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Simple Design Approach for Shared Digital Twins

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Abstract

The collaborative utilization of data becomes increasingly important in industry and requires increased consideration of interoperability and data sovereignty aspects. Distributed systems play a decisive role in this context, which allow for a closer communication between the stakeholders involved and are characterized by the shared use of data and devices. At the same time new concepts emerge that enable a structured mapping of data. These include Digital Twins, which primarily allow a holistic digital representation of an entire asset lifecycle. Digital Twins offer significant potential for distributed systems and form a suitable basis for the collaborative utilization of an asset's lifecycle data. Although studies assume an increased use of Digital Twins in cross-company networks, they are still predominantly used as a purely company-internal concept. In the context of this publication, we demonstrate how to get started easily with the design of Digital Twins intended for use in collaborative distributed systems.

Keywords: Digital Twins, Design Principles, Asset Administration Shell, Industrie 4.0, Distributed Systems

1. Introduction

The design of Shared Digital Twins, used in a collaborative network of different participants, is still very rarely considered in the scientific literature on Digital Twins. In general, there is a lack of prescriptive literature regarding the design of Digital Twins. This refers in particular to the cross-company utilization of Digital Twins, which is addressed in the context of this paper. Nevertheless, the cross-company use of Digital Twins is becoming increasingly important in both academia and industry. Thus, there are already several publications within literature that increasingly deal with this topic (see Ramm et al. (2020), Uhlenkamp et al. (2020), Wang and Wang (2019)). Overall, these publications have a descriptive focus and neglect prescriptive instructions on how to create Digital Twins suitable for cross-company utilization. The cross-company utilization of Digital Twins also gains increasing relevance in practice. By 2025, almost 80% of all applications of Digital Twins are expected to be cross-company (Weber & Grosser, 2019). At the same time, however, it is also apparent that companies do not currently have the conceptual knowledge to instantiate such artifacts (Weber & Grosser, 2019). This article makes a decisive contribution to addressing this conceptual knowledge.

Research Objective: *Development of design principles that allow for easy instantiation of Shared Digital Twins usable in distributed and collaborative networks.*

The main objective of this paper is to develop design principles for Shared Digital Twins. The approach followed here bases on the publication by Haße et al. (2022). In the context of this publication, however, the authors choose a different approach. The development of design principles for Shared Digital Twins based on Haße et al. (2022) is essentially about taking into account expert knowledge from industry. The design principles derived in this context thus represent all the requirements that a Shared Digital Twin has to fulfill from the industry's point of view. Nevertheless, this research approach merely depicts a target idea of what an ideal type of Shared Digital Twins should look like. What is less considered is a realistic feasibility of the concept. Therefore, the goal within this paper is to develop design principles for Shared Digital Twins based on an existing instantiation. The basis for this is the RIOTANA-Asset-Administration-Shell (RIOTANA-AAS), a composite component consisting of an IoT architecture, an asset administration shell and a security architecture, which is regarded as a lean instantiation of a Shared Digital Twin (Haße et al., 2020).

This paper is structured as follows. After the introduction, we first explain the theoretical background of Digital Twins and Shared Digital Twins in section 2. Next, in section 3, we explain the basic methods that we use to develop the design

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principles. In Section 4, we focus on the description of the design principles themselves, followed by an evaluation of these principles in Section 5. Finally, in Sections 6 and 7, we describe the contribution and limitations of this paper and conclude with a final outlook.

2. Theoretical Background

2.1 Digital Twins: Origin and Definition

There are different interpretations regarding the conceptual foundation of Digital Twins in literature. A majority of publications refer to the NASA Apollo space project as the first application of Digital Twins (see Bergs et al. (2019), Barth et al. (2020) and Zhuang et al. (2018)). In this context, NASA deployed an identical capsule in the ground station for continuous monitoring of the space capsules (Rosen et al., 2015). Here, the constant monitoring of the physical counterpart describes an essential purpose of Digital Twins (see Aivaliotis et al. (2019)), however, it is less possible to refer to a Digital Twin in the sense of a digital representation. The origin of the concept of the Digital Twin as a digital representation dates back to Professor Michael Grieves of the Florida Institute of Technology in 2003 (Grieves, 2014). Michael Grieves introduced the concept of Digital Twins as an integration technology to holistically represent virtually all data generated during the lifecycle of an asset (Grieves, 2014). The most commonly applied definition is provided by Glaessgen and Stargel (2012) (Tao et al., 2019). Accordingly, a Digital Twin forms "*an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic […] integrates sensor data […] maintenance history and all available historical and fleet data obtained*." (Glaessgen & Stargel, 2012, p. 7). Table 1 shows the essential properties of Digital Twins.

