Concept for interoperable digital twins for wind turbines based on a digital thread

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Abstract

Digital Twins offer great potential for wind energy by combining different data and analysis methods to leverage optimization potential or develop new value-adding services. However, the data availability and interoperability of relevant lifecycle data across system and organizational boundaries is still a challenge in wind industry, as data silos and high data heterogeneity still remain prevalent. This paper p[1]resents a concept for the creation of standards-based interoperable digital twins for wind turbines. The objective of the concept is to link all data that arise in the life cycle of a wind turbine in a digital thread to simplify their search and exploitation and to enable a semi-automatic creation of standard-based interoperable Digital Twins. For this purpose, a Digital Thread consisting of three main components is presented, which consists of a unified cross-domain information model, a DT data navigation and extraction tool and a range of interfaces for data consuming external software tools.

Keywords: Digital Twin, Wind Energy, Digital Thread, Information Model.

1. Introduction

The wind industry is a fast growing renewable energy source with electricity generation capacity increase of 77,6 GW (up 9%) in 2022 [1]. Since it is constantly competing with other energy sources, the industry is constantly looking for ways to further reduce the cost of electricity. Much-discussed approaches for further cost reductions are related to the use of advances in digital technologies, such as artificial intelligence (AI), the Internet of things (IoT), cloud computing or big data analytics. One tool to enable the application of these new technologies is the digital twin (DT). Due to their high cost-saving potential during the operation and maintenance phase, wind turbines are a particularly attractive application field for DTs. Physical work at the turbine, as e.g. repairing or changing parts for maintenance is often difficult as their main components are of considerable size and located at high altitudes. Furthermore, their installation sites are often in remote areas – a considerable cost factor that becomes increasingly relevant with rising shares of offshore turbines on the market.

Consequently, research and industry are currently investigating Digital Twins in the wind energy industry for particular applications, such as the reliability analysis of e.g. wind turbine support structures [2] or the prediction of the remaining useful life [3]. However, the increasing number and complexity of data-driven applications of DTs in wind energy can lead to the amplification of a general problem for potential users of lifecycle data. Useful information sets still exist in individual data silos

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and, due to different formats and data structures, are only usable with considerable integration effort for more advanced analyses [4]
Across the life-cycle of a single instance of any given product, the amount of information relevant to each individual product as well as the number of disparate types, formats and systems involved is proportional to the amount of different parties involved in each phase of the product's life. This makes it extremely difficult to find and exploit the necessary data to support a task. To enable DT applications, the data required for the application systems must be available, comprehensible and of sufficient data quality. To increase the usability of the diverse data landscape through better findability and connectivity, they should be catalogued in a coherent information model and searchable via a suitable user interface.
Wind energy related DT concepts so far lack a modelling of the overall context and data siloes are considered a well-known problem. Missing is an overarching description of the essential elements of a DT and the technical means to access them by both humans and machines across organizational (social) and technical system boundaries. An interesting approach is the use of the concept of the Digital Thread, in conjunction with wind-specific information models, such as RDS-PP or IEC 61400-25 and cross-industry standards, such as ECLASS or the asset administration shell (AAS). The DT concept interpretation presented in this paper proposes semantic data mapping using a Digital Thread and a navigation platform for plant-specific data and information. The concept aims at making the different information interoperable and available over the life cycle of a turbine. This format ensures that the wind-specific data and information is understandable across industries and organization networks and mitigates interface problems between the different stakeholders along the life cycle of a wind turbine. The following chapters introduce its components that consist of a suitable information model in the form of an ontology and a web-based user interface that can search and visualize the various information sets based on it and provide a connectable API to use it for services and analyses applications that are more advanced.

2. Background

The concepts of Digital Twin and Digital Thread are still relatively new, and their distinction is still the subject of debate. We will therefore briefly place them in the context of this paper in this paragraph.
Digital Twins and the Digital Thread are concepts that have emerged in the course of product lifecycle management (PLM) [4].
PLM can be seen as the combination of strategies, methods, tools, and processes to manage and control all aspects of the product lifecycle of multiple products. These aspects might include integrating and communicating processes, data, and systems to various groups across the product lifecycle [5]. Over the last few years, two additional concepts have been added to PLM in the form of the Digital Twin and the Digital Thread, each of them suitable to enable some specific PLM functions

