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Bridging The Gap: A Framework For Structuring The Asset Administration Shell In Digital Twin Implementation For Industry 4.0

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Abstract

The digital twin is a core technology for implementing Industry 4.0 scenarios in scientific and industrial applications. One upcoming variant of the digital twin is the concept of the asset administration shell, representing an approach to standardization. This approach must be adapted to specific use cases and applied in a target-oriented manner. However, no comprehensive guidance exists on structuring and implementing asset administration shells based on the digital twin in manufacturing environments. This issue pertains to defining and organizing the relevant data and mapping domain-specific limitations and characteristics within the hierarchical structure of the asset administration shell's components. This paper introduces an approach to structuring the asset administration shell to address this gap. This approach capitalizes on domain-specific expertise, industry standards, and established best practices, providing a framework. We validate the presented approach by applying it to the use case of distributed high-rate electrolyser production. The overarching objective of this research is to bridge the gap between theoretical concepts and practical applications.

Keywords

Digital Twin; Asset Administration Shell; Systematic Structuring; Digital Manufacturing; Industry 4.0

1. Introduction

Hydrogen has been identified as one of the relevant energy carriers of the future in the German government's national hydrogen strategy [1]. Thus directly contributing to the EU Green Deal, that states as one of its objectives that no more net greenhouse gases should be emitted by 2050 [2]. The demand for hydrogen is subject to ongoing estimation, and current estimates forecast an increasing demand. According to Fraunhofer ISE's hydrogen roadmap, Europe will have a hydrogen demand of 800 TWh in a low scenario and 2,250 TWh in a high scenario in the year 2050. Meeting these hydrogen requirements will necessitate a proportional expansion of electrolysers capable of producing green hydrogen [3]. This results in the necessity of producing electrolysers in large numbers and with sufficient capacity. Due to its technical properties, PEM electrolysis has proven to be particularly suitable for meeting the dynamic challenges of the future [4]. In principle, high-performance electrolysers are already available on the market, but they are often still assembled by hand in insufficient numbers. Implementing series production of electrolysers is also necessary to counter the cost aspects resulting from time-consuming manual assembly [5].

The H2Giga-FRHY project is dedicated to researching the high-volume production of industrial-grade electrolysers. It involves a diverse group of researchers from various Fraunhofer Institutes located at different sites focusing on different aspects of the high-throughput electrolyser production. The digitalized and

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standardized descriptions of electrolyser production, encompassing product-related information, involved manufacturing resources, production processes, and process data, play a crucial role in the series production of electrolysers. Especially in distributed manufacturing systems, seamless data exchange among disparate systems is imperative. In this sense, digital twin (DT) technologies structure a digital representation of distributed manufacturing systems for electrolyser production.

This paper presents an approach for structuring a digital representation based on the Asset Administration Shell (AAS) for distributed manufacturing systems. This work follows from previous research that has focused on the specification of service functionalities to enable use-case oriented modelling of the AAS [6]. As a result, various relevant norms, industry standards, best practices, and domain-specific expertise are utilized, thereby providing a framework. We validate our approach by applying it to the use case of distributed electrolyser production within the research project H2Giga-FRHY.

2. Initial situation and problem description

The software services within the software-defined manufacturing system (SDMS) that enable high-rate series production require a cross-site and cross-process representation of products and processes. Those are typically engendered and processed through domain-specific software applications in different phases of the product life cycle as a courtesy of various vendors. This scenario consequently leads to the formation of individual data silos. This holds particularly true where data is dispersed across disparate and incompatible systems employing various technologies. It further elaborates on three specific problems. First, data sources and resulting data types are highly heterogeneous. Secondly, there is an insufficiency for standardization of relevant entities, terms, and attributes relationships. And lastly, the semantic context is lacking. Therefore production-specific data is often captured and managed without metadata and context, preventing its use by multiple stakeholders [7]. DTs are expected to disrupt this silo pattern, fostering a more cohesively networked production system. Despite the proposition of numerous DTs of production equipment and systems in the past decade [8], the absence of interoperability between individual DTs and a systematic framework for structuring and implementing networked DTs remains a significant impediment realizing high-rate distributed manufacturing systems.