Table 1. Basic properties of Digital Twins

Properties	Sources
Use of multiple data sources	Qi and Tao (2018), Preuveneers et al. (2018)
Semantic description of data	Rosen et al. (2015), Um et al. (2017), Negri et al. (2019)
Representation of the asset life cycle	Modoni et al. (2019), Monteiro et al. (2018), Orive et al. (2019), Merkle et al. (2019)
Digital representation of objects, processes and systems	Eckhart and Ekelhart (2018), Eisenträger et al. (2018), Guerra et al. (2019)
Analysis capabilities (simulation, monitoring, data processing, etc.)	Cimino et al. (2019), Alam and El Saddik (2017), Minos-Stensrud et al. (2018)

2.2 Shared Digital Twins

Shared Digital Twins combine the concept of digital representation of assets with the use of their lifecycle data in distributed systems. The understanding of Digital Twins provided so far in this paper remains valid in the context of distributed systems (see Table 1). This essentially includes the integration of data from various data sources (see Lutze (2019), Qiao et al. (2019)) and their semantic annotation with metadata, enabling a semantic description of the respective data models (see Rosen et al. (2015), Zehnder and Riemer (2018)). In addition, Digital Twins are capable of determining the state and behavior of assets based on these characteristics (Korth et al., 2018). When developing Shared Digital Twins, the aim is to transfer these properties to a distributed network of companies. The basic purposes of such distributed systems are essentially the sharing of data, devices and computing power (van Steen & Tanenbaum, 2017). Transferring the purposes of distributed systems to the concept of the Digital Twin, new business models can be considered that promote closer collaboration between companies involved in a value chain. For example, companies that offer a Shared Digital Twin generally pursue a collaborative business model (Uhlenkamp et al., 2020).

The term Shared Digital Twin is still largely unknown and requires a more precise delineation. In the course of further investigation of Shared Digital Twins, both concepts, distributed systems and Digital Twins, must first be considered more specifically (see Table 2). The goal of this paper is therefore to develop design principles for Shared Digital Twins that build on existing approaches for instantiating such an artifact. This approach provides an easy entry point to the development of Shared Digital Twins, as the design principles developed here build on existing solutions. Furthermore, this represents a new approach, as prescriptive research in the context of Digital Twins has been largely neglected.

Table 2. Implications for Digital Twins in distributed systems

Design goals of distributed systems according to van Steen and Tanenbaum (2017)	Implications
Shared use of resources	A Shared Digital Twin must be able to make data and data models available to the actors of the distributed system.
	Depending on the level of cooperation, the actors of the distributed system can access the respective resources of the Digital Twin and even adapt and extend it.
Transparency	A Shared Digital Twin must be able to provide the actors with a complete overview of the submodels released in each case
	Depending on the depth of cooperation, the actors of the distributed system can use different areas of the Digital Twin, extend it, or use it for their own applications
Openness	A Shared Digital Twin must have standardized elements so that the actors of the distributed system have the most barrier-free access to the elements possible.
	Depending on the depth of cooperation, this allows the actors to exchange semantically interoperable data models more easily and to integrate data into their own systems without barriers
Scalability	A Shared Digital Twin must be sufficiently scalable so that its use is possible for a large number of different actors
	Depending on the depth of cooperation, this allows the Shared Digital Twins to be used within different, complex use cases.

2.3 Examples of Shared Digital Twins

The scientific literature concerning Digital Twins rarely mentions specific examples or instantiations for Shared Digital Twins. Exceptions in this context are the publications by Ramm et al. (2020) and Haße et al. (2020). In their publication, Ramm et al. (2020) describe the development of the Co-TWIN concept, which focuses on the collaborative use of operational data in mechanical and plant engineering. The core of this concept is a collaborative Digital Twin that holistically captures all essential data across all phases and thus provides the basis for further analyses. Overall, this concept is to be embedded in a platform so that all stakeholders involved in the value creation process can benefit from it. Overall, however, it is not apparent on the basis of the publication how exactly this artifact is constructed. Another approach is offered by Haße et al. (2020), providing a holistic description of the RIOTANA-AAS, which is a Digital Twin suitable for the utilization in a collaborative network, consisting of various stakeholders. In contrast to Ramm et al. (2020), this publication provides a deeper insight into the technical design of the architecture (see Figure 1). This includes precise information on the structure of the security architecture and analysis functions. Furthermore, the architecture described includes the deployment of an Asset Administration Shell (AAS) by the German Initiative *Plattform Industrie 4.0*.

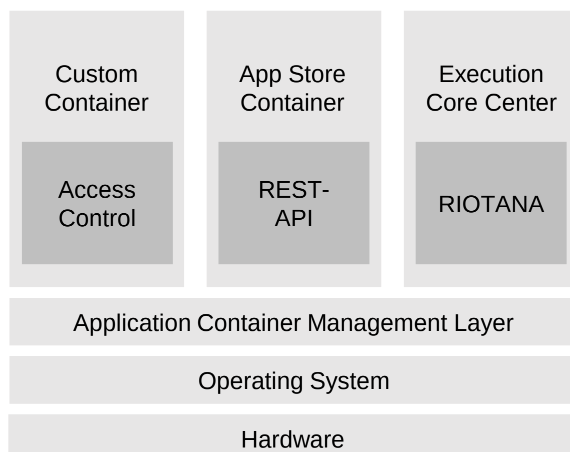

Figure 1. Simplified illustration of the RIOTANA-AAS architecture (Haße et al., 2020)

The AAS is the most mature model of a Digital Twin and enables the description of assets in a standardized format over their entire lifecycle (Bächle & Gregorzik, 2019; Seif et al., 2019). Due to the extensive and detailed technical description of the RIOTANA-AAS, this artifact forms the suitable basis for deriving the design principles in the further course of this publication.

