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Opportunities And Challenges Of The Asset Administration Shell For Holistic Traceability In Supply Chain Management

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Abstract

Due to changing regulatory environments, evolving sustainability requirements, and the need to perform effective supply chain risk management, traceability systems have become an increasingly important aspect of supply chain management. However, globalized, interconnected supply chains require a dynamic mapping of direct and indirect relationships between companies and assets, driving traceability systems' complexity. Here, the standardization of data formats provides an essential aspect to facilitate asset-related information sharing across companies. In this regard, the Asset Administration Shell is available as a holistic standardized digital representation of an asset. The representation of an asset via an Administration Shell includes data ensuring a clear identification of the Administration Shell and its assets as well as data describing aspects of the asset's technical functionality in so-called submodels. Based on current literature and available prototypical concepts, this paper identifies the opportunities and challenges of the Asset Administration Shell when aiming to map interconnected multi-tier supply chains holistically and contextualizes their role in achieving holistic supply chain traceability.

Keywords

Supply Chain Management; Interconnected Supply Chains; Asset Administration Shell; Traceability; Industry 4.0

1. Introduction

The importance of traceability for contemporary supply chains increases to address the growing demands from customers, supply chain partners, and regulatory bodies [1]. Emerging regulations aim to assign companies responsibility for compliance with social and environmental standards along their entire supply chain. This includes national regulations, such as the German 'Act on Corporate Due Diligence Obligations for the Prevention of Human Rights Violations in Supply Chains' [1], as well as international initiatives, such as the "EU rules on due diligence in supply chains" [2]. Here, traceability is a vital instrument for monitoring the compliance of supply chain partners along the entire value chain. Furthermore, traceability improves a company's ability to deal with supply chain disruptions by enabling more effective decision-making [3]. Olsen and Borit define traceability as "the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle by means of recorded identifications"[4]. In contrast to the term visibility, which is sometimes used in a similar context, traceability focuses on an object to be traced and not on information on a supply chain level [5]. In a supply chain, the object to be traced is a product or service. For a given object, traceability systems capture the origin, processing history, and

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location through supply chains [6]. Traceability focuses on the idea of product provenance [3,5]. To ensure a record of provenance, a traceability system must provide end-to-end traceability on an object or asset level [6]. Corresponding traceability systems require the capability to capture and store information for every relevant object-related supply chain event along the supply chain [6]. At the same time, supply chains have evolved into interconnected supply networks and display dynamic changes regarding the relationships and roles of the involved actors [7], driving the complexity of traceability systems. Standards can address the high complexity of traceability systems [6].

Standardized data formats and interfaces are also required in Industry 4.0 to advance interoperability as an aim of Industry 4.0 [8,9]. Therefore, the 'Initiative Industry 4.0' promotes the adoption of the Asset Administration Shell (AAS) [10], which provides a "standardized digital representation of an asset" [11]. The reference architecture model for industry 4.0 (RAMI 4.0) models the basic components of Industry 4.0 [12]. The RAMI 4.0 introduces the term Industry 4.0 component to consolidate the architecture requirements for a single subsystem [13]. Therefore, an Industry 4.0 component links an AAS and the corresponding asset, combining the physical and digital worlds [8,12]. The AAS uses several core concepts to create interoperable digital representations. The first concept describes distinct aspects of the asset in sematic submodels. Different submodels can relate to different stages of the lifecycle of an asset [11]. Submodels can be standardized and become templates to be shared in repositories. Another essential concept is identification. The AAS assigns unique identifiers to AASs, assets, instances, and templates of submodels and property definitions [10,11]. Figure 1 illustrates the fundamental structure of an AAS representing an assembly consisting of several components.

