INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.166

Digital Twins and Product-Service Systems: A Synergy with Challenges and Opportunities

F. N. Laukotka ✉, C. Rennpferdt and D. Krause

Hamburg University of Technology, Germany

✉ fabian.laukotka@tuhh.de

Abstract

Digital Twins and Product-Service Systems are just two of the recent trends in product development. While many presented approaches seem promising, their implementation often face challenges. This is especially true if existing approaches are transferred onto new applications. Diving into these topics this paper presents the basics but also challenges as well as synergies emerging between them. The objective is set, to move from specialised applications to broader approaches that can provide benefit to a range of applications and ease the entrance, particularly, for smaller enterprises.

Keywords: *digital twin, product-service systems (PSS), supportive technologies, technology development, challenges*

1. Introduction

Over the last years, different trends arose in product development. The ongoing move to integrate services to products and, thus, create *Product-Service Systems* (PSS) (Alonso-Rasgado and Thompson, 2006; Rennpferdt and Krause, 2020) and the goal to improve the acquisition, storage, and usage of all kind information about the product, especially during the use-phase in form of *Digital Twins* (Stark *et al.*, 2020; Laukotka *et al.*, 2020) are just two of these trends. The topic of digitalisation in combination with innovation and PSS is also becoming increasingly important in research (Mertens *et al.*, 2021).
Additionally, while these trends are often emerging from an ideal point of view and with relatively simple products or applications in mind, different literature describe, how the actual implementation faces various challenges (Matschewsky *et al.*, 2018; Moro *et al.*, 2020). These currently simultaneous emerging approaches also lead to an ambiguous wording. Regarding more compound products, they usually are not manufactured by one big company but rely on subcontractors that supply components. Often these subcontractors are very focused and specialised small- and medium enterprises (SMEs). To accomplish the holistic implementation of the described trends their products need to be able to be seamlessly integrated into the bigger context. Yet, besides other challenges they often do not have the resources and knowledge to implement the required adaption or smartification of their products.
The aim of this research is to analyse reasons for the challenging implementation of PSS in formerly mostly mechanical orientated products and to illustrate the suitable synergy between the PSS and Digital Twins. While this synergy may be promising, the subsequent aim is to analyse its own challenges but also demonstrate how the common ground across fields of applications can lead the way to overcome them. While this is not yet fully solved, the goal is to present the first steps towards a better adaption from the many current individual specialised solutions and inspire the community to benefit from the presented synergy as well.

2. Methodology and introduction to Product-Service Systems and Digital Twins

Despite being broadly discussed topics, literature reviews show occasionally different understandings, hence the research background and the author's understanding of Product-Service Systems and Digital Twins is presented in this chapter.

2.1. Methodology

The methodology used in this research is based on the DRM approach by Blessing and Chakrabarti (2009), focusing on its first half. By analysing and summarising the state of the art of Digital Twins and PSS in Section 2 a common grasp of these research topics is achieved. In addition, the challenge to keep up with the rise of these trends and new technologies is presented. In Section 3 this is followed by an in-depth analysis of challenges in PSS implementation based on literature and complementary empirical knowledge from current industry projects. The possibility to overcome these challenges utilising the concept of Digital Twins is introduced in Section 4. The resulting common understanding of the overall challenge, which corresponds to stage 1 and 2 of the DRM, can now be used as a starting point for further research regarding this topic. A first glance at a respective approach and how the synergy of these trends may enable enterprises prospectively to accomplish the required smartification of their products is suggested in the end of Section 4. Finally, a conclusion is given in Section 5.

2.2. Product-Service Systems as enabler for innovative Business Models

Global megatrends are causing long-lasting changes in markets and business environments. As a result of globalisation, cost pressure is increasing for manufacturing companies and at the same time customers are demanding an increasingly high degree of individualisation of their products (Krause *et al.*, 2013; Rennpferdt and Krause, 2020). In order to adapt to this development, more and more companies are combining their conventional products with additional service elements to create so-called Product-Service Systems (PSS) (Alonso-Rasgado and Thompson, 2006; Rennpferdt and Krause, 2020). A wide spectrum of terms and definitions exist for PSS, but the main common feature is that PSS represent a customer-oriented solution consisting of tangible products and intangible services which are adding value for the customer (Alonso-Rasgado and Thompson, 2006; Tukker, 2004). How products and services are combined can vary according to the characteristics of the PSS and the company's business model (Tukker, 2004). Products as tangible goods and services as intangible goods need to be considered differently in general, especially in product development (Isaksson *et al.*, 2009; Rennpferdt and Krause, 2020). In addition to the added value for the customer, providing PSS can enable a number of advantages for the manufacturing company. The customer loyalty is strengthened, new markets can be accessed and the solution space for the realisation of the customer demands is widened (Tukker, 2004; Alonso-Rasgado and Thompson, 2006; Isaksson *et al.*, 2009; Sundin *et al.*, 2009; Vasantha *et al.*, 2012). One major disadvantage of PSS is the increasing complexity (Zou *et al.*, 2018), mainly caused by the higher number of components, their interactions with each other and the increasing variety of product and service components (Rennpferdt and Krause, 2020). Another frequently mentioned disadvantage of PSS is the increasing complexity for the company caused by the growing system (Rennpferdt and Krause, 2020). Besides the increasing number of product and service components, the increasing effort for data and knowledge management is also a complexity driver (Tukker, 2004; Zou *et al.*, 2018; Rennpferdt *et al.*, 2022).

