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Shaping Extended Product Design and Development with Predictive Maintenance Capability for Digital Servitisation

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Traditional business models of selling a product as a single item can no longer satisfy the growing service-oriented needs of customers. Service-oriented business models, like servitisation or product-service systems (PSS), have been introduced to respond to this market demand. Predictive maintenance (PdM) strategy is regarded as a key element in the development of such business models because of its effective role in maximising the availability and usability of products. The PdM strategy requires technologies including, sensing, data acquisition, data analytics algorithms and decision support tools. In traditional business models, these technologies are typically developed by third parties when products are already commissioned or in service, which is sub-optimal. It can be argued that PdM technologies developed by original equipment manufacturers (OEMs) can significantly reduce development costs and increase competitiveness. This paper proposes a new framework for guiding OEMs to develop and integrate relevant PdM technologies during the development of new products in support of their new journey in a digital servitisation business model. This encompasses the full life cycle of the product from customers' needs/values analysis to after-sales service. The model-based system engineering (MBSE) approach was adopted to implement the proposed framework using the selected system modelling language (SysML) tool, namely Capella, and to verify it in an industrial case study.

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Keywords: Extended Products; Product Service Systems (PSS); Servitisation; Predictive Maintenance; MBSE; SysML; Analytic Hierarchy Process (AHP)**1. Introduction**

The emerging digital society has indeed fundamentally changed the way industrial companies provide products and services. Compared to the past, the customer's focus when purchasing a product has shifted from ownership of a physical product or system to a guaranteed benefit based on the product provided. As a result, offering a single (tangible) product is no longer competitive in the global market. In response to this shift, Jansson & Thoben [1] developed a hierarchical model for building an extended product approach, as illustrated in Fig.1. Extended products are divided into three layers: the first layer is called the "core product", which is closely related to the core function of the product, the most indispensable part for a product to meet the design requirements. The second layer is

called the "tangible product", which is the packaging of the core functions of the product. This packaging can increase customer attractiveness and is the driving factor of the product's marketability. The third layer is the "non-tangible product" summarising all the surroundings. These intangible product assets are often information- and knowledge-intensive and can consist of engineering, software, maintenance, customer support services, and many others.

This extended product concept is embodied in the servitisation, also known as the product-service-system (PSS) business models that have existed for a considerable duration. However, their adoption within industries has surged dramatically since the beginning of the digitalisation era [2]. As these business models mainly offer "outcomes as a service," the

need for assured and optimised product availability has significantly increased, which poses a new challenge. In the context of this research, it is important to note here that product and asset are the same entity. Original equipment manufacturers (OEMs) call the entity a product, meanwhile, the end-users /customers call it an asset.

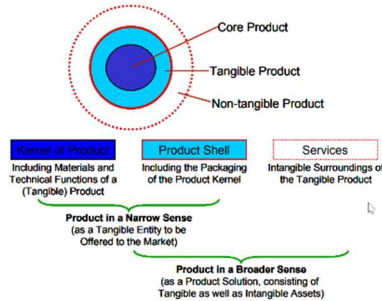


Fig. 1. Basic concept of an extended product, reproduced from [1].

To address this challenge, the predictive maintenance (PdM) strategy has emerged as a crucial component in shaping such business models. The PdM strategy enables businesses to proactively monitor and maintain their products, reducing downtime and improving customer satisfaction [3-5]. Applying the PdM strategy demands a range of technologies encompassing sensing, data acquisition, data analytics encompassing algorithms, and decision support tools.

In traditional business models, these PdM technologies are typically developed by external parties once products have already been created and deployed. These third-party entities lack prior insights into the product's performances and behaviours. Consequently, additional research and development (R&D) is required to gain the insights. These efforts may include activities like failure mode and effect analysis (FMEA) and/or resource-intensive accelerated life tests, all aimed at achieving a partial understanding of the product's performances and behaviours.

Moreover, this supplementary R&D sustains considerable financial investment, which could be effectively minimised or avoided altogether if the OEMs were responsible for technology development [5,6]. The conventional approach, arguably sub-optimal, thus calls for a novel methodology/framework to enable OEMs to create PdM-relevant technologies during new product development. This novel approach would not only optimise resource allocation but also streamline the integration of PdM into servitisation business models, ultimately fostering more efficient and sustainable outcomes.