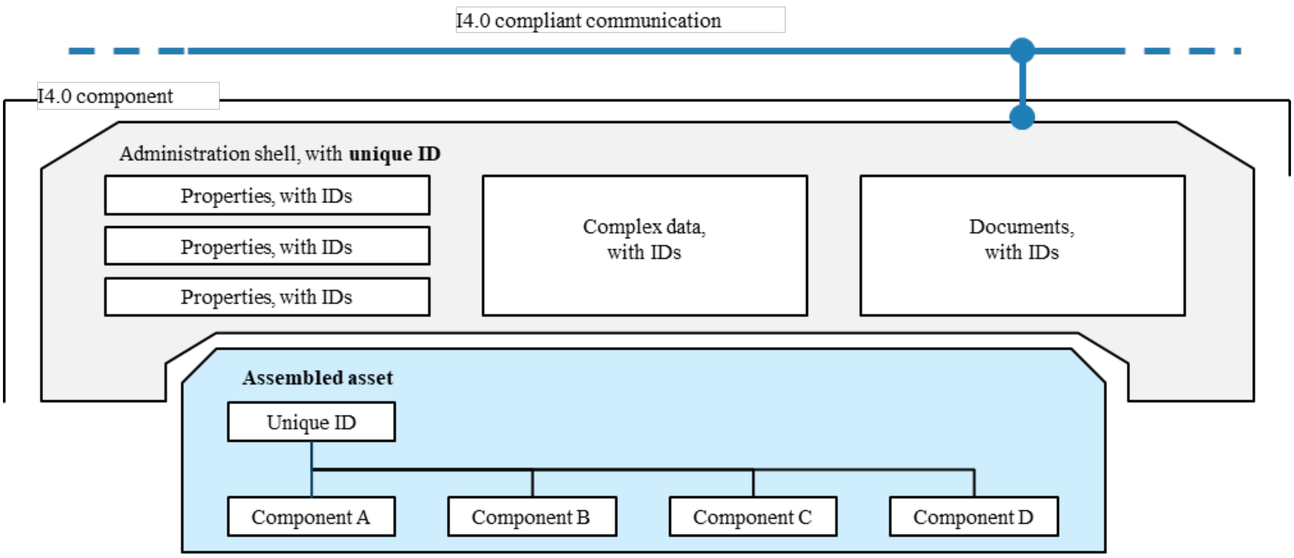

Figure 1: Asset Administration Shell (adjusted from [11])

Consequently, the AAS holds a pivotal role in achieving interoperability between objects and applications in smart factories and value chains to realize the goals of Industry 4.0 [11,14].

2. Rational and methodology of the paper

End-to-end traceability includes the ability to query data from upstream and downstream supply chains, which requires extensive sharing of relevant data between partners across a supply chain [6]. With the complexity and dynamic nature of connections in supply networks [7], organizing this data exchange without compromising the quality of traceability information becomes a complex task. Standardization in identification, sharing, and capturing traceability enables the efficient use of traceability systems [6]. Since the AAS represents the asset in a standardized digital way [11], AAS shows promising capabilities when applied in traceability systems. Some research addresses important aspects of AAS for traceability systems. Deuter and Imort investigate the use of AAS through several lifecycle phases of a product [15]. They, however, do not address the exchange of the product and the corresponding AAS between different organizations. Hang et al. describe the channeling of AAS between organizations for a production scenario [16] without addressing traceability specifically. Al Assadi et al. show the potential of AAS to serve as a basis for environmental impact analysis [17]. Their implementation was limited to one inter-organizational process and therefore did not consider traceability requirements. Adisorn et al. recognize the potential of the AAS for sharing product data over the whole product lifecycle and through the whole supply chain by suggesting it as a means of implementing digital product passports [18]. Plociennik et al. expand this idea and the AAS to implement a digital product passport for e-waste sorting [19]. Although AAS shows conceptual promise and is used in neighboring contexts, there are no papers addressing the concept of supply chain traceability. Therefore, this paper investigates the use of AAS in traceability systems. Initially, this paper infers requirements for storing and sharing traceability data from technical standards for traceability systems and applications scenarios for supply chain traceability and maps them to the features of the AAS. Furthermore, the paper investigates specific opportunities for AAS in supply chain traceability and analyzes the challenges that AAS faces in this application scenario.

