Tailored Digital Twins for Lifecycle Assessment & Management

Stakeholder centered Digital Twin Framework Design for Product Lifecycle Managements and Assessment

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***Abstract*— The notion of sustainability is gaining more attention across the whole world, thereby serving as a predictor of future economic gain. Emerging technologies like Digital Twins (DT) could help meet Circular Economy objectives such as the UN Sustainable Development Goals. Although using a framework to develop DT is widespread, it is often not directly suited to answer the information requirement that the stakeholders desire fully. Shortcomings in design are therefore discovered to late when the concept of the Twin is already implemented. As such, this paper aims to provide a requirement-based framework for designing a sustainable Digital Twin that satisfies several parties involved in its conception and use. The proposed framework is therefore designed on the one hand to filter out the most valuable information requests for the stakeholders. On the other hand, the design requests are turned in the design phase to recommendations for the outlaying of the architectural implementation. This is shown as an example application for an e-bike with different stakeholders involved. Therefore, the use case features five different stakeholder groups with their own information request to show how these influence the final setup of such a twin. The proposed framework lays the path for improving the current lifecycle assessment while ensuring the optimization of Digital Twin design flexibility and therefore its application for a variety of different products.**

Keywords - Stakeholder Information Requirement; Digital Twin; Product Lifecycle; Framework Design, Circular Economy

I. INTRODUCTION

The current product usage leads globally more and more to a massive production of waste. Therefore, the question of product life prolonging techniques and measurements is on an all-time high. Especially in the context of Circular Economy, the condition assessment of products is a frequently mentioned topic.

Sustainable consumption and production are also important topics for society and ecology in general regarding the increasing world population [1]. Furthermore, the UN defined 17 sustainability goals in order to accelerate environmental and socially friendly usage of resources and products [2]. However, in order to apply the measurements detailed information about a product's current state, product life and usage are required. For example, the correct assessment of a product's condition is needed to decide, if a product can be used further or if the manufacturing of a new product would be more beneficial. This is where Digital Twins can come into usage; digital counterparts of physical products which can be used to monitor its state and optimize its usage. However, it is not simply sufficient to just monitor a product randomly. In order to gain the most out of a Digital Twin, its usage and functionality should be determined before implementing the potential architecture. The framework is therefore laid out to help stakeholders designing a Digital Twin for their expense with the most beneficial information generation capabilities. The target of this paper is to support the conception process of Digital Twins for a product and satisfy specifically the stakeholders information request due to a new framework design. The question of a suitable approach for Digital Twin Design in order to improve information value by simultaneously decreasing expense is tried to be answered while also addressing the limitations of the framework. This lie especially in the limited generation of new, unpredicted information that may be gained due to correlation of sensor data. This is addressed in a subchapter in order to discuss the limitations of the framework approach. It should be stated, however, that this is a concept which still needs validation and testing.

The paper consists of different subsections, describing the initial structure of the research work. In section II the current State of the Art of the Digital Twin-based research in terms of framework design is summarized. The section III describes the initial problem, followed by the used research methodology described in section IV. The main part consists of the framework design explained in section V and its use case application in section VI. The paper closes with a final conclusion in section VII.

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II. STATE OF THE ART

This section aims to provide a brief overview of some of the currently proposed frameworks for digital twins, highlighting relevant studies and works related to the present paper. Over the years, the digital twin concept has evolved from just being the virtual mirror of a physical asset [3] to include digital twin data and services for static as well as dynamic information flow between both entities [4][5]. Over the time various digital twin frameworks have been proposed as the digital twin concept has been extending to more scientific and industrial fields.

Tao et al. [4] define a framework known as Digital Twin-driven Product Design (DTPD), which focuses on creating the digital twin of a physical asset, then applying the acquired generated knowledge in the redesigning process of the asset. In essence, it is a design framework that transforms big data into useful information that are used in the following process to guide decisions during the different design phases of the asset.

Zhang et al. [6] worked on a data- and knowledge-driven framework for the Digital Twin of a Manufacturing Cell (DMTC). The physical, digital, data, knowledge, and social spaces make up the five-dimensional space of this framework, which collectively promote the capacity of the digital twin for self-control functionalities as well as self-assessing capabilities. Thereby, rendering the manufacturing cell autonomous while maintaining flexibility and lowering cost.

D'Amico et al. [7] propose a conceptual framework for the evaluation of the Remaining Useful Life (RUL) of a product. The aim is to improve the availability of the product and minimize expenses throughout its life cycle by increasing the level of understanding of this asset. Thus, this framework focuses on an efficient exchange of information through its three main layers, which include the data architecture, modules, and connection of the modules to one another.

Onaji et al. [8] provide a framework that supports some essential functionalities in digital twin applications such as tools and functionalities for prognosis and diagnosis of behavior, simulations of the related system, monitoring and controlling of the system as well as its optimization [6][9][10]. It is made up of six components that work together to enable the manufacturing sector to benefit from features like integration, interconnectivity, flexibility, analytics, and supported decision-making.

A three-layered structure is conceived by Traoré [11] that combines the various perspectives on Digital Twins to clarify the concept that already has diverse understandings. This framework has a data layer, a capability layer, and a service layer, which provide a modular conceptual foundation that can aid in the adaptive or dynamic design of specific solutions. Practically, the framework was sampled to create the Digital Twin of an energy-efficient building and a smart manufacturing shop floor.

A proposal of a structure which incorporates the basic functionalities, initial requirements and guiding definitions for standardized components of Digital Twin is proposed by Nwogu [12]. It is a requirement-driven, technology-agnostic structure that can be applied to different situations based on their unique requirements. Hence, creating a close relationship between the Digital Twin requirements and the components in the suggested framework.

