7th Conference on Production Systems and Logistics

Developing And Piloting A Procedure For Systematically Deriving The Digital Twin Based On The Asset Administration Shell

Henry Himmelstoß[1], Monika Risling[1], Jannik Rohde[1], Dachuan Shi[1], Thomas Bauernhansl[1,2]

[1] *Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Nobelstraße 12, 70569 Stuttgart, Germany*
[2] *Institute of Industrial Manufacturing and Management, University of Stuttgart, Allmandring 35, 70569 Stuttgart, Germany*

Abstract

The H2Giga-FRHY research project aims to investigate the high-rate production of electrolysers. In this context, an enabling IT infrastructure and software services will be implemented. A central enabling technology in this context is the digital twin based on the asset administration shell. Overall, there are still very different concepts of the digital twin in academia and industry, and in addition there is often a lack of direction in its implementation and application. The concept of the asset administration shell also needs further elaboration in its conceptualisation and implementation to support practitioners. This paper presents a procedure for deriving the digital twin based on the asset administration shell. The applied approach builds up on previous research, which is consolidated and detailed in this work. It includes the use case-specific and requirements-based modelling, gap analysis and the development of the asset administration shell data model. By enabling a software service for product evaluation, the approach is being tested in the H2Giga-FRHY research project. The service intended to facilitate data-driven product development by providing the user with information and hints for possible product improvements, thus supporting in the decision making-process while keeping the user in charge.

Keywords

Digital Twin; Asset Administration Shell; Procedure; Manufacturing; Industry 4.0

1. Introduction

The updated German national hydrogen strategy forecasts a demand for hydrogen of 95-130 TWh for 2030 and of 290-440 TWh in 2045 – with the goal of climate neutrality in 2045 [1]. The meta-study on hydrogen by Fraunhofer ISI summarises that demand for hydrogen and synthesis products in 2050 is anticipated in studies of 400 to almost 800 TWh [2]. To meet these needs, large-scale hydrogen production is required, as well as the production and supply of electrolysers [3]. High-performance electrolysers are already available on the market but are often still assembled by hand in limited quantities. The start of mass production of electrolysers is crucial to solve the cost problems associated with labour-intensive manual assembly. These processes are not only costly, but also time-consuming and prone to errors [4].

The H2Giga-FRHY project is researching the large-scale production of industrial-grade electrolysers. It consists of a diverse group of researchers from several Fraunhofer Institutes across different locations who are working on a variety of aspects of the high-throughput production of electrolysers. The digitalised and standardised description of electrolyser production includes product-related information, manufacturing resources, production processes and process data. Especially in distributed manufacturing systems, seamless data exchange between different systems is necessary. For this purpose, the concept of Digital Twin (DT)

DOI: https://doi.org/10.15488/18860
ISSN: 2701-6277

technologies plays an important role in integrating distributed manufacturing systems for electrolyser production into a virtual overall line – in the project, the DT is implemented with the concept of the asset administration shell (AAS).

This paper builds on previous publications, consolidates their concepts and presents an approach to systematically derive the digital twin in the form of the asset administration shell. First, the concepts of previous publications and the state of the art are addressed. The resulting approach is then presented, and the individual steps are explained. The focus lies on the conceptual definition of a data model in the sense of the AAS. A prototype implementation of a software service is used to test the application of the approach. The paper is concluded with a discussion and a final outlook. Possible AI based approaches building on this or requirements for the IT architecture are explicitly not covered here.

A fundamental problem with the adoption and use of DT is the lack in uniform definition and uniform understanding of the concept. According to Liu et al. [5], in addition to the lack of a widely accepted definition, despite the long existence of the concept, no uniform process for the development and provision of DT is available. The grand vision of covering every aspect of an asset has not yet been achieved [5]. This is also underlined by the statement by Tao et al. [6] that no consensus has yet been reached on the modelling of DT and that generic methods and processes for modelling are needed. Digital representation of cross-location and cross-process products and processes plays an important role in the target image of a software-defined manufacturing system envisioned in this project. It is essential to open the data silos. This is accompanied by problems such as very heterogeneous data sources and types, insufficient standardization of entities, terms and attribute relationships and a lack of semantic context [7]. These data silos are to be opened by using the DT in the form of the AAS and the data is to be made available for multiple software services. The software service to be enabled is intended to empower data-supported product development by providing the user with hints and indicators to identify potential for product improvements. The use of product data and its provision by DT for the development or optimisation of systems is highly important, although implementations in practice are still at an early stage of maturity [8].