3. The AAS in supply chain traceability

This section explores the use of AAS in supply chain traceability, starting with the requirements for sharing traceability data. Based on these requirements, this section analyzes the opportunities and challenges of AAS in a supply chain traceability context.

3.1 Requirements

Traceability in supply chains can serve different purposes. There is initial evidence that high levels of supply chain traceability positively affect an organization's environmental and cost performance [23]. Furthermore, traceability can help combat counterfeiting and other illegal activities, reducing companies' reputational risks and facilitating supply chain cooperation [20]. However, while traceability systems collect and store relevant information regarding the traced object, this may not be sufficient to achieve the business objectives. Consequently, gaining useful insights from traceability data can require further analysis and the application of methods such as artificial intelligence [21].

Traceability systems require the mapping of the supply chain in an information system. In complex supply chains, this constitutes a difficult task and requires suitable models [22]. Recording object-related supply chain events throughout objects' lifecycles is an important part of this mapping [6]. Derived from the specifications of the Event Product Code Information Services (EPCIS) standard, the following generic object-related supply chain events emerge [23]:

- *Object events*. An event describing something that happens to one or more objects (e.g., the creation of an object).
- *Aggregation events*. An event where two or more objects aggregate into a new object. The traceability data of the aggregated object contains the information on the objects used for aggregation.
- *Transformation events*. An event where an object is fully or partially consumed and one or more other objects are created as output of the event.
- *Transaction events*. An event where an object is involved in a business transaction (e.g., the transfer of ownership)

Traceability data refers to the data used to describe the individual event [6]. This data should include key data elements (KDE) identifying the traced object(what?), the parties involved (who?), the location of the event (where?), the time of the event happening (when?), and the business transaction the event relates to (why?). Depending on the traceability systems' purpose, traceability data requirements can increase. For example, when aiming to manage sustainability within the traceability system, specific information such as CO^2 or water consumption of material and processes must be available [24,25].

To attain end-to-end traceability object related traceability data must be exchanged between supply chain partners. GS1 defines the modes of organizing the exchange of traceability data in supply chains [6]:

- *One step up- one step down*. The 'one step up- one step down' model [6] refers to the exchange of traceability data only with immediate supply chain partners. While it is still common practice to use this model, it provides limited visibility and eventually leads to overall limited knowledge of supply chains [26].
- *Centralized*. In a centralized approach, all traceability data is collected and managed in a central repository [6]. The repository requires a central trusted authority to provide infrastructure and enforce standards for the supply chain [25]. In a complex and dynamic supply chain agreeing on a central authority can be challenging to achieve [10]
- *Networked*. In networked approaches, participants store their own data and enable all participants to query traceability data [6]. This model requires control mechanisms to manage the permissions of data access. In addition, effective querying requires standards regarding the available data [23].
- *Cumulative*. In cumulative traceability systems, participants cumulate data at every step of the supply chain to achieve a complete mapping of the downstream supply chain [6]. This model creates an asymmetry between the participants. Downstream participants receive more data to increase their visibility. Simultaneously those companies must store and process greater amounts of data [6].
- *Decentralized*. Combining mechanisms from the cumulative and networked model, the decentralized model replicates end-to-end traceability data and stores it distributed with all participants using, for example, blockchain technology [6]. While this model can create a distributed storage of traceability data, the processing and storage capability in this model is limited [27].

End-to-end traceability cannot be ensured by using the "one-up one-down" model, and the centralized model has limited viability in complex supply chains. Therefore, those models will not be considered when inferring requirements of AAS for supply chain traceability. The efficient use of networked and cumulative traceability systems requires the standardization of traceability data. Decentralized traceability systems are limited in their storage and processing performance. Adopting this model may necessitate separate storage and processing capabilities. Thus, organizing traceability systems with some degree of decentralization requires standardized data formats. In addition, the possible business applications of traceability systems cause more complex data about the traced objects and the supply chain events to be stored and communicated. Therefore, traceability systems require a standardized data interface capable of mapping complex attributes and functionalities.