Zhao et al. [13] noticed issues with the usage of digital twins in the Construction industry, such as the misalignment of data integration and data standards, and a lack of information within each component. To tackle those obstacles, a conceptual framework is suggested to enable a broader application and implementation of digital twins for facility management throughout the Operation and Maintenance phase. Also, the framework takes into consideration stakeholders who are struggling with facility management decision-making processes. Moreover, the framework has six layers: preparation layer, data acquisition layer, data processing layer, data transmission and modeling layer, model logic layer with intelligence tools, and application presentation layer.

The aforementioned brief literature review shows that multiple specific frameworks for various uses exist that integrate existing Digital Twin viewpoints in one way or another. Our research is distinctive in that it suggests a framework that facilitates the process of evaluating product conditions to improve sustainability with special consideration of the stakeholder requirements.

III. PROBLEM STATEMENT

Stakeholders have in general a high interest in acquiring information regarding the product and its usage by the consumer. In the case of a Digital Twin this is usually the virtual counterpart of the physical product which, when combined to one another, creates a cyber-physical entity. The kind of information extracted from the Digital Twin and received by the stakeholders can therefore vary widely and is usually limited by the technological borders of the respective product like data acquisition methods, product features or transmission capabilities [31]. However, before the information can be transmitted and processed, the governing question regarding the kind of information the stakeholders want to receive out of their Digital Twin must be answered in order to achieve a model which not only satisfies the specific stakeholders' needs but also is sustainable in terms of the selection and shortage of an unnecessary information overflow (redundancies). This leads to the two assumptions that can therefore be stated:

1. The selection of stakeholder information requirements is a highly important factor when designing Digital Twins
2. The use of a “smart” digital twin framework design could prevent insufficient or over-dimensioned DT designs that lead to more resource wastage and consumption than necessary

The later proposed framework takes the physical entity properties and its environment into account and ties them directly to the framework design considerations. The information generation is therefore highly guided by the stakeholders needs and can be separated based on the two governing principles of the utilizability of a specific type of information for the targeted Stakeholder group and the technical capabilities of the information generation system [32]. To highlight the needs of the stakeholders, the type of stakeholder connected to a specific product must be determined first. Based on the number of information interests *in(1…m)(1…n)* for each of the *stakeholders (1….m)*, the result of the total number of relevant information factors can thereby be determined. This setup/configuration has a significant impact on the general sensing capabilities of the digital twin, as well as the overall structure of the framework [33]. The next section will describe the initial situation of a product with a diverse stakeholder composition.

A. Initial Scenario: E-Bike Sharing Service

In order to explain the procedure of designing a tailor-made Digital Twin, a e-bike sharing ecosystem is selected as use case. E-bikes are on an all-time rise since the increased transition of urban traffic ecosystems towards more sustainable mobility services [22].

In general, such ecosystems consist of a variety of different stakeholders [23][24]. Manufacturers, Clients, Service Providers and Product Maintainers as well as Recyclers and even Resellers can be viewed as examples of stakeholders that are part of the bike sharing ecosystem. In terms of the application of a digital twin of an e-bike, all of those stakeholders have specific information requests which they are interested in being fulfilled. On the one hand, these demands are not necessarily the same and are therefore of different value for each of the stakeholders. On the other hand, there are information demands, which are shared mutually by different shareholders and therefore have a higher value for all of them. Therefore, it is necessary to deal with the information requests of the stakeholders in order to find the highest information benefit at a given cost for the achievement of the former. Disregarding the stakeholder’s information request can lead to unsatisfying decisions concerning the product’s life because of a lack of information, that is not in the sense of a sustainable product usage and the Circular Economy in general.

IV. Research Methodology

In order to acquire a sufficient knowledge base on different types of information requests served by Digital Twin technology and framework designs, the authors used research papers and articles which were acquired by searching for different keyword combinations in order to create search strings to find suitable research papers. The search was conducted using google scholar and science direct as main tools in order to find suitable references. For the acquiring process the reference search for Digital Twin related papers was conducted by the setup sections of the digital twin and their relevance for Circular Economy related topics. The proposed frameworks in the state of the art section were assessed based on the following five key features [28][29]:

- Communication (between Digital Twin, physical entity and entity environment)
- Data acquisition
- Data processing
- Application Services
- Adjunct Adaption and reutilization

Based on the above-named features, the referenced papers were selected as research foundation for the designed Digital Twin framework. The main setup of the proposed frameworks was analyzed and the above-mentioned key features were further concretized in order to specify the layer structure of the later proposed information requirement-driven Digital Twin Framework.

Digital Twins have been used vastly within the last few years. However, most of the proposed Digital Twin Designs are centered around the product and the information that can be extracted by configuring data acquisition tools for the specific cause [30]. The goal of this paper is the design approach for a stakeholder requirement-driven framework which allows the configuration based on the final information that is desired by the stakeholders in order to use them in their field of application. The section therefore clarified the used research methodology and outlined the purpose of the work. The following section of the paper outlines the various requirements that stakeholders may have based on their branch and endeavors to establish a categorization of the required information.

V. Framework Components

The design of a framework for Digital Twins must necessarily address the needs of its stakeholders, that require the information which will be generated by it. Therefore, it is of uttermost importance to take the environment and its stakeholders into account when setting up the framework. The general environment of the Digital Twin is highly versatile and will change drastically depending on the product which is subject to the Twin. This is not only caused by the different products affecting the properties of a specific Twin but as well by the types of stakeholders and their specific information requests. Further, the

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environmental influence is governed by the technical limitations of the sensing and acting devices, which results in a highly specific environmental composition for each product type. The idea of requirement-driven frameworks, however, is not totally new and has already been described by Nwogu et al. [34]. The basic difference between the approach presented by Nwogu et al. and the framework design stated here is the integration of the Stakeholder Layer necessary to form not only the requirements addressed to the required features but as well the requirements based on the basic information type. The Digital Twin Framework is as well not restricted merely to the data flow from the Framework to the adjunct sensing and acting systems but is receiving, as well a stream based on additional information and knowledge generated by preceding systems. However, the general foundation of the proposed framework is based on the one presented 2020 by Lu, C. et al. [35].