This study aims to develop a novel framework to guide OEMs in developing and/or integrating relevant PdM technologies during new product development. The remainder of this paper is structured as follows. Section 2 presents related works identified in the scientific literature. Section 3 presents the development of a novel framework to support OEMs integrating PdM technologies when developing new products. Section 4 presents a case study selected from the public domain. Section 5 discusses an attempt to implement the developed framework of the case study using a Model-Based System Engineering (MBSE) approach on the selected open-source software tool, i.e., Capella. Section 6 presents the conclusion and future work.

2. Related Work

An extensive literature review covering extended products, servitisation, frameworks for new product development and PdM technologies development was performed, for example, see [5-9]. A general framework to support manufacturing enterprises in improving their design and development capabilities is developed in [6]. The authors believe that trends such as digitization, sustainability, and service-oriented fundamentally change the conditions for manufacturers to develop and provide new products. However, the development and/or integration of relevant PdM technologies during new product development is not considered in this framework.

As stated in [7], data-driven product design has emerged with the advent of new-generation digital technologies. To address this, the authors proposed a digital twin (DT)-driven product design framework. However, the framework does not consider PdM technologies integration in the early product development phase.

The emergence of digital technologies has penetrated many sectors including maintenance. In [8], the authors proposed a framework based on utilising a DT for implementing the PdM strategy on critical assets in operation. However, the framework lacks the application and/or integration of PdM technologies in the early stages of product design. A generic data-driven maintenance planning integrating reliability and maintenance management processes is proposed in [9]. However, this framework does not consider PdM technologies integration during new product development.

In summary, it can be stated that there is still a significant gap in the scientific literature concerning a methodology and framework for OEMs to develop extended products or PSS with PdM capabilities to support their servitisation business models.

3. Framework development

3.1. Methodology

The process of designing the framework architecture involved several essential steps. The essential step is to formulate fundamental questions enabling a more thorough investigation. The framework's structure was further solidified through the development of a comprehensive diagram categorising components into smart product design, technology, maintenance, customer management, continuous improvement, optimizations, and operations. The framework was designed to facilitate collaboration between different customer segments and departments, ultimately forming a cohesive whole.

3.2. Selection of a tool for building the framework

In this study, Cacao, a cloud-based diagramming software tool was selected to develop and build the framework. Cacao is a free and easy-to-use online graphic design tool that supports multiple people working together online and can help users create more creative flow charts and diagrams [10].

3.3. Framework design

Based on the methodology discussed earlier and the selected software tool, the novel framework was developed as shown in Fig. 2. The framework is divided into 6 different components.

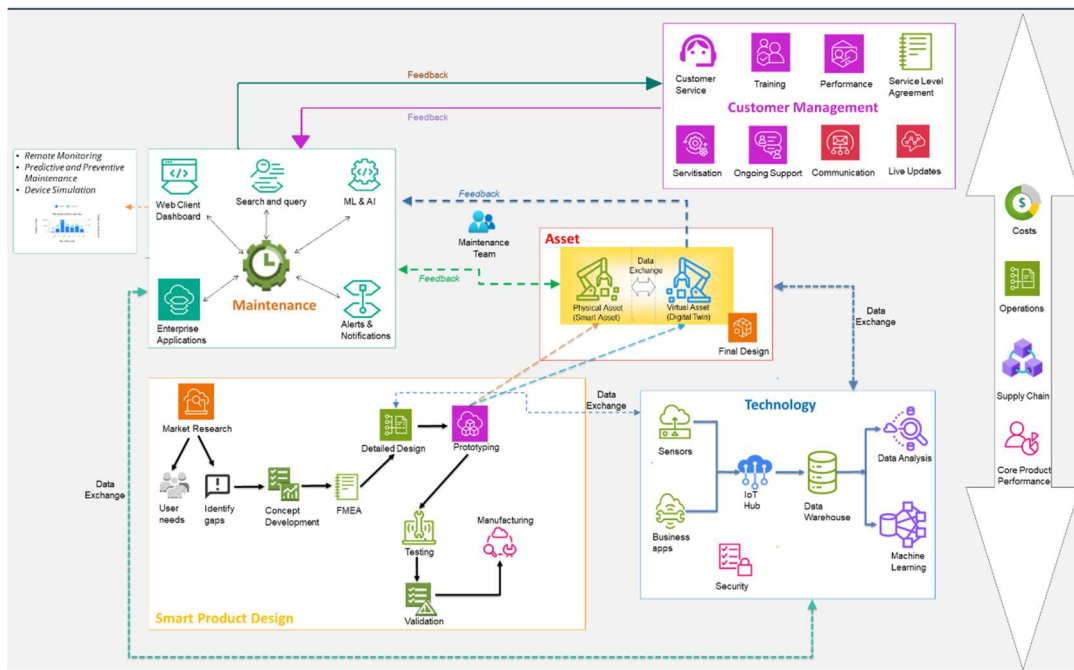


Fig. 2. The proposed high-level framework.