In literature, the term Business Model (BM) is used in a similarly diverse way as PSS (DaSilva and Trkman, 2014). However, in a nutshell, a BM can be described as the mechanism by which the company generates its value (Rennpferdt *et al.*, 2021). PSS enable a variety of different BM that can be clustered into different categories. In the literature different classifications can be found, either as single publications, e.g., (Adrodegari *et al.*, 2021; Gaiardelli *et al.*, 2014; van Ostaeyen *et al.*, 2013; Oliva and Kallenberg, 2003) or in reviews e.g., (Salwin and Kraslawski, 2020). The clustering is done based on the service focus (Oliva and Kallenberg, 2003), business models (Adrodegari *et al.*, 2021; van Ostaeyen *et al.*, 2013) or a combination of existing approaches (Gaiardelli *et al.*, 2014). One of the most common classifications is the clustering of PSS by Tukker (2004) into the three categories *product oriented PSS*,

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

use oriented PSS and *result oriented PSS* (see Figure 1). Its setup is rather simple but helpful to understand the basic ideas of PSS. Each of the named categories is composed of subcategories, e.g., the category *use oriented PSS* is subdivided into *product lease*, *product renting/sharing* and *product pooling*.

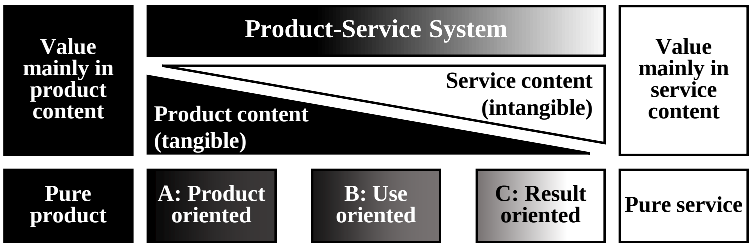

Figure 1. Categories of PSS according to (Tukker, 2004)

Rabetino *et al.* (2021) analysed current trends in servitization, which describes the transformation of the industry towards a more service-oriented economy. One identified frequently named topic is the product-centric servitization with special focus on the digital servitization (Rabetino *et al.*, 2021).
For product-centric BM and especially for the development of digital services, it is necessary to adapt the products to fit the changing requirements (Rennpferdt *et al.*, 2021). This is because the role of the tangible product depends on the degree of value creation through services. For example, for product oriented BM, it is important to adapt the tangible product to fit the customer's needs, while for result oriented BM, the product only enables the provision of services (Rennpferdt *et al.*, 2021). The data and information required for the provision of digital service-based BM must be captured by the product and forwarded to the manufacturer or other partners for processing. This requires sensors or smart machine elements and suitable communication interfaces.

2.3. An introduction to the concept of Digital Twins

Within this chapter the origin of the term and concept Digital Twin is presented and the concomitant challenge of the terminology of this rising topic is shortly elaborated on.
The very basic idea of using available data of an existing product to create a (digital) representation can be traced back to the late 60s and NASA's Apollo mission with their use of the simulators during Apollo 11 and 13 (Stephen Ferguson, 2020), albeit it wasn't yet named a Digital Twin. With over 4000 publications listed on Scopus for the years 2019 - 2021 the concept has just recently reached a new peak.
With regards to products and product development the goal of the concept of Digital Twins is to keep track of as many information a needed or possible of products and to do so especially after their creation. While the type of information that is acquired and where it is stored depends on the specific application, each individual product has its own digital representation; For each instantiated Physical Twin there is a Digital Twin - hence there is the Twofold of Twins (Laukotka *et al.*, 2021). Most concepts presented in literature describe the Digital Twin as a combination of a Digital Master Model - a template originating from the product development - and a Digital Shadow - a dataset acquired from the Physical Twin (Stark *et al.*, 2020; Laukotka *et al.*, 2021; Wilking *et al.*, 2021).
Besides the many scientific publications adhering to the presented concept, there is no clear definition that everybody relates to and a trend to call every digital representation a Digital Twin. Strictly speaking, according to the present basis of the concept, representations prior to the product creation or instantiation are no Digital Twins, because there is no Physical Twin yet. Instead, they may be a digital mock-up or digital prototype or simply put just a model that eventually will become a product. However, most of these terms are not clearly defined either and in reality, there can be seen a blurred use of synonyms. Even within scientific publications the terms like Digital Twin, Digital Shadow and Digital Master are not always used compossible or it is unclear whether the Digital Twin refers to the overall concept or the specific digital representation itself. Despite current efforts to organise and classify the terminology like the work of Wilking *et al.* (2021), there is no clear overarching image of a Digital Twin, what it is capable of doing and in particular how it can be implemented. Especially, how the data is acquired, how it is transferred, managed and stored is rarely described in detail or very specific to individual implementations and applications. While some implementations focus on geometric information, others

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

may be limited to simple sensor-data. For example, the previously described rising service-aspect within Product-Service Systems often requires a (partly) digitalisation of the original product. A big part of this digitalisation is based on the implementation of such sensors. Thus, the formerly mostly mechanical orientated products now incorporate more and more information-technologies and require the knowledge to do so. This ambiguity in terminology impedes the implementation of new applications, especially for these parties that have formerly been focused on mechanical products.