2. Central concepts for the approach

There is no uniform definition of DT, but several approaches clarify its concept and current state. An early concept was described in 2002 by Grieves as an informational construct about a physical system [9]. Grieves also differs between a DT prototype and a DT instance. The DT prototype describes the prototypical physical artefact containing necessary information to describe and produce a physical version, whereas the DT instance describes a specific corresponding instance. This DT instance could include exemplary aspects such as operational states, either predictions or derived from sensor data, a bill of material, and a bill of process or a service record. According to this concept, elemental components of the DT are the real product in real space, the virtual product in virtual space, as well as the link between them for the data flow from real space to virtual space, and the information flow from virtual space to real space [10,9]. Scientific publications about the DT increased in particular from 2011, with a steep rise from 2014 [6]. Especially being viewed as a paradigm shift for NASA and U.S. Air Force vehicles by Glaessgen and Stargel [11]. Building on Grieves' concept with its three elementary components of a DT, Tao et al. propose a DT concept with two additional components: In addition to the physical product, the virtual product and the link between them, it also includes data and services [6,12]. We always refer to DT based on the AAS when we talk about DT in the context of our project. The AAS is a concept for a standardised digital representation and an approach for implementing the DT. In the context of the AAS, the DT is considered a digital representation that is sufficient to meet the requirements of a set of use cases, while a digital representation must be considered an information that represents the characteristics and behaviours of an entity. Such an entity may be a physical or logical object owned by, or under the custodial duties of, an organisation [13]. The service that the AAS is enabling supports the product development, which has the primary goal to enable the industrial

production of a product [14], in a way that the developers are receiving hints in how to optimise a product. The complete electronic description of a virtual product is cited as a necessary criterion for this [14,15]. Additionally, the AAS provides a standardized and semantic data model that supports decentralized and autonomous manufacturing processes, addressing the unique challenges of distributed manufacturing systems [16].

In the framework of AAS, interoperability is primarily ensured through the standardised AAS metamodel, the standardised submodel templates (SMTs), and the standardised concept descriptions for submodel elements (SMEs). The AAS metamodel is already standardised in the standard IEC 63278-2. SMTs serve as the reusable empty submodels. The users can fill them with specific values to create specific submodel instances in their applications. To ensure interoperability, it is necessary to establish standardised SMTs for every relevant aspect of an asset, ensuring the consistency of submodels across different applications and systems. Despite this objective, there were previously neither standardised submodels nor a methodology for developing and standardising these SMTs. To bridge this gap, the "Industrial Digital Twin Association" (IDTA) was founded in September 2020, by VDMA, ZVEI, and 20 well-known industrial companies [17]. The first two submodel templates, "Digital Nameplate for industrial equipment" [18] and "Generic Frame for Technical Data for Industrial Equipment in Manufacturing" [19], were published by ZVEI in November 2020. With the commencement of IDTA's operational work in March 2021, IDTA took over the further development of the AAS submodels [20]. Nowadays, the development and standardisation of SMTs are being continuously promoted by IDTA, together with the whole AAS community [21].

3. State of the art

The following section outlines the current state of the art. This includes anaylsed literature and relevant tools. Previous work and publications on which the consolidated approach is based are also important elements. The approach presented here builds on the previously published work and represents a further development and consolidation of these.

3.1 Analysis of literature

A literature search has already been carried out to find out which procedures for deriving a DT already exist in the context of data-driven product development – the AAS has also been included in this search. On the one hand, all procedures found were assigned to the category of phases and grouping of tasks and not to operational tasks [22] - even if this procedure categorisation is not always entirely clear [23]. Secondly, none of the publications considered DT in the sense of the AAS [22]. Research that included approaches similar to procedure categorisation are Sakurada [24], Schnicke [25], Stamer [26] and Deuter [27]. Concentrating on digitizing industrial assets, [24] uses a leveraging agent-based AAS approaches, developers can digitalise and monitor assets, simulate scenarios, and implement AI-driven decision-making. This fosters adaptable product design that aligns with dynamic production and operational demands, contributing to the smarter, more resilient manufacturing systems envisioned by Industry 4.0. Schnicke [25] highlighted diverse applications of AAS in design and manufacturing, showcasing its versatility in enabling efficient product data sharing, integration with high-speed data sources, and real-time design improvements. Stamer [26] extended the application of AAS into business model-oriented design, encouraging its use within frameworks that define value propositions and stakeholder engagement. This approach helps designers align design objectives with market and production demands, ensuring functionality and market fit. Deuter [27] highlighted AAS's role in Product Lifecycle Management, emphasizing its capability to integrate data across the Product Lifecycle process, enhancing decision-making and design continuity. However, these publications lack consensus, leading to inconsistent implementation. Existing models focus narrowly on aspects like data flow but fail to support dynamic, multi-directional integration and the general procedure for developing a DT. Frameworks address components like data and services but lack standardisation for diverse industries. Standardisation efforts remain incomplete, with limited libraries and methodologies. This

research addresses these gaps by developing frameworks with standards, comprehensive libraries, robust methodologies, and mechanisms for integration.