3. Methodology

Approaches to developing design principles vary and depend on the research context (see Koppenhagen (2013), Daiberl et al. (2019) and Meth et al. (2015)). The approach adopted for the development of design principles bases on the process model according to Möller et al. (2020b) and merges various steps in the context of design-oriented research. Table 3 shows the approach chosen for this publication. The perspective is purely reflective, as the design principles have its foundation in the RIOTANA-AAS. The authors follow a qualitive research design, as we derive knowledge based on a specific instantiation of a Shared Digital Twin for Shared Digital Twins in general. We do derive meta-requirements for the development of the design principles, based on a taxonomy, which allows for direct extraction of the design principles based on the artifact characteristics. The derivation of meta-requirements is particularly useful in the context of supportive approaches, but is generally not mandatory (Möller et al., 2020b).

Table 3. Design principles development approach (Möller et al., 2020b)

Dimension	Characteristics
Perspective	Reflective
Research Design	Qualitative
MR Source	Taxonomy
DP Design	Extracted
Iterations	Single
Evaluation	Argumentation
Formulation	Based on Template

In the context of the investigation presented here, we use a single iteration, performing an argumentative evaluation. The formulation of the design principles itself follows the formulation guideline according to Chandra et al. (2015), as there is a meaningful subdivision of the design principles into *material property*, *activity of user* and *boundary conditions* (see Table 4).

Table 4. Design principle formulation (Chandra et al., 2015, p. 4045)

Design Principle Formulation
"Provide the system with [material property—in terms of form and function] in order for users to [activity of user/group of users—in terms of action], given that [boundary conditions—user group's characteristics or implementation settings]"

3.1 Design Principle Development

Design principles form an essential object of consideration within the scope of design theories and represent an artifact themselves (Möller et al., 2020b). The goal of design principles is generally the codification of design knowledge as well as the specification of prescriptive instructions for action, which in turn enables an instantiation of design knowledge (Chandra Kruse et al., 2016; Gregor & Hevner, 2013; Heinrich & Schwabe, 2014). In general, design principles can be considered as a "*a recommendation or suggestion for a course of action to help solve a design issue*" (McAdams, 2003, p. 357). The development of the design principles follows a certain process, illustrated in Figure 2. The first step is to extract individual meta-requirements based on a meaningful framework. For this purpose, the authors choose the taxonomy of Digital Twins according to van der Valk et al. (2020). Once we have derived the meta-requirements, we can use this as a basis for determining the design principles through logical content aggregation.

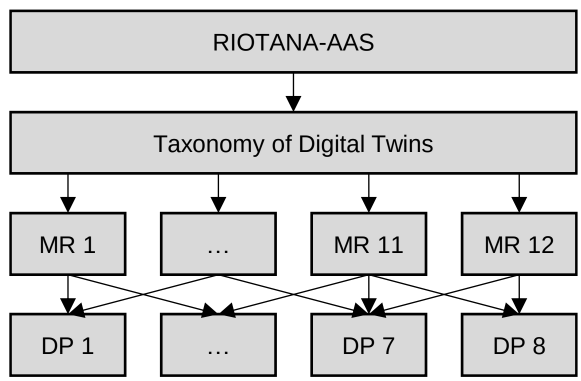

Figure 2. Adjusted development of design principles according to Walls et al. (1992), Koppenhagen et al. (2012), Chandra et al. (2015) and Möller et al. (2020a)

3.2 Artifact Characteristics

Before deriving the design principles based on the RIOTANA-AAS, it requires an intermediate step that allows a meaningful categorization of the characteristics of this artifact. Basically, taxonomies form a suitable basis for the development of design principles, since there is an interweaving of the domain constructs in both artifacts (Möller et al., 2021). The taxonomy chosen here is a suitable starting point for this, since it follows the approach of enabling a holistic conceptual characterization of Digital Twins (see van der Valk et al. (2020), van der Valk et al.

(2022)). Table 5 shows the taxonomy with the identified characteristics of the RIOTANA-AAS. The characteristics identified here form the basis for the derivation of the design principles.

Table 5. Deriving meta-requirements from design options based on the taxonomy of Digital Twins according to van der Valk et al. (2022)

Dimension	Characteristics		
Data Acquisition	Automated		
Data Source	Multiple Sources		
Synchronization	With		
Data Input	Raw Data	Preproces-sed Data	
Data Governance	Rules Applied		
Data Link	One-Directional		
Interface	HMI	M2M	
Interoperability	Fully		
Purpose	Pro-cess-ing	Trans-fer	Re-pository
Accuracy	Partial		
Conceptual Elements	Bound		
Time of Creation	Physical First		

4. Design Principles for Shared Digital Twins

Figure 3 illustrates the connection between the meta-requirements collected on the basis of the classification of the RIOTANA-AAS within the taxonomy (see Table 5) and the final design principles extracted from them. In total, we derived eight design principles for Shared Digital Twins.