3. Challenges during implementation of PSS

As described in Section 2.1, PSS can unlock many benefits and strengthen a company's competitive position in the long term. However, there are many challenges when implementing PSS. There are several publications in the literature that provide an overview of the challenges identified. These are, among others, the following: Di Francisco Kurak *et al.* (2013), Matschewsky *et al.* (2018) and Moro *et al.* (2020). More than 80 different barriers and challenges for the implementation of PSS were analysed to identify similarities and difference in the existing publications. The challenges were clustered according to their topic by sorting them into the six categories shown in Table 1. Due to the fact that in literature different clusters for the challenges are defined which are not fully comparable (see (Matschewsky *et al.*, 2018; Moro *et al.*, 2020; Di Francisco Kurak *et al.*, 2013)) the authors defined six general categories. The categories were defined based on a content analysis of each challenge done manually by the authors. For example the category *Knowledge* was chosen because many challenges literally name knowledge as a challenge, e.g., "Lack of knowledge related to PSS" (Matschewsky *et al.*, 2018) or challenges could be traced back to a lack of knowledge, e.g. "Service-related data processing and interpretation" (Ulaga and Reinartz, 2011). The other categories are defined identically.

Table 1. Clustered barriers for PSS implementation

Category	Example	References (excerpt)
Knowledge (related to the provision of PSS)	Lack of knowledge related to PSS; reuse of information; acquiring necessary level of knowledge; Service-related data processing and interpretation	[1], [2], [3], [6]
Processes (internal processes of the PSS-provider)	New competence requirements for PSS design; Design-to-service; PSS design	[1], [2], [3], [4], [5], [6]
Technology (technology required to offer PSS)	Lack of an effective information management system; Service-related data processing and interpretation	[1], [2], [3], [6]
Organisation (the organisational structure of the PSS-provider)	Strategic alignment; Cultural acceptance; Embedded product–service culture	[1], [2], [3]
Customers (specific customers of PSS)	resistance to consumption without possession	[1], [2], [3]
Market (group of potential PSS customers)	Market segment and value proposition	[2]

[1] (Moro *et al.*, 2020) [2] (Di Francisco Kurak *et al.*, 2013) [3] (Matschewsky *et al.*, 2018)
[4] (Baines *et al.*, 2009) [5] (Isaksson *et al.*, 2009) [6] (Ulaga and Reinartz, 2011)

Table 1 clearly illustrates that the challenges for implementing PSS are manifold. For the frequently mentioned challenges that can be traced back to the ongoing transformation of a manufacturing company to a solution provider (Martinez *et al.*, 2010), various supports are provided in the literature. These challenges include a high initial effort for the implementation of PSS, or process-related barriers, such as a lack of competences for the development of PSS (Annarelli et al., 2016) or the need for new methods for the development of PSS (Isaksson et al., 2009).
The barriers that can be categorised as *Knowledge* and *Technology* are often more specific challenges related to knowledge and data management in the context of PSS. As the addition of services to the

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

product range greatly increases external variety (Rennpferdt and Krause, 2020) and thus the internal variety of components, the demand for data and knowledge management also increases. This applies in particular to services, as they are often provided to a high degree by human resources who need to access specific information in order to provide the services. But also, services that are arising with new technologies like AI or machine learning require a solid management and availability of data. Unlike tangible products, services are produced and consumed simultaneously (Alonso-Rasgado and Thompson, 2006), so information required for service delivery must be made available just-in-time. Barriers in this context are for example complex information management (Mahut et al., 2017) or sharing information with business partners to deliver a PSS (Baines et al., 2009). Other barriers related to data management are modelling respectively simulation of PSS (Isaksson et al., 2009) and data processing in the service context (Ulaga and Reinartz, 2011).

The literature findings are in line with the authors' experience from a number of industry-related research projects. The goal of entering new market segments through new PSS-based business models presents great challenges, especially for small companies in the mechanical and plant engineering sector (Rennpferdt et al., 2021). Since entirely changing the business model would be too risky, the aim is rather to extend an existing business model with additional service components. Since resources are limited, the new and existing customers must be offered the same products wherever possible. For instance, one approach here is to enable the existing products to provide PSS-based business models through additional sensor technology. However, it should be noted that small companies, such as component manufacturers, will not set the standards for entire industries, but rather focus on developing the adapted products so that they are compatible with as many communication standards or other products, etc. as possible.