3.2 Tool support for derivation of the DT

In the world of AAS, new tools are constantly being developed and existing ones expanded with new functions. Many focus on implementation in software, but there are only a few tools available for the derivation of submodels and general modelling. A combination of AAS and non-AAS tools can simplify the derivation of AAS submodels, which are briefly presented here. In classic spreadsheet programs the AAS submodels can be documented using columns for the properties of the objects such as names, descriptions values, and dependencies. This helps describe the hierarchy of the individual elements in the data structure, useful in later modelling. Submodel templates can be a great help in creating the structure in the table. The AAS tool AASX Package Explorer [28] can provide support by exporting these submodels as spreadsheet tables, providing a ready structure for filling. Since new columns can be added for additional information that is not allowed by the AAS standard but useful at a later stage of development, spreadsheets offer some flexibility. In addition to the fixed values, references to systems or database queries can be stored here. A graphical representation of the developed table serves as another useful addition for communication and discussion. The level of detail can be minimised here if the table already contains all the details. The hierarchy levels should be recognizable when selecting the form of presentation. Options here include a mind map, an object diagram or a class diagram. The AASX Package Explorer also offers a visual representation of the submodel or an export as PlantUML [29] file – other AAS-independent tools for visualisation with a standardised modelling language are also suitable Tools such as the AASX Package Explorer or the AAS Manager [30] are then suitable for modelling the data in the final form of an Asset Administration Shell. The tools offer a user interface with various functions for modelling submodels as well as importing and exporting different formats. The table from the first step can serve as the basis for modelling the AAS submodel, from which the data is transferred either manually or via import from a customized table. An automated transfer of the data from a CSV table can also be carried out using tools such as the aas-core3.0-cli-swiss-knife [31] from aas-core-works, which transfers the AAS into the correct JSON format. The AAS created can then be read, processed or converted into another form and used by other applications in the AAS ecosystem.

3.3 Preliminary work for deriving the DT based on the AAS

The first procedure for deriving the contents of the AAS, on which the procedure presented here is based, was published by Himmestoss et al. and is based on work from the X-Forge PLCEaaS research project. Figure 1 shows this very procedure in a simplified visualisation [32]. It should be noted here that we speak of the derivation of an AAS when we talk about the conceptual use case-specific design of an AAS for an asset type, while we speak of the generation of an AAS when an AAS is generated (automatically) for an instance of an asset.

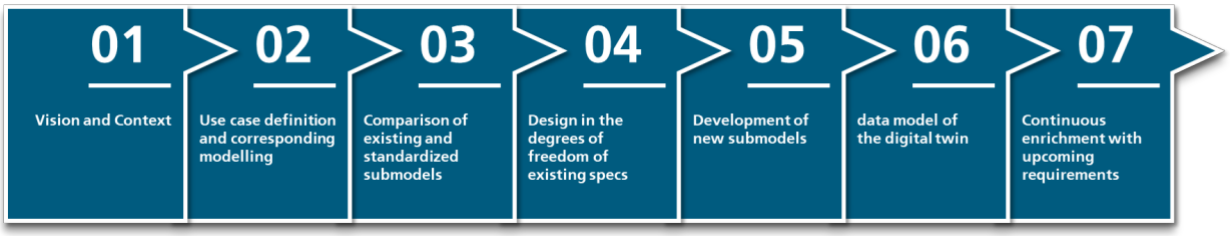

Figure 1: Procedure for creating a use case specific DT based on the AAS [32]

The individual steps of [32] can be outlined as follows: The initial starting point is a desired objective, for example through a corporate vision or a project-specific context, from which a use case can be recognised. The next step is to detail this use case so that a common understanding of it is created within the team. The

project achieved this using a series of methods that utilised established methods from requirements engineering such as QFD or pairwise comparison in workshops. This also resulted in the first non-standardised modelling of use cases. This captured the common understanding in the team and was the basis for more detailed modelling using the UML notation. Class, sequence and component diagrams were used for a holistic description of the use cases. With a uniform understanding of a use case in the research team and its detailed description, the extent to which existing submodels of the AAS can be used was now considered. Both standardised and in-house proprietary submodels were considered. The degrees of freedom of existing specifications can be used, for example, to extend existing submodels or derive new ones. The submodels ultimately required were derived from the elements and relationships of the UML diagrams of the use cases – as also shown schematically in Figure 1.

3.4 Preliminary work for structuring the DT based on the AAS

A second procedure was developed in the H2Giga-FRHY research project. This serves to structure the AAS. This approach will also serve as the foundation for this paper and has already been published by Risling et al. [7]. Figure 2 shows the second procedure in a simplified visualisation.

Figure 2: Procedure for structuring a use case specific DT based on the AAS [7]

The individual steps of the procedure for structuring the AAS can be outlined as follows [7]: This approach also begins similarly, in that a goal is defined based on a fundamental business vision or project context, which can be used as the backbone for a use case. Again, requirements engineering methods are used. In the current project, the requirements of the project partners were captured using phrase templates and assigned to individual functionalities in a functional architecture. The use cases are then modelled again. The project used use case diagrams to identify the so-called observable manufacturing elements (OME) in accordance with the IoT framework for digital twins in manufacturing of ISO 23247-1:2021 [33]. In such cases, these are assets that are also the subject of consideration in the use case and the decision must be made as to the extent to which the asset requires a DT in the form of the AAS. The structuring of the DT should be domain-specific fulfil the respective use cases best. For this reason, the relevant standards and specifications were used as a guide. In particular, IEC 62264, which standardizes the integration of enterprise and control systems, and the I4.0 Core Information Model, which defines the fundamental digital structure for assets and processes in Industry 4.0, were identified [34]. The understanding of product definition, process segments and product segments contained therein is also compatible with the understanding of types and instances from RAMI 4.0 [35], which is also reflected in the AAS. When making these considerations, submodels identified in parallel can be considered in the structure. Any optimisation loops should also be planned as part of the implementation and testing of the AAS.