The AAS is a standard for the DT’s standardization and interoperability information framework of the DT. It describes an asset's technological features as a core element of the Reference Architectural Model for Industry 4.0 – also known as RAMI 4.0 [9,10]. The AAS offers prospects for integrating these data silos. It is achieved by employing standardized semantics and syntax. These are given throughout product life cycles, the vertical hierarchy levels within an enterprise, and the horizontal value chain [11].

Structuring a digital representation aims to build information models in a machine- and human-readable form that enables semantic interoperability. However, the information modeling process for developing standardized submodel templates and the standardization of data specifications poses tremendous challenges, as it depends heavily on specific domain expertise and lacks a universal methodology. In practice, a group of domain experts usually develops these. The modeling approach varies depending on the experts and the domain.

With this consideration, a general framework offering guidance on structuring the AAS-based DT could prove beneficial in expediting the procedures of development and standardization. The ultimate goal is to create the AAS-based representation of distributed manufacturing systems that enables end-to-end, cross-process control and product adaptation from development to the end of the manufacturing process.

The proposed framework can also be applied to future production-specific projects, capitalizing on the project's decentralized structure, utilization of modern tools, and the involvement of various stakeholders. This is based on the assumption that when considering discrete manufacturers in the abstract, a relevant number of similarities can be defined as a digital representation that also serves as a basis for deriving further use case-specific DTs. Established standards are used to pick up these similarities in discrete production. The considerations and requirements arising from this project establish an ideal structure for administering the AAS that can be applied to other production-specific endeavours.

3. State of the art of digital twin usage

In scientific investigation and industrial application, diverse viewpoints concerning DT prevail. The concept of DT was first mentioned by Grieves, who defined it as three components. These components consist of the physical product in real space, the virtual product in virtual space, and the link for the data and information flow [12]. Tao et al. built on Grieves' concept and suggested two additional components: data and services [13,14]. There are attempts to describe DT based on several existing descriptions. For example, Kritzinger et al. [15] describe the central common feature that DT represents the digital counterpart to physical objects. Valk et al. [16] conducted an extensive literature review and identified the most cited commonalities. These include, among others, a bi-directional data connection, that the physical object is usually created first, or that it can contain both raw and pre-processed data.

The DT concept is employed in connection with the AAS framework, designating it as a comprehensive digital representation that effectively fulfils a specific set of use cases. The AAS is a repository for recording and delivering production and product-associated data. *IEC 63278* focuses on the general concepts and structure of a single AAS rather than a representative concept of a complex manufacturing system consisting of a heterogeneous landscape of manufacturing assets that are interrelated and interdependent. Data inputs are integrated into our production scenario, establishing it as SDMS [17]. The standardized syntax refers to the standardized meta model of AAS and the standardized submodel templates. These specify the rules and formats determining how the information is structured and represented for the specific use cases. The semantic pertains to the data specifications of the information encapsulated in the AAS. This involves leveraging standardized vocabularies and ontologies defined by the IEC Common Data Dictionary [18] and ECLASS [19]. This ensures consistent interpretation of data across diverse systems and contexts, and facilitates accurate comprehension by humans and machines.

The SDMS that prevails here using the data and use case-based software services provided by DT enables the actors in the system to optimize product and process configurations in continuously faster cycles. For example, by showing correlations between product defects and product characteristics or deviations from target processes. Thus, the SDMS fulfils the characteristics of cloud-based manufacturing and thus takes into account the decentralisation prevailing in the project due to the distributed production locations. Cloud-based manufacturing can be described by characteristics such as connected manufacturing, scalability, IoT, and as-a-service like software-as-a-service, among others [20].

4. Production and manufacturing domain-specific standards and guidelines

This chapter shows relevant standards and guidelines on DT manufacturing and structuring. We describe the reasoning behind the chosen approach and selected standard. In this context, we classify the standards and guidelines and exclude irrelevant standards for systematically structuring production-focused DTs. We then further introduce industry-specific standards that can be adapted to our use. We did not perform a systematic literature review but evaluated the standards described based on relevance in the literature, specifics, generalisation, and suitability for manufacturing.