2.1. Digital Thread

Digital Thread describes a framework to ensure an integrated flow and a uniform view of data over the life cycle of a product across traditionally siloed functional perspectives [6]. It aims to enable better data management, and to ensure continuity and traceability of information [7]. It should therefore enable a consistent view of the product, link data coherently and thus enable uniform and seamless communication between different software applications and systems in the product life cycle. A common objective of Digital Threads is to serve as a definitive repository using authoritative information and model integration [8]. For decision-makers to use the Digital Thread, it must allow efficient data management so that information can be organized precisely and promptly. Currently, the applications of Digital Threads are predominantly concentrated in the manufacturing industry and there hasn´t been research on Digital Threads for the wind industry. Its ability to integrate data, information and models from different systems and stakeholders across the lifecycle, enabling a comprehensive view of assets, can make the Digital Thread a foundational infrastructure for some Digital Twin applications [9]. DT applications that would particularly benefit from a Digital Thread include, for example, when different system levels and components need to be integrated or when connections to external systems in the value chain are necessary [7].

2.2. Digital Twin

The DT is a concept that was first introduced by Grieves and has since found adoption in various application fields, such as manufacturing and aerospace or wind energy [10]. The concept consists of a virtual and a physical space that exchange data and information [4]. The virtual part of the DT mirrors its physical counterpart and improves it with additional or optimized capabilities, features and processes along its life cycle through new (combinations of) data [10]. These should include information about various aspects of their physical counterpart, including their individual design, state and behaviour [11]. As DT data can be provided by different stakeholders along a value chain, the benefits of a DT can be distributed among many parties. Various applications of DTs for wind turbines have already been presented – ranging from improving design of new systems [12], to optimized maintenance strategies [13] or remaining useful life estimations [14]. However, little research has been done so far to explore the cornerstones of Digital Twins, such as a continuous Digital Thread in the wind energy domain.

2.3. MBSE

Model-based development is of central importance in virtual product development. Models can be, for example, topological, physical, process-oriented, geometric or mathematical models. In model-based systems engineering (MBSE), models are used for the description and specification in order to facilitate the structuring of complex technical problems. The methods of model-based systems engineering can help to describe a multidisciplinary product in an abstract way. For us, MBSE methods are useful because they can help to provide suitable models for connecting data.

3. Related Work - Interoperability and integration of lifecycle data

Interoperability of data, systems and views is an ongoing challenge for industry and there is a general need for cross-enterprise collaboration, the connection of systems and interoperable data in industry. The major goal for enabling the Digital Thread is linking heterogeneous information systems and data sets across the various domains of the product lifecycle. We have identified various enablers for this task that we subdivided in three categories:

3.1. Semantic Data Integration

A long-established approach to improve data interoperability and reduce its heterogeneity is data integration based on semantic definitions. Data heterogeneity refers to diverse types, formats, structures, and semantics within a dataset or across multiple datasets. Integrating heterogeneous data landscapes in a structured way into a single coherent system for all stakeholders requires a high level of abstraction of the represented concepts.

To address this problem, research has, for example, applied ontologies and semantic web technologies. Ontologies have the advantage that they describe the data connections semantically and are therefore

readable and understandable for both humans and machines. The term ontology-based data integration (OBDI) refers to the use of ontologies to enrich multiple data sources with implicit knowledge and to create semantic interoperability between them by using (networks of) ontologies [15]. Several authors have investigated this in a variety of application areas: Panetto et al. elaborated a mapping of STEP and the IEC 62264 standard in their newly developed OntoPDM ontology [16]. Kwon proposed an approach to fuse design data represented in STEP and inspection data represented in QIF in an ontology with knowledge graphs [17]. However, work to date has tended to be limited to the early product life cycle phases, leaving a large part of the Digital Thread unmapped.
Our Digital Thread therefore focusses specifically on information in the middle-of-life and on the wind energy domain.

3.2.Standardized Interfaces

The integration of IT tools that make further use of the data stored in the Digital Thread is another area in which interoperability can streamline existing processes. There is a need to reduce the effort required to connect the various possible elements in the increasingly confusing IT infrastructures. This results in the need to consider the integration of industry-wide recognized standards and APIs in the Digital Thread. Examples of such standards include Open Services for Lifecycle Collaboration (OSCL), which is based on the W3C Resource Description Framework (RDF) and REST and offers a universal communication service definition and several technical protocols (e.g., service search and querying) [18].