4. Consolidated and applied approach

The following section presents the new version of the procedure for deriving the DT based on the AAS. This is a consolidated procedure from the approaches shown so far.

Vision and Context were the starting points in both previous approaches and are still regarded as elementary in defining the underlying conditions. The second step is the requirements-based use case definition, whereby the method used is a matter of choice - both the visualisation of the use case in the form of modelling

and the language-based specification of requirements according to record templates are possible. The third step is to create a list of properties that provides information about the type of data, metadata or implicit knowledge required to implement the use case. The third step is listing of properties to indicate what kind of data, metadata or implicit knowledge is necessary to implement the use case. The fourth step, the plausibility check, is built on that. Here, the properties list is used to check whether or to what extent implementing the defined use case is possible. If it is determined that not all necessary data is available or that the required knowledge base cannot be mapped, the procedure leads back to the steps of defining the vision and mission or the use case understanding. If the plausibility check shows that the data required for the use case is available, step five, the gap analysis, follows. On the one hand, it is checked which assets must have an AAS to implement the use case, and on the other hand, it is checked to what extent standardised submodels can be applied and to what extent proprietary submodels need to be relied on or developed. If there is a need to dervive proprietary submodels, it should also be ensured that they are defined in an interoperable manner. This is primarily facilitated using concept descriptions. Each SME can be associated with a concept description that links to existing vocabularies within external repositories, such as the IEC Common Data Dictionary (CDD) [36] and ECLASS [37]. For example, ECLASS provides standardised terminologies and professional vocabularies in the form of an ontology, covering a broad spectrum of product and service categories. Typically, SMT developers define SMEs based on the specific requirements of use cases, applicable standards, domain expertise, or established conventions. These proprietary definitions, often characterised by attributes like "idShort" and "description", may be highly specialised for particular use cases. To ensure that these SMEs are interpretable and unambiguous across diverse systems, developers often attempt to link these proprietary SMEs to standardised vocabularies via concept descriptions. In our prior work, we developed a data mapping and semantic search tool based on a large language model to support this process [38,39].

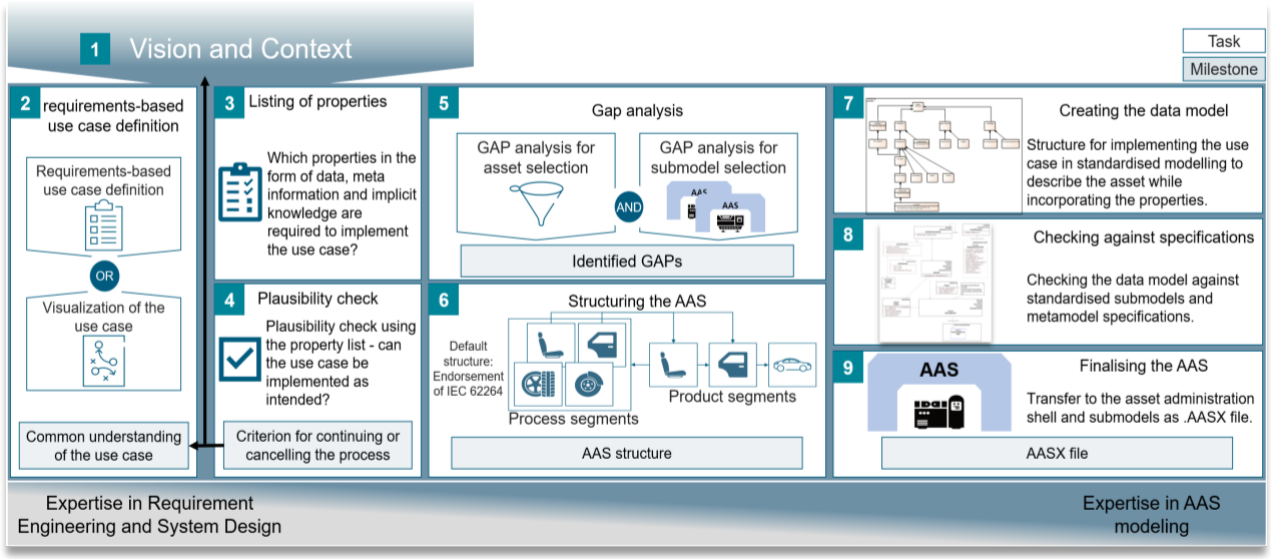

Figure 3: Consolidated procedure for creating a use case specific DT based on the AAS

The next step is about structuring the AAS: The representation of key aspects by the submodels is be embedded in a structure orientated towards IEC 62264 and, therefore, suitable for the manufacturing domain. The product definition represents the definition of a product and thus corresponds to a product type. The process segments represent potential process steps for manufacturing a product and a product segment is a specific sequence of process segments and represents a specific, manufactured product. A product segment thus corresponds to a product instance. This is followed by the seventh step 'creating the data model': the development of the use case in detail. To obtain the best possible comprehensible definition in the form of a data model, it is documented using standardised and well-known modelling methods such as UML notation. The eighth step describes the checking against specifications and the AAS metamodel. In the ninth and final

step ‘finalising the AAS’, the data model is then converted into the AASX Explorer-specific aasx-data file format. Figure 3 illustrates this procedure.