Currently, DTs are primarily research-based. There are no generally acknowledged standards for developing and deploying DTs [21–23]. However, ongoing standardization initiatives make an effort to standardize several DT components. ISO, IEC, ITU, and IEEE standardizations are among them. Since these organizations could not agree on a definition of DT, Wang et al. [24] identified and categorized them into five main categories: physical entities, virtual entities, data, connections, and services. Wang et al.'s systematic literature review of the technology standards group is our primary source for investigating the appropriate DT standards due to its coverage. The categories chosen for the literature review can be seen in Figure 1, including a classification of the essential DT standards into the mentioned categories. Most of the standards are specific to a single field, such as sensor technology (*IEEE 2888*), data sharing (*IEC 62714-1*), or data on cutting tools. However, many of these are too general compared to the necessity of manufacturing. The AAS described in *IEC 63278-1* ED1 and the general DT norm *ISO 23247* are two standards written for manufacturing. The AAS is described in detail in the chapters before.

ISO 23247 is a multi-layered DT framework standard for manufacturing. The layers describe the observable manufacturing elements, data collection and device control entity, core entity, and user entity. The standard includes a reference architecture, data examples, and network protocols. The standard gives a fundamental and necessary understanding of a DT framework in manufacturing [25].

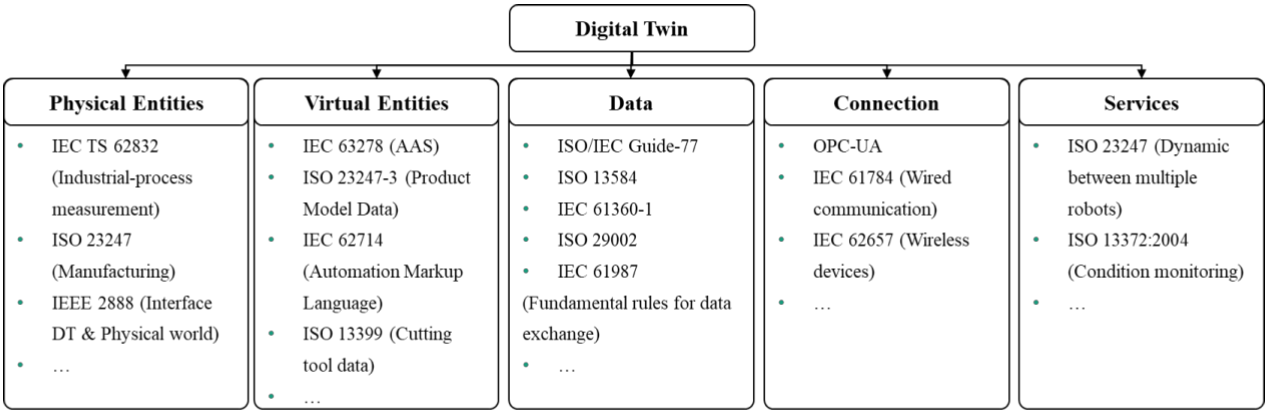

Figure 1. Division of the digital twin into five sections and associated standards excerpt from [24]

The *I4.0 Core Information Model* is a standardized data model specifically designed for the manufacturing domain within the context of Industry 4.0. It provides a comprehensive framework for describing entities, attributes, and relationships relevant to manufacturing processes. By enabling the integration of heterogeneous data sources and supporting analytical use cases, the *I4.0 Core Information Model* facilitates interoperability and data exchange, ultimately enhancing operational efficiency in industrial settings. Similar to the *IEC 62264*, the semantic is divided into product, process segment, product segment, and equipment. It also contains the physical asset model as in the AAS and a parameter model. The *I4.0 Core Information Model* and AAS, both based on resource description framework (RDF), serve distinct purposes in DT design. The *I4.0 Core Information Model* provides a standardized data model for integrating heterogeneous data sources and analytical use cases. At the same time, DT architectures like AAS enable DTs' semantic description and real-time data exchange. Combining these models allows for comprehensive DT solutions, facilitating knowledge graph creation, real-time updates, and advanced control of physical assets within the Industry 4.0 context [7].