I. Smart Product Design – This is our first and most important stage for extended product development. During this stage, we research what the needs are and incorporate intelligent technologies, connectivity, and data-driven functions. Cost considerations should be integrated throughout the entire smart product development lifecycle. Every choice is grounded in cost considerations and the available budget. It is important to balance innovation with financial sustainability. The cost of different smart components can vary based on factors such as quality, features, and manufacturer. Also, during this stage, we link to technologies available and create a prototype based on a physical asset and virtual asset where further decisions can be made before creating the final design ‘Asset’ – A smart asset and Digital twin for design allowing designers to simulate and test various design iterations virtually before physically manufacturing the product. This can reduce the need for costly physical prototypes and accelerate the development process. A detailed framework focusing on smart product design is shown in Figure 3.

II. Technology – various technologies are required to create innovative smart products. The choice of technology can significantly impact both the functionality and the cost of the final product. The following are the most crucial technologies for product design.

- Sensors – Varies with the data we want to collect. Correct sensors in place can support the decision-making in the servitisation process. The type and number of sensors used can affect the product's capabilities and cost.
- Connectivity modules and processors (IoT).
- Data Storage and Cloud Services – despite the different types of data storage, the most beneficial is a cloud system with real-life data for the full benefits.
- Analytics, Machine Learning and Artificial Intelligence (AI) – these functionalities enable products to make intelligent decisions based on data analysis. Integrating AI might be complex and can increase the cost of the product.
- Security – Implementing the right security measures like encryption and authentication is crucial to protect user data.

Usually, incorporating additional technologies demands a higher number of approvals and checks, thereby increasing the overall time of the process.

- Digital Twin (DT) – in this framework, this is separated and built into the ‘Asset’ component of the framework. In the design phase, integrating sensors into the product allows for real-time monitoring of its performance. Data collected from these sensors can be used to create a digital twin that predicts when maintenance or repairs might be needed, optimizing the product's lifespan, and reducing downtime.

III. Asset – Smart Asset and Digital Twin for PdM – Both physical and digital assets work as a mirror. The operations rely on each other's data exchange. Any feedback within all components will always support any decision made by the maintenance team and should have a positive impact on operations, customers, and the lifecycle of the product.

IV. Maintenance – in this case, maintenance is driven as part of technology. The focus is on the feedback from technologies available (including digital twin) and how the information is displayed to the maintenance team and customer. Technologies like dashboards, apps, alerts, and notifications help with servitisation and enhance customer satisfaction. The maintenance team can perform remote monitoring and software updates.

V. Customer Management – there would not be servitisation without the customer being the centre of it. The developed framework focuses on the customer-centric approach. Product and operations need to meet customer needs via communication, customer service, data from the product and more, deepening the product type and the service level agreement. Nowadays, organisations focusing on the PSS business models retain long-term customer relationships.

VI. Cost, Operations, Supply Chain, Core Product Performance (vertical arrow on the right side) – it is difficult to present all those elements in the general framework. These are essential factors throughout each step of the design and servitisation to support the business model. Operations will

also have an impact on the technology and locations. Not all Over the Air (OTA) could be implemented the same way as that could be affected by the product location and regulations in that specific country. The link between technology and cost is often intertwined. More advanced and feature-rich technologies generally lead to higher development, manufacturing, and operational costs. Therefore, it is important to carefully evaluate the trade-offs between technology features, product functionality, and cost constraints. Conducting a thorough cost-benefit analysis for each technology choice can help ensure that a smart product remains financially viable, competitive, and aligned with user expectations.