5. Application of the procedure and enabling of a software service by the AAS

In the context of testing and domain-specific instantiation of the general, consolidated procedure, the scope and vision were set by the project in the form of a project proposal. On the one hand, the requirements were captured from the project partners with the help of phrase templates, but at the same time the use cases were also modelled in the form of use case diagrams to create a uniform understanding within the team. In order to find out as early as possible which data and product- and production-specific parameters are available, rough parameter lists were initially created and supplemented or replaced by actual parameter lists of the production processes as the project progressed. In principle, the premises for implementation appeared to be fulfilled based on the existing and anticipated data. In a GAP analysis, the already published submodels of the IDTA were analysed for their applicability in the project - in particular the time series submodel is often used. Proprietary submodels had to be derived, for example to provide the output of Bayesian networks in an AAS-compliant manner. It was also analysed which assets require an AAS for the implementation of the use case, focusing on the end and sub products. Rather than strictly adhering to established standards and specifications for structuring the AAS, IEC 62264 was utilised as a general guideline due to its broad applicability across various aspects of the manufacturing domain. This structure is also reflected in the modelling of the asset's data model, which is transferred to the final AASX file in compliance with the specifications and the AAS metamodel.

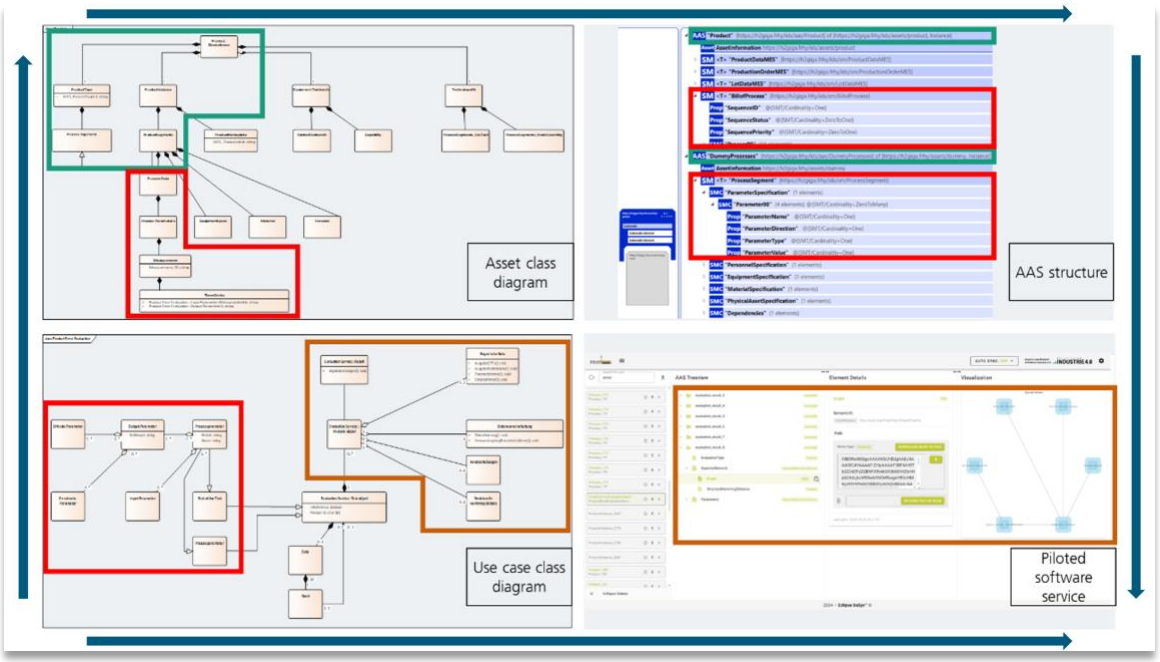

Figure 4: Pictogram indicating the influence of previous modelling on service and data modelling