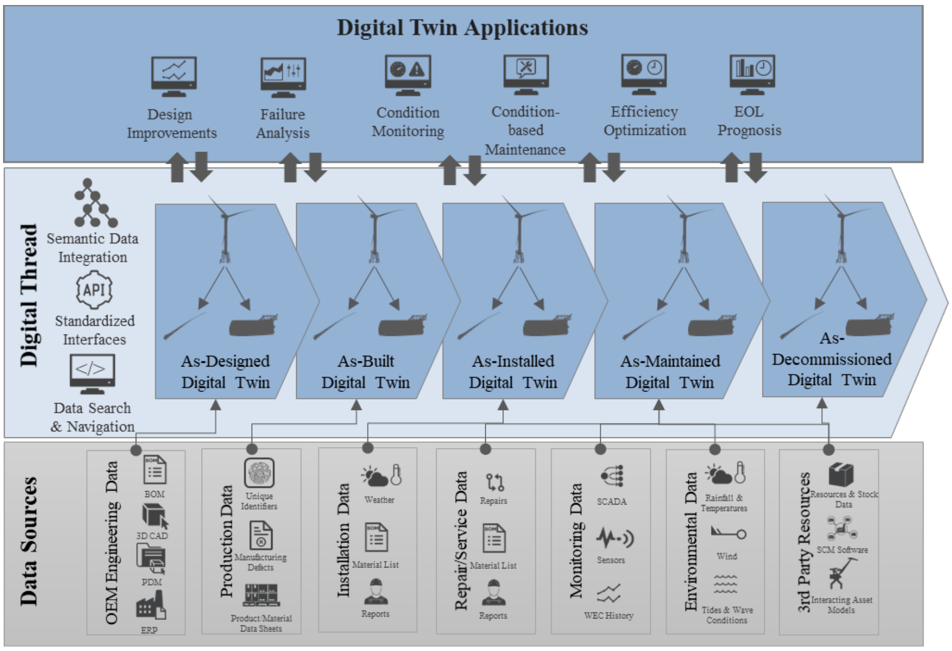

Figure 1: Concept for Integration of Digital Twin Information based on a Digital Thread

A more recent attempt is the development of the Asset Administration Shell (AAS) by the "Plattform Industrie 4.0". The AAS is an industry-neutral standard that aims to ensure cross-manufacturer interoperability and communication capability of "assets" [19]. PLM information on assets in the form of i.a. characteristics, properties, behaviours, functions, relationships can be described in a standardized way by using the AAS data model. Although there is no standardized implementation of AAS, there are several initiatives that are intended to demonstrate prototypical access to AAS via interfaces.

These include, for example, the open source software “AASX Package Explorer” to make AAS accessible via OPC-UA or MQTT. Another group is developing Basys4.0, a middleware that aims to implement manufacturer-specific AAS. However, much of the potential of the administration shell still remains to be exploited, as the exact design of its sub-models in various sectors has not yet been defined.

3.3.Single Source of Information

Another technology is the so-called Single Source of Information (SSI) or "Authoritative Source of Truth“ [8, 20], which is intended to represent the central reference point for models and data throughout the entire product life cycle. The SST combines the overarching information model with a database and enables the storage and retrieval of standardized models and data, thus enabling a continuous representation of the physical system throughout its life cycle. So far, they have played a particularly important role in the design phase - this is the main reason why research here has focused on Model-Based Definition (MDB). However, semantic web technologies are increasingly seen as a key driver for the Digital Thread, especially when the usage phase of products becomes interesting - this is particularly evident in research on Industry 4.0.

4. Concept Description

In this chapter, we present our concept for navigating and accessing cross-hierarchical Digital Twin data of wind turbines using a Digital Thread.
Figure 1 shows the relationship between the Digital Twin and Digital Thread concepts in the context of WT data sources and their subsequent applications. The Digital Thread concept can contain and link several Digital Twins. Its purpose is to link the various data-providing and data-consuming systems - depending on the scope, this can be across systems, departments or organizations. The Digital Twin, on the other hand, is related to the individual product instance. It obtains its data through the digital thread, thus creating an up-to-date data slice from plant-specific data that can be used for subsequent application scenarios, such as customized data analyses or error predictions. The results of the applications feed back into the digital twin via the digital thread.
The foundation for this integration are the three enabling categories for a Digital Thread mentioned above (Section 3). It consists of a common **information model** (semantic data integration), a **data navigation and extraction tool** (single source of information) and a range of **APIs** (standardized interfaces) for data consuming external software tools.