The AAS addresses those requirements. As a standardized digital representation of an object, the AAS meets the standardization requirement [10]. The AAS allows flexible and holistic mapping of assets, with Wagner et al. expecting a convergence of the terms AAS and digital twin [28]. Therefore, the AAS meets the requirements of digitally mapping complex attributes and functionalities.

3.2 Opportunities

Opportunities of the AAS in supply chain traceability mean potential improvements in the traceability system, which can be achieved using AAS to share traceability data. Table 1 summarizes the identified opportunities.

Table 1: Opportunities of the AAS

Opportunity	Explanation	Source
Decentralized networks	Traceability systems can avoid the potential disadvantages of centralized networks while maintaining data quality.	[16],[29]
Standardized data interfaces	Standardized data interfaces simplify participation in traceability systems.	[30]
Machine-readable data	Structure and semantic modeling of the data allows automated analysis of the data.	[31]

Decentralized networks. Traceability systems require a high degree of quality of their traceability data [6]. Coordinating the exchange and maintaining the data quality can be a central authority's task. Yui names three disadvantages of centralized traceability systems [32]:

- *Single-point of failure.* Central authorities in traceability act as a single point of failure. A full or partial breakdown in a central system can endanger the integrity of the whole traceability record.
- *Processing capability.* A central authority in traceability systems must assume the costs of providing the necessary processing power and maintaining the infrastructure, as dealing with the data created by many objects in complex supply chains requires a lot of processing power.
- *Storage.* Similar to the processing capability, central authorities must provide sizeable amounts of storage space to store the traceability data of every object in the system.

Companies tend to dislike centralized data-sharing models because they fear losing control over sensitive data [33]. Especially in dynamic supply chains without dominant focal companies, a commitment of all participants to one central authority is unlikely [26]. As centralized traceability systems carry these disadvantages, decentralized solutions can be advantageous. AAS allows a standardized peer-to-peer sharing of object-related data [16,29] traceability system circumventing the need for a central coordinator while maintaining high data quality.

Standardized data interfaces. AASs' core concept is improving interoperability between components [14]. The structure of the AAS achieves this by standardizing the representation of the asset data [30]. Standardized data interfaces allow end-to-end traceability in supply chains [6,34,23]. Integrating every new supply chain partner into the traceability system without agreeing upon standards is complex and requires effort. In addition, as emerging supply networks display dynamic changes in the composition and interactions of participants [7], the challenge of coordinating data exchange becomes more complex. Implementing standardized data interfaces allows companies to participate in traceability systems for supply chains they are only temporally a part of without requiring implementation efforts.

Machine-readable data. Besides enabling data exchange between different actors in value chains, interoperability extends to the communication between machines [30]. The semantic modeling of the information contained in the AAS connects the data with a self-description [31]. Thus creating smart interfaces between machines, allowing not only the exchange of data but also conveying information about the meaning of the data [35]. This property can facilitate the integration of external data sources, such as machinery, into the traceability system. Furthermore, it can enhance the data contained in the AAS to analyze the traceability systems' business purpose.

3.3 Challenges

Challenges of the AAS in supply chain traceability refer to potential implementation barriers for AAS in traceability systems. Table 2 summarizes the identified challenges.

Table 2: Challenges of AAS in supply chain traceability

Challenges	Explanation	Source
Data sovereignty	Participants require control over the access and usage of their traceability data to avoid misuse of sensitive data.	[11],[29],[36], [37],[38]
Data inconsistencies	Traceability data requires end-to-end consistency. Different formats and interfaces can cause inconsistencies when exchanging AAS	[14],[15],[36], [16],[39],[40]
Consistent IDs	AAS requires globally unique identifiers.	[10],[11]
Data granularity	The granularity of the data models used in the traceability systems is undetermined.	[14],[13]
Available models	Submodels mapping relevant aspects of the object are required to be available.	[14]