The initial use case, based on requirements from experts in the electrolyser stack, is intended to provide the user with information for product improvement by revealing relationships between end-of-line test results and production process parameters. For this purpose, Bayesian networks were evaluated as particularly suitable in a qualitative comparison of methods [40]. For similar use cases, their implementation and operation has already been described, e.g. by Dienst [41]. This involves deriving network structures that represent the parameters as nodes and the conditional dependencies between them as edges. Bayesian networks are learnt in two steps. Firstly, the network structures are generated from the training data for given variables. Then the conditional probability tables (CPT) are calculated with the conditional probabilities that

are assigned to the edges of the network. If sufficient training data is available, the conditional probabilities can be estimated by counting the occurrences of parameters [42]. This functionality is to be provided by a software service. The service enabled by the AAS analyses data from the end-of-line test in the piloted service and identifies influencing relationships between parameters. On the one hand, this outputs the network structure of the Bayesian network and thus visualises these influence relationships. On the other hand, the CPTs are also output. The latter can be very extensive and difficult to interpret. For this reason, marginal distributions are also output to show parameter distributions without conditional influence and the structural Hamming distance, which uses a single value to compare the analysed network structure with a default structure by specifying how many changes are required to convert one network structure into the other. This default grid structure is assigned to an electrolyser that has been assessed as fault-free. These indicators provide a rough indication of the extent to which further consideration of the conditional probability tables is required. Figure 4 shows schematically how individual components of the modelling of the software service and use case affect the final data model and application. The functionalities of the software service were already defined in the initial use case modelling – just like the data required for this, which was then also incorporated into the modelling of the electrolyser stack and classified in the structure already described. The data and structure were then transferred directly into AAS for product definition and process segments as well as in the form of specific submodels, such as the standardised times series submodel in this case. The product segments, meaning the AAS that represent the actual product instance, are instantiated from the product definition and only exist in code.

6. Discussion and outlook

This paper addresses the challenge of systematically model DTs using the AAS framework. While DT technologies hold significant potential for advancing product development and operational efficiency, their adoption is hindered by the lack of standardised definitions, methodologies, and tools. Current approaches are often fragmented, focusing narrowly on specific aspects such as data flow or modeling, without providing a unified framework adaptable to diverse industrial applications. The proposed solution, based on previous works, involves creating a systematic framework to derive DTs tailored to specific use cases. This framework emphasizes the integration of product data, manufacturing resources, and processes in a virtual environment, enabling seamless data exchange across systems. The approach is structured around defining objectives, capturing requirements, conducting plausibility checks, and modeling data to align with manufacturing standards like IEC 62264. However, it should be noted that although the use of the framework provides a framework and orientation, it does not replace the need to deal with the specifications of the AAS – expertise is still required for this. The procedure described in the framework and its first iterations were also trailed in very similar use cases in the production context. While the first iteration of the approach was trialled by a heterogeneous team with very different technical backgrounds, the team that trialled the consolidated approach was much more homogeneous, and all team members came from an IT background. In particular, but not only in the case of the heterogeneous team, a large part of the effort was spent on creating a common understanding of the use case, while the following steps could be processed in a much more straightforward manner. The testing proved to be favourable, but further applications in other use cases in the production domain would put the procedure on a firmer foundation or possibly provide further valuable information for enriching the framework. With regard to the service and the associated use of Bayesian networks, it can be said that the derivation of a network structure involves a high computational effort, especially with many parameters and relationships between them, and that the CPTs created are difficult to interpret due to their size. The next iteration of this service will therefore utilise methods of causal discovery and inference.

Acknowledgements

This research is part of the H2Giga-FRHY project funded by the German Federal Ministry of Education and Research (BMBF) since 2021 under grant number 03HY112C.

References

[1] Federal Ministry for Economic Affairs and Climate Action (BMWK), 2023. Fortschreibung der Nationalen Wasserstoffstrategie. https://www.bmwk.de/Redaktion/DE/Wasserstoff/Downloads/Fortschreibung.pdf?__blob=publicationFile&v=4. Accessed 26 November 2024.

[2] Wietschel, M., Zheng, L., Arens, M., Hebling, C., Ranzmeyer, O., Schaadt, A., Hank, C., Sternberg, A., Herkel, S., Kost, C., Ragwitz, M., Herrmann, U., Pfluger, B., 2021. Metastudie Wasserstoff: Auswertung von Energiesystemstudien. Studie im Auftrag des Nationalen Wasserstoffrats. https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/metastudie-wasserstoff.html. Accessed 14 May 2024.

[3] Töpler, J., Lehmann, J., 2017. Wasserstoff und Brennstoffzelle. Springer Berlin Heidelberg, Berlin, Heidelberg.

[4] Project Management Jülich, 2021. How the H2Giga flagship project aims to mass produce electrolysers for the production and scale-up of hydrogen. Federal Ministry of Education and Research (BMBF). https://www.wasserstoff-leitprojekte.de/projects/h2giga. Accessed 15 May 2024.

[5] Liu, M., Fang, S., Dong, H., Xu, C., 2021. Review of digital twin about concepts, technologies, and industrial applications. Journal of Manufacturing Systems 58, 346–361.

[6] Tao, F., Zhang, H., Liu, A., Nee, A.Y.C., 2019. Digital Twin in Industry: State-of-the-Art. IEEE Trans. Ind. Inf. 15 (4), 2405–2415.

[7] Risling, M., Himmelstoss, H., Brandstetter, A., Shi, D., Bauernhansl, T., 2023. Bridging The Gap: A Framework For Structuring The Asset Administration Shell In Digital Twin Implementation For Industry 4.0. publish-Ing.

