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Modelling The Digital Twin For Data-Driven Product Development - A Literature Review

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Abstract

Due to advanced connectivity and increasing distribution of product-service, more and more data is available from the products used and produced. Scientific publications often describe that this product data can be applied in product development to make it more efficient and that the digital twin can play a central role in data provision and interoperability. However, less attention is paid to how the digital twin should be designed for this purpose and how it should be adequately modelled for these use cases. Therefore, this paper presents a structured literature review to analyse which methods are already described in science to model digital twins in a target-oriented way for use cases of data-driven product development. Not only are the procedures interesting, but also the type of digital twin for which they are intended and whether they describe the procedure at the level of a rough macrostructure or detailed microstructure.

Keywords

Digital Twin; Asset Administration Shell; Product Development; Digital Manufacturing; Industry 4.0; Literature Review

1. Introduction

Fraunhofer ISE's hydrogen roadmap projects a demand between 800 TWh (low scenario) and 2250 TWh (high scenario) in Europe by 2050. [1]. To meet this anticipated demand, a significantly larger electrolysis capacity is required. That is why the H2Giga-FRHY project is concerned with the high-rate production of electrolysers. The competencies of various Fraunhofer institutes are bundled in this project. Fraunhofer IPA is responsible for the IT reference architecture, the digital representation concept, and evaluation services. These services analyse product defects and performance based on various parameters and help in making decisions about product configurations [2]. The Digital Twin (DT), implemented through the Asset Administration Shell (AAS) concept, is the enabler technology that makes the evaluation services possible by providing the necessary data.

The DT is considered a core technology [3], which enables companies to collect, manage and deliver the data of an asset along its lifecycle. For this reason, DT has also received special attention in scientific considerations and practical applications for several years, and the number of scientific publications has increased, especially since 2014 [4]. However, views and definitions of the digital twin are not uniform, and there are many different definitions in both academia and industrial applications. The concept of the DT was mentioned very early by Grieves, who defined it with three central components: the physical product in real space, the virtual product in virtual space, and the connections of information and data between the virtual and real products [5]. Building on Grieves' concept, Tao et al. suggested adding two components: data and services [4,6]. However, there is not yet a unified approach to modelling DTs [4]. For approaches to

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innovation and development, DT is much less often the object of consideration. DT's focus is often on stand-alone applications that meet the needs of a specific use case [7]. ISO 23247 provides a digital twin framework for manufacturing, outlining general principles, reference models, functional, informational, and networking views. However, it lacks detailed guidance for user-specific use case implementation and model development [8–11]. The AAS, in turn, represents a relatively new concept for DT implementation that is currently still part of standardisation activities. In the context of the AAS, the DT is described as a digital representation sufficient to meet the requirements of a set of use cases. A digital representation is, in turn, described as information that represents the characteristics and behaviours of an entity [12]. According to this definition, the use case for the AAS plays a central role. The AAS should be designed for the respective use case, and the necessary submodels should be implemented. This raises the question of a procedure that describes how to design or set up an AAS for a possible application. This paper therefore systematically analyses scientific papers to determine which methods are already described to model a DT – especially for data-driven product development that the evaluation services in the H2Giga-FRHY project will support. Because the AAS can be considered a particular manifestation of a DT, methods for deriving both the AAS and the DT are being researched. Because the concept of DT has been around for some time, it is hoped that more results will be obtained by studying it, too. Although the focus in the project is on the AAS.

2. Method and data

Our goal of systematically searching and analysing literature was to find appropriate methods for deriving the digital twin for data-driven product development to follow or build upon. For this purpose, an overview of already existing approaches will be given here. The applied procedure is oriented towards the framework for literature reviewing described by Brocke et al. and the steps in conducting research literature reviews described by Fink [13,14]. Thus, from the previous section, the question arises about the approaches described in the literature for deriving a DT for data-driven product creation. Therefore, the first research question is:

RQ1: Which approaches to derive a digital twin for data-driven product development are described in the literature?

