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Corresponding Author	Family Name	**Bertoni**
	Particle	
	Given Name	**Marco**
	Prefix	
	Suffix	
	Role	
	Division	Department of Mechanical Engineering
	Organization	Blekinge Institute of Technology
	Address	Karlskrona, Sweden
	Email	marco.bertoni@bth.se

Abstract

Digital Twins (DTs) are among the most hyped technologies of the 2020 s. Yet, the research dealing with the use of DTs in early Product-Service Systems design remains insufficiently systematized. Based on the findings of multiple-case studies in the Swedish manufacturing industry, the objective of this paper is to collect and present a set of 'questions that need to be answered' to foster the development and utilization of DTs in the PSS realm. The results highlight how the DTs should be composed of several layers to boost value co-creation in design, in a way to incorporate the digital 'counterpart' for more abstract entities, from processes to human behaviors to more intangible assets.

Keywords (separated by '-'): Product-Service Systems - Digital Twins - Servitization - Circularity

Boosting Value Co-creation in Design Through the Product-Service System Digital Twin: Questions to Be Answered

Marco Bertoni(✉)

Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden
marco.bertoni@bth.se

Abstract. Digital Twins (DTs) are among the most hyped technologies of the 2020 s. Yet, the research dealing with the use of DTs in early Product-Service Systems design remains insufficiently systematized. Based on the findings of multiple-case studies in the Swedish manufacturing industry, the objective of this paper is to collect and present a set of 'questions that need to be answered' to foster the development and utilization of DTs in the PSS realm. The results highlight how the DTs should be composed of several layers to boost value co-creation in design, in a way to incorporate the digital 'counterpart' for more abstract entities, from processes to human behaviors to more intangible assets.

Keywords: Product-Service Systems · Digital Twins · Servitization · Circularity

1 Introduction

The use of exact duplicates to manage complex systems dates back to NASA's moon missions of the 1960 s and 1970 s [1]. NASA used mirrored systems, the precursor of Digital Twins (DTs), to rescue the Apollo 13 crew when it ran into trouble. Nearly 50 years later, DTs have long left NASA's labs, and are on the verge of a widespread adoption across a wide range of businesses. Intuitively, when manufacturers can see real-time data on how their products are operating, they can make dramatic improvements in design, innovation, efficiency, and production [2]. Twinning physical products in the digital realm enables them to run different scenarios to assess the long-term consequences of their decisions [3], to avoid costly and time-consuming situations ahead, such as potentially costly breakdowns.

In the realm of Product-Service Systems (PSS), DTs are regarded as one of the most relevant digital technologies for designing, operating, and supporting servitized solutions. Pirola and colleagues [4] describe how they can be used to raise decision makers' awareness about the interplay between hardware and services in operations, to know more about the behavior of customers and their latent needs, to map failures and plan interventions accordingly. They can also be used to support the construction of decision-making models based on the outcome of several virtual test-drives (i.e.,

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simulations) of various circular strategies in ultra-realistic scenarios [5]. Much before the new hardware and services are launched, engineers can know more about the value generated by their innovative solution concepts and business models, assessing if they are able to fulfil availability, quality, and risks mitigation requirements [6].

Yet, even though several real and theorized examples of DTs are discussed in academia and industry, a gap remains between their expected vs. realized potential of DTs when it comes to support engineers in ‘intentionally designing’ PSS solutions. Current research is often not able to describe how DTs can lead to a more informed, expedited, and innovative design process, one that benefits from the coevolution between physical and digital objects since an early stage. The objective of this paper is to present a list of ‘questions that need to be answered’ by future research aimed at fostering the development and utilization of DTs in PSS design. The remainder or this paper presents and discusses 14 questions - across 4 different layers - that are believed to be relevant for the PSS community to further elaborate upon ‘in what areas’ and ‘in which ways’ are DTs able to support the early-stage design activities of innovative circular and servitized solutions.