Besides DT standardizations, we identified manufacturing-specific norms and standards that are crucial as well. Guidelines and standardizations for manufacturing, as well as enterprise architecture frameworks for structuring the DT can supplement the absence of structure and guidance for a manufacturing use case in the DT. The *IEC 62264* standard provides terminology, information, and activity models for manufacturing operations. Its origins are on the *ANSI/ISA 95* standard that clarifies the functionalities of manufacturing operations management and the associated information usage and defines the terminology and operation models for manufacturing organizations. The standard consists of six parts. To fill the gap in developing enterprise IT architecture in new construction settings, it is vital to pay attention to parts 1 and 3 of the paper since they deal with object models, manufacturing operations attributes, and activity models, respectively [26]. According to Deuter's and Pethig's Digital Twin Theory [27], the productivity increase in the digitalized industry is essentially based on the seamless connectivity of all actors and systems, both horizontally and vertically. The horizontal connectivity of the value chain is achieved through a DT. The improvement of vertical connectivity is based on the hierarchical levels according to *IEC 62264* as well as the procedures and services based on it. For example, horizontal connectivity is improved by enabling development, production and use of a product to be mapped across the DT, while vertical connectivity is improved, for example, by enabling "plug and play" applications [27,26].

Complementary to the Manufacturing Operations Management standard *IEC 62264*, the Association of German Engineers published the manufacturing execution systems (MES) standard *VDI 5600*. It guides a task-oriented description of MES and their potential applications. It provides a view that better reflects the concerns of European manufacturers. The focus of this guideline is to describe the tasks and benefits of MES [28]. *Zachman's methodology*, *TOGAF*, *FEA(F)*, *DoDAF*, and the *Gartner Framework* are the top five enterprise architecture frameworks [29–31]. *TOGAF*, however, is the only framework among these that is appropriate for designing, planning, implementing, and managing systems for SDMS[32]. In [17], the importance of *TOGAF* is shown, *ISO 23247*, and *IEC 62264* for a manufacturing use case. The publication shows the compatibility of the standardizations.

5. Approach to structuring the asset administration shell

The approach can be divided into eight steps: vision and context, stakeholder requirements, use case definition, asset selection, selection of norms and guidelines, comparative analysis with separately modeled submodels, standard mapping to the AAS structure, and the validation of the representation concept. The steps of the structuring approach are based on the *TOGAF* steps like vision, architecture, requirements management, opportunities, and solutions. However, those steps are customized to the needs of the AAS and DT, given by *IEC 63278-1* and *ISO 23247*.

Figure 2 shows the practical implementation of these steps: The first step is the initial description and further detailing of the vision and the context. An initial conceptual idea is meticulously refined, serving as a driving force for the advancement of solution development. The stakeholder requirements establish a foundation for a purpose-driven concept of virtual representation, accommodating domain-specific challenges.

This second step in the approach capsules all pertinent stakeholder requirements, as elaborated in [17]. This includes a systematic formulation, a categorization and bundling to higher-level functionalities of the requirements. The virtual representation concept is a pivotal pillar and enabler of the SDMS. Requirements management is also the center of *TOGAF*.

The third step is executed based on extracting and prioritizing the acquired requirements. The use case definition engages in the comprehensive modeling of use cases. It results in a deeper understanding of the use case and shows all stakeholders involved as well as interaction objects.

This is necessary for the asset selection. It selects significant manufacturing assets for integration into an AAS system based on their alignment with specific use cases. The approach follows an asset-centric orientation, organizing information and services in line with *IEC63278* guidelines. Assets are chosen according to *ISO 23247*'s definition of manufacturing elements, which correlates with *IEC 62264* [33] and predefined information models forming the groundwork for submodel development as per [11].

The fifth step is the selection of norms and guidelines. It conducts comprehensive research and meticulous selection of standards, guidelines, and specifications in alignment with the specific domain like [7]. This step is time-consuming and also requires specific domain knowledge, but it also offers the chance for domain-specific aspects taken into account in the structure of the AAS.