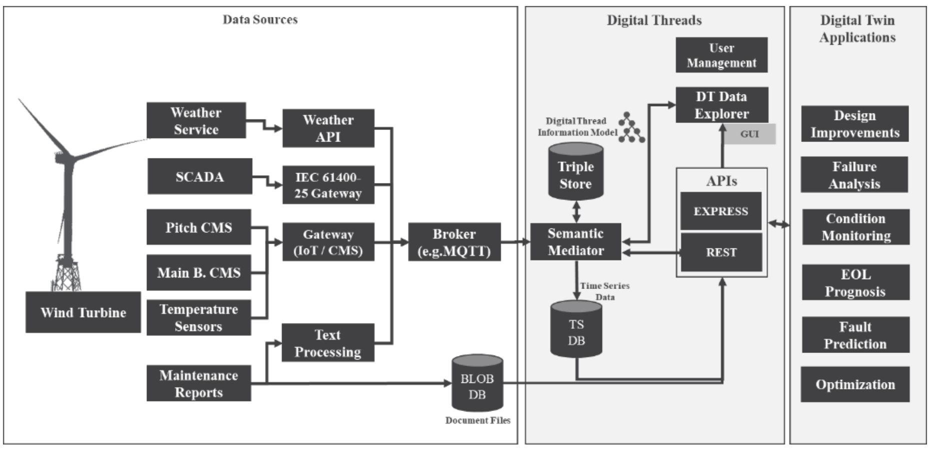

Figure 2: Main technical components to realize core functionalities of the Digital Thread concept

The concept is based on a micro service architecture and its main components are briefly shown in **Figure 2**. For ease of understanding, we have illustrated it in the context of typical (time-series based) WT usage data with a data pipeline and typical data sources (left). Further data from the design or maintenance of the system can be stored in the form of documents on other (non-time-series) databases, for example. The following subchapters briefly describe how these three categories can be implemented in the context of wind energy and which requirements must be met.

4.1. Digital Thread Requirements

General requirements for the Digital Thread derive from its intended purpose to serve as a middle layer for DTs and to form the basis for an architecture that enables a connected database (data lake) and data fusion. It maps all available lifecycle data of wind power plants on different levels (farm, turbine, and component) in a structured and interoperable way.
We conducted several interviews with employees from different wind energy stakeholders (highlighted in ***bold***) about particular application scenarios for a seamless data availability through a Digital Thread. We have condensed the results in the form of an Ontology Requirements Specification Document based on [21], the most important points of which are briefly listed here:

User Groups: Users of the information model are potentially all stakeholders across the lifecycle of a WT. In order to structure the stakeholders for WTs coherently, we use work from the preliminary standard "plant documentation systems for renewable energy plants" [22]. Based on this, the final information model should be able to support application scenarios for the following user groups: ***WT manufacturers (OEMs)***, *WT (OEM) suppliers*, ***plant operators***, *plant managers*, *experts* and ***surveyors***, ***maintenance service providers***, *local authorities*, *plant constructors* and *planners*.

Application Scenarios: At this stage, the Digital Thread should enable DT applications relating to the design and operation phase of a wind turbine. This includes:
1: Condition Monitoring & Condition based Maintenance: Condition evaluation and self-diagnostics for components in single WT / WT throughout farm / WT throughout the fleet with similar loads to move from planned to condition-based maintenance and to decrease unavailability for subsystems due to unplanned downtime.
2: Design Improvements: Analysis of operational data to find mechanical and electrical design improvements (better root cause analysis due to better data basis). Component performance comparison, based on differences in i) supplier, ii) turbine design, iii) turbine operation (environment).
3: Lifetime Extension: Load monitoring of main structural components.
4: Lifetime Efficiency Optimization: Load/lifetime consumption for direct marketers, linked to energy prices.
5: Sensor Cost: Cost out estimations for sensor replacements.

Functional Requirements: Groups of Competency Questions:
Based on the application scenarios, the ontology should be able to answer the following competency questions:
CQ1: What is the design of a WT or WT system?
CQ2: What data and documentation is available for an individual WT, WT system or component?
CQ3: What is the state of a WT, WT system or component?
CQ4: What is the behaviour of a WT, WT system or component?
CQ6: What are the failure rates of certain components, based on environmental parameters and design decisions?
CQ6: What failure indicators and analyses are available for a component?

Non-Functional Requirements: Integration of existing Information Models

In order to be able to provide interoperable semantic descriptions of data, it is essential to base the Digital Thread on common industry-wide recognized standards. As outlined in chapter 3, attempts to develop a standards-based Digital Thread for the initial product lifecycle phases (design data, manufacturing data, quality assurance data) already exist. However, in the context of Digital Twins, the standards-based provision of usage data is of paramount importance, especially in the wind energy domain.

Abstract information models are already used in a wide range of applications in the wind industry. We identified four information models that we believe are crucial to represent core information of WT DTs.

RDS-PP and *RDS-PS* are reference designation systems for (wind) power plants and systems that use basic principles of the IEC 81346 international standards series to designate system parts within a power plant (
Figure 3). They describe the structure of wind power plants by describing function and location of each equipment component using system keys and are designed to be applicable in several technical fields (process, mechanical, electrical and structural design). Their machine-readable system codes are important for planning and construction, as well as for the software-driven operation and maintenance of a plant and therefore suitable for providing a universal language for different actors along the life cycle of wind turbine components.