In short, each of the components presented in the proposed framework works on the data exchange and feedback. This will in turn drive continuous improvement. Available technology, maintenance and servicing play a vital role in shaping customers' perceptions of a product and brand. Companies that prioritise effective maintenance, efficient repairs, and positive servicing experiences can create a strong foundation for customer satisfaction, loyalty, and positive word-of-mouth recommendations. On the other hand, neglecting maintenance and offering subpar servicing can lead to customer frustration, decreased loyalty, and potentially damage the company's reputation.

3.4. Sub-framework detailing Smart Product Design

This section expands the framework in Fig. 2, emphasising new product development with PdM capabilities. This sub-framework as shown in Fig. 3, is highlighted by five main steps namely (i) preliminary conceptual design, (ii) detailed design, (iii) feasibility of PdM technologies, (iv) informed decision-making for business strategy and (v) data analytics for PdM implementation.

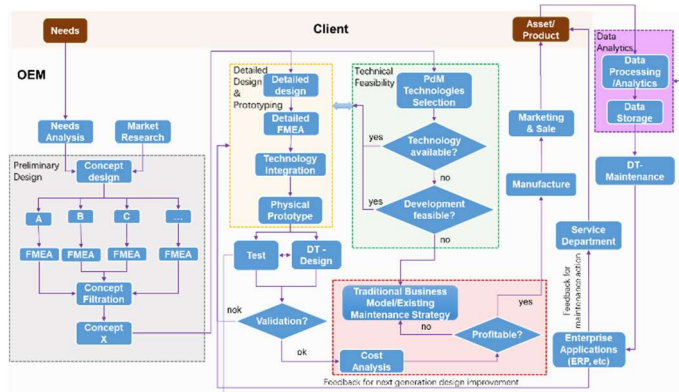


Fig. 3: Sub-framework detailing Smart Product Design

The customer values and requirements are analysed through market research and customer relationship management (CRM). The customer needs identified from this analysis will enable the design team of an OEM to generate multiple concepts undergoing pre-defined design KPIs analysis and preliminary FMEA. Based on these analysis results, the highest-ranked concept is to be selected (e.g., Concept X in Fig. 3) and a detailed design including a detailed FMEA is subsequently generated by the design team. In parallel, the detailed FMEA report from the design team will enable the OEM R&D team to perform a technical feasibility study to investigate whether it is feasible to integrate off-the-shelf or develop new PdM technologies into the new product. If not

feasible, the OEM may stay with the traditional business model or embrace the new servitisation business model with the existing maintenance strategy. If feasible, the PdM technologies are considered in the final design and a physical prototype of the new product is manufactured and tested to ensure the physical prototype's performances (i.e., KPIs) align with the expectations. A DT for design is established for the physical prototype validation and refinement. If not validated, some iterations to fine-tune the final design are required until the performances align with the expectations. Once the prototype's performances are under the expectations, a cost-benefit analysis needs to be carried out to ensure profitable business. Note that further inputs from the customers might be required at this stage. If profitable, the next steps go to production and marketing. If non-profitable, the OEM may keep the existing business model or embrace the servitisation business model journey with traditional maintenance strategies.

Notably, unlike the traditional approach, within the proposed framework, a DT-Maintenance for the PdM strategy implementation can already be established from the early phase. As shown in Fig. 3, relevant data for PdM is generated during the physical prototype testing. This dataset is stored on the OEM data analytics platform and analysed. Predictive models for maintenance management (planning and scheduling) can be derived with the help of Artificial Intelligence (AI) technologies. The predictive models can be enhanced further by integrating the unique domain expertise knowledge and know-how across the OEM teams/departments.

After the product is released to the market and deployed at the client's site, more datasets are generated and stored on the OEM data analytics platform. These gradually stored datasets will improve further the predictive models in the DT-Maintenance. When a potential issue is predicted by the DT-Maintenance, the enterprise application (e.g., ERP) notifies the service department/team to perform necessary actions on the product/asset based on the DT-Maintenance recommendations. Once the actions are completed, the service team will provide relevant feedback to the OEM data analytics platform for further improvements on the predictive models. The design team can also use this logged information for the development of a next-generation product.

4. Case Study

A literature review was conducted to identify an industrial case study from the public domain to test the proposed framework, yielding a case study from the railway sector [11]. Hitachi, as an OEM of trains, realised the service market to keep the trains running and to build relationships with customers on this basis. To respond to this market demand, Hitachi announced a partnership with its customers to retrofit remote condition monitoring (RCM) systems to train wheels.