The comparative analysis with separately modeled submodels determines the relevance of standardized submodels for the identified use cases. This step identifies potential gaps and discerns missing structures needed to accommodate data, services, and models that require representation. However, it also presupposes that work on the content of submodels is carried out in parallel. Therefore, it highlights the importance of standards for submodel development in [11]. It will reference pertinent standards and sections on relevant standards in the use case template.

The seventh step, standard mapping to the AAS structure, conducts the mapping of standards, guidelines, and specifications to the structure, ensuring that domain-specific aspects are suitably addressed. Furthermore, this should ensure that previously identified submodels are integrated within the structure.

Lastly, the validation of the representation concept is fulfilled. The validation assesses the achievement of the use case objectives. In the event of a use case behaving differently in practice, it necessitates the modification of both the use case and the structure of the AAS.

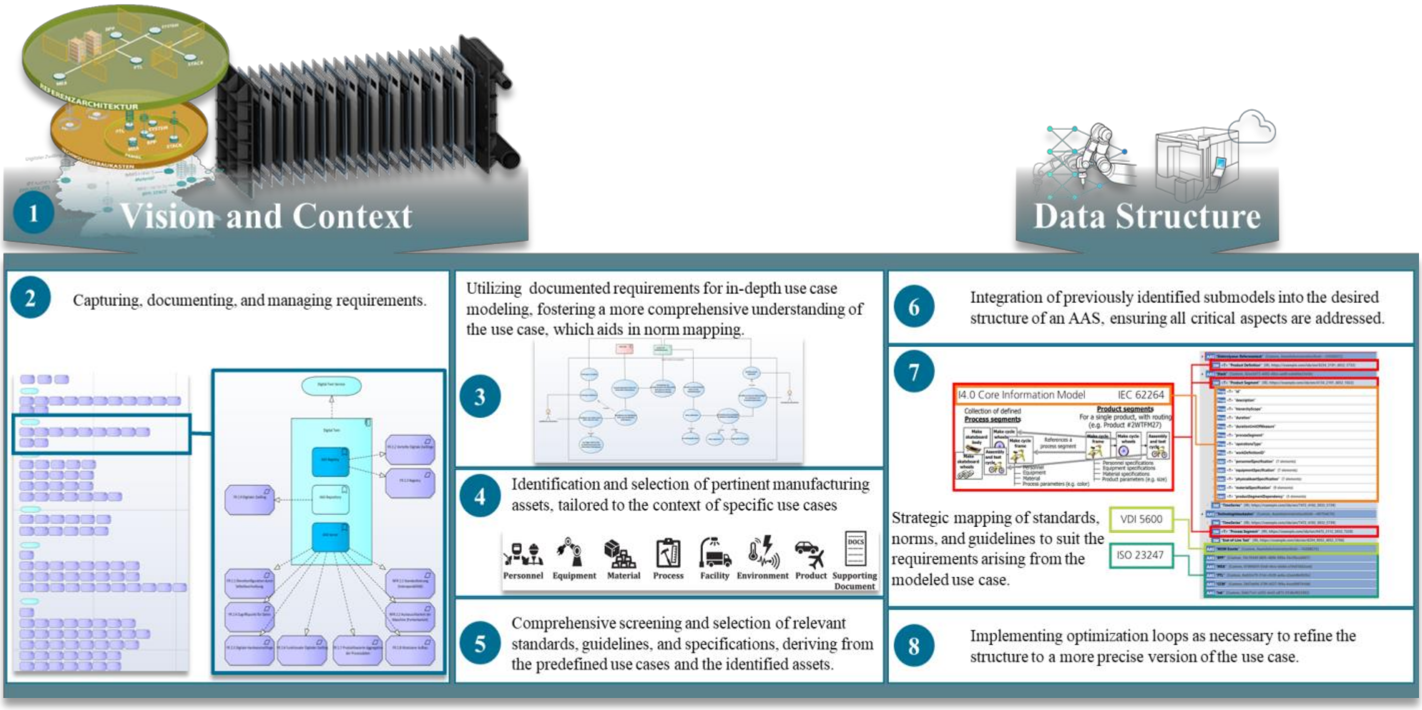

Figure 2: Approach used in the project to structure the asset administration shell