2 Towards the PSS DT: A Review of Main Efforts and Themes

In recent years, the manufacturing industry has invested heavily in the development of service-based business models. Pay-for-performance and pay-per-use are some of the schemes that have been proposed in literature to fulfil increasingly sophisticated customer needs for availability, quality, and reduced risks [7]. Yet, many real-life implementations of have been observed to be commercially unsuccessful [8], often due to the lack of transparency of the customers’ behavior and to the difficulties in tracking the current state of the PSS hardware during the use phase [9].

In servitization studies, digitalization is advocated as a major strategy to overcome these issues, and to leverage the way value is captured and co-created in service-based business models [10]. The adoption of emerging digital technologies and Industry 4.0 - namely, smart sensors, internet of things (IoT), cloud computing, data analytics, blockchain, AI, 5G, cyber-physical systems, or augmented reality – is seen as a major opportunity for the product manufactures to take a step forward in their servitization journey [11]. With the adoption of digital technologies, companies can develop smart and connected products with highly software-enabled systems, which enable capabilities such as monitoring, control, optimization, and autonomy [12] as well as ecosystem collaboration [10]. Among the digital technologies discussed today, DTs are among the most hyped ones [13], due to their ability of providing a consolidated access point to various lifecycle information, in a way that enables better real-time remote monitoring and control, enhanced intra- and inter-team synergy and collaborations, more efficient and informed decision support system, increased personalization of products and services, as well as predictive and remote services through new value propositions and business models [14].

2.1 Major Initiatives at the PSS, Digitalization, and Circularity Intersection

The increasing interest on PSS to break today's linear 'take-make-use-dispose' pattern of consumption can be tracked down to the Circular Economy Action Plan (CEAP) [15], which is a main planning document synced with the European Green Deal [16], Europe's new agenda for sustainable growth. While stressing how 80% of products' environmental impacts are determined at the design phase, the CEAP spotlights the need to incentivize manufacturers in adopting product-as-a-service models - where producers keep the ownership and responsibility of the product throughout its lifecycle. Several projects in the EU FP7 framework programme have already explored the role of servitization to cope with the needs of the new generation of consumers, such as SERVICEGAP (id: 244552), T-REX (id: 609005), USE-IT-WISELY (id: 609027) and FLEXINET (id: 608627). The CEAP further stresses the important role played by digitalization in this transformative journey. The PROSECO project (id: 609143) and the ProSSaLiC exchange program (id: 269322) have been among the first European initiatives elaborating on the role played by ICT solution to support the adoption of a product-as-a-service model. In Horizon 2020, more projects have explored the opportunity offered by digital technologies to support the servitization transformation, such as DIVERSITY (id: 636692), ICP4Life project (id: 636862), FALCON (id: 636868) and PSYMBIOSYS (id: 636804). Innovation actions such a ReCiPSS (id: 776577) and CIRCUSOL (id: 776680) have been exploring with more detail how to decouple resource consumption through PSS, yet without a distinctive focus on how the information generated by digital models can enable this transformation.

Both the quantity and heterogeneity of the research efforts at European level can be seen as a proxy for the increased interest in servitised business models and circularity. Yet, the landscape of applications and demonstrators is not only scattered but also mostly oriented towards considering digitalization as an 'end product' of the act of design (i.e., when a physical resource is replaced by a digital service) rather than a means to an end (i.e., that of helping the team in 'intentionally designing' the PSS). The great deal of research focused on the development of technology enablers is not counterbalanced by the development of practices on how to use digitalization for generating PSS concepts and evaluating them. Little is said about how to facilitate an 'effective and efficient' design process for circular and servitized solutions using digital technologies, and a gap is seen when it comes to propose 'design guidelines' that can be reused across industrial sectors and specific applications.