The proposed framework, shown in Figure 1 integrates a ***Product Stakeholder Layer (1)***, where the Stakeholders along with their information requests will directly contribute to the setup of the Digital Twin. The classification of the Stakeholders as well as their individual information request are thereby guiding the information generation boundaries of the resulting Digital Twin. Possible Stakeholders of physical products are for example the Designers, Manufacturers, Distributors, Maintenance Service Providers, Remanufacturers, Recyclers and of course the actual users of the product. The Stakeholders have different requests for information since they influence the product at different stages of its lifecycle [36]. The goal of the Layer is therefore the determination of the stakeholders' information demands as well as the selection of those demands based on the governing cost of the information generation. This will result however in a catalogue of information demands, which are then used in the adjunct Design & Conception Layer to create the architecture of the Digital Twin.

Due to the main driving requirement of information-based framework design, the Design phase of the actual structure is integrated as a central part of the concept. This results in an initial ***Design Block (2)*** integrated into the framework. In the Design & Conception Layer the Stakeholder request are evaluated and sorted in order to select the proper design of the resulting Digital Twin. Therefore, the exact setup of the respective Twin is modelled in terms of the establishment of communication between the different subsystems (synchronization frequency, type of transmission), the usage of different tools to produce the required information and the implementation of the generated results and the thereby resulting control over the actuation systems [37]. The planned design is therefore affecting the subsequent systems of the framework to a large extend. After setting the governing features of the respective Digital Twin for a product, the in-depth planning of the subsequent systems is conducted. The first section which is thereby accounted is the ***Data Block (3)*** with the Data acquisition, Data processing and Data validation Layer. The type of data acquisition is naturally limited by the technical limitations of the information request type and the necessary data collection system which is used in this context. Data acquisition therefore covers all types of data transmission whether it might be collected via sensing devices or by other data sources like historical usage data, production and design data or data concerning the product's usage after reaching the end of its lifecycle. The Data acquisition Layer is hereby the foundation of the Digital Twin and is therefore highly affecting the quality of the resulting information and knowledge. Data processing is equally important to the acquisition of the data since it adds the necessary properties to generate the desired information which allows the classification of the raw data. The processing is therefore a crucial task in order to use the data in the subsequent applications. The first step is hereby the data preparation, where the raw data is cleansed of flawed values and redundancies in order to use them in the process of information generation. The type of processing used is based as well on the initial information requirement and can as well differ drastically between its processing cycle and its amount of processed data in one iteration. The location of the processing step is also a governing factor for the Digital Twin, although the development of scalable far- and near-edge technology are currently bridging the selection of the processing location and therefore enabling system scalability [38]. The next step is the validation of the data and its transmission to the adjunct Evaluation block. Data validation is the third column of the data concerned block and is the "reality check" of the generated information to prevent the transmission of illogical and false information. The validation is therefore the second iteration of the transmission check. The basic difference between the processing and validation layer is the "item" which is evaluated: whereas the processing layer evaluates and filters the raw data, the validation layer accounts the plausibility of the initial databased and generated information. As well as the adjunct processing layer, the other data and information transferred to the acquisition layer by the different systems are also evaluated [39]. The ***Service Block (4)*** is the subsequent unit after the data-concerned section. In this section, the previously created data and information are transmitted to the different service branches in order to generate follow-up information to answer the initial information requests. For example, the question for lifecycle estimation, future product life assessment, and construction optimization can be answered. The block is separated into three distinguished layers: Preassessment, Prognosis, and Evaluation. The preassessment layer is used for the preparation of the gathered information in order to use it in the subsequent application. This includes the refrainment of the validated information and the classification in order to use them for simulations, prognosis, or recommendation functionalities. The selection of the right setup is here as well highly dependent on the type of required information and, subsequently the digital service which is selected

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afterward [40]. These services are implemented in the Service Layer. This layer is in contrast to the beforementioned layer more versatile since it can consist of a high variety of different tools, tailor-made for the specific use case, and therefore complex in its internal structure. The layer is the core section of the Digital Twin in terms of adjunct functionalities, and combines the features around the utilization of the generated information for the specific application [41]. Therefore, the layer is built in a modular approach which can integrate different types of simulation systems that can be separated based on their calculation methodology and the overall model, on which they are built. Examples here for are modular dynamic simulations and Monte-Carlo Simulations, which are used in a variety of different simulation applications [42]. This concept is already in use and is carried out for different types of products and systems. As an example, the usage of Object-Oriented Modelling and Simulation (OOMS) can be seen as an approach to tackle highly complex simulation environments [43]. Further, the usage of prognosis tools is highly anticipated in order to assess the products behavior throughout its lifetime. As an example, this was already described in order to predict the behavior of bearing components used in the railcar industry. The conducted research clearly showed, how Artificial Intelligence (AI) is already in use in order to prognosticate the behavior and wear of components and can therefore be integrated and coupled to its adjunct layers [44]. The last layer of this block is the evaluation layer. This layer can as well be based on AI technology, but in contrast to the prediction layer, it is the third subsystem of the proposed framework and is used for validation of the two preceding layers of the block. The newly generated, and mostly artificially created information is therefore undergoing a last reality check in order to assess meaningfulness. This step is highly important regarding the overall acceptance of AI based systems and their capability of managing and deciding process steps.