6. Use Case: Digital twin concept in hydrogen production

The proposed procedure in chapter 5 was used and adapted to the H2Giga-FRHY project and is represented in this chapter. The H2Giga-FRHY project includes six process steps for electrolyser production divided among five locations. It aims for a connected distributed production with focus on the subparts bipolar plate (BPP), porous transport layer (PTL), and catalyst-coated membrane (CCM) as part of the membrane electrode assembly (MEA). Each process step is assigned to a production site, and various design possibilities are presented as different processes are not completely clear at the beginning of greenfield manufacturing design. The manufacturing system of this project is designed according to our definition in [17]. Challenges for the DT of the project include the high-rate scalability, interoperability, and decentralisation of the production through various production sites. Central points of reference for structuring the AAS are the *I4.0 Core Information Model*, based on *IEC 62264*.

In particular, the relationship between product definition, product segment, and process segment is taken up and applied from *IEC 62264*. The product definition is characterized by three aspects: product production, bill of material, and bill of resources. In our case, the product definition represents the reference stack, the central point and benchmark for production activities. Although it is defined, changes can also be made during the project. In turn, the product segment is defined as the information overlap between the product production rules and the bill of resources. The product segment describes a job with one or more work elements. In our case, the product segment represents the actual electrolyser produced. The product definition relates to the product segment, like the product type to the product instance. Therefore, the product definition contains the target values of the electrolyser to be produced, and the product segment contains the actual values of an produced electrolyser. When it says that the product segment consists of work elements, it references process segments in an ordered and defined sequence. The sequence again depends on the requirements of the product definition. The unordered collection of process segments includes all available processes for manufacturing the product and its sub-products. Process segments that have the same task but different properties can also occur. In our case, the collection of process segments is called a technology kit. This contains all the processes considered in the project for producing the electrolyser, the reference stack. Optional, redundant, or potential processes for electrolyser production are also included, described, and documented. In the course of the project, different processes are tested and first defined. Accordingly, the product segments may also change, which is served by the collection of process segments.

Thus, the structure also follows the Common Model of the *I4.0 Core Information Model (orange in Fig.3)*. Figure 3 shows an example of the aspects that can be found in the structure of the AAS and filled with content. On the right you can see the structuring of the AAS of the example project with assigned standards on the left. Among other things, the physical asset is listed as a central component in this model. The structuring according to *IEC 62264,* is divided into three primary components product definition, product segment and process segment (red). In our case, the electrolyser is the most relevant physical asset to map as the main AAS. The product itself is one of the observable manufacturing elements mentioned in *ISO 23247* and, thus, a potential asset for digital representation in the manufacturing context. Therefore, the BPP, MEA, PTL, CCM and Ink sub products are also represented in addition to the reference stack (dark green). The events are described according to *VDI 5600* (light green).