Lindemann presents a differentiation of concepts within product development. He describes a continuum ranging from micro to macro logic. Within this spectrum, he identifies four different concept types, depending on the level of detail and resolution of the process. These are ordered from micro to macro logic: ‘Elementary thought processes and action processes’, ‘operational tasks’, ‘phases and grouping of tasks’, and a ‘full project or concept’ [15]. 'Elementary thought processes and action processes' are cycles of analysis, synthesis, and evaluation that occur in seconds in the user’s mind. Processes can be described and analysed on an operational level ('operational tasks') or more abstractly on the level of work stages or phases ('phases and grouping of tasks'). However, suppose the goal is to obtain a complete project overview. In that case, it makes sense to map processes with low resolution ('full project or concept') to reduce complexity and maintain an overview. It should also be noted that using systems thinking, it might be necessary to switch between these levels of process granularity and that process models can also be assigned to several levels because these are not always clearly separable. Figure 1 gives an overview of the described differentiation between the approaches in product creation along the spectrum between micro- and macro-logic.

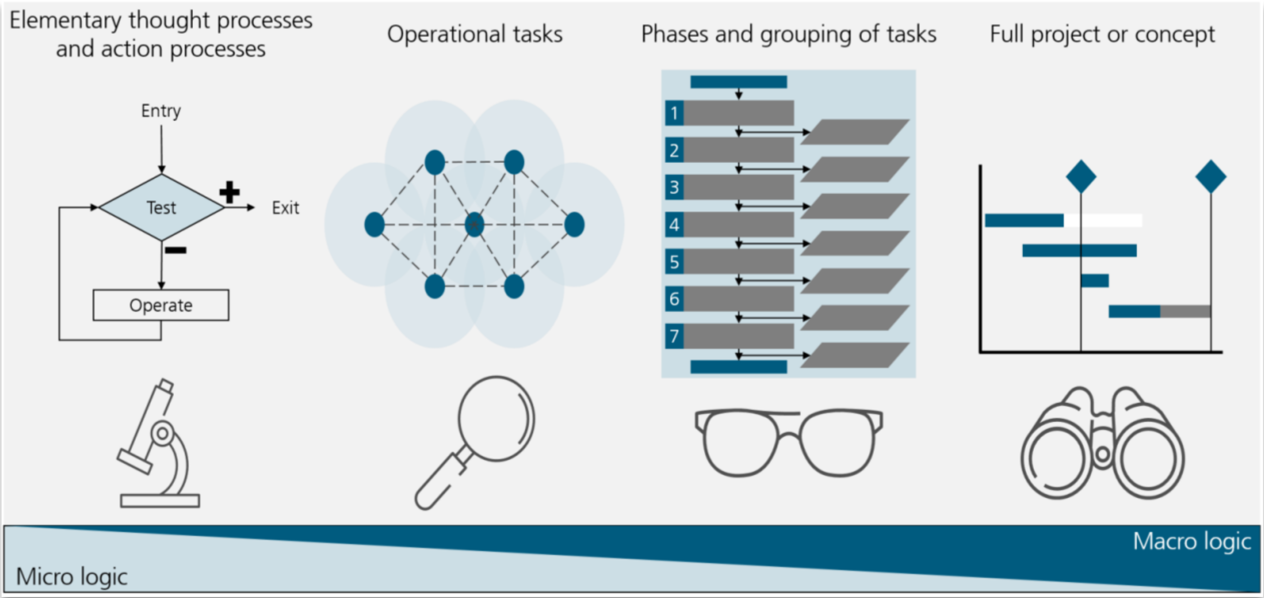

Figure 1: Different degree of resolution of procedures in the product creation in connection with different perspectives according to [16,15]

This leads to the second research question:

RQ2: How do the concepts fit into the differentiation of concepts in product development?

Because AAS will be applied in the H2Giga-FRHY project, the extent to which concepts can be transferred to AAS will be examined. This leads to the third research question:

RQ3: How can approaches from the concepts be transferred to the application of the AAS?

2.1 Search process and selection of literature

In the first step, a search matrix was set up with the aspects relevant to the search. Table 1 shows an overview of the aspects and the associated search terms. The aspects were combined with the AND operator and the search terms with the OR operator to form a search string. Before using the final search string, different ways to combine the aspects were tried. All of them were applied to searches in the same databases. The databases are ACM, IEEE, Scopus, and Web of Science. The search was conducted in August 2023.

Table 1: Relevant aspects and search terms to form the search string.