The difference between mechanical and plant engineering and other industries, such as aviation, is evident when comparing the products and possible associated PSS. In aviation, very complex products, such as aircraft engines, are developed for a well-defined group of customers. Billing according to use (power-by-the-hour) is comparatively easy to implement because the engines already have a multitude of sensors installed and the operating conditions are well known. In comparison, the customer structure in mechanical and plant engineering is often much more heterogeneous, so that the PSS offered must be much more adaptable. Furthermore, the products from mechanical and plant engineering are often not yet equipped with sensors to such an extent and the operating conditions are often not as precisely defined. Compared to the example of aircraft engines, data acquisition and transfer as well as analysis of usage is much more difficult. Simple scalable solutions that can be used for a wide variety of use cases are preferable in mechanical and plant engineering, as different customers have different needs and demand products that are tailored to their individual requirements. Additionally, the products are often not used on their own but part of a bigger plant.

In summary, it can be seen that many of the challenges in implementing PSS mentioned within the literature can be traced back to data and knowledge management and technological barriers. Based on experiences from industry projects, it becomes evident that solutions to these challenges have to vary from industry to industry, as different boundary conditions exist depending on the industry and product, and the needs of companies are very diverse.

4. Digital Twins and PSS - Synergetic Opportunity and Challenge

As described in Section 2 with the rise of Product-Service Systems there is an adaption of the business models. This shift is accompanied by challenges (see Section 3) occurring because of the required extension in know-how and adaption of products. As can be seen in Table 1 in Section 3, many of the challenges that hinder the implementation of PSS are related to technology hurdles or lack of knowledge regarding the acquisition and handling of the required data to enable the services of PSS.

Nevertheless, some sectors, like aviation, have already made some progress and most notably the engines of commercial aircrafts can already be seen as established Product-Service Systems. They are not specifically part of the sold aircraft, but are sold as a service. Data about the state of the engines is continuously collected and send to its manufacturer using the available data-links (Ward and Graves, 2007; Kerr and Ivey, 2001). In case of maintenance or repairs, the engine is swapped with an identical one and the work is conducted while the aircraft can continue to operate. Once the work is done, the

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

engine is available to be mounted onto another aircraft if its engine needs maintenance. In this specific field, the formerly mentioned challenges of data-acquisition and -handling, as well as monitoring, analytics and data-exchange have already been solved. Formerly the revenue was mostly created during the sale and the circle ended at the end of the product creation (Figure 2 left circle). Afterwards the engines may need maintenance from time to time but the customer as the owner of the engine could also let the maintenance be performed by several different market players (Figure 2 right inner circle). The combination of the PSS-based Services and a Digital Twin allows the manufacturer to remain the owner and instead establish a business model based on Operability-as-a-Service or complementary services like health monitoring and predictive maintenance (Figure 2 right circle). An additional benefit is, that the manufacturer can now utilize the gained detailed information about the product's usage and performance for the next cycle of product creation and, thus, further improve future product generations.

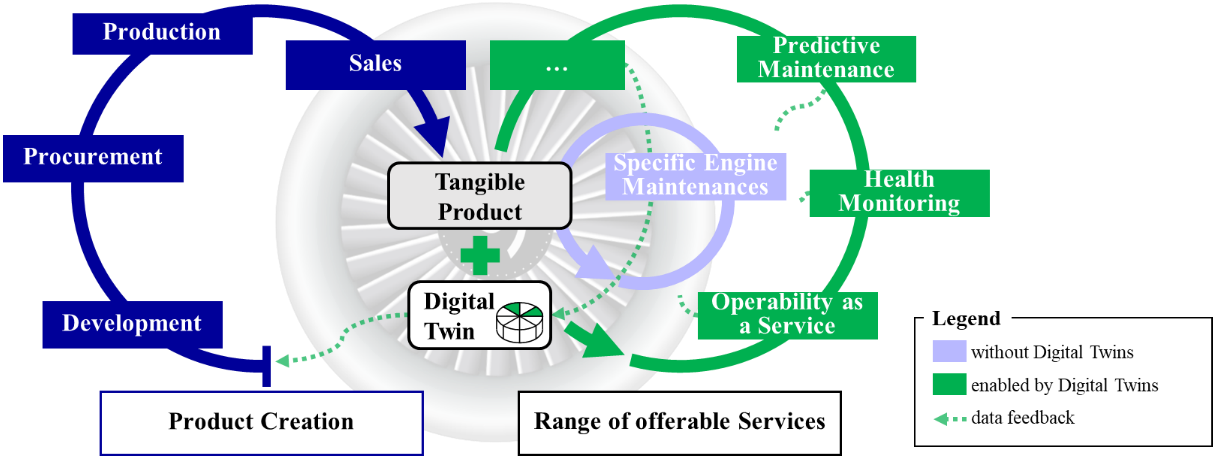

Figure 2. Digital Twins as an enabler for Services using the example of aircraft engines, adapted from (Laukotka *et al*., 2020)

Meanwhile other sectors, especially the field of mechanical and plant engineering still has a way to go. As described in Section 3, within this field the boundary conditions vary broadly to those of aviation. All this leads to the situation, that especially smaller enterprises (SMEs) often face these challenges bigger companies already have somewhat sorted out. With regards to digitalisation, they often perform much worse, which also has an effect on their potential to open up new market segments (Zimmermann, 2021). However, with the likewise rise of the concept of Digital Twins there are approaches to enable at least some of these adaptions without starting completely from scratch. As can be seen in the visualisation in Figure 3 the data-acquisition and services based on this can make use of this concept.