The last block implemented in the internal framework is

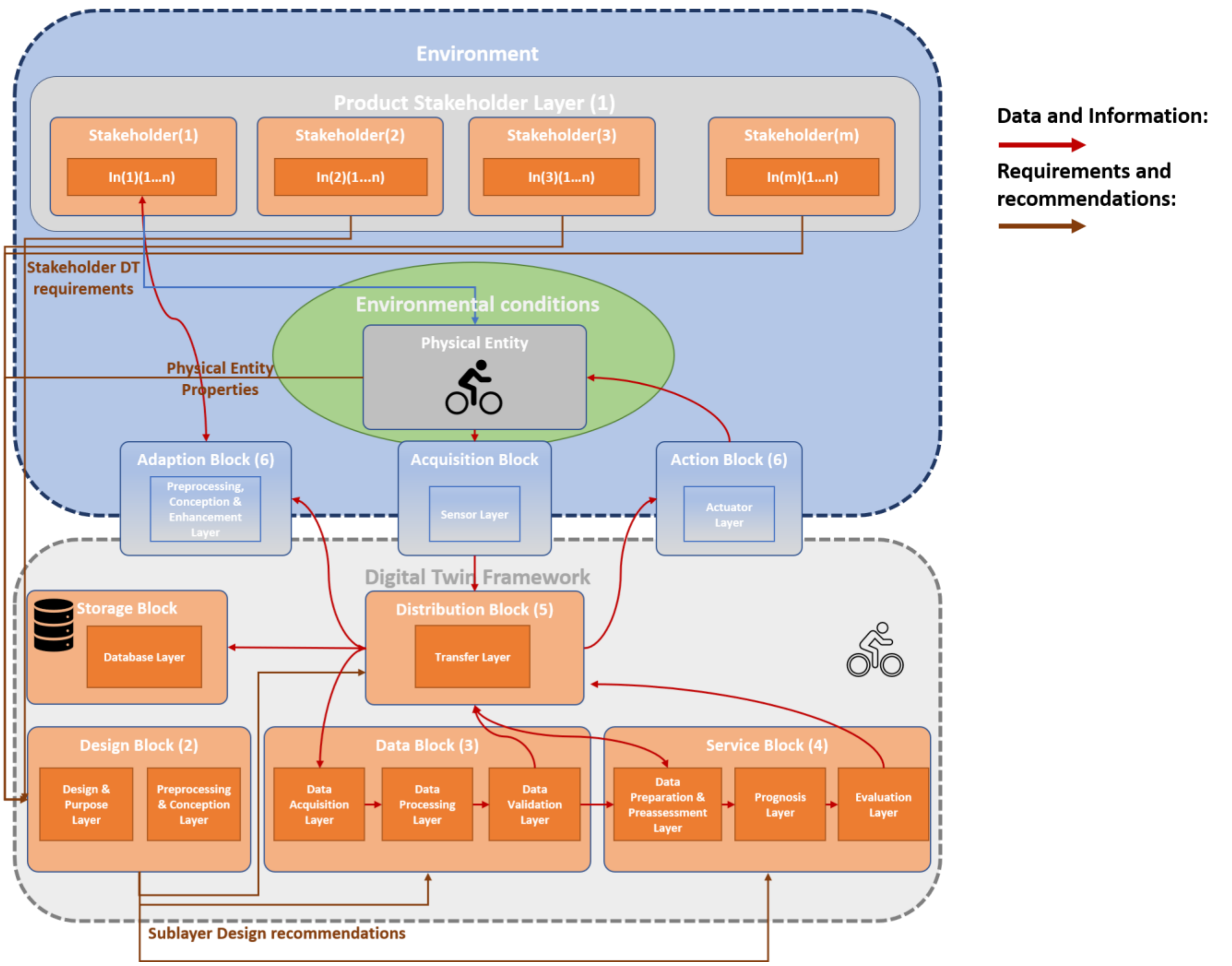

Figure 1: Stakeholder Driven Digital Twin Framework Design (inspired by [35])

the ***Distribution Block (5)***. This layer ensures the storage and communication with the adjunct entities outside the internal Digital Twin framework towards the environment. The Transfer layer is affected as well by the neighboring subsystems, especially in terms of the processing of the different types of data and information. Due to the different processing requirements of the product the overall complexity of the Transfer Layer can vary. This variety includes the usage of edge and cloud computing and the distribution of tasks to the different processing devices [38]. Further, the selection of a fitting transmission technic is as well part of the Layer.

The two sections that complete the overall framework proposal are the ***Action and Adaption Blocks (6)***. These blocks are responsible of adjusting the Twins behavior via the actuators and managing the generated information in order to transform it into wisdom which is reused by the Stakeholders in the different application like design, manufacturing or maintenance [45]. The actuator block consists therefore of the actuator systems of the physical product and carries out the control tasks in order to optimize the product usage in case of automated subsystems. Therefore, a life-prolonging operation state of the product can be enabled and changes in the product's environment can be tackled accordingly to prevent increased wear [46]. The Adaption concerned block consists of all methods that implement generated wisdom, lessons learned, and guidelines into the Stakeholders' processes. The transformation of the transferred information is thereby as well highly dependent on the stakeholders' need and is subject of the overall design process of the Digital Twin. However, the two beforementioned blocks are hybrids between the environment, the physical product, and the digital twin and are therefore located in the overall framework between the different subframes. In the following subchapter, the presented Framework and its Layers illustrated in Figure 1 are applied onto the initially mentioned use case.

VI. USE CASE APPLICATION

The application of the framework is utilized in the following section onto the initially described use case and is shown graphically in Figure 2 As described in the framework introduction, the first step is the determination of the information demands. Therefore, the participating stakeholders of the specific product environment have to be assessed at first.

In order to reduce the complexity of the presented use case, the Stakeholders are summed up in groups based on their common information requirements [33][47, p. 4]:

1) *Designer & Manufacturer*

While the product designer and the product manufacturer don´t have to be necessarily the same Stakeholder, this is the case for a variety of different products. The information requirements for this Stakeholder group cycles around the possibility to increase the monetary value and the improvement of their product. This leads us to the general assumption, that the majority of the information a producer is interested in will be information on current usage lifecycles of a product as well as the overall condition of products throughout the same. Further, the Stakeholder might be interested in information regarding the saving of material by optimized design based on the information of the Digital Twin.