	Aspect 1	Aspect 2	Aspect 3	Aspect 4	Aspect 5
Operaters	AND	AND	AND	AND	AND
Term 1	framework	"digital twin"	"product creation"	"data driven"	production
Term 2	procedure	"digital shadow"	"product development"	"production data analysis"	manufacturing
Term 3	approach	"asset administration shell"	"product innovation"	"user data analysis"	"industrie 4.0"
Term 4	technique	"virtual twin"	"product design"	"data collection"	"industry 4.0"
Term 5	"process model"		"product planning"	"data mining"	
Term 6			"product improvement"		
Term 7			"generation planning"		

For example, the aspect of product development was removed, and approaches to derive DT in a production context were searched for. This represents the first search string. Here, 994 results were found - no further examination took place. This search string delivered too many results for the available resources, labelled as search string no. 1 in Table 2 Another search string was formed by searching only for the DT in the expression of the AAS and without the production context. After filtering duplicates, this search string yielded 22 results, but they were not considered relevant after screening the title, abstract, or text, labelled as search string no. 3 in Table 2. Using the entire search string, 70 publications were found – labelled as search string no. 2 in Table 2.

Figure 2 shows how the original results were filtered. Filtering in English and by the publication period 2018 to 2023 made no difference. Some publications were found twice, and some only in the form of proceedings, without the information of whether a paper alone meets the requirements of the search string. Most of it was filtered out by screening the abstracts and texts. The selected papers are limited to papers covering the DT in a form that considers it a digital asset or a representation of an asset. Papers were also not included if an analytical or statistical method or a simulation model was referred to as a DT. Thus, there are six remaining papers in total: Barth et al. [17], Che et al. [18], Jeong et al. [19], Josifovska et al. [20], Niu et al. [21] and Riedelsheimer et al. [22].

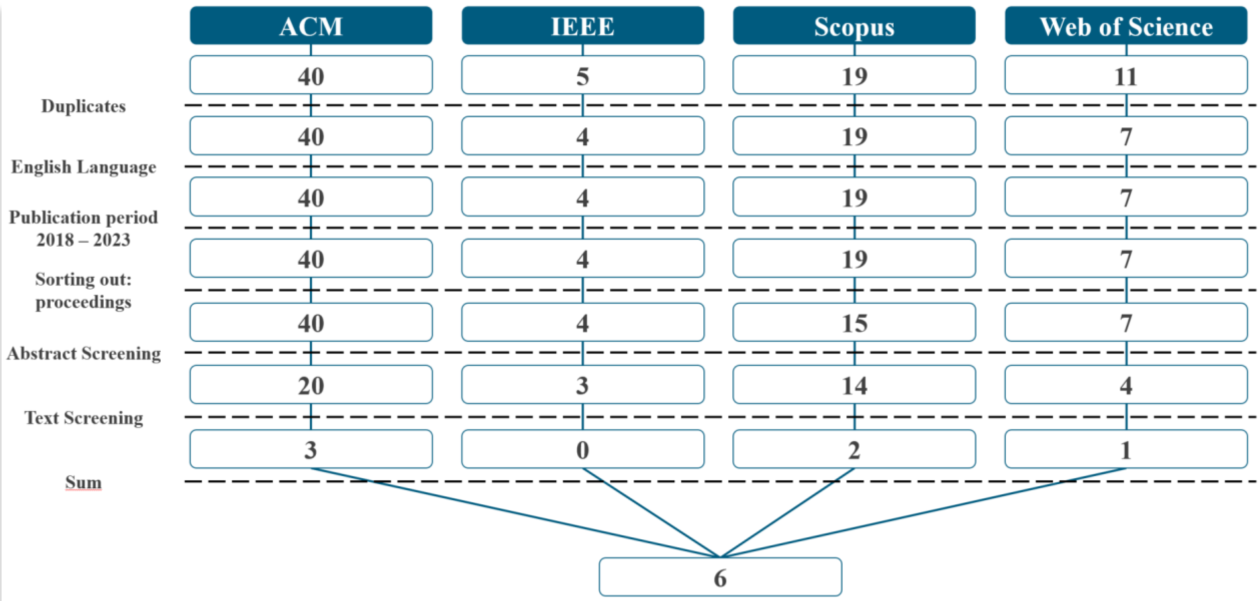

Figure 2: Filtering of the papers and the used databases (August 2023)

Table 2: Overview of the applied search strings.