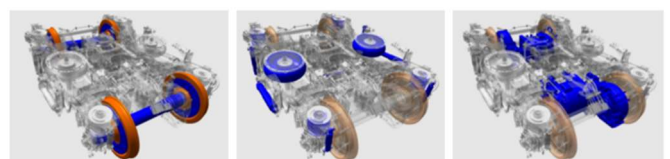


Fig. 4. Three visual representations of critical components that affected train performance on the wheelsets [12]

The critical components of the wheelsets that affect trains' performance could be identified through FMEA [12] as highlighted in Fig.4. Hitachi developed the RCM technology that is easy to retrofit on existing trains and requires no external maintenance [11] to remotely monitor the conditions of such critical components. This technology is equipped with an electromagnetic energy harvester that converts the mechanical energy generated by vibration into electrical energy to power wireless sensor nodes. These nodes transmit real-time data back to the asset operator's desktop or mobile device. It is claimed that the energy harvester would last more than 100 years without maintenance and the sensor node has a life of 20 years.

5. Implementation of the Proposed Framework Using a Model-Based System Engineering (MBSE) Approach

Considering the complexity of high-value asset/product development (e.g., airplanes, trains, cars, etc.), the model-based systems engineering (MBSE) paradigm is adopted in this study. The development process includes design, analysis, requirements verification, etc. [13,14]. MBSE provides an orderly system engineering method, which uses graphical models and other visual tools to describe the system and its components, interactions, and relationships. This gives MBSE advantages in simplifying the system engineering (SE) processes, reducing development costs by avoiding rework and late-stage design changes, ensuring traceability, and improving system performance and reliability. That is why MBSE is increasingly being adopted in many industries, including aerospace, automotive, and healthcare [15].

To support the implementation of MBSE, systems modelling language (SysML) is required. It is a general-purpose graphical modelling language that supports the specification, analysis, design, verification, and validation of complex systems that may include hardware devices, software data, people, programs, facilities, and other man-made and natural system elements. SysML facilitates the application of MBSE methods to create a cohesive and consistent system model. There are about 15 SysML software tools on the market, four of which *Capella*, *Modelio*, *Papyrus*, and *Gaphor* are open-source software tools [16]. By applying the Analytic Hierarchy Process (AHP) method [17] to the four open-source software tools, *Capella* was selected in this research.

5.1. Model development in the Capella platform

In the MBSE paradigm, all diagrams from the system level to the subsystem level are integrated and interconnected in the project module of the *Capella* software. This way, model creation in the same software environment allows for better information/model sharing between internal teams and enables model integration across different teams.

Capella's workflows follow the MBSE paradigm, where five main steps including (1) *operational analysis*, (2) *system analysis*, (3) *logical architecture*, (4) *physical architecture*, and (5) *end-product breakdown structure (EPBS)*, need to be modelled. Building a detailed physical product is out of the scope of this research. Thus, only the first three steps are modelled in the *Capella* environment. The paragraphs below discuss the implementation of each step for the Hitachi case

study in *Capella*'s environment. More emphasis goes to the logical architecture step which demonstrates the proposed framework. Within *Capella*, blank diagrams are the most used diagrams allowing the developer/architect to decide which elements should appear on the diagram.

(1) Operational Analysis

The operational analysis step focuses on capturing and consolidating operational needs from the stakeholders (i.e., various teams at the OEM and client). In this step, the developer/architect also needs to define what the users (i.e. clients) of the extended product/PSS must accomplish. Furthermore, entities, actors, roles, activities, and concepts must be identified. At this step, four blanks, namely Operational Activity Interaction Blank (OAIB), Operational Architecture Blank (OAB), Operational Capabilities Blank (OCB), and Operational Entity Breakdown Diagram (OEBD), need to be completed. In OEBD, OEM (Hitachi) and client (train operator) are considered as participants and an extended product or PSS as entities. In OCB, the operational capability is defined as production and sales, which involve both OEMs and clients. In OAB, two possible "scenarios" referring to the traditional business model or servitisation business models are defined.