2.2 Value Co-creation in Design with the PSS DT

DTs are often discussed as one of the most promising tools in the engineering toolbox to cope with the ambiguities that characterize early-stage development activities of circular business solutions and PSS [17]. Yet, while most of the current efforts are concentrated on manufacturing and maintenance issues, much less is known about the use of DTs for innovation and development purposes [18, 19]. In 2019, only 2 studies were deemed relevant by Zhang et al. [20] with regards to how the DT can enhance service offerings. Most of the literature being analyzed was found to be out-of-scope from a design standpoint, mainly because it largely focused on some forms of maintenance services for production equipment and large assets. A later review from Bertoni and Bertoni [21] showed how this stream of research often concentrates on the development of standalone applications that match with the requirements of a specific case study. The development of 'frameworks' and 'methods' - rather than of models, tools, and algorithms – was also found to be a major matter of concern, particularly when addressing early-stage decision making. Existing contributions were also seen to address the 'realization' and 'support functionality' life cycle stages of the PSS without discussing the benefit vs. cost of using the DT during early design.

From a value co-creation viewpoint, the DT is seen as a major tool to support cross-functional collaboration and knowledge sharing, and to integrate insights from the various actors taking part to the PSS design process. The main 'value' of the PSS DT, as discussed by West et al. [22], is that of making possible to translate the raw data into information and knowledge, and ultimately into wisdom, so to facilitate joint decision-making activities across all the actors within the PSS ecosystem. In practice, DTs facilitate a process where technical considerations are translated into a business context to help identify the consequences of different options, hence highlighting the opportunity around a design decision - and the value co-creation process itself - rather than focusing on the technology per se.

3 Research Methodology

The questions presented in Sect. 4 are based on the findings from a multiple-case study approach [23] involving 4 manufacturing companies headquartered in Sweden, in 3 separate industrial sectors (Fig. 2). The research effort is framed by the Design Research Methodology (DRM) framework [24]. The DRM consists of four stages: Research Clarification (RC), Descriptive Study I (DS-I), Prescriptive Study (PS) and Descriptive Study II (DS-II). The work presented in this paper covers a review-based RC, a comprehensive DS-I and PS, and an initial DS-II. The 4 case companies were selected through a logic of literal replication to find similar results in different contexts, with the intention to provide compelling arguments for the themes and questions proposed in the following sections.

Common to the different cases is an interest on the use of DTs to support the servitization transformation in manufacturing, creating new opportunities for services, platforms, intelligent products, and novel business models. As stated by Company A, a major Swedish construction equipment manufacturer, the adoption of DT technologies is foreseen to accelerate the development of smart and connected products with highly software-enabled systems, The latter are expected to unlock value-adding capabilities for the systems being designed, such as monitoring, control, optimization, and autonomy, as well as ecosystem collaboration, offering for instance diagnostic, predictive and remote services through new value propositions and business models. In the aerospace sector, as stated by Company D, real-time connected digital models are of great interest for the development of decision environments where alternative solutions concepts (that mix hardware, software, and service aspects) can be evaluated considering more than just performances and cost, but rather sustainability and value co-creation at system and super-system level.