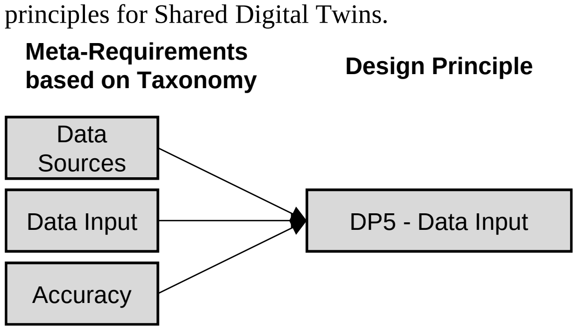

Figure 3. Exemplary relation between the meta-requirements based on the taxonomy and the final design principles

4.1 Data Link

DP-1: Data Link
Provide the Digital Twin with uni-directional data link capabilities in order for users to have a direct connection between the physical counterpart and the Digital Twin, given that the Digital Twin serves for cross-company and multilateral data sharing.

The first design principle relates to the data link and refers to the connection between the physical asset and the Digital Twin. The use of a merely unidirectional connection provides the lowest possible threshold for the instantiation of a Shared Digital Twin. This avoids the need to implement an additional interface. This feature has the disadvantage that the data can not be transferred from the Digital Twin to its physical counterpart. Nevertheless, a simple, unidirectional connection is sufficient in many cases (see Banerjee et al. (2017), Dahmen and Rossmann (2018)).

4.2 Purpose

DP-2: Purpose
Provide the Digital Twin with customized functionalities in order for users to process, transfer and store data, given that the Digital Twin's purpose is to enable cross-company and multilateral data sharing.

The intended purpose of a Shared Digital Twin varies depending on the use case. Digital Twins can generally be used in numerous different use cases and allow for a complete semantic description of all data being integrated (see Zehnder and Riemer (2018)). In general, Table 1 provides a sound overview of the basic properties of Digital Twins, which continue to be relevant in the context of the purpose of Shared Digital Twins.

4.3 Interface

DP-3: Interface
Provide the Digital Twin with Interfaces in order for users to interact with the Digital Twin on the one hand and on the other to allow for a direct and human independent communication between distributed systems, given that the Digital Twin serves for cross-company and multilateral data sharing.

In the context of a distributed use of Digital Twins in a collaborative network, it is important to allow as many actors as possible to access the Digital

Twin. This is directly related to the design of a distributed system according to van Steen and Tanenbaum (2017) (see Table 2). Accordingly, in the case of a Shared Digital Twin, it must be possible to ensure to use primarily those technical components that allow for an easy access to the system. Regarding the interface, this could simply be a user interface that provides an overview of all important process parameters (see Zhu et al. (2019)).

4.4 Synchronization

DP-4: Synchronization
Provide the Digital Twin with convenient synchronization functionalities in order for users to receive both a constant real-time update of incoming data and on demand also a non-real-time data update, given that the Digital Twin enables cross-company and multilateral data sharing.

This design principle describes the synchronization between the Shared Digital Twin and its physical counterpart. In this context, the RIOTANA-AAS features both characteristics, a real-time synchronization as well as a synchronization on demand. This design principle also directly relates to the design goals of distributed systems stated by van Steen and Tanenbaum (2017). Many stakeholders in a distributed system will technically not be able to synchronize the Shared Digital Twin in a fully automated way. Therefore, the characteristic of an on-demand synchronization is of importance.

4.5 Data Input

DP-5: Data Input
Provide the Digital Twin with capabilities to process both raw data and processed data in order for users to have a complete data set of the counterpart, given that the Digital Twin enables cross-company and multilateral data sharing.

The ability to support both processed and unprocessed data is an important approach to having a complete digital representation of the physical counterpart under consideration. The design principle is in line with the requirement of a distributed system to provide the respective users with a complete overview of all submodels of the Shared Digital Twin (see Table 2).

4.6 Data Acquisition

DP-6: Data Acquisition
Provide the Digital Twin with functionalities to obtain a fully-automated data acquisition in order for users to have the least possible effort in recording these data, given that the Digital Twin enables cross-company and multilateral data sharing.

This design principle emphasizes the need to keep the utility effort of a Shared Digital Twin as low as possible. In this context, an automated data acquisition should be a priority, since any manual intervention would involve unnecessary effort. As with the previous design principles, there is also a direct link to the design goals of distributed systems, since a primarily automated data acquisition ensures an easy access for all stakeholders (see Table 2).

4.7 Interoperability

DP-7: Interoperability
Provide the Digital Twin with established standard interfaces that allow users to share data as seamlessly as possible within the distributed system, given that the Digital Twin enables cross-company and multilateral data sharing.

Interoperability is an essential characteristic for using a Shared Digital Twin in a distributed collaborative system. The lowest entry point here requires that all stakeholders involved agree on a common interoperability standard. In this context, the AAS forms the interoperability component. The use of the AAS makes assets visible within the Industrie 4.0 network and essentially provides semantic interoperability between these assets (Chilwant & Kulkarni, 2019). Accordingly, the component is able to link different actors within this network and enable the cross-company sharing of data.

4.8 Data Security

DP-8: Data Security
Provide the Digital Twin with security concepts that allow for restricting access to the data and for preventing unauthorized access to the data, given that the Digital Twin enables cross-company and multilateral data sharing.