Figure 3 shows the Business Model Graph (BMG) introduced by Rennpferdt et al. (2021). The visualisation has been developed to support the identification of potential PSS-based business models. The solution space is spanned by the PSS continuum according to Tukker (2004) as horizontal axis and the value chain as vertical axis. More detailed information on the BMG can be found in the literature (Rennpferdt et al., 2021). In order to unlock a new business model, either further activities along the value chain can be expanded, or other types of compensation can be implemented. The solution space is limited by strategic or technological boundaries. For example, a usage-based business model (pay per service unit) can only be implemented if the provider can record the usage in detail. If the information required for this cannot be obtained and processed, this business model cannot be implemented.

As shown in Section 3, data and knowledge management is one of the key challenges in implementing PSS. Hence, the solution space for PSS-based business models is usually very limited (see blue box in Figure 3). Nevertheless, the solution space and, thus, also the possible market segments, can be significantly expanded through the use of Digital Twins. Either (vertically) along the value chain, by expanding the merit for the customer, or (horizontally) through innovative data-based services.

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

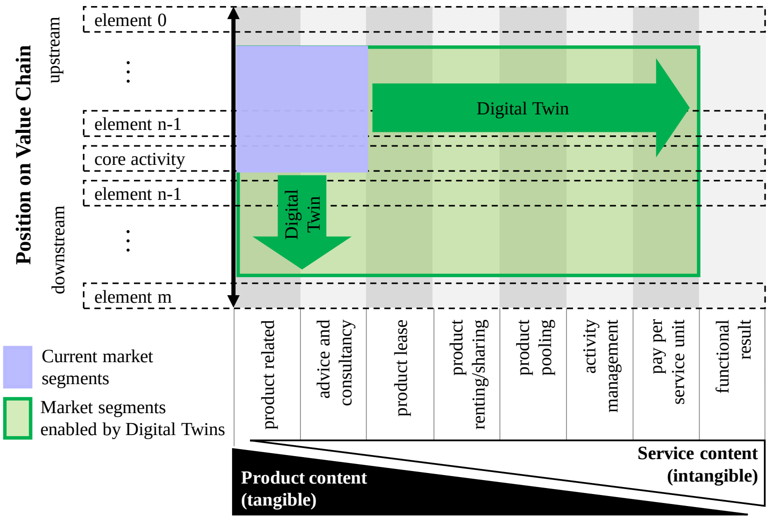

Figure 3. Business Model Graph (BMG) with Digital Twin as enabler for new business models, based on (Rennpferdt *et al.*, 2021)

As already mentioned, a way to achieve this is through the implementation of Digital Twins, as they the required data-acquisition and information-management is the very core of the concept of Digital Twins. Once this main task of data-handling is handled, usage of the stored information for e.g., for simulations can be implemented more easily. With the data digitally available, interfaces to partners like OEM are solely a task of data-management und security, for which there already are many established solutions.

Based on a recent cooperation, Figure 4 illustrates what range of services could be enabled by Digital Twins, analogous to Figure 2, but in this case using the example of industrial valves. With none or only limited data about the usage of the tangible products, they can usually only be sold and the possible services are limited e.g., to maintenance (Figure 4 right inner circle). By using Digital Twins and the accompanying data management, services can be offered on a larger scale and PSS are enabled (Figure 4 right outer circle). Examples of these services are predictive maintenance or in general a Pay-per-X BM. In addition, the data collected through the services can be used as feedback in the development of future product generations and, thus, fit the requirements of PSS-based BM even better.

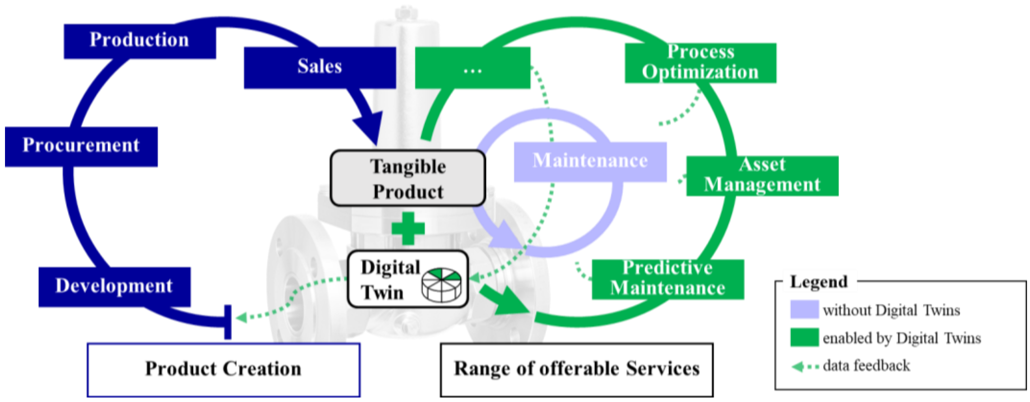

Figure 4. Digital Twins as a possible enabler for Services using the example of industrial valves, adapted from (Laukotka *et al.*, 2020)