[8] Gausemeier, J., Meyer, M., Steglich, S., Eva-Maria, G., Rasor, R., 2022. Strategie Advanced Systems Engineering: Leitinitiative zur Zukunft des Engineeringund Innovationsstandorts Deutschland. acatech – Deutsche Akademie der Technikwissenschaften. https://www.acatech.de/publikation/die-advanced-systems-engineering-strategie/. Accessed 20 February 2023.

[9] Grieves, M., Vickers, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in: Kahlen, F.-J., Flumerfelt, S., Alves, A. (Eds.), Transdisciplinary Perspectives on Complex Systems. Springer International Publishing, Cham, pp. 85–113.

[10] Grieves, M., 2015. Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

[11] Glaessgen, E., Stargel, D., 2012. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles, in: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii. American Institute of Aeronautics and Astronautics, Reston, Virigina.

[12] Tao, F., Zhang, M., 2017. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. IEEE Access 5, pp. 20418–20427.

[13] Bader, S., Barnstedt, E., Bedenbender, H., et al., 2022. Details of the Asset Administration Shell: Part 1 - The exchange of information between partners in the value chain of Industrie 4.0. Specification. Accessed 4 November 2022.

[14] Dombrowski, U., Karl, A., 2022. Ganzheitlicher Produktentstehungsprozess für die Zulieferindustrie. Springer Berlin Heidelberg.

[15] Eigner, M., Stelzer, R.H., 2009. Product-lifecycle-Management: Ein Leitfaden für Product Development und Life-cycle-Management, 2.th ed. Springer, Berlin, Heidelberg, p. 434.

[16] Risling, M., Oberle, M., Bauernhansl, T., 2024. Analyzing The Purpose And Technologies Of Digital Twins In Distributed Manufacturing: A Systematic Literature Review. Procedia Computer Science 232, 368–376.

[17] Federal Ministry for Economic Affairs and Climate Action (BMWK), 2020. Weiche Schale, harter Kern - Gründung der „Industrial Digital Twin Association“: „Industrial Digital Twin Association“ bringt mit

Verwaltungsschale ein Schlüsseltechnologie von Industrie 4.0 in den Mittelstand. https://www.plattform-i40.de/IP/Redaktion/DE/Pressemitteilungen/2020/2020-09-24-Weiche-Schale-harter-Kern_Gruendung-Nutzerorganisation.html. Accessed 27 May 2025.

[18] Bedenbender, H., Billmann, M., Bondza, A., Dogan, A., Fay, A., Garrels, K., Hadlich, T., Hankel, M., Heidel, R., Hillermeier, O., Hoffmeister, M., Jochem, M., Neidig, J., Orzelski, A., Pollmeier, S., Schaber, V., Stein, S., Weber, I., Wollschlager, M., Zhan, Y., 2020. Submodel Templates of the Asset Administration Shell: ZVEI Digital Nameplate for industrial equipment (Version 1.0). https://www.plattform-i40.de/IP/Redaktion/EN/Downloads/Publikation/Submodel_templates-Asset_Administration_Shell-digital_nameplate.html. Accessed 27 May 2024.

[19] Bader, S., Bedenbender, H., Billmann, M., Bondza, A., Boss, B., Erler, S., Garrels, K., Hadlich, T., Hankel, M., Hillermeier, O., Hoffmeister, M., Kiele-Dunsche, M., Neidig, J., Orzelski, A., Pollmeier, S., Rauscher, B., Rieder, W., Stein, S., 2020. Submodel Templates of the Asset Administration Shell: Generic Frame for Technical Data for Industrial Equipment in Manufacturing (Version 1.1). https://www.plattform-i40.de/IP/Redaktion/EN/Downloads/Publikation/Submodel_templates-Asset_Administration_Shell-Technical_Data.html. Accessed 27 May 2025.

[20] ZVEI e. V., 2021. Start der Industrial Digital Twin Association (IDTA). Industrial Digital Twin Association e.V. https://www.zvei.org/themen/start-der-industrial-digital-twin-association-idta. Accessed 28 May 2024.

[21] Industrial Digital Twin Association e.V. (IDTA), 2024. Registered AAS Submodel Templates. Industrial Digital Twin Association e.V. (IDTA). https://industrialdigitaltwin.org/en/content-hub/submodels. Accessed 28 May 2024.

[22] Himmelstoss, H., Bauernhansl, T., 2023. Modelling The Digital Twin For Data-Driven Product Development - A Literature Review. publish-Ing.

[23] Lindemann, U., 2009. Methodische Entwicklung technischer Produkte. Springer, Berlin, Heidelberg.

[24] Sakurada, L., Leitao, P., La Prieta, F. de, 2022. Agent-Based Asset Administration Shell Approach for Digitizing Industrial Assets. IFAC-PapersOnLine 55 (2), pp. 193–198.