This design principle emphasizes the utilization of a simple and proven security concept to prevent unauthorized access to the Shared Digital Twin. A proven concept here is an attribute-based access control, which controls access rights on the basis of so-called attributes (Bader et al., 2019). This is a suitable concept which the AAS also utilizes (Bader et al., 2019). Generally, the aspect of data security is of important significance in the context of a Shared Digital Twin. Only a sufficient security concept can ensure that as many players as possible agree to participate in the distributed system.

5. Evaluation

The design principles for Shared Digital Twins elaborated here provide an easy entry into the instantiation of such artifacts. At the same time, the design principles developed in the context of this publication differ in four essential aspects from those of Haße et al. (2022). Both publications take a different approach to developing the design principles. In Haße et al. (2022), the authors develop eight design principles for Shared Digital Twins based on a qualitative interview series. The identification of the relevant characteristics thus reflects a certain expectation of the industry with regard to the construction of such a Digital Twin. In the context of this paper, the RIOTANA-AAS forms the basis for the development of the design principles, which serves as an exemplary template of a Shared Digital Twin and represents a composite component of different technologies. We therefore follow here the approach of a reflective derivation based on an existing instantiation of a Shared Digital Twin (Möller et al., 2020b). A central and novel aspect of this contribution is the feasibility of the RIOTANA-AAS, which has been confirmed in various test runs (Haße et al., 2020). The classification of this artifact within the taxonomy (see Table 5) thus results in specifications that are fully feasible and have already been implemented in this way.

Table 6. Comparison of the varying design principles from both contributions.

This contribution	Haße et al. (2022)
Data Link	
uni-directional	bi-directional
Data Aquisition	
fully automated	semi-automated
Interoperability	
fully interoperable	via translator
Data Security	
access control	usage control

Table 6 shows the differences between the two approaches. Especially with respect to the adoption of common standards and access control, this paper highlights the conceptual differences in terms of ease of implementation. With regard to the *Data Link* and *Data Acquisition*, the approach presented here maintains the use of such technologies, which are associated with a lower implementation effort compared to Haße et al. (2022). In the case of a uni-directional *Data Link*, for example, it does not require any further interface on the physical counterpart. Regarding a fully automated *Data Acquisition*, there is no need for additional functionality that enables a manual acquisition, thus resulting in a significantly lower implementation effort in the approach described within this contribution.

6. Contribution and Limitations

The contents developed within this paper form an important contribution for the use of Digital Twins in distributed systems and cross-company networks. This applies to both the scientific and the practical contribution. Regarding this contribution it becomes apparent that Digital Twins are an important core building block for the creation of cross-company networks. A key aspect here is the integration of all relevant lifecycle data, supplemented by a complete semantic description, allowing for collaborative use in distributed systems to develop new, data-driven business models. In the context of the **scientific contribution**, this paper provides another essential input regarding the development of prescriptive knowledge related to the instantiation of Shared Digital Twins. This subject area continues to be rarely included in the context of the scientific literature on Digital Twins. This applies both to Digital Twins in general as well as to the use of Digital Twins in collaborative networks. With regard to the **practical contribution**, this publication offers a suitable guidance for the instantiation of Shared Digital Twins. The distinctive addition in this context stems from the focus on a comparatively easy-to-implement solution, based on an already existing instantiation. Generally, the design principles for Shared Digital Twins are suitable for workshops, where experts with both performative and epistemic expertise can work together to develop these types of Digital Twins (see Weinstein (1993)). Nevertheless, we need to consider the **limitations** of the present contribution. When developing design principles, the general challenge is to keep them sufficiently generic so that they address a class of artifacts and not just one instance (Sein et al., 2011). Furthermore, the design principles developed in this contribution base on a pre-existing instantiation of a Shared Digital Twin, thus investigating a different instantiation would certainly have produced different characteristics. Overall, however, it must be noted that the RIOTANA-AAS provides a suitable basis for investigating the essential characteristics of Shared Digital Twins.

7. Outlook

The results of this paper offer a sufficient number of starting points for further, more in-depth considerations of the topic of Shared Digital Twins. In general, the topic of the cross-company use of Digital Twins is comparatively unexplored and requires more extensive examination. The design principles developed in this context can be seen as a suitable basis for further investigation of concepts that include aspects from the area of cloud computing in particular. The use of cloud technologies represents a significant success factor in the context of Shared Digital Twins. However, it remains unclear in this context which concepts from the field of cloud computing are best suited for the use of Shared Digital Twins. Furthermore, the subject area of the Shared Digital Twin must be considered from various perspectives that go beyond technical aspects and have a legal and organizational context. This refers in particular to standardization efforts that must be advanced in the course of the cross-company use of Digital Twins. In particular, this relates to current and future developments within the German Initiative *Plattform Industrie 4.0* and *Industrial Digital Twin Association*. Thus, the results of this paper have the potential to be regarded as a basis for facilitating the prioritization of further development steps in the context of the *Industrie 4.0 Asset Administration Shell*.