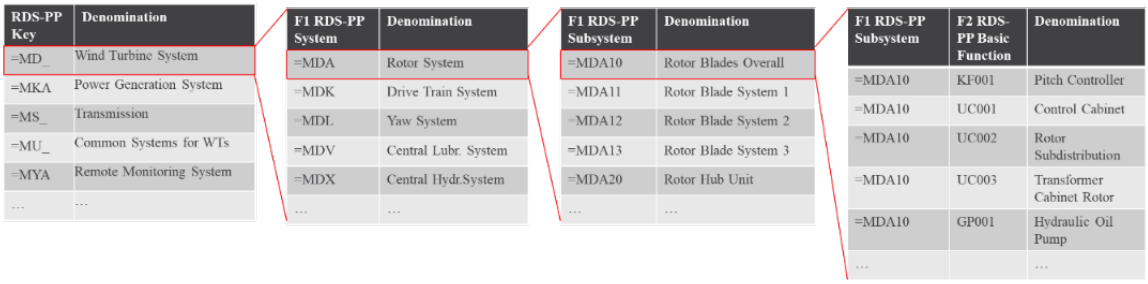

Figure 3: Example for partitive relationship between different system levels of RDS-PP component functions of main system "Energy Conversion"

We use their function reference for WT systems / subsystems and components to provide a template for WT component hierarchies (system compositions). These compositions need to be independent of their physical realisation, as components can be replaced and have a limited lifetime. The system compositions are created in the design process of each turbine generation and generally do not change (in contrast to their individual physical characteristics). They are therefore suitable for forming the backbone of the Digital Thread across all life cycle phases.

IEC 61400-25-2 is an extension of IEC 61850 that defines a unique information model that only applies to wind power plants (WPPs) and unifies their information exchange for monitoring and control [23]. It defines wind turbine-related features, such as rotor blade (yaw angle, rotor speed, etc.), power generation information or other specific components. It is also considered to represent a consensus on core information technology for the future transition of the electric distribution grid towards a smart grid [24]. The modelling approach of IEC 61400-25-2 uses abstract definitions of classes and services such that the specifications are independent of specific communication protocol stacks, implementations, and operating systems. The modelling approach follows a hierarchy, in which the highest level is called the logical device. We use the information model of the IEC 61400-25 series to provide an interoperable catalogue of data elements in the form of standardised SCADA sensor names, which forms the majority of sensor and control data for a wind turbine.

ECLASS is a cross-industry product classification standard that defines product categories and associated product property definitions. It supports the vendor independent digital exchange of product and service descriptions based on IEC 61360 properties. We use ECLASS as a catalogue for relevant master data (attributes of components) connected with a product instance. Relevant product classes are products used as WT components, such as e.g., rotor blades, electric motors (e.g., pitch motors), ball bearings (blade bearing, main bearing, etc.), hydraulic gear and much more. The information reflects the properties of the physical instances of the functional classes (e.g. the specific model, the manufacturer or a serial number of a product) and can therefore be used as interoperable templates for DT core data sets.

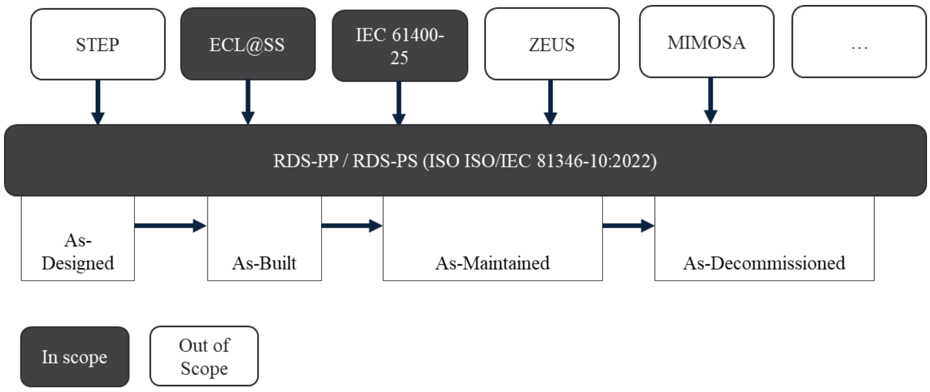

Figure 4: Included standards in the reference data mapping highlighted in grey

Figure 4 shows the use of existing standards as a basis for an interoperable Digital Thread can be used for wind turbine Digital Twins.