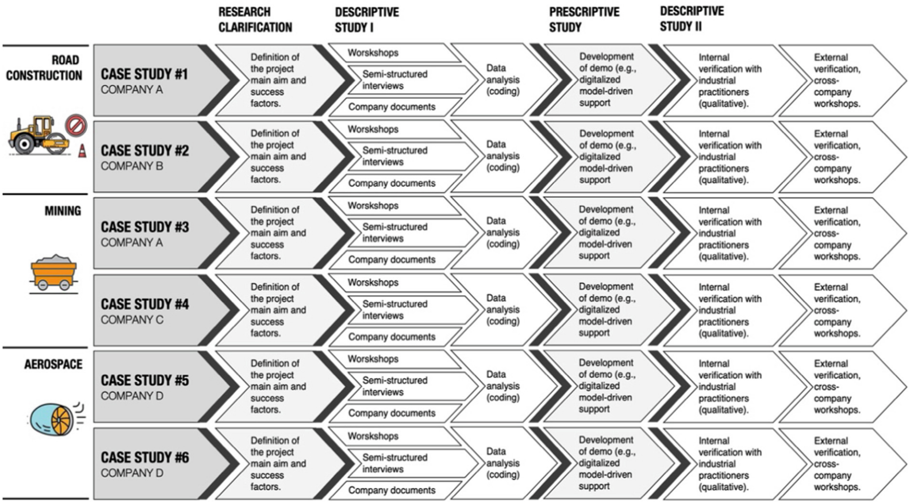

Fig. 1. Research methodology.

The list of questions proposed in Sect. 4 has emerged from the analysis of field data gathered through multiple channels (interviews, workshops, analysis of working documents, model demonstrations and more) in a way to ensure triangulation of the research results. The data collected from these different means were coded and analyzed to identify suitable topics for the development of suitable proof-of-concepts to be used in the PS phase to elicit even more requirements for the different components of the PSS DT. External verification activities (e.g., multi-day dissemination events) have been conducted in the frame of an ongoing 'research profile' initiative at the author home institution to verify and ensure the generalizability of the presented findings. These have involved a total of 8 manufacturing companies with different industrial backgrounds.

4 Questions to Be Answered

The findings from the DS-I phase show how the case companies forecast DTs to soon become a commodity in engineering design decision making. DTs are seen as a precious instrument to obtain richer information about customers' affordances, as well as to detail functional requirements and constraints. DS-I also highlighted how companies are still far from fully realizing the vision of a digital-driven PSS design process. This requires a coordinated research effort to catalyze best practices from several domains along the whole digital PSS lifecycle, such as product design, sustainable business development, service engineering, enterprise modelling, signal processing, telecommunication, big data analytics, IoT technologies, interoperability, and more. For this reason, the PSS DT is envisioned to expand from the seminal vision of Grieves and Vickers [25], to incorporate the digital 'counterpart' for more abstract entities, such as human behaviors to more intangible assets [26]. Four main research themes and related questions are then seen to frame future research on the PSS Digital Twin (Fig. 1).

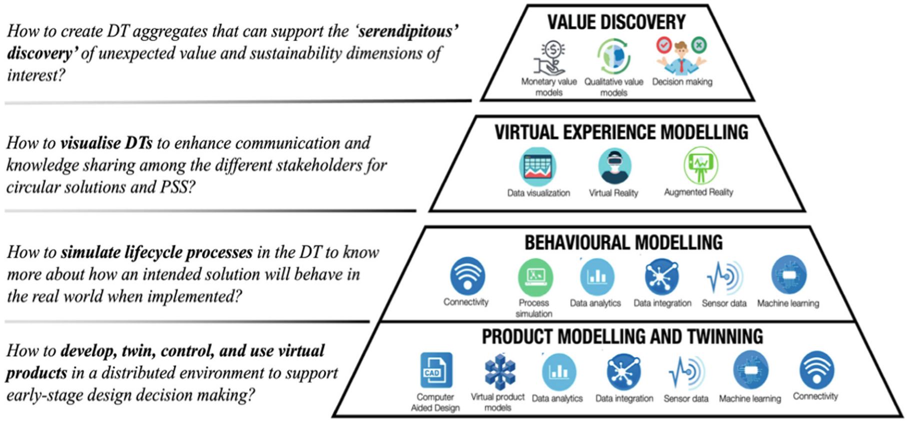

Fig. 2. Research themes for the PSS Digital Twin

4.1 Product/Hardware Modelling and Twinning

DTs hold much promise when it comes to simulate a PSS under varying conditions, to predict the availability of the hardware, to inform about the features needed to make a solution more circular, and to forecast the expected performances of new designs in operation. Yet, questions remain concerning (1) the cost-benefit trade-off of developing, twinning, controlling, and using virtual products in a distributed design environment, and (2) how to make practical use of the DTs in a cross-functional decision-making - communicating the results from alternative scenarios across heterogeneous disciplines and knowledge domains. In the words of Company A, the different DT model components quickly become highly 'complicated' and difficult to be used in real-time simulation. Hence, a major aspect of interest for PSS DT research is related to the development reduced-order models or more manageable data-driven models that sacrifice 'resolution' to foster cross-functional collaboration.

