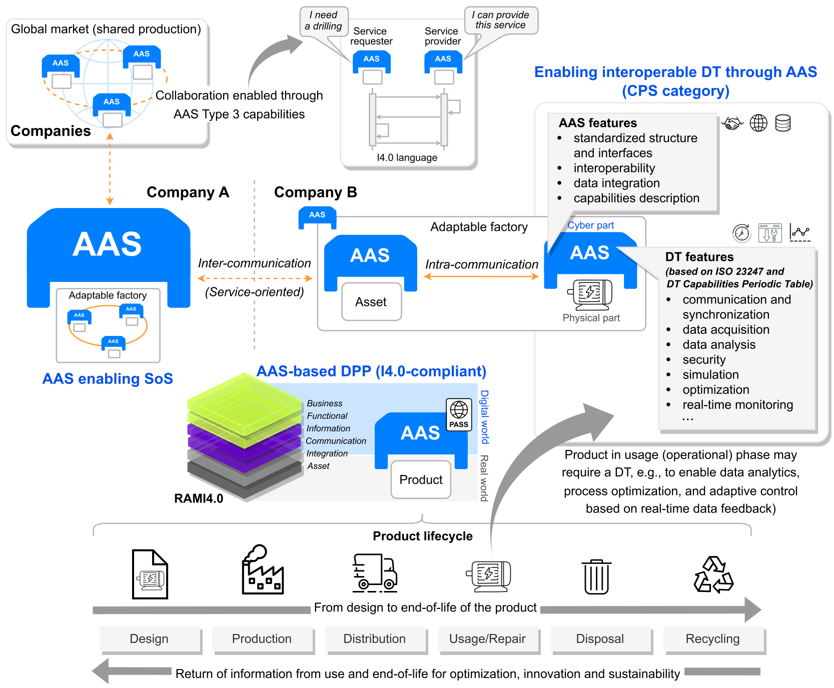


**FIGURE 8.** The AAS multifaceted role in enabling/supporting the implementation of DPP, DT, CPS, and SoS.

contribute to its realization by providing a standardized structure and interfaces that enable interoperable data access and exchange. On the other hand, according to [20], AAS Type 3 is considered the most nearly complete approach to enable the full implementation of a DT due to its enhanced capabilities.

Furthermore, the I4.0 component, comprising the AAS (cyber part) and the asset (physical part), can be classified as a standardized CPS category. Although AAS Types 1 and 2 do not constitute advanced CPS, AAS Type 3 has the potential to provide the intelligence, autonomy, and collaborative capabilities required to realize such advanced CPS. In addition, the AAS can serve as a foundational building block for the development of SoS architectures, supporting composite asset representation (co-managed or self-managed entities) and enabling complex and interconnected industrial systems, recalling the principles of the holonic paradigm [167].

Finally, through AAS, particularly with the capabilities of AAS Type 3, new forms of collaboration that were previously challenging or even impossible may now be achievable. This advancement enables the realization of I4.0 scenarios [168], such as the adaptable factory scenario, characterized by high flexibility and responsiveness to changing demands through Plug-and-Produce capabilities. Additionally, it enables shared production [98] scenarios that extend beyond company boundaries, allowing assets, systems, and stakeholders to interact (particularly through service-oriented principles) seamlessly across organizational borders, moving toward a truly connected world.

Despite the potential of AAS, particularly Types 1 and 2, in enabling interoperability and seamless data exchange within I4.0 environments, which can already support a wide range of industrial applications, including DPP implementations, the full realization of the envisioned future for AAS depends on its advanced form, namely AAS Type 3, as discussed above. This advanced type enables the transition from passive and reactive behaviors to active and proactive ones. However, it is important to note that AAS Type 3 is still in its early development stages and should be revisited in the future for a more detailed comparison, particularly regarding its alignment with DT requirements and its support for proactive capabilities, such as higher levels of autonomy, intelligence, and collaboration (e.g., inspired by MAS).

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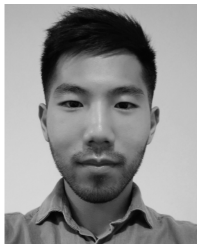

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