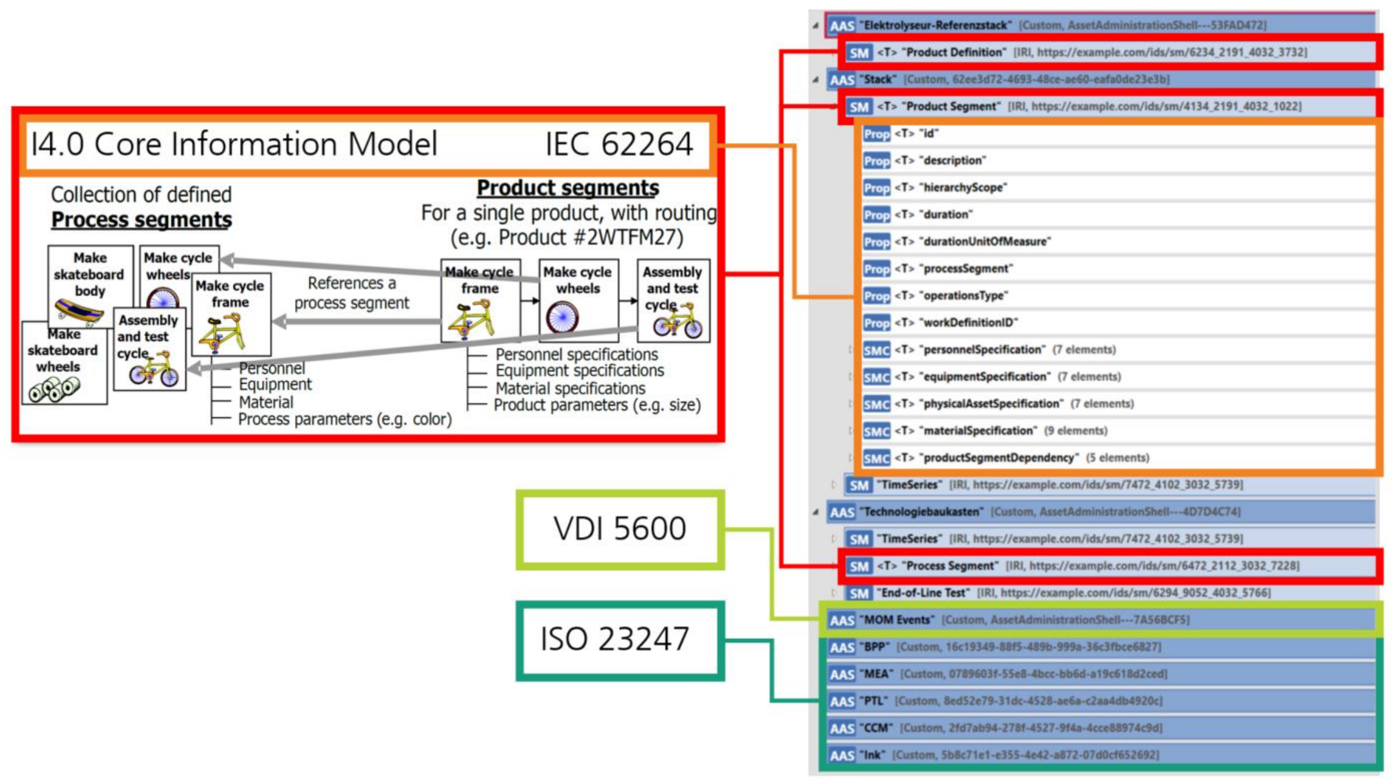

Figure 3: Derivation of a general AAS structure

As a result, we obtain a structure for the AAS that presumably could be applied to multiple use cases in a production-specific context. However, it is recommended to apply the described approach to ensure that all relevant aspects of a specific use case are reflected in the structure of the corresponding AAS.

7. Critical reflection and outlook

The procedure from a production-specific point of view was elaborated, and the AAS was applied in the production environment. The structure was determined by standards typical for it. In the form shown here, it is a reasonably general structure that can be applied similarly to many production-specific use cases. Following such a structure, primarily if it is based on widely used standards, can save time in designing the digital twin. Likewise, structuring the AAS for specific use cases from other domains can follow the approach presented here and thus provide orientation. Still, it also exhibits a few features of more specific domains. With clearly limited knowledge of all the domains that can be mapped in the production context, it is difficult to say to what extent there are always appropriate standards to incorporate specific characteristics into the structure.

The widespread adoption of AAS in industrial applications, the significance of shared data spaces, and the necessity for operability across diverse assets will be crucial to its success. A procedure for structuring the AAS according to domain-specific requirements can serve as orientation for users and thus improve the acceptance of the concept. It also facilitates that all necessary aspects are considered in the modeling and no element is left out. In addition, a structured approach can save time in modelling a digital twin and thus also pays off on the cost aspect.

With the presented approach, a possible structure of the AAS was derived. More value can be generated if the systematic development of the content complements the systematic development of the structure. The effectiveness of the approach presented here and the structure of the AAS derived for the project must also be reviewed for optimization potential when it comes to the technical realization and implementation of the project. An adequate method for this could be a gap analysis to check whether the AAS enables the use cases to be realized. There also needs to be a fundamental look at the system to discuss which asset in that very system needs an AAS.

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Biography

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