4.2. Digital Thread Information Model

Figure 5 shows an excerpt of the Digital Thread information model, which forms the core of the data integration. It is described in the formal ontology language rdf and hosted by a Triple Store. It performs two functions:
i) The Digital Twin Ontology aims to consolidate data located in different data silos and arrange it in a product-centric manner around Digital Twins of the physical WT systems and components. In this context, we understand a Digital Twin to be a product-centric information management approach in which data and interaction options are bundled around virtual representations of individual product instances (at different system levels) in order to organize and facilitate access to distributed and very heterogeneous data landscapes. More advanced applications can use the Digital Thread to search and query Digital Twins and their networked data and feedback their insights. For this purpose, the Digital Thread contextualizes the data by providing additional metadata for DT data collections, as e.g. the relationships between them, their position in the product life cycle or data authorship and usage rights.

ii) The Reference Data Catalogue Ontology allows authorized users to create highly interoperable Digital Twins semi-automatically by using a mapping of different domain-specific standards. The mapping links standards-based functional WT system structures (based on RDS-PP or RDS-PS), which form the basis for navigating between Digital Twins of different system hierarchies (e.g. component, system, turbine, farm), with standards-based templates for related additional DT core data (i.a. product features based on ECLASS properties and SCADA data objects based on IEC 61400-25-2). This makes it possible to create user-friendly, relevant sub-models that can be understood and used across stakeholders throughout the entire life cycle and value chain.

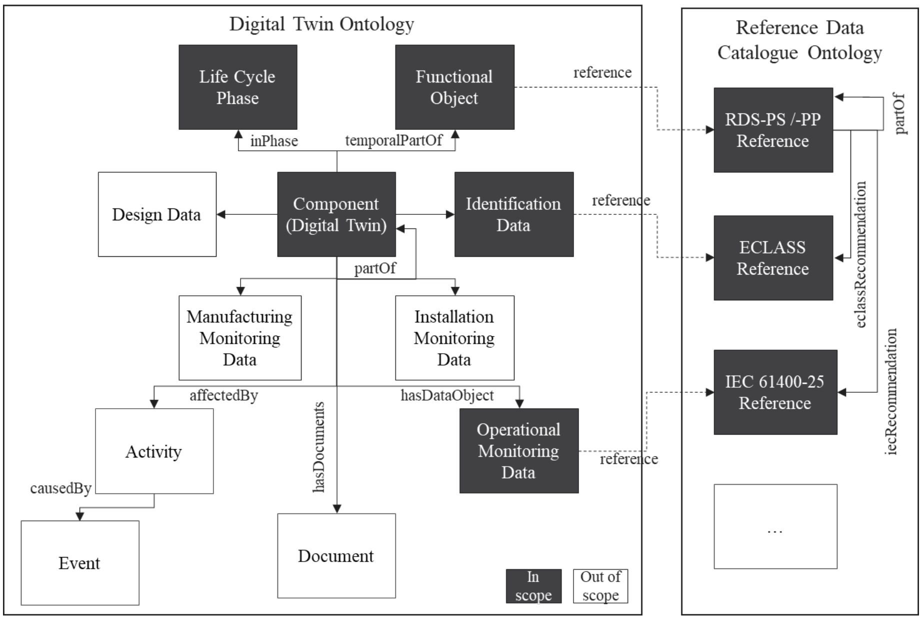

Figure 5: Excerpt of the information model

The Triple Store contains both the reference data catalogue ontologies and their mapping, as well as the linking of the data records with further metadata, such as the assignment to a functional RDS-PP system function or a life cycle phase. Each DT data record is marked with a uniform ID in the Triple Store.

The Digital Thread allows DT data to be stored both materialized in the ontology (as a shared database) and virtually integrated by storing data about data sources. Since both approaches have advantages and disadvantages, individual decisions need to be made as to whether a data type is materially stored directly in the ontology. For the data currently under consideration, we will only store the identification data (UID and master data) directly in the ontology and link the other data virtually and integrate it using interface descriptions.

4.3. Digital Thread Data Explorer

The DT Data Explorer is a web-based User Interface that serves as a central access point for DT datasets. It is responsible for supporting the user in searching, retrieving and creating the data that is linked in the Digital Thread. The Data Explorer manages access to the data collections of the DT datasets and their connection to further applications. The data is arranged product-centrically around DTs of the physical WT systems and components and, where possible, standardized for relevant disciplines through interlinked reference data catalogues of the Digital Thread information model. The Data Explorer contextualizes the DT data by visualizing the metadata from the Digital Thread Information Model, e.g. the relationships between DTs, their position in the product life cycle or data authorship and usage rights. The navigation interface visualizes these contexts to simplify navigation for users in this very heterogeneous data landscape. In addition to data search the Data Explorer also includes the option of accessing the data via suitable interfaces. Based on a role-based user management system, users can either retrieve data directly (for data that has been physically stored in the ontology) or establish a link by retrieving the specific API documentation. Data stored directly in the ontology is normalized by the Semantic Mediator and translated into a standardized format.