Data sovereignty. Data sovereignty describes "meaningful control, ownership, and other claims to data or data infrastructures" [41]. Ensuring data sovereignty requires procedural or administrative measures as well as technical considerations [42]. Industrial actors in supply chains risk giving up much of their specific deep knowledge when participating in data exchange ecosystems that do not ensure their data sovereignty [43]. Both primary data and metadata have to be part of data sovereignty considerations [42]. Traceability systems require sharing data with known or unknown actors in supply networks. Without data sovereign exchange mechanisms, companies face the risk of competitors benefitting from their sensitive data. Reservations concerning the appropriate use of their data can inhibit companies from sharing data [33]. Regarding the AAS, data sovereignty is often discussed in terms of access management [29,36]. Several papers propose approaches for ensuring that every participant can only access the data it is authorized to by using connectors [29,38], encryption [36], or network access [37]. Usage control extends the idea of access control by enabling the data owner to influence its use after sharing the data [44]. Usage control could be achieved by sharing AAS through International Data Spaces networks [38].

Data inconsistencies. Meaningful end-to-end traceability is achieved by combining traceability data from different participants. During this process, the consistency of traceability must be ensured. Inconsistent data can lead to faulty provenance records and difficulties in gaining traceability insights. Since the submodel concept of the AAS allows flexible creation, there is a risk of high numbers of submodels and emerging ontologies [14]. When multiple participants model traceability data using different ontologies the overall record looses consistency Traceability systems might include IoT systems automatically capturing traceability data [6] or integrating data from other systems such as ERP or CAD. There is a challenge integrating these external data sources in the AAS [15,39,40] and, therefore, in the traceability systems. Furthermore, objects in supply chains can change their object-related data when experiencing certain supply chain events. Therefore, a traceability system with shared data requires a version control mechanism that works across different supply chain partners [39].

Consistent IDs. A key aspect of the AAS is the identification of ASs, assets, and submodels [10,11]. To ensure interoperability, the AAS requires globally unique identifiers. Inconsistent identification causes problems within the logistical processes as well as services in the product lifecycle [10]. As the AAS does not require a central authority to manage the identifiers, their global uniqueness is challenging to achieve [10]. Logistical objects might be identified in several contexts (e.g., part numbers, order numbers). There is a risk of mixing different identification schemes and violating the identification's consistency [12].

Data granularity. The AAS tries to model an object comprehensively and allows for nested models. However, in the application, the issue of model granularity arises [13,14]. Communicating and storing overly granular and, therefore, big data models in traceability systems is costly in terms of infrastructure. Furthermore, the effort of modeling highly granular models might deter actors from participating in traceability systems.

Available models. Wei et al. explain that the current AAS applications focus on the smart manufacturing domain [14]. Therefore, submodels describing aspects of the object relating to supply chain management or logistics might be missing. A traceability system could, however, require these models to provide traceability data for application scenarios.

4. Results and conclusion

The challenges identified in the analysis show that the AAS by itself is not sufficient to holistically map supply chains for traceability but instead should be integrated into a traceability system. We propose a high-level framework exemplifying the possible role of AAS in a traceability system ordered in a physical layer, a product data layer, and an event layer in Figure 2. End-to-end traceability starts with the creation of the product on the physical layer. Simultaneously, on the product data layer, an AAS as the digital representation of the product is created. Here, the product is assigned a unique identifier, and its properties are described in submodels. An object event described by the five KDE of the EPICS standard is recorded on the event layer. Unique identification of the physical product is a central concept of the AAS as well as a KDE of the EPICS standard connecting the product data layer and the event layer.