2) *Distributor and Maintenance*

The products' distributor is the second Stakeholder group and is directly in contact with the user of the given product. While the distributor has a high interest in increasing its monetary outcome by selling the product, the overall information required regarding the actual product and its usage might not be as high when compared to the other stakeholder groups. This is mainly caused by the fact that the main interest lies in the actual distribution and sale of the product. This changes when the maintenance of the

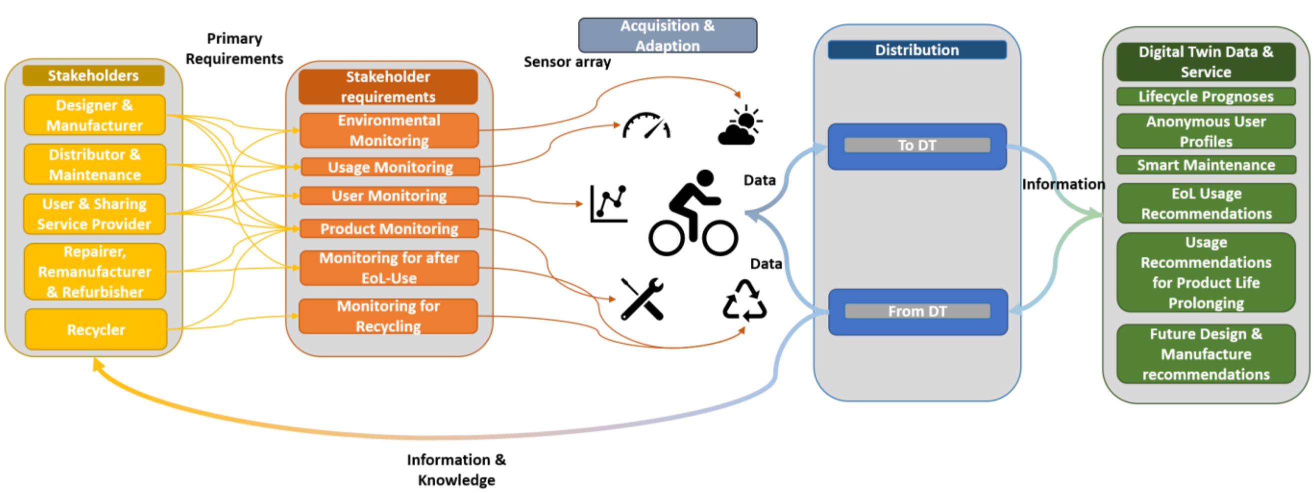

Figure 2: Framework applied to E-Bike

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product is included as well in the assumption. The information requirement is therefore shifted to a lifecycle-centered one with focus on duration and maintenance optimization information of the regarding Product.

3) User & Sharing Service Provider

The third basic stakeholder group is the user & the service provider. The user's interaction with the product will greatly influences its overall condition and thus directly influences the product lifecycle. Nonetheless, the information interest of the digital twin is requested in terms of current usage behavior and information for lifecycle prolonging measures. Further the possible failure of different parts under the current usage profile is a highly valued information for the user of a given product. In the case of a ridesharing service, users are mainly focused on the reliability and availability of the product. These two factors will as well directly affect the sensing and transmission design of the hardware setup and therefore the Digital Twin itself.

4) Repairer, Remanufacturer & Refurbisher

The fourth basic stakeholder group consists of the stakeholders, that are involved in the handling of the e-bike after reaching its End-of-Life (EoL). However, the focus of this group is to enable the product to be used further in its original context. The focus is therefore reinstating the original functionality of the bike. The stakeholders have therefore a major information request regarding the current and future condition of the e-bikes and its parts as well as the potential time of disfunction in order to assess the requirements for reinstating the functional state. For the Digital Twin, this requires a high accuracy of the prognosis service as well as the EoL recommendation in order to satisfy the information requirements.

5) Recycler

The last stakeholder group deals with the inevitable fate of a product, when it is damaged beyond any form of repair. Recyclers are therefore mostly interested in information regarding the product type and its potential hazards in order to plan the dismantling and recycling process as well as the quantity of valuable resources which were used in the products manufacturing process. The recycler requires the information when the product reaches its EoL and the reinstating of its functionality is not desirable.

Generally speaking, the most desirable information for the different stakeholders can therefore be summarized as all information concerning the product life, usage and optimization. These information types are subsets of a lot of information labels and can therefore be seen as supergroups for the subsequent information [48].

For the product of the mentioned use case this concerns especially the monitoring of the motor, the accumulator and the frame of the bike, since these are the most expensive parts of an e-bike. Therefore, the sensor array should be designed to acquire condition information about the bike based on usage behavior and environmental influences [49]. The sensor array should on the one hand monitor the condition of the parts and on the other hand it must monitor the user behavior and environmental impact on the components. In order to deliver the data required to answer the questions above, the sensor array could consist of temperature, humidity, and photosensitive sensors for the evaluation of the environmental conditions and of strain gauge, triaxial sensors, and data from the Battery Management System (BMS) for the monitoring of the components [50].

In case of the E-Bike, the location of the Digital Twin and the transmission frequency will influence the overall setup greatly. As mentioned before, the Stakeholders may have different requirements based on the frequency of the transmissions and must find an agreement. For example, for the E-Bike, the highest frequency need would be the advisable way to plan the data transmission installations. For the previously described use case of Bike Sharing, the transmission could be established, for example either by the user's mobile device via mobile communication or while loading the E-Bikes at the different sharing points via wireless LAN.