4.4. Digital Thread Semantic Mediator and Standardized APIs

The semantic mediator is responsible for ensuring the exchange of information between the data-specific database interfaces and the requesting software applications. In this function it also represents the connecting element between the navigation interface and the data stored in the Digital Thread. In this role, it can implement suitable queries to retrieve data or to change, create or delete individuals and their relationships. A roles and rights management system is also integrated into the semantic mediator, which allows the management of login and user accounts.
The APIs act as a link to external systems and other applications. The aim of APIs is to enable cross-value chain collaboration between different stakeholders (including across companies). The requirement for APIs is therefore that they must be applicable across industries. We therefore follow the IDTA specifications for Asset Interface Descriptions as part of the Industrie 4.0 Asset Administration Shell [25]. In particular, we use their recommendations for standardized documentation for the interface descriptions and base content and structure of the Digital Thread API descriptions on the W3C Web of Things Thing Description (WoD TD). In a first step, we will implement the most widely recognized protocols - so far HTTP and MQTT. In a next expansion stage, the integration of further protocols would be interesting - OPC UA in particular is interesting, as a companion specification for IEC 61400-25 data is already under development.

5. Conclusion and Outlook

A wide range of stakeholders with various tasks participate in the lifecycle of WTs. The completion of the tasks require data and information that are traditionally stored in the IT systems of the data owners. Innovative technologies such as AI offer additional benefits by means of new data based types of services and process optimizations. This results in a complex information network with very heterogeneous data formats that is very difficult to manage. Supporting these tasks and services by providing the required and editable data and information in a manageable way is therefore a core concern of this paper. In order to provide the various stakeholders along the lifecycle with the right data at the right time, this paper presents a Digital Thread concept for data integration and search that makes use of the concept of the Digital Twin. It consists of an overarching information model in the form of an ontology that organizes different data sets around so-called Digital Twins and places them in a common context. The Digital Thread is designed to provide interoperable access to life cycle data. A major hurdle for users is the time required to store the data in a standard-compliant manner. To overcome this hurdle, four standardized reference data catalogues were combined in the Digital Thread. This mapping supports in a semi-automated definition of interoperable Digital Twins that i) are based on standardized functional objects (RDS-PS /-PP), integrate standardized sensor data objects (IEC 61400-25) and can be described using standardized feature descriptions (ECLASS). The user can call up these functions via a navigation interface, which is designed to enable a user-friendly search and access of data. Generic interfaces ensure that the data stored or linked in the Digital Thread can be retrieved and used by applications.
However, the implementation of our concept is still in its infancy. Future research will focus on a dynamic connection between the navigation interface and the semantic mediator and on integrating real life data sets in the Digital Thread. It is particularly important in this regard to ensure a consistent link between the function calls of the data explorer and the information model using the semantic mediator to ensuring reliable and compliant data records if new DT data records are to be created via the Data Explorer. in the future and integrated into the information model in compliance with the rules.
Another challenge is the potential integration of other standardized information models, such as MIMOSA for maintenance data or the integration of production (e.g. QIF) and design (e.g. STEP) data

directly in the information model so that further life cycle phases and data views can be mapped in the Digital Thread.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] Council, Global Wind Energy, „Global Wind Report 2023,“ Global Wind Energy Council, Brussels, 2023.

[2] K. Sivalingam, M. Sepulveda, M. Spring und P. Davies, „A review and methodology development for remaining useful life prediction of offshore fixed and floating wind turbine power converter with digital twin technology perspective,“ *2nd international conference on green energy and applications,* pp. 197-204, March 2018.

[3] R. Pacheco-Blazquez, J. Garcia-Espinosa, D. Di Capua und A. Pastor Sanchez, „A Digital Twin for Assessing the Remaining Useful Life of Offshore Wind Turbine Structures,“ *Journal of Marine Science and Engineering,* Bd. 12, Nr. 4, p. 573, 2024.

[4] M. Grieves, „Digital twin: manufacturing excellence through virtual factory replication,“ *White Paper,* pp. 1-7, 2014.

[5] A. Corallo, M. E. Latino, M. Lazoi, S. Lettera, M. Marra, S. Verardi, B.-S. Liu und T.-M. Choi, „Defining Product Lifecycle Management: A Journey across Features, Definitions, and Concepts,“ *ISRN Industrial Engineering,* p. 170812, 2013.