8. References

Aivaliotis, P., Georgoulias, K., & Alexopoulos, K. (2019). Using Digital Twin for Maintenance Applications in Manufacturing: State of the Art and Gap Analysis. In *Proceedings of the IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1–5). IEEE. https://doi.org/10.1109/ICE.2019.8792613

Alam, K. M., & El Saddik, A. (2017). C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems. *IEEE Access*, *5*, 2050–2062. https://doi.org/10.1109/ACCESS.2017.2657006

Bächle, K., & Gregorzik, S. (2019). *Digital Twins in Industrial Applications: Requirements to a Comprehensive Data Model.* Industrial Internet Consortium. https://www.iiconsortium.org/news/joi-articles/2019-November-JoI-Digital-Twins-in-Industrial-Applications.pdf

Bader, S., Barnstedt, E., Bedenbender, H., Billmann, M., & Boss, B. (2019). *Details of the Asset Administration Shell: Part 1 - The exchange of information between partners in the value chain of Industrie 4.0 (Version 2.0).* Plattform Industrie 4.0; ZVEI - Zentralverband Elektrotechnik- und Elektronikindustrie. https://www.zvei.org/presse-medien/publikationen/details-of-the-asset-administraion-shell/

Banerjee, A., Dalal, R., Mittal, S., & Joshi, K. P. (2017). Generating Digital Twin models using Knowledge Graphs for Industrial Production Lines. In *Websci'17: Proceedings of the 2017 ACM Web Science Conference : June 25-28, 2017, Troy, NY, USA* (pp. 425–430). ACM Association for Computing Machinery. https://doi.org/10.1145/3091478.3162383

Barth, L., Ehrat, M., Fuchs, R., & Haarmann, J. (2020). Systematization of Digital Twins. In *ACM Digital Library, Proceedings of the 2020 The 3rd International Conference on Information Science and System* (pp. 13–23). Association for Computing Machinery. https://doi.org/10.1145/3388176.3388209

Bergs, C., Heizmann, M., Hartmann, D., & Carillo, G. L. (2019). Novel method for online wear estimation of centrifugal pumps using multi-fidelity modeling. In *Proceedings, 2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS 2019): Howards Plaza Hotel, Taipei, Taiwan, 06-09 May, 2019* (pp. 185–190). IEEE. https://doi.org/10.1109/ICPHYS.2019.8780197

Chandra, L., Seidel, S., & Gregor, S. (2015). Prescriptive Knowledge in IS Research: Conceptualizing Design Principles in Terms of Materiality, Action, and Boundary Conditions. In T. X. Bui & R. H. Sprague (Eds.), *48th Hawaii International Conference on System Sciences (HICSS), 2015: 5 - 8 Jan. 2015, Kauai, Hawaii* (pp. 4039–4048). IEEE. https://doi.org/10.1109/HICSS.2015.485

Chandra Kruse, L., Seidel, S., & Purao, S. (2016). Making Use of Design Principles. In J. Parsons (Ed.), *Lecture notes in computer science Information systems and applications, incl. Internet/Web, and HCI: Vol. 9661. Tackling society's grand challenge with design science: 11th international conference, DESRIST 2016, St. John's, NL, Canada, May 23-25, 2016 : Proceedings* (Vol. 9661, pp. 37–51). Springer. https://doi.org/10.1007/978-3-319-39294-3_3

Chilwant, N., & Kulkarni, M. S. (2019). Open Asset Administration Shell for Industrial Systems. *Manufacturing Letters*, *20*, 15–21. https://doi.org/10.1016/j.mfglet.2019.02.002

Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of Digital Twin Applications in Manufacturing. *Computers in Industry*, *113*, Article 103130. https://doi.org/10.1016/j.compind.2019.103130

Dahmen, U., & Rossmann, J. (2018). Experimentable Digital Twins for a Modeling and Simulation-based Engineering Approach. In *4th IEEE International Symposium on Systems Engineering: October 1-3, 2018, Rome Marriott Park Hotel, Roma, Italy : 2018 symposium* *proceedings* (pp. 1–8). IEEE. https://doi.org/10.1109/SysEng.2018.8544383

Daiberl, C. F., Oks, S. J., Roth, A., Möslein, K. M., & Alter, S. (2019). Design principles for establishing a multi-sided open innovation platform: lessons learned from an action research study in the medical technology industry. *Electronic Markets*, *29*(4), 711–728. https://doi.org/10.1007/s12525-018-0325-2

Eckhart, M., & Ekelhart, A. (2018). A Specification-based State Replication Approach for Digital Twins. In D. Lie & M. Mannan (Eds.), *Proceedings of the 2018 Workshop on Cyber-Physical Systems Security and PrivaCy - CPS-SPC '18* (pp. 36–47). ACM Press. https://doi.org/10.1145/3264888.3264892

Eisenträger, M., Adler, S., Kennel, M., & Möser, S. (2018). Changeability in Engineering. In *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1–8). IEEE. https://doi.org/10.1109/ICE.2018.8436295

Glaessgen, E., & Stargel, D. (2012). The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In *Structures, Structural Dynamics, and Materials and Co-located Conferences: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference* (1-14). American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2012-1818

Gregor, S., & Hevner, A. R. (2013). Positioning and Presenting Design Science Research for Maximum Impact. *MIS Quarterly*, *37*(2), 337–355. https://doi.org/10.25300/MISQ/2013/37.2.01