The service concerned applications can differ as well widely based on the composition of the Stakeholders. Possible service applications for the E-bike could be for example DT data-based Finite Element Method (FEM) simulations to determine component wear over time or the prognose of accumulator loading capacity decreasement over time due to the usage behavior (Loading cycles, loading environments etc.) [51]. These applications can deliver information desirable for the different Stakeholders and can thereby enable subsequent services like predictive maintenance or future-life-planning of the components.

The transmission technology onto the Adaption and Action concerned block will usually in the case of E-Bikes be the same as the one that connects the Data and Service concerned block to one another (since the E-Bike will most properly not be outfitted with a processing device powerful enough to carry the simulations out on spot). Therefore, the information will be transmitted once again via the Transfer Layer to the above-mentioned Layers. The Actuator Layer is in case of the E-Bikes restricted to the optimization of the running conditions of the electrical motor and the battery system, since these two components are the only devices outfitted with controlling and managing subsystems. The Adaption concerned Layer integrates, as described in the corresponding section in the previous chapter, the information into knowledge or lessons learned. In case of the use case, the Layer could provide specific recommendations on how to optimize the components in order to increase their durability and overall lifetime as well as create patterns in order to enhance the stakeholder's services like the maintenance operations carried out by the provider or the business model adjustments regarding the distribution of the rented E-Bikes after reaching their technical obsolescence [51].

B. Tailor Made vs Research Driven DT-Design

The presented design is faced to provide a framework solution under two major premises: the first one is the DT-design for Digital Twins which are used in applications were a scarcity of resources is expected and therefore careful design approaches are mandatory. The second one is the extensive domain knowledge of the stakeholders regarding the overall Digital Twin Design. This includes as well the requirement of a well-researched domain, where there are nearly no unknown factors which could affect the physical entity in its usual environmental behavior. However, it should be noticed that the framework is therefore not suitable for use cases which are still not well researched and where domain knowledge is limited. The framework can be deployed in digital twin applications like the above-mentioned E-Bike, where the physical counterpart and its usual environmental influence have already been researched widely. In other applications however a different Digital Twin design approach, which is targeted more clearly to increase the overall data acquisition by measuring a lot of different parameters with a broad sensor array might be the better solution. The described tailor-made framework has on the other hand the benefit of decreasing resource input by pre-selecting the measuring capabilities.

VII. CONCLUSION

The main motivation of this research is to provide a framework usable to design tailor-made Digital Twin systems based on the initial requirement of the stakeholders. The proposed framework was set in context with a described use case regarding the lifecycle management of an E-Bike. The application of the initially described use case showed clearly, on one hand, the necessity of requirements- driven Digital Twin Frameworks in order to fulfill the needs of the Stakeholders as well as the functionality of an architecture setup for Digital Twins based on the proposed design pattern. The governing factor of the information requirement proved to be essential for designing fitting and energy optimized Digital Twins. The integration of the design of the Digital Twin as central part of the Framework design allows the initial collection of information requests and allows simultaneously the retrofitting of already in use architectures for the own purpose by reconsidering the previously made selections in the design phase. However, the selection of the required information by the Stakeholders in order to assess the final architecture of the physical entities' corresponding Digital Twin is still up for debate. The information selection phase therefore requires its own set of rules and algorithms in order to grant a fair and even distribution of information interest among the different Stakeholders. In general, the hereby proposed framework concept can be seen as a first step in order to conduct research in the area of stakeholder information requirement driven DT design. Using requirement driven frameworks could therefore not only pave the way for an enhancement of current lifecycle assessments but can as well optimize Digital Twins in general in terms of energy consumption, sensor implementation, and data and information redundancy based on the approach of tailor-made architecture designs for different products. However, it should be stated, that the concept still needs testing and validation in order to confirm its general expressiveness.

REFERENCES

[1] L. Elke, F. Swiaczny, A. Genoni, N. Sander, and R. Westermann, "Global population development. Facts and Trends" Bundesinstitut für Bevölkerungsforschung, Jul. 2021. doi: 10.12765/bro-2021-01.

[2] Redaktion: Lois Jensen, Vereinte Nationen, "Goals for a sustainable development Report 2022." 2022. [retrieved: Mai, 2023] Available: https://www.un.org/Depts/german/millennium/SDG-2022-DEU.pdf

[3] M. Grieves and J. Vickers, "Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems," in *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, F.-J. Kahlen, S. Flumerfelt, and A. Alves, Eds. Cham: Springer International Publishing, 2017, pp. 85–113. doi: 10.1007/978-3-319-38756-7_4.

[4] F. Tao *et al.*, "Digital twin-driven product design framework," *Int. J. Prod. Res.*, vol. 57, no. 12, pp. 3935–3953, 2019.

[5] Q. Lu *et al.*, "Developing a Digital Twin at Building and City Levels: A Case Study of West Cambridge Campus," *J. Manag. Eng.-ASCE*, vol. 36, no. 3, 2020.

[6] C. Zhang, G. Zhou, J. He, Z. Li, and W. Cheng, "A data-and knowledge-driven framework for digital twin manufacturing cell," *Procedia CIRP*, vol. 83, pp. 345–350, 2019.

[7] D. D'Amico *et al.*, "Conceptual framework of a digital twin to evaluate the degradation status of complex engineering systems," *Procedia CIRP*, vol. 86, pp. 61–67, 2019.

[8] I. Onaji, D. Tiwari, P. Soulatiantork, B. Song, and A. Tiwari, "Digital twin in manufacturing: conceptual framework and case studies," *Int. J. Comput. Integr. Manuf.*, pp. 1–28, 2022.

[9] G. S. Martinez, S. Sierla, T. Karhela, and V. Vyatkin, "Automatic generation of a simulation-based digital twin of an industrial process plant," in *IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 3084–3089.

[10] C. Zhang, W. Xu, J. Liu, Z. Liu, Z. Zhou, and D. T. Pham, "A reconfigurable modeling approach for digital twin-based manufacturing system," *Procedia Cirp*, vol. 83, pp. 118–125, 2019.