Albeit, the implementation of the Digital Twins has its challenges as well. First of all, because of the diversity of possible applications and especially the ambiguity of the terminology there is no clear framework that can be followed to plan and implement Digital Twins on their own. Instead, they are faced with a plethora of ideas, concepts and approaches that in total describe Digital Twins as kind of a universal remedy. Hence, they first need to invest resources and try to distinguish between them and find an approach that matches their individual situation. Besides these overarching or strategic

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

challenges there are issues regarding the system integration, performance or security that are faced when implementing Digital Twins and were identified in literature (Perno *et al.*, 2022). While many of these challenges are faced during the initial implementation of a new application, there is already technology in place, that can solve them and they indeed have often already been solved, albeit in a different use-case and for a different application. Besides their different usages, a further analysis of the previously described examples shows common elements that are required for the establishment of Digital Twins in that manner. However, at this point, this will only be briefly described hereafter: Obviously, both examples need sensors to acquire the relevant data. The data has to be transmitted from the product to the service provider at some point where it needs to be stored in some way. For simple sensorial data a time-series database may be sufficient, while more complex products may additionally require an overarching management in form of a PLM system or system-models storing metadata. Besides these data-flow related elements, additional factors like the ownership of the data and whether it is intellectual property are conceivable. This initial generic description (Figure 4) of PSS related Digital Twins can now be the starting point for further detailing the required elements and infrastructure to eventually improve the transferability and ease the establishment of more and more applications.

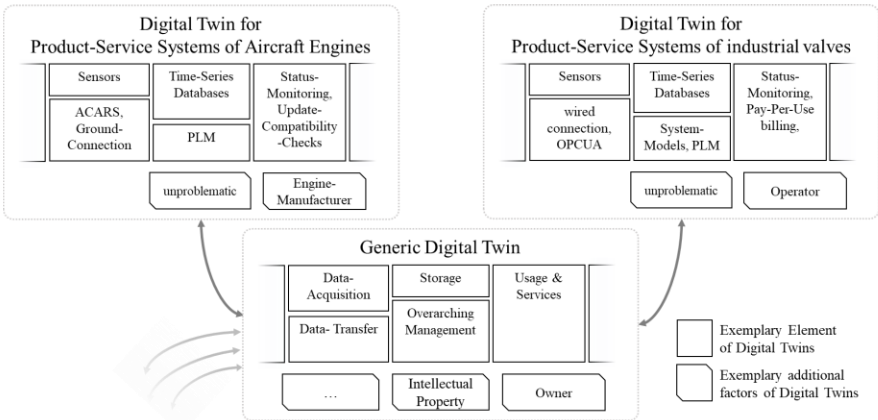

Figure 5. The concept a Generic Digital Twin for multiple individual implementations

Especially with regards to products that are not standalone but part of a bigger application like smart valves in an industrial complex the transferability has additional factors that need to be considered. Thus, all the implementations of Digital Twins of these components need to be compatible to each other or at least use a common standard. As such a standard has not been established, using an overarching framework is a good first step to lead the way. However, until that point more research has to be done.

5. Conclusion and Outlook

With Digital Twins and Product-Service Systems (PSS) there are two uprising trends in product development that each provide benefits to a variety of different applications but both also come with their own challenges. An introduction two these, at a first glance independent topics was given consisting of a description of their general concepts and opportunities but also challenges.

Based on these independent introductions the synergetic relationship of these concepts was introduced while presenting its benefits regarding implementations and consecutively Business Models; Although implementing Digital Twins has its own challenges, the many approaches currently found in literature have many commonalties that, combined can provide a benefit to more than the sum of itself and ease the challenges the implementation of PSS come with, especially for smaller enterprises. As there are currently many different and individually focused approaches and no common standards, the strike for the goal to establish an overarching framework or template to allow for a better understanding and transfer of knowledge was finally briefly introduced. Further detailing this broadly described concept is part of future work. Finally, the concept is to be applied in case-studies with the very industry partners the challenges were identified with in the first place. However, the setting of the presented work is currently quickly evolving and it remains to be seen, what kind of frameworks emerge and become prevalent. Yet, keeping the bigger picture in mind would provide a benefit to the whole community.

Acknowledgments

Parts of this work are part of the research project InDiCaT (Intelligent Digital Cabin Twin, contract number 20D1902C), funded by the Federal Ministry for Economic Affairs and Energy as part of the Federal Aeronautical Research Programme LuFo VI-1. Other parts are based within the project MODERATED (contract number 02K20K502) belonging to the program "KMU-innovativ: Produktionsforschung" funded by the German Federal Ministry of Education and Research.

The authors would like to thank all involved parties for their funding and support.