Grieves, M. (2014). *Digital Twin: manufacturing Excellence Through Virtual Factory Replication.*

Guerra, R. H., Quiza, R., Villalonga, A., Arenas, J., & Castano, F. (2019). Digital Twin-Based Optimization for Ultraprecision Motion Systems With Backlash and Friction. *IEEE Access*, *7*, 93462–93472. https://doi.org/10.1109/ACCESS.2019.2928141

Haße, H., van der Valk, H., Möller, F., & Otto, B. (2022). Design Principles for Shared Digital Twins in Distributed Systems. *Business & Information Systems Engineering.* Advance online publication. https://doi.org/10.1007/s12599-022-00751-1

Haße, H., van der Valk, H., Weißenberg, N., & Otto, B. (2020). Shared Digital Twins : Data sovereignty in logistics networks. Advance online publication. https://doi.org/10.15480/882.3119

Heinrich, P., & Schwabe, G. (2014). Communicating Nascent Design Theories on Innovative Information Systems through Multi-grounded Design Principles. In *Proceedings of the 9th International Conference on Design Science Research in Information Systems and Technology,* Miami: USA.

Koppenhagen, N. (2013). *Design Principles for Supply Network Systems*. https://madoc.bib.uni-mannheim.de/35382/

Koppenhagen, N., Gaß, O., & Müller, B. (2012). Design Science Research in Action - Anatomy of Success Critical Activities for Rigor and Relevance, 1–12. https://doi.org/10.5445/IR/1000055012

Korth, B., Schwede, C., & Zajac, M. (2018). Simulation-Ready Digital Twin for Realtime Management of Logistics Systems. In *2018 IEEE International Conference on Big Data (Big Data)* (pp. 4194–4201). IEEE. https://doi.org/10.1109/BigData.2018.8622160

Luntovskyy, A., & Gütter, D. (2020). *Moderne Rechnernetze*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-25617-3

Lutze, R. (2019). Digital Twins in eHealth – : Prospects and Challenges Focussing on Information Management. In *Proceedings of the IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1–9). IEEE. https://doi.org/10.1109/ICE.2019.8792622

McAdams, D. A. (2003). Identification and Codification of Principles for Functional Tolerance Design. *Journal of Engineering Design*, *14*(3), 355–375. https://doi.org/10.1080/0954482031000091095

Merkle, L., Segura, A. S., Torben Grummel, J., & Lienkamp, M. (2019). Architecture of a Digital Twin for Enabling Digital Services for Battery Systems. In *Proceedings, 2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS 2019): Howards Plaza Hotel, Taipei, Taiwan, 06-09 May, 2019* (pp. 155–160). IEEE. https://doi.org/10.1109/ICPHYS.2019.8780347

Meth, H., Mueller, B., & Maedche, A. (2015). Designing a Requirement Mining System. *Journal of the Association for Information Systems*, *16*(9), 799–837. https://doi.org/10.17705/1jais.00408

Minos-Stensrud, M., Haakstad, O. H., Sakseid, O., Westby, B., & Alcocer, A. (2018). Towards Automated 3D Reconstruction in SME Factories and Digital Twin Model Generation. In *Iccas 2018: 18th International Conference on Control, Automation and Systems* (pp. 1777–1781). IEEE.

Modoni, G. E., Caldarola, E. G., Sacco, M., & Terkaj, W. (2019). Synchronizing physical and digital factory: benefits and technical challenges. *Procedia CIRP*, *79*, 472–477. https://doi.org/10.1016/j.procir.2019.02.125

Möller, F., Guggenberger, T. M., & Otto, B. (2020a). Design Principles for Route Optimization Business Models: A Grounded Theory Study of User Feedback. *15th International Conference on Wirtschaftsinformatik, March 08-11, 2020, Potsdam, Germany*, 1084–1099. https://doi.org/10.30844/wi_2020_j10-moeller

Möller, F., Guggenberger, T. M., & Otto, B. (2020b). Towards a Method for Design Principle