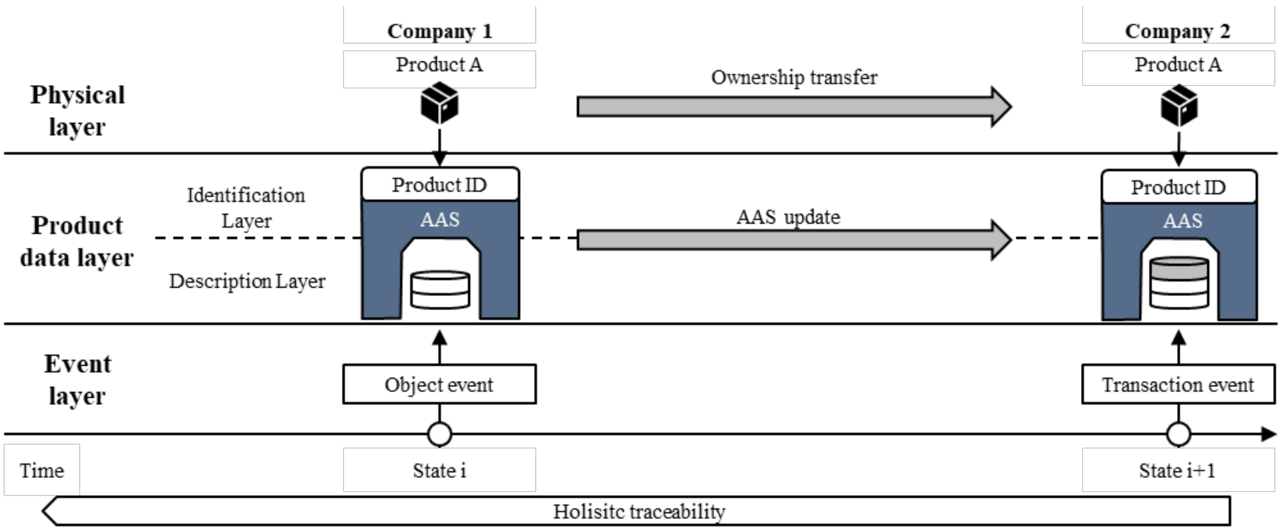

Figure 2: Framework for holistic supply chain traceability considering AAS

After the creation event, the product will experience other supply chain events along its value chain. Figure 2 exemplifies a subsequent event, namely the transfer of product A from company 1 to company 2 on the physical layer. On the event layer, this is represented by a transaction event that records the connected KDE. Any supply chain event causes an AAS update on the product data layer. In traceability systems, the AAS update process requires three elements depending on the specific event.

Identification. Each product receives a unique identification included in the AAS. In case of a product transfer, the ownership of the AAS changes; however, the AAS maintains its unique identification.

Data access. In case of a transaction event, the new owner needs the ability to access the data inside the submodels of the AAS.

Product data update. Every event needs to be recorded in the AAS and consequently causes a change in at least one submodel of the AAS.

Efficiently organizing these AAS updates relates to several challenges and is yet to be solved. Maintaining consistency of the identification and the data inside the submodels of an AAS across the entire supply chain presents a challenge that requires further research into methods and best practices. Emerging technologies, such as the blockchain, show the potential to ensure global uniqueness of identification. However, further research needs to explore a possible combination of such approaches. As AAS can include sensitive business information, organizations require meaningful control over the data they share in AAS. Initiatives such as International Data Spaces or Gaia-X [45] address the need for sovereign data exchange between organizations. Initial research into the combination of AAS with International Data Spaces is already being conducted [46] and should continue to support the emergence of holistic supply chain traceability.

Traceability in supply chains bears potential both in terms of improving the performance of supply chains and meeting the expectations of external stakeholders and regulators. Existing solutions, however, reach limitations when trying to establish end-to-end traceability in dynamic supply chains. This paper highlights the potential of AAS to improve traceability systems by providing standardized data formats for the exchange of traceability data capable of handling complex data structures. This leads to a more decentralized exchange of traceability data, reducing the complexity for participants in traceability networks. Based on the identified opportunities of AAS in supply chain traceability and considering the challenges elaborated in the analysis, this paper proposes a high-level framework outlining the role of AAS in a supply chain traceability system. The framework underlines the process of updating and sharing AAS at traceability events as a central challenge indicating the need for further research into this process.

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