References

Adrodegari, F., Saccani, N. and Rapaccini, M. (2021), "PSS Business Models: A Structured Typology", in Kohtamäki, M., Baines, T., Rabetino, R., Bigdeli, A.Z., Kowalkowski, C., Oliva, R. and Parida, V. (Eds.), *The Palgrave Handbook of Servitization*, Springer International Publishing, Cham, pp. 57–71. http://doi.org/10.1007/978-3-030-75771-7_4.

Alonso-Rasgado, T. and Thompson, G. (2006), "A rapid design process for Total Care Product creation", *Journal of Engineering Design*, Vol. 17 No. 6, pp. 509–531. http://doi.org/10.1080/09544820600750579.

Annarelli, A., Battistella, C. and Nonino, F. (2016), "Product service system: A conceptual framework from a systematic review", *Journal of Cleaner Production*, Vol. 139, pp. 1011–1032. http://doi.org/10.1016/j.jclepro.2016.08.061.

Baines, T.S., Lightfoot, H.W. and Kay, J.M. (2009), "Servitized manufacture: Practical challenges of delivering integrated products and services", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 223 No. 9, pp. 1207–1215. http://doi.org/10.1243/09544054JEM1552.

Blessing, L.T. and Chakrabarti, A. (2009), *DRM, a Design Research Methodology*, Springer London, London. http://doi.org/10.1007/978-1-84882-587-1.

DaSilva, C.M. and Trkman, P. (2014), "Business Model: What It Is and What It Is Not", *Long Range Planning*, Vol. 47 No. 6, pp. 379–389. http://doi.org/10.1016/j.lrp.2013.08.004.

Di Francisco Kurak, C., Barquet, A.P.B. and Rozenfeld, H. (2013), "Challenges for PSS Implementation: Identification and Classification", in Meier, H. (Ed.), *Product-Service Integration for Sustainable Solutions*, *Lecture Notes in Production Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 275–285. http://doi.org/10.1007/978-3-642-30820-8_24.

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R. and Albores, P. (2014), "A classification model for product-service offerings", *Journal of Cleaner Production*, Vol. 66, pp. 507–519. http://doi.org/10.1016/j.jclepro.2013.11.032.

Isaksson, O., Larsson, T.C. and Rönnbäck, A.Ö. (2009), "Development of product-service systems: challenges and opportunities for the manufacturing firm", *Journal of Engineering Design*, Vol. 20 No. 4, pp. 329–348. http://doi.org/10.1080/09544820903152663.

Kerr, C.I.V. and Ivey, P.C. (2001), "A strategic review of the large civil aeroengine market and the paradigm shift to a service-", *The Aeronautical Journal*, Vol. 105 No. 1047, pp. 287–293. http://doi.org/10.1017/S0001924000012100.

Krause, D., Beckmann, G., Eilmus, S., Gebhardt, N., Jonas, H. and Rettberg, R. (2013), *Integrated Development of Modular Product Families: A Methods Toolkit, Advances in Product Family and Product Platform Design*, Springer New York, pp. 245–269.

Laukotka, F., Hanna, M. and Krause, D. (2021), "Digital Twins of Product Families in Aviation based on an MBSE-assisted approach", *Procedia CIRP*, Vol. 100, pp. 684–689. http://doi.org/10.1016/j.procir.2021.05.144.

Laukotka, F., Hanna, M., Schwede, L.-N. and Krause, D. (2020), "Lebensphasenübergreifende Nutzung Digitaler Zwillinge", *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 115 No. s1, pp. 101–104. http://doi.org/10.3139/104.112332.

Mahut, F., Daaboul, J., Bricogne, M. and Eynard, B. (2017), "Product-Service Systems for servitization of the automotive industry: a literature review", *International Journal of Production Research*, Vol. 55 No. 7, pp. 2102–2120. http://doi.org/10.1080/00207543.2016.1252864.

Martinez, V., Bastl, M., Kingston, J. and Evans, S. (2010), "Challenges in transforming manufacturing organisations into product-service providers", *Journal of Manufacturing Technology Management*, Vol. 21 No. 4, pp. 449–469. http://doi.org/10.1108/17410381011046571.

Matschewsky, J., Kambanou, M.L. and Sakao, T. (2018), "Designing and providing integrated product-service systems – challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies", *International Journal of Production Research*, Vol. 56 No. 6, pp. 2150–2168. http://doi.org/10.1080/00207543.2017.1332792.

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press

Mertens, K.G., Rennpferdt, C., Greve, E., Krause, D. and Meyer, M. (2021), “Current Trends and Developments of Product Modularisation - A Bibliometric Analysis”, *Proceedings of the Design Society*, Vol. 1, pp. 801–810. http://doi.org/10.1017/pds.2021.80.

Moro, S., Cauchick-Migue, P.A. and Mendes, G.H.d.S. (2020), “Product-service systems benefits and barriers: an overview of literature review papers”, *International Journal of Industrial Engineering and Management*, Vol. 11 No. 1, pp. 61–70. http://doi.org/10.24867/IJIEM-2020-1-253.

Oliva, R. and Kallenberg, R. (2003), “Managing the transition from products to services”, *International Journal of Service Industry Management*, Vol. 14 No. 2, pp. 160–172. http://doi.org/10.1108/09564230310474138.