No.	Search string	Number of results	Remaining results
1	(framework OR procedure OR approach OR technique OR "process model") AND ("digital twin" OR "digital shadow" OR "asset administration shell" OR "virtual twin") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining")	994	/
2	(framework OR procedure OR approach OR technique OR "process model") AND ("digital twin" OR "digital shadow" OR "asset administration shell" OR "virtual twin") AND ("product creation" OR "product development" OR "product innovation" OR "product design" OR "product planning" OR "product improvement" OR "generation planning") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0")	70	6
3	(framework OR procedure OR approach OR technique OR "process model") AND ("asset administration shell") AND (production OR manufacturing OR "industrie 4.0" OR "industry 4.0") AND ("data driven" OR "production data analysis" OR "user data analysis" OR "data collection" OR "data mining")	22	0

3. Analysis and findings

This section addresses the research questions, with RQ1 and RQ2 being answered together in a common course, while RQ3 will be addressed separately.

Barth et al. point out that a lack of a shared conceptual framework for DTs complicates cross-functional discussions. In their work, a systematic literature was conducted, and they proposed the main dimensions of DTs in the form of an ontology and conducted a conceptual framework from it [17]. Josifovska et al. are point out that in the application of cyber-physical systems; there are still many challenges in designing and realizing one. One of the challenges is described as the need for DTs as high-fidelity mirroring images. Nevertheless, no blueprint offers the main building blocks to construct a DT, which hinders best practices. They performed a systematic literature review and proposed a framework that specifies the main building blocks of a DT in terms of structure and interrelations. They identified the main building blocks as Physical Entity Platform, Virtual Entity Platform, Data Management Platform, and Service Platform and described their structural properties [20]. Niu et al. state that it is crucial to effectively capture, share, and manage design-related information in complex design environments due to changing market and customer needs and, therefore, evolving product design and development. They deem a comprehensive product design lifecycle information model (PDLIM) essential. Despite the DT's significant potential for gathering and managing product lifecycle data, they have identified a gap in this area. In their work, they propose, in part, a structure for the PDLIM and have explored the key design information items against product lifecycle stages [21]. Barth et al. [17], Josifovska et al. [20], and Niu et al. [21] do not address process models but rather frameworks that have individual structures, elements, or aspects that can make up a DT. Some of these are so general that they can be applied to a wide range of use cases. According to Niu et al., identifying and reviewing the necessary components that can form a DT is essential. These components may include relationships between elements of the DT, which are highlighted in their study. In some cases, they specifically address hierarchical relationships or links to product development phases. However, the three concepts described in the papers have in common that they do not describe a procedure in terms of processes at a different level of abstraction. Therefore, it is impossible to classify them according to the von Lindemann's classification of product development concepts.

Che et al. [18] explain the use of the Digital Twin-Based Definition (DTBD) and outline a highly abstract process that links product development, manufacturing, and the customer. In doing so, they illuminate that divergent objectives between design and manufacturing can lead to suboptimal design or manufacturing outcomes. In this context, a thorough examination of operational data, fault data and processes a provides an effective method for problem solving and optimisation of the DTBD model. Again, the background is that a lack of methods for defining a digital model has been identified that can be used from design, manufacturing, and up through the product management process. This sequence should, therefore, be understood more as an abstract basic concept because it merely explains the steps of application and the associated development, respectively, optimization steps at the particular stakeholder. The detailing of the procedure describes further modules and functions. The functions of the data analysis model are kept general so that, for example, only PCA, clustering analysis, and data classification are mentioned. The product model is also described with components such as digital twin tech, measuring tools, and the associated dataset. Since the development steps of the DTBD can be described as a sequence of phases, it can be categorized into Lindemann's concept of 'phases and grouping of tasks' as described in section 2 [15]. Jeong et al. [19] present a process built on generic phases for production logistics. It consists of five dimensions the physical environment, virtual environment, data, data exchange connections, and services utilized by production logistics staff. Activities were specifically named and are assigned to the dimensions in the respective phases so that users have a sequence and concrete steps for orientation when designing DTs. Since activities are named and assigned to dimensions but not described in detail, this process is attributed to the grouping of tasks. Riedelsheimer et al. [22] have tested established approaches to product development against their criteria. The approaches tested are V-model for mechatronic systems, V-Modell XT, Waterfall model, Spiralmodell, R(UP) and SCRUM. Whereas the criteria tested against are interdisciplinarity, system complexity and diversity, level of detail, flexibility, relevance, sustainability, variant management and simplicity. The result of their evaluation is that the identified methods pay too little attention to the criteria of sustainability or do not sufficiently fulfil the integration of one or more domains, since there is often a focus on mechatronics or software development and less on the development of services or data engineering. To fill the identified research gap, the paper builds on the V-Model to specifically address the criteria of interdisciplinarity, system complexity and diversity, sustainability and variant consideration for the development of a DT. The resulting and presented approach is called Digital Twin-V-model (DT-V-model), builds on the already-known V-model and also contains several domains and development cycles with different versions of the product, services and DT [22]. While according to Dombrowski, the V-Modell could be classified in both categories 'operational tasks' or 'phases and grouping of tasks', Lindemann assigns it to the category 'phases and grouping of tasks' - which is why the extended DT-V-Model is also classified in this category in this work [15]. The central aspects of the described papers are summarised in Table 3.