Another important issue is 'scalability'. While most of the examples presented in literature target the development of a single-object DT, the descriptive study points to the need of demonstrating the ability of scaling up DT instances into DT aggregates, going from capturing the behavior of a small set of objects to simulating thousands of context-aware and integrated twins. Two more questions of interest deal with (1) the application of machine learning algorithms to extract relevant knowledge from the data collected by the DT, and (2) the use of artificial intelligence applications to reduce the computational time needed to verify all the scenarios generated by the twin.

Table 1. Research questions – product modelling and twinning.

RQ ID	Description	Timeframe
RQ1.1	How should virtual product models be developed, and twinning be realized between the physical and virtual world, to support early-stage design decision making?	Short-term
RQ1.2	How should product data be pre-processed, and algorithms customized, to predict the behavior of products in a circular business model and PSS?	Short-term
RQ1.3	How should DTs become context-aware, and able to consider the situation of the entities surrounding it?	Short term
RQ1.4	How should the virtual product be represented, communicated, and shared across the distributed cross-functional team?	Short-medium term

4.2 Behavioral Modelling

Having synchronized digital replicas of the various PSS lifecycle processes is believed to be critical to know more about how products and services can be improved, how interventions can be planned and how reactive and agile quality improvement processes can be implemented. Future research will need to push the PSS DT beyond the State-of-the-Art for pure products, enabling the representation of a wide range of lifecycle processes that influence value provision for customers and stakeholders. The goal should be that of (1) developing a systematic approach for determining the level of granularity and precision needed by the DT to be able to simulate (and hence benchmark) alternative PSS embryos during early design, and (2) understanding how behavioral models should be used to increase the awareness of the design team of critical system performances of the PSS. The possibility of accessing data from already existing related products - together with the deployment of data analysis approaches to populate upfront simulations - are seen as a critical aspect to be investigated in this domain.

Table 2. Research questions – behavioral modelling.

RQ ID	Description	Timeframe
RQ2.1	How should data collection strategies be designed to create relevant behavioral models for circular PSS processes (including manufacturing, delivery, maintenance, decommissioning and more?)	Short-term
RQ2.2	How should behavioral models be continuously updated to allow the simulation of engineering trade-offs in the PSS DT considering the uncertainty of future PSS operating contexts?	Short term
RQ2.3	How should the results from the behavioral models be communicated to the cross-functional design team to enhance decision making awareness in a globally distributed environment?	Short-medium term

4.3 Virtual Experience Modelling

The case study companies have expressed a growing interest towards the use of Augmented Reality (AR) and Virtual Reality (VR) applications to enable the design team to 'immerse' itself in the solutions being designed. Literally, AR and VR have been discussed as means to plunge 'into the shoes' of the customers to know more about the tangible and intangible value creation aspects of alternative PSS concepts. The value of these technologies is found both in their ability to support distributed design verification sessions, and in the opportunity to exploit multisensorial stimuli to know more about the intangible aspects related to the PSS service experience. AR and VR are discussed as an opportunity for designers to 'virtually experience' the benefits and drawbacks of a PSS concept early in the process. AR and VR can are seen as a key technology in the process of gamifying the design work, so that a PSS embryo can be embodied and tested without delay in different scenarios – e.g., probing its ability to trigger a sustainable behavior among customers and consumers - much like what can be done today in computer games.

Table 3. Research questions – Virtual experience modelling.