Perno, M., Hvam, L. and Haug, A. (2022), “Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers”, *Computers in Industry*, Vol. 134, p. 103558. http://doi.org/10.1016/j.compind.2021.103558.

Rabetino, R., Kohtamäki, M., Brax, S.A. and Sihvonen, J. (2021), “The tribes in the field of servitization: Discovering latent streams across 30 years of research”, *Industrial Marketing Management*, Vol. 95, pp. 70–84. http://doi.org/10.1016/j.indmarman.2021.04.005.

Rennpferdt, C., Dambietz, F.M. and Krause, D. (2021), “Business Models and Product-Service System Design - Introducing the Business Model Graph”, paper presented at 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). http://doi.org/10.1109/IEEM50564.2021.9672798.

Rennpferdt, C. and Krause, D. (2020), “Towards a Framework for the Design of Variety-Oriented Product-Service Systems”, *Proceedings of the Design Society: DESIGN Conference*, Vol. 1, pp. 1345–1354. http://doi.org/10.1017/dsd.2020.108.

Rennpferdt, C., Kuhl, J. and Krause, D. (2022), “Tools for the Variety-Oriented Product-Service System Design”, in Andersen, A.-L., Andersen, R., Brunoe, T.D., Larsen, M.S.S., Nielsen, K., Napoleone, A. and Kjeldgaard, S. (Eds.), *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems: Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference (CARV2021) and the 10th World Mass Customization & Personalization Conference (MCPC2021)*, Springer International Publishing, Cham, pp. 798–806. http://doi.org/10.1007/978-3-030-90700-6_91.

Salwin, M. and Kraslawski, A. (2020), “State-of-the-Art in Product-Service System Classification”, in Ivanov, V., Trojanowska, J., Pavlenko, I., Zajac, J. and Peraković, D. (Eds.), *Advances in Design, Simulation and Manufacturing III*, *Lecture Notes in Mechanical Engineering*, Springer International Publishing, Cham, pp. 187–200. http://doi.org/10.1007/978-3-030-50794-7_19.

Stark, R., Anderl, R., Thoben, K.-D. and Wartzack, S. (2020), “WiGeP-Positionspapier: „Digitaler Zwilling“”, *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 115 No. s1, pp. 47–50. http://doi.org/10.3139/104.112311.

Stephen Ferguson (2020), “Was Apollo 13 the First Digital Twin? Blog-entry for Siemens Simcenter”, available at: https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/ (accessed 26 October 2021).

Sundin, E., Lindahl, M., Comstock, M., Sakao, T. and Shimomura, Y. (2009), “Achieving mass customisation through servicification”, *International Journal of Internet Manufacturing and Services*, Vol. 2 No. 1, p. 56. http://doi.org/10.1504/IJIMS.2009.031340.

Tukker, A. (2004), “Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet”, *Business Strategy and the Environment*, Vol. 13 No. 4, pp. 246–260. http://doi.org/10.1002/bse.414.

Ulaga, W. and Reinartz, W.J. (2011), “Hybrid Offerings: How Manufacturing Firms Combine Goods and Services Successfully”, *Journal of Marketing*, Vol. 75 No. 6, pp. 5–23. http://doi.org/10.1509/jm.09.0395.

van Ostaeyen, J., van Horenbeek, A., Pintelon, L. and Duflou, J.R. (2013), “A refined typology of product–service systems based on functional hierarchy modeling”, *Journal of Cleaner Production*, Vol. 51, pp. 261–276. http://doi.org/10.1016/j.jclepro.2013.01.036.

Vasantha, G.V.A., Roy, R., Lelah, A. and Brissaud, D. (2012), “A review of product–service systems design methodologies”, *Journal of Engineering Design*, Vol. 23 No. 9, pp. 635–659. http://doi.org/10.1080/09544828.2011.639712.

Ward, Y. and Graves, A. (2007), “Through-life management: the provision of total customer solutions in the aerospace industry”, *International Journal of Services Technology and Management*, Vol. 8 No. 6, p. 455. http://doi.org/10.1504/IJSTM.2007.013942.

Wilking, F., Schleich, B. and Wartzack, S. (2021), “Digital Twins - Definitions, Classes and Business Scenarios for Different Industry Sectors”, *Proceedings of the Design Society*, Vol. 1, pp. 1293–1302. http://doi.org/10.1017/pds.2021.129.

Zimmermann, V. Dr. (2021), “Marktumfeld und Wettbewerbsstrategien prägen die Innovations- und Digitalisierungs- tätigkeit mittelständischer Unternehmen”, in *KfW Research: Fokus Volkswirtschaft*, *Fokus Volkswirtschaft*, Vol. 347, Frankfurt.

Zou, W., Brax, S.A. and Rajala, R. (2018), “Complexity in Product-Service Systems: Review and Framework”, *Procedia CIRP*, Vol. 73, pp. 3–8. http://doi.org/10.1016/j.procir.2018.03.319.

https://doi.org/10.1017/pds.2022.166 Published online by Cambridge University Press