Table 3: Summary of central concepts for deriving the DT from the literature analysed.

No.	Paper	Central concept for deriving the DT	Concepts in product development
1	Barth et al.	▪ Literature-derived ontology and framework based on it structure DT into three qualitative dimensions: Data Resources, External Value Creation, and Internal Value Creation. ▪ Conceptual models and ontologies are pivotal in requirements engineering, aiming to clearly represent a system's principles and functionalities. These models should achieve four key goals: enhancing understanding, facilitating communication among stakeholders, providing a design reference, and documenting the system for future collaboration.	Not applicable
2	Che et al.	▪ Digital Twin-Based Definition (DTBD) framework, a tool for product design that supports creation, optimization, and management of physical product models and their Digital Twins, is described and proposed. It includes the following aspects: Design model, process model, product model, virtual model, data analysis model and file model. ▪ The paper illustrates the DTBD model's application and development, detailing an abstract optimization cycle based on process capability and design requirements, facilitating collaboration between design and manufacturing entities.	'phases and grouping of tasks'
3	Jeong et al.	▪ The design process for Digital Twins in production logistics hinges on five dimensions: the physical environment, virtual environment, data, data exchange connections, and services utilized by production logistics staff. ▪ A process for the design of DTs is shown that consists of involves pre-study, conceptual, and detailed design phases. This process encompasses activities that align with the dimensions and stages inherent to the design of Digital Twins in production logistics.	'phases and grouping of tasks'
4	Josifovska et al.	▪ Reference Framework for DTs within Cyber-Physical Systems that specifies the main building blocks of a DT in terms of structure and interrelations. ▪ The identified main building blocks of the DT as a framework are: Physical Entity Platform (PEP), Virtual Entity Platform (VEP), Data Management Platform (DMP) and Service Platform (SP).	Not applicable
5	Niu et al.	▪ The Product Design Lifecycle Information Model (PDLIM) provides a structure referred to as a 'wardrobe,' with designated 'drawers' for organizing and storing key information classified by a product's lifecycle. ▪ The drawers are thereby designated as optional and it explained how the key information items at each design phase associated with both in-house and crowdsourcing design environments.	Not applicable
6	Riedelsheimer et al.	▪ A methodology to develop DTs of physical IoT-based products, the so called DT V-Model, is proposed. It aims to optimize the systems sustainability, specifically environmental aspects. ▪ This approach is an enriched V-model for smart product development, supplemented with additional roles and strategies for the development of DTs.	'phases and grouping of tasks'

4. Transfer to the modelling of the AAS.

This section addresses RQ3: How can approaches from the concepts be transferred to the application of the AAS? This is intended to show the extent to which the findings from the work could also be used for the design and implementation of the AAS.