[11] M. K. Traoré, "Unifying Digital Twin framework: simulation-based proof-of-concept," *IFAC-Pap.*, vol. 54, no. 1, pp. 886–893, 2021.

[12] C. Nwogu, G. Lugaresi, A. Anagnostou, A. Matta, and S. J. Taylor, "Towards a Requirement-driven Digital Twin Architecture," *Procedia CIRP*, vol. 107, pp. 758–763, 2022.

[13] J. Zhao, H. Feng, Q. Chen, and B. G. de Soto, "Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes," *J. Build. Eng.*, vol. 49, p. 104028, 2022.

[14] F. Tao, B. Xiao, Q. Qi, J. Cheng, and P. Ji, "Digital twin modeling," *J. Manuf. Syst.*, vol. 64, pp. 372–389, Jul. 2022, doi: 10.1016/j.jmsy.2022.06.015.

[15] D. Piromalis and A. Kantaros, "Digital Twins in the Automotive Industry: The Road toward Physical-Digital Convergence," *Appl. Syst. Innov.*, vol. 5, no. 4, p. 65, Jul. 2022, doi: 10.3390/asi5040065.

[16] A. Martínez-Gutiérrez, J. Díez-González, R. Ferrero-Guillén, P. Verde, R. Álvarez, and H. Perez, "Digital Twin for Automatic Transportation in Industry 4.0," *Sensors*, vol. 21, no. 10, p. 3344, May 2021, doi: 10.3390/s21103344.

[17] Y. K. Liu, S. K. Ong, and A. Y. C. Nee, "State-of-the-art survey on digital twin implementations," *Adv. Manuf.*, vol. 10, no. 1, pp. 1–23, Mar. 2022, doi: 10.1007/S40436-021-00375-W/TABLES/8.

[18] K. Schade, M. Hübscher, F. zur Lage, J. Schulze, and J. Ringel, "Integrating Retail into an Urban Data Platform from a Stakeholder Perspective: Network Approaches in Leipzig (Germany)," *Sustainability*, vol. 14, no. 10, p. 5900, May 2022, doi: 10.3390/su14105900.

[19] A. Luthfi, M. Janssen, and J. Crompvoets, "Stakeholder Tensions in Decision-Making for Opening Government Data," in *Business Modeling and Software Design*, vol. 391, B. Shishkov, Ed. Cham: Springer International Publishing, 2020, pp. 331–340. doi: 10.1007/978-3-030-52306-0_23.

[20] V. Gitelman, "Exploring safety-related behaviours of e-cyclists on urban streets; an observational study," *Eur. Transp. Eur.*, no. 85, pp. 1–15, Dec. 2021, doi: 10.48295/ET.2021.85.2.

[21] J. Jiao, H. K. Lee, and S. J. Choi, "Impacts of COVID-19 on bike-sharing usages in Seoul, South Korea," *Cities*, vol. 130, p. 103849, Nov. 2022, doi: 10.1016/j.cities.2022.103849.

[22] T. Koska, "The Path to Sustainable Mobility Systems – 8 Theses on a digital mobility transition," p. 33.

[23] L. Aarikka-Stenroos, D. Chiaroni, J. Kaipainen, and A. Urbinati, "Companies' circular business models enabled by supply chain collaborations: An empirical-based framework, synthesis, and research agenda," *Ind. Mark. Manag.*, vol. 105, pp. 322–339, Aug. 2022, doi: 10.1016/j.indmarman.2022.06.015.

[24] L. Saari, J. Heilala, T. Heikkilä, J. Kääriäinen, A. Pulkkinen, and T. Rantala, *Digital product passport promotes sustainable manufacturing*. VTT Technical Research Centre of Finland, 2022.

[25] X. Chen and H. Jiang, "Detecting the Demand Changes of Bike Sharing: A Bayesian Hierarchical Approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 5, pp. 3969–3984, May 2022, doi: 10.1109/TITS.2020.3037791.

[26] C. H. Lee, J. W. Lee, and Y. J. Jung, "Practical method to improve usage efficiency of bike-sharing systems," in *ETRI Journal*, Apr. 2022, vol. 44, no. 2, pp. 244–259. doi: 10.4218/etrij.2021-0408.

[27] M. Bertoni and A. Bertoni, "Designing solutions with the product-service systems digital twin: What is now and what is next?," *Comput. Ind.*, vol. 138, Jun. 2022, doi: 10.1016/j.compind.2022.103629.

[28] W. Hu, T. Zhang, X. Deng, Z. Liu, and J. Tan, "Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges," *J. Intell. Manuf. Spec. Equip.*, vol. 2, no. 1, pp. 1–34, Aug. 2021, doi: 10.1108/JIMSE-12-2020-010.

[29] M. Bertoni and A. Bertoni, "Designing solutions with the product-service systems digital twin: What is now and what is next?," *Comput. Ind.*, vol. 138, p. 103629, Jun. 2022, doi: 10.1016/j.compind.2022.103629.

[30] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the Digital Twin: A systematic literature review," *CIRP J. Manuf. Sci. Technol.*, vol. 29, pp. 36–52, May 2020, doi: 10.1016/j.cirpj.2020.02.002.

[31] D. Adamenko, S. Kunnen, R. Pluhnau, A. Loibl, and A. Nagarajah, "Review and comparison of the methods of designing the Digital Twin," *Procedia CIRP*, vol. 91, pp. 27–32, 2020, doi: 10.1016/j.procir.2020.02.146.

[32] A. Kantaros, D. Piromalis, G. Tsaramirsis, P. Papageorgas, and H. Tamimi, "3D Printing and Implementation of Digital Twins: Current Trends and Limitations," *Appl. Syst. Innov.*, vol. 5, no. 1, p. 7, Dec. 2021, doi: 10.3390/asi5010007.