[6] C. Leiva, „Demystifying the digital thread and digital twin concepts,“ *Industry Week,* Bd. 1, 2016.

[7] T. Y. Pang, J. D. P. Restrepo, C.-T. Cheng und H. A. Yasin, „Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0' Shipyard,“ *Applied Sciences,* Bd. 11, Nr. 3, p. 1097, 2021.

[8] Q. Zhang, J. Liu und X. Chen, „A Literature Review of the Digital Thread: Definition, Key Technologies, and Applications,“ *Systems,* Bd. 12, Nr. 3, 2024.

[9] M. Helu, A. Joseph und T. Hedberg Jr, „A standards-based approach for linking as-planned to as-fabricated product data,“ *CIRP Annals,* Bd. 67, Nr. 1, pp. 487-490, 2018.

[10] J. F. Uhlenkamp, J. B. Hauge, E. Broda, M. Lütjen und M. &. T. K. D. Freitag, „Digital twins: A maturity model for their classification and evaluation,“ *IEEE Access,* Nr. 10, pp. 69605-69635, 2022.

[11] K. C. G. M. F. &. M. G. Hribernik, „Autonomous, context-aware, adaptive Digital Twins—State of the art and roadmap,“ *Computers in Industry,* Bd. 133, p. 103508, 2021.

[12] M. Jahanshahi Zeitouni, A. Parvaresh, S. Abrazeh, S. R. Mohseni, M. Gheisarnejad und M. H. Khooban, „Digital twins-assisted design of next-generation advanced controllers for power systems and electronics: Wind turbine as a case study.,“ *Inventions,* Bd. 5, Nr. 2, p. 19, 2020.

[13] J. &. Z. G. Xia, „Operation and maintenance optimization of offshore wind farms based on digital twin: A review,“ *Ocean Engineering,* Bd. 268, p. 113322, 2023.

[14] A. Baldassarre, A. Ceruti und D. N. V. a. P. Marzocca, „A Review and Mothodology Development for Remaining Useful Life Prediction of Offshore Fixed and Floating Wind turbine Power Converter with Digital Twin Technology Perspective,“ in *2nd international conference on green energy and applications (ICGEA),* IEEE, 2018.

[15] H. Wache, T. Voegele, U. Visser, H. Stuckenschmidt, G. Schuster, H. Neumann und S. Hübner, „Ontology-based integration of information-a survey of existing approaches,“ *Ois@ ijcai,* August 2001.

[16] H. Panetto, M. Dassisti und A. Tursi, „ONTO-PDM: Product-driven ONTOlogy for Product Data Management interoperability within manufacturing process environment,“ *Advanced Engineering Informatics,* Bd. 26, Nr. 2, pp. 334-348, 2012.

[17] S. Kwon, L. V. Monnier, R. Barbau, Bernstein und W. Z., „Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs,“ *Advanced Engineering Informatics,* Bd. 46, p. 101102, 2020.

[18] OASIS OSLC, „Open Services,“ [Online]. Available: https://archive.open-services.net/wiki/index.html. [Zugriff am 11 03 2024].

[19] A. Deuter und S. Imort, „Product Lifecycle Management with the Asset Administration Shell,“ *Computers,* Bd. 10, Nr. 7, p. 84, 2021.

[20] C. Gorringe, E. Gould und I. Neag, „Standards-Based Digital Thread as Authoritative Source of Truth,“ *IEEE AUTOTESTCON,* p. 2023, August 2023.

[21] M. C. Suárez-Figueroa, A. Gómez-Pérez und B. Villazón-Terrazas, „How to write and use the ontology requirements specification document,“ in *On the Move to Meaningful Internet Systems: OTM 2009: Confederated International Conferences, CoopIS*, Vilamoura, Portugal, 2009.

[22] DIN Deutsches Institut für Normung e. V, „Bestandteile und Struktur einer Lebenslaufakte für Erneuerbare-Energie-Anlagen,“ *DIN SPEC 91303:2015-03,* 2015.

[23] IEC Central Office, „IEC 61400-25-2: Wind turbines - Part 25-2: Communications for monitoring and control of wind power plants - Information models,“ *International Standard,* 2015.

[24] G. Reddy und Y. Kumar, „Smart grid communication and networking: review of standards.,“ *International Conference on Applied and Theoretical Electricity (ICATE),* 2021.

[25] Industrial Digital Twin Association, „IDTA 02017-1-0 Asset Interface Description,“ Industrial Digital Twin Association, Frankfurt am Main, Januar 2024.