Development in Information Systems, 208–220. https://doi.org/10.1007/978-3-030-64823-7_20
Möller, F., Haße, H., Azkan, C., van der Valk, H., & Otto, B. (2021). Design of Goal-Oriented Artifacts from Morphological Taxonomies: Progression from Descriptive to Prescriptive Design Knowledge, *46*, 523–538. https://doi.org/10.1007/978-3-030-86790-4_36
Monteiro, J., Barata, J., Veloso, M., Veloso, L., & Nunes, J. (2018). Towards Sustainable Digital Twins for Vertical Farming, 234–239. https://doi.org/10.1109/ICDIM.2018.8847169
Negri, E., Fumagalli, L., Cimino, C., & Macchi, M. (2019). FMU-Supported Simulation for CPS Digital Twin. *Procedia Manufacturing*, *28*, 201–206. https://doi.org/10.1016/j.promfg.2018.12.033
Orive, D., Iriondo, N., Burgos, A., Sarachaga, I., Alvarez, M. L., & Marcos, M. (2019). Fault injection in Digital Twin as a means to test the response to process faults at virtual commissioning. In *Proceedings, 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA): Paraninfo Building, University of Zaragoza, Zaragoza, Spain, 10-13 September, 2019* (pp. 1230–1234). IEEE. https://doi.org/10.1109/ETFA.2019.8869334
Preuveneers, D., Joosen, W., & Ilie-Zudor, E. (2018). Robust Digital Twin Compositions for Industry 4.0 Smart Manufacturing Systems, 69–78. https://doi.org/10.1109/EDOCW.2018.00021
Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*, *6*, 3585–3593. https://doi.org/10.1109/ACCESS.2018.2793265
Qiao, Q., Wang, J., Ye, L., & Gao, R. X. (2019). Digital Twin for Machining Tool Condition Prediction. *Procedia CIRP*, *81*, 1388–1393. https://doi.org/10.1016/j.procir.2019.04.049
Ramm, S., Wache, H., Dinter, B., & Schmidt, S. (2020). Der Kollaborative Digitale Zwilling: Herzstück eines integrierten Gesamtkonzepts. *ZWF Zeitschrift Für Wirtschaftlichen Fabrikbetrieb*, *115*(special), 94–96. https://doi.org/10.3139/104.112319
Rosen, R., Wichert, G. von, Lo, G., & Bettenhausen, K. D. (2015). About The Importance of Autonomy and Digital Twins for the Future of Manufacturing. *IFAC-PapersOnLine*, *48*(3), 567–572. https://doi.org/10.1016/j.ifacol.2015.06.141
Seif, A., Toro, C., & Akhtar, H. (2019). Implementing Industry 4.0 Asset Administrative Shells in Mini Factories. *Procedia Computer Science*, *159*, 495–504. https://doi.org/10.1016/j.procs.2019.09.204
Sein, Henfridsson, Purao, Rossi, & Lindgren (2011). Action Design Research. *MIS Quarterly*, *35*(1), 37–56. https://doi.org/10.2307/23043488
Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Y., & Nee, A. Y. C. (2019). Digital Twin-Driven Product Design Framework. *International Journal of Production Research*, *57*(12), 3935–3953. https://doi.org/10.1080/00207543.2018.1443229
Uhlenkamp, J.-F., Hribernik, K., & Thoben, K.-D. (2020). Wie Digitale Zwillinge Unternehmensgrenzen überwinden: Ein Beitrag zur Gestaltung von Digitalen Zwillingen mit unternehmensübergreifenden Anwendungen im Produktlebenszyklus. *ZWF Zeitschrift Für Wirtschaftlichen Fabrikbetrieb*, *115*(special), 84–89. https://doi.org/10.3139/104.112304
Um, J., Weyer, S., & Quint, F. (2017). Plug-and-Simulate within Modular Assembly Line enabled by Digital Twins and the use of AutomationML. *IFAC-PapersOnLine*, *50*(1), 15904–15909. https://doi.org/10.1016/j.ifacol.2017.08.2360
van der Valk, H., Haße, H., Möller, F., Arbter, M., Henning, J.-L., & Otto, B. (2020). A Taxonomy of Digital Twins. In *AMCIS 2020 Proceedings*. AIS.
van der Valk, H., Haße, H., Möller, F., & Otto, B. (2022). Archetypes of Digital Twins. *Business & Information Systems Engineering*, *64*(3), 375–391. https://doi.org/10.1007/s12599-021-00727-7
van Steen, M., & Tanenbaum, A. S. (2017). *Distributed systems* (Third edition (Version 3.01 (2017))). Pearson Education.
Walls, J. G., Widmeyer, G. R., & El Sawy, O. A. (1992). Building an Information System Design Theory for Vigilant EIS. *Information Systems Research*, *3*(1), 36–59. https://doi.org/10.1287/isre.3.1.36
Wang, X. V., & Wang, L. (2019). Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. *International Journal of Production Research*, *57*(12), 3892–3902. https://doi.org/10.1080/00207543.2018.1497819
Weber, U., & Grosser, H. (2019). *Digitale Zwillinge: Wegbereiter für Ökosysteme von morgen*. https://www.detecon.com/drupal/sites/default/files/2019-10/ST_Digitaler_Zwilling_final_online_091019_0.pdf
Weinstein, B. D. (1993). What is an expert? *Theoretical Medicine*, *14*(1), 57–73. https://doi.org/10.1007/BF00993988
Zehnder, P., & Riemer, D. (2018). Representing Industrial Data Streams in Digital Twins using Semantic Labeling. In *2018 IEEE International Conference on Big Data (Big Data)* (pp. 4223–4226). IEEE. https://doi.org/10.1109/BigData.2018.8622400
Zhu, Z., Liu, C., & Xu, X. (2019). Visualisation of the Digital Twin data in manufacturing by using Augmented Reality. *Procedia CIRP*, *81*, 898–903. https://doi.org/10.1016/j.procir.2019.03.223
Zhuang, C., Liu, J., & Xiong, H. (2018). Digital Twin-Based Smart Production Management and Control Framework for the Complex Product Assembly Shop-Floor. *The International Journal of Advanced Manufacturing Technology*, *96*, 1149–1163. https://doi.org/10.1007/s00170-018-1617-6