RQ ID	Description	Timeframe
RQ3.1	How should AR and VR be used to create 'virtual experiences' able to communicate both tangible and intangible values of a PSS concept?	Medium term
RQ3.2	How should AR and VR be used to support distributed collaborative work in PSS design?	Medium term
RQ3.3	How can the gamification of the PSS design process be supported using AR and VR applications?	Medium-long term

4.4 Value Discovery

The study further points to the need of developing of an additional layer of simulation capabilities for the DT to tackle so called 'unknown unknowns'. These are generally defined as unexpected or unforeseeable phenomena (e.g., risks, but even value creation opportunities) that cannot be foreseen simply because they cannot be anticipated based on experience or investigation. This is a main limiting factor of virtual testing (and Digital Twins) compared to physical-based investigations and prototypes [27], whose main added value is that of revealing such phenomena. Facilitating the discovery of such 'unknown unknowns' (e.g., at super-system level) through DT aggregates has been often underscored as a major topic for future research. How to setup the DT (including visualization) to support such a 'serendipitous' discovery of unexpected value and sustainability dimensions of interest is a major aspect to be tackled by future initiatives.

Table 4. Research questions – Value discovery.

RQ ID	Description	Timeframe
RQ4.1	How should DT instances be aggregated and connected to be able to measure value creation for a solution at super-system level?	Short-medium term
RQ4.2	How should DTs be designed to facilitate the discovery of new value and sustainability dimensions of interest for circular and servitized solutions?	Medium term
RQ4.3	How should qualitative and quantitative data be gathered from the physical world to discover new and unknown dimensions of value for circular solutions and PSS?	Medium term
RQ4.4	How should value-related dimensions for circular/servitized solutions be modelled in the DT to support decision making?	Medium term

5 Discussion

The four-layer framework and related research questions presented in Fig. 2 aim to provide a snapshot of the main issues raised across industries and cases about the role of the PSS DT in design. The opportunity to boost value co-creation in the PSS design process using DTs is widely acknowledges by the industrial partners involved in this research. Yet, it is works noticing that 14 questions proposed in Sect. 4 originate from case studies dealing with the development of 'complex' systems (i.e., following the classical Systems Engineering V-model [28]) and within companies mainly active in the Business-to-Business (B2B) market, meaning that Business-to-Consumers (B2C) aspects have not been strongly emphasized by the partner companies during the study.

The development of the PSS DT along the proposed themes is expected to positively impact industrial value chains by creating an understanding of how to link customer value - moving from experienced-based data management to real-time data management to support new services and to contribute to new digitalized business model knowledge.

DTs are seen not only as a tool to optimize procedures and act at the right time, but also to avoid making unwitting assumptions when the problem domain is dominated by a high degree of uncertainty and ambiguity. This is typical when working with the design of solutions (PSS) rather than products, which is when having value as main driver for design decision making instead of requirements (such as when comparing traditional one-sale offers against circular and servitized solutions). The ability to use simulation and digital technologies to mitigate uncertainty/ambiguity - and to take a first step when coping with such wicked problems - is of great interest for the business partners when it comes to plan for the design and implementation of the DT concept.

6 Conclusions

The results of this work point to the need of understanding, crafting, and verifying DT-enabled design processes, 'connecting the dots' and making clear how current processes for PSS design should make the best out of the DT opportunity. Future work will look at the development of decision support systems that are able to exploit the data-driven updating mechanisms of the DTs to explore the value generated by alternative digitalized services and new business models already in early design. In doing so, the interoperability and applicability issues will be in the spotlight to realize the integration of different modules in a single decision-making platform.

At the same time, more evidence is needed from the application of the PSS DT in a range of case studies with regards to the real benefit of replacing more qualitative approaches with data-intensive methods and tools (or just to complement them). A major aspect to consider is how the DT can be used in a cross-functional team setting where not everybody is a simulation expert. The role of data visualization and representation should not be underestimated in this respect.

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