[25] Schnicke, F., Kuhn, T., Klausmann, T., Gruner, S., Porta, D., 2022. Architecture Blueprints for the Application of the Industry 4.0 Asset Administration Shell, in: 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA). 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), Stuttgart, Germany. 06.09.2022 - 09.09.2022. IEEE, pp. 1–8.

[26] Stamer, F., Maier, S., Peukert, S., Lanza, G., 2022. Adaptive and Dynamic Feedback Loops between Production System and Production Network based on the Asset Administration Shell. Procedia CIRP 112, pp. 79–84.

[27] Deuter, A., Imort, S., 2021. Product Lifecycle Management with the Asset Administration Shell. Computers 10 (7), p. 84.

[28] Hoffmeister, M., Orzelski, A., Mendes, M., Grote, J., Göllner, D., Bischof, S., 2024. AASX Package Explorer. https://github.com/eclipse-aaspe/package-explorer. Accessed 21 November 2024.

[29] PlantUML, 2024. https://plantuml.com. Accessed 21 November 2024.

[30] RWTH AAchen, 2024. AAS Manager. https://github.com/rwth-iat/aas_manager. Accessed 22 November 2024.

[31] Zurich University of Applied Sciences, TU Dresden, RWTH Aachen, IDTA, conplement AG, 2024. aas-core3.0-cli-swiss-knife. https://github.com/aas-core-works/aas-core3.0-cli-swiss-knife. Accessed 22 November 2024.

[32] Himmelstoss, H., Hall, R., Vojanec, B., Thieme, P., Bauernhansl, T., 2023. Conceptualizing A Digital Twin Based On The Asset Administration Shell For The Implementation Of Use Case Specific Digital Services. publish-Ing.

[33] International Organization for Standardization, 2021. Automation systems and integration: Digital twin framework for manufacturing 25.040.40.

[34] DIN German Institute for Standardization, 2014. Enterprise-control system integration: Part 1: Models and terminology (IEC 62264-1:2013). Beuth Verlag GmbH,VDE-VERLAG GMBH IEC 62264.

[35] Plattform Industrie 4.0, 2018. RAMI 4.0 – Ein Orientierungsrahmen für die Digitalisierung. https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/rami40-eine-einfuehrung.pdf?__blob=publicationFile&v=7. Accessed 12 June 2024.

[36] International Electrotechnical Commission. IEC 61987 - IEC/SC 65E - Common Data Dictionary (CDD - V2.0018.0002). International Electrotechnical Commission. https://cdd.iec.ch/cdd/iec61987/iec61987.nsf. Accessed 28 May 2024.

[37] ECLASS e.V. An introduction to the standard. ECLASS e.V. https://eclass.eu/en/eclass-standard/introduction. Accessed 28 May 2024.

[38] Shi, D., Liedl, P., Bauernhansl, T., 2024. Interoperable information modelling leveraging asset administration shell and large language model for quality control toward zero defect manufacturing. Journal of Manufacturing Systems 77, pp. 678–696.

[39] Shi, D., Meyer, O., Oberle, M., Bauernhansl, T., 2025. Dual data mapping with fine-tuned large language models and asset administration shells toward interoperable knowledge representation. Robotics and Computer-Integrated Manufacturing 91, p.102837.

[40] Neubach, M., 2010. Wissensbasierte Rückführung von Produktnutzungsinformationen in die Produktentwicklung im Rahmen einer Product-Lifecycle-Management-(PLM)-Lösung. Zugl.: Bochum, Univ., Diss., 2010. Shaker, Aachen.

[41] Dienst, S., 2014. Analyse von Maschinendaten zur Entscheidungsunterstützung bei der Produktverbesserung durch die Anwendung eines Feedback Assistenz Systems. Doctoral Thesis, Siegen.

[42] Ertel, W., 2021. Grundkurs Künstliche Intelligenz. Springer Fachmedien Wiesbaden, Wiesbaden.

Biography

Henry Himmelstoß (*1991) is a research associate and project leader at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany. Since 2019 he has been working in the department IT-Systems for Production as an expert for implementation Methods for IT Solutions.

Monika Risling (*1997) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021. As a part of the department for IT-Systems for Production, her research focuses on Corporate Information Systems.

Jannik Rohde (*1995) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021 where he is working in the department IT-Systems for Production and in the field of smart manufacturing. He focuses on solutions for interoperability in industrial applications with the help of digital twins and intelligent industrial network technologies.

Dachuan Shi (*1990) is working at Fraunhofer Institute for Manufacturing Engineering and Automation IPA as a postdoctoral researcher since 2022. His research focuses on digital twin and predictive maintenance for industrial applications.

Prof. Dr.-Ing. Thomas Bauernhansl (*1969) has been head of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart and the Institute for Industrial Manufacturing and Factory Management IFF at the University of Stuttgart since September 2011. Bauernhansl studied mechanical engineering at the RWTH Aachen and received his doctorate in 2002. He then worked for Freudenberg, most recently as Director of the Technology Centre at Freudenberg Sealing Technologies. His scientific focus areas include personalised production, the biological transformation and Industry 4.0.