[33] S. Lawrenz, M. Nippraschk, P. Wallat, A. Rausch, D. Goldmann, and A. Lohrengel, "Is it all about Information? The Role of the Information Gap between Stakeholders in the Context of the Circular Economy," *Procedia CIRP*, vol. 98, pp. 364–369, 2021, doi: 10.1016/j.procir.2021.01.118.

[34] C. Nwogu, G. Lugaresi, A. Anagnostou, A. Matta, and S. J. E. Taylor, "Towards a Requirement-driven Digital Twin Architecture," *Procedia CIRP*, vol. 107, pp. 758–763, 2022, doi: 10.1016/j.procir.2022.05.058.

[35] Q. Lu *et al.*, "Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus," *J. Manag. Eng.*, vol. 36, no. 3, p. 05020004, May 2020, doi: 10.1061/(ASCE)ME.1943-5479.0000763.

[36] R. Rasor, D. Göllner, R. Bernijazov, L. Kaiser, and R. Dumitrescu, "Towards collaborative life cycle specification of digital twins in manufacturing value chains," *Procedia CIRP*, vol. 98, pp. 229–234, 2021, doi: 10.1016/j.procir.2021.01.035.

[37] J. Friederich, D. P. Francis, S. Lazarova-Molnar, and N. Mohamed, "A framework for data-driven digital twins of smart manufacturing systems," *Comput. Ind.*, vol. 136, p. 103586, Apr. 2022, doi: 10.1016/j.compind.2021.103586.

[38] J. Protner, M. Pipan, H. Zupan, M. Resman, M. Simic, and N. Herakovic, "Edge Computing and Digital Twin Based Smart Manufacturing," *IFAC-Pap.*, vol. 54, no. 1, pp. 831–836, 2021, doi: 10.1016/j.ifacol.2021.08.098.

[39] M. Pregnolato *et al.*, "Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure," *Autom. Constr.*, vol. 141, p. 104421, Sep. 2022, doi: 10.1016/j.autcon.2022.104421.

[40] Y. Yu, D. M. Yazan, V. Junjan, and M.-E. Iacob, "Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies," *J. Clean. Prod.*, vol. 349, p. 131335, May 2022, doi: 10.1016/j.jclepro.2022.131335.

[41] Benjamin Schleicha*, Marc-André Dittrichb, Till Clausmeyerc, Roy Damgraved, John Ahmet Erkoyuncue, Benjamin Haefnerf, Jos de Langed, and Denys Plakhotnikg, Wieben Scheidelh, Thorsten Wuest, "Shifting value stream patterns along the product lifecycle with digital twins." [retrieved: Mai, 2023] https://reader.elsevier.com/reader/sd/pii/S2212827120300639?token=4058F61DD11A9AB2896848BF7756F22597A54B0D6AD3B05F9AABF1DF8AA149180EF2E6521509C796DBDD1B53895F6BE9&originRegion=eu-west-1&originCreation=20220609142727

[42] K. Binder, "Ein drittes Standbein der Forschung neben Experiment und (analytischer) Theorie," *Phys. J.*, p. 6, 2004.

[43] C. Cimino, A. Leva, E. Negri, and M. Macchi, "An integrated simulation paradigm for lifecycle-covering maintenance in the Industry 4.0 context," *IFAC-Pap.*, vol. 53, no. 3, pp. 307–312, 2020, doi: 10.1016/j.ifacol.2020.11.049.

[44] I. Daniyan, R. Muvunzi, and K. Mpofu, "Artificial intelligence system for enhancing product's performance during its life cycle in a railcar industry," *Procedia CIRP*, vol. 98, pp. 482–487, 2021, doi: 10.1016/j.procir.2021.01.138.

[45] Y.-X. Zhang *et al.*, "Digital twin accelerating development of metallized film capacitor: Key issues, framework design and prospects," *Energy Rep.*, vol. 7, pp. 7704–7715, Nov. 2021, doi: 10.1016/j.egyr.2021.10.116.

[46] D. Romero, T. Wuest, R. Harik, and K.-D. Thoben, "Towards a Cyber-Physical PLM Environment: The Role of Digital Product Models, Intelligent Products, Digital Twins, Product Avatars and Digital Shadows," *IFAC-Pap.*, vol. 53, no. 2, pp. 10911–10916, 2020, doi: 10.1016/j.ifacol.2020.12.2829.

[47] Ostfalia University of Applied Sciences, 38302 Wolfenbüttel, Germany, L. Kintscher, S. Lawrenz, H. Poschmann, and P. Sharma, "Recycling 4.0 - Digitalization as a Key for the Advanced Circular Economy," *J. Commun.*, pp. 652–660, 2020, doi: 10.12720/jcm.15.9.652-660.

[48] S. Blömeke *et al.*, "Recycling 4.0: An Integrated Approach Towards an Advanced Circular Economy," in *Proceedings of the 7th International*

Conference on ICT for Sustainability, Bristol United Kingdom, Jun. 2020, pp. 66–76. doi: 10.1145/3401335.3401666.

[49] A. P. Barquet *et al.*, “Sustainable Product Service Systems – From Concept Creation to the Detailing of a Business Model for a Bicycle Sharing System in Berlin,” *Procedia CIRP*, vol. 40, pp. 524–529, 2016, doi: 10.1016/j.procir.2016.01.127.

[50] C. Kiefer and F. Behrendt, “Smart e-bike monitoring system: real-time open source and open hardware GPS assistance and sensor data for electrically-assisted bicycles,” *IET Intell. Transp. Syst.*, vol. 10, no. 2, pp. 79–88, Mar. 2016, doi: 10.1049/iet-its.2014.0251.

[51] T. Buchert *et al.*, “Design and Manufacturing of a Sustainable Pedelec,” *Procedia CIRP*, vol. 29, pp. 579–584, 2015, doi: 10.1016/j.procir.2015.02.168.