(2) System Analysis

This step aims to formalise the extended product/PSS requirements. The developer/architect needs to identify the PSS boundaries and consolidate the requirements. Furthermore, the developer/architect needs to define what the PSS must accomplish for the clients. Besides, functional dataflows and dynamic behaviour of the PSS also need to be modelled. In this step, six blanks including (i) Contextual System Actors (CSA), (ii) Missions Blank (MB), (iii) Missions Capabilities Blank (MCB), (iv) System Architecture Blank (SAB), (v) System Data Flow Bank (SDFB) and (vi) System Function Breakdown Diagram (SFBD), need to be completed. As an example, in the MCB, four new capabilities are defined, namely PSS with PdM capabilities, provision of maintenance services, creation of DTs, and iterative product upgrades.

(3) Logical Architecture

This step aims at developing a logical architecture of the PSS. This will enable the developer/architect to see the PSS as a white box and ensure that the PSS will work to fulfil expectations. A first tradeoff analysis might be required in this step. The logical architecture is established based on the proposed sub-framework shown in Fig. 3. Two logic diagrams/blanks namely, Logical Component Decomposition (LCBD) and Logical Architecture Blank (LAB), need to be completed. Subsystems are defined in LCBD, while LAB can tightly display all functions and interactions.

An initial implementation of the developed framework in Fig. 3 for the Hitachi case study is demonstrated in the LAB as shown in Fig. 5. As seen in the figure, two participants are involved, namely a railroad operator ("Client") and Hitachi ("OEM"). The contents of the "Technical feasibility" block in Fig. 3 correspond to the "Application of PdM techniques" block in Fig. 5. The "Creation of DT" block in Fig. 5 is a refinement of creating the "DT-Design" and "DT-Maintenance" blocks in Fig. 3. The "provide maintenance" and "iterative product upgrades" blocks in Fig. 5, are refinements of the functions of an OEM to provide maintenance services and product upgrades

in the sub-framework shown in Fig.3. Note that different logical functions are connected by function chains of different colours.

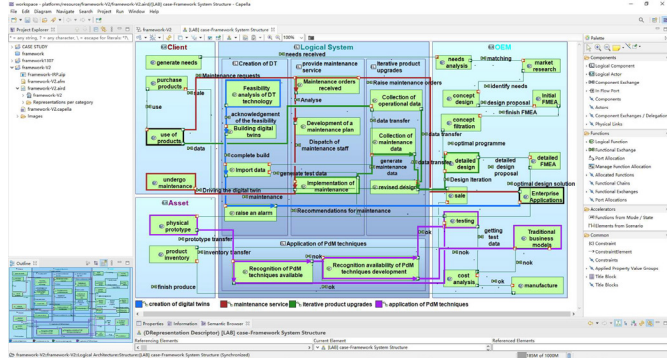


Fig. 5. [LAB] Framework System Structure.

It is worth mentioning here that it is not the purpose of this research to establish a complete model for the Hitachi case study due to the lack of data. The purpose is rather to demonstrate a step-by-step implementation of the developed framework using the MBSE approach.

6. Conclusion and Future work

Servitisation is still in its infancy and only several businesses have successfully been able to make use of it. A product-centric model is no longer viable in today's industry. Now, predictive maintenance (PdM) capability and subsequent servitisation are important for original equipment manufacturers (OEMs) to compete and remain relevant in their servitisation journey.

A PdM-powered servitisation framework was proposed in this paper to guide OEMs in developing new products with PdM capabilities. This framework adopted the use of smart product design, technology incorporation, maintenance strategies, customer management, continuous improvement, and optimisation. The framework indicated the flow, feedback and data exchanges between these critical elements when considering new product development.

The integration of PdM into servitisation business models during early product development represents a transformative approach to value creation. By harnessing the power of data analytics and sensor technology from the early stage of the product life cycle, businesses can not only enhance customer satisfaction but also optimise operational efficiency and reduce maintenance costs. As technology continues to advance, the potential for extended product offerings with PdM capabilities continues to expand, reshaping industries and paving the way for a more connected and efficient future.

Given the complexity of high-value products/assets, the model-based system engineering (MBSE) paradigm was adopted to implement the framework for an industrial use case (Hitachi) as an example. A first attempt to model the extended product/PSS for the Hitachi use case using the Capella software tool is presented and discussed.

Due to the lack of data from the Hitachi case study, the MBSE implementation on the Capella software tool could not be discussed more in-depth. Besides, building digital twins

(DTs) for product development and PdM purposes to support the PSS and what algorithms and software tools to process measurement data need further research. Furthermore, the cost-benefit analysis of applying the proposed framework to real PSS needs to be performed rigorously. These open questions will be addressed in future works.

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