On the one hand, approaches can be identified that provide the user with reusable elements and elements that are already predefined to a certain degree, which are intended to cover partial aspects of a DT. These are not procedures and can, therefore, not be classified according to the categories established by Lindemann. This is the case for the work of Barth et al., Jorifovska et al., and Niu et al. The ontology shown by Barth et al. and the dimensions based on it that can help to structure a DT can also be of use in structuring the AAS by trying to map the different dimensions and thus systematically holistically map the DT. Jorifovska et al. present the main building blocks mentioned in Table 3 and their associated properties. Application scenarios such as "optimization of production process in an industrial production line" are also mentioned in the framework. These structural properties of the presented DT framework can also be used to design the DT based on the AAS to obtain a holistic representation of an asset. Niu et al. have proposed PDLIM structure that is composed of key information perspectives based on the product life cycle, which in turn are also assigned key design information items. This structure was then, in turn, mapped to a generic perspective model that includes, for example, the perspective of the customer and the perspective of the product. In the conception of the AAS, rough guidelines can be obtained regarding which key design information items from various phases of the product lifecycle are relevant when creating a DT for an asset. It is important to note that these are only rough guidelines, as key information encompasses highly heterogeneous aspects.

Che et al. rather describe how their DTBD is applied with the involvement of different stakeholders and less how to derive a DT for a specific use case with the approach. The focus is also strongly on geometric properties such as tolerance, size, or structure. It is, therefore, not generally applicable to other use cases in the domain of data-driven product development [18]. Therefore, no aspects of the approach shown can be inferred for the design or derivation of the AAS. The framework described by Jeong et al. can be used to orient the structure of the AAS through the dimensions mentioned. In addition, at least some properties of the DT can be derived from the activities that are assigned to the respective phases in the work - e.g., when it comes to the requirements or application purpose of the DT. The framework described by Jeong et al. can be used to orient the structure of the AAS through the dimensions mentioned. In addition, at least some properties of the DT can be derived from the activities that are assigned to the respective phases in the work - e.g., when it comes to the requirements or application purpose of the DT. Several conclusions for the design of AAS can be drawn from the work of Riedelsheimer et al. On the one hand, it shows systematically and sequentially how the steps for creating the DT are integrated – such as the analysis of restrictions and the definition of the capabilities and functions of the DT up to the development of the DT. In this context, the initial tasks can also be applied to the AAS because as described in Section 1, a DT has to fulfil the requirements of a set of use cases in this context, therefore functions and capabilities represent a central aspect. On the other hand, the DT verification in the model's later stages is also covered. The AAS should also be continuously checked to see whether it meets the requirements placed on it and, if necessary, adapted. It also describes how to use (partially) predefined design elements for the DT [22]. However, according to the paper, these represent basic elements of a DT that consider, for example, hardware, software, data, and IT components. However, this differs from the submodels in terms of the AAS, which are all technically separated from each other, and each refers to well-defined subject matters. It should also be noted that the Methodology specifically addresses a use case where a DT is being developed for a product that has already been developed and is in use - so there is no parallel development of the product and the DT. Chet et al., Jeong et al., and Riedelsheimer et al. outline methods for constructing or implementing a DT. Accordingly, they can be categorized under Lindemann's classification, specifically within the 'phases and grouping of tasks' category. When developing new procedures to derive an AAS for specific use cases, it can make sense to map the activities contained therein to or around existing procedure models.

5. Conclusion and outlook

For this paper, a systematic literature review was conducted, searching for scientific publications on the derivation of DTs for data-driven product development in the context of Industry 4.0. The central concepts of the publications were summarised, and the research questions underlying the review were addressed.

First, it can be stated that only a small proportion of the papers found provide the user with approaches to guide him in deriving a DT for data-driven product development. It would be possible to expand or further optimise the literature search. However, examining the actual search string applied suggests that there are only few concepts to guide users for this. Using Lindemann's categories of development processes according to their level of resolution, it can be seen that not all levels of detail of development processes are addressed, which could be another indicator that the topic is not yet very well researched. To be more precise, all the procedures considered belong to the category 'phases and grouping of tasks'. In particular, there is a need for procedures that denote more concrete operational tasks and would fall into the category of the same name because there is also a presumption of a practical level of resolution that could provide guidance to the user.

Considering that the concept of AAS must be applied in the H2Giga-FRHY project, it is particularly noteworthy that no approach in the literature reviewed addresses an approach to derive an AAS. Thus, another research gap can be identified here. In this project, we attempt to develop a general approach for deriving a use-case-specific AAS while working on different AAS. This approach will be tested by developing an AAS to provide the assessment services described at the beginning and the actual transferability of the aspects described in section 4 must be verified.

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Biography

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