Designing solutions with the product-service systems digital twin: What is now and what is next?

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ABSTRACT

Digital Twins (DT) are of particular interest in the domain of Product-Service Systems (PSS), to predict hardware availability, to inform about the needed features of new solutions, and to forecast the expected performances of new configurations in operation. The aim of this paper is to shed light on the extent to which 'twins' are applied today across the PSS life cycle, and to spotlight the ability of DT-related case studies to capture a full value perspective vs. simply attempting to represent hardware and services in the digital realm. By means of a systematic literature review combined with a mapping study, the paper reveals how only a minimal part of the existing literature is able to demonstrate how real-time physical-to-virtual and virtual-to-physical connections can be used to improve the design of servitized solutions. The analysis shows how contributions in the topic are mostly proposing frameworks and methods, as opposed to models and tools, as well as how 'evaluation', 'validation' tasks are largely neglected. As a result, the paper proposes a specialized definition of the PSS DT, together with a set of research questions that need to be answered to empower the engineering teams with relevant DT for PSS design.

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1. Introduction

Digital Twins (DT) are listed by the global research and advisory firm Gartner, Inc. as one of the most hyped technologies of the 2020 s (Nguyen et al., 2021). Digital Twins and Digital Threads are topping the Hype Cycle for Emerging Technologies diagram (https://www.gartner.com/en/research/methodologies/gartner-hype-cycle) since 2018 and are expected to achieve the so-called 'plateau of productivity' between 3 and 12 years from 2021. DT are 'poised for proliferation' according to several analysts. As an example, a 2019 survey among 599 organizations in 6 countries - having an annual revenue greater than $50 million- shows that 13% percent of the sample already used DT in conjunction with Internet of Things (IoT) projects, while 62% were either in the process of establishing DT use or planning to do so (Lheureux et al., 2019).

The DT hype is driven by recent advances in Industry 4.0, data management, and data processing technologies, and by the strong academic and industrial interest in data-driven and digital manufacturing initiatives. Several cases and industrial applications are currently listed in literature (see Liu et al., 2020), mainly with regards to product and infrastructure development. The topic of DT is a hotspot in the European research agenda, with several projects (e.g., IoTwins, Grant agreement ID: 857191; ARtwin, Grant agreement ID: 856994; COGITO, Grant agreement ID: 958310) exploring the use of virtual models (of processes or products) that digitally reproduce with maximum accuracy the behavior and performance of its real-life counterpart to which it is twinned.

DT hold many promises when it comes to simulating the behavior of systems under varying conditions, predicting the outcome of scenarios given the status of the system at the time of the analysis, and moving prototyping and testing of complex systems to the virtual realm (Jones et al., 2020). They are of particular interest in the domain of Product-Service Systems (PSS) as a means to predict hardware availability, to inform about the needed features of new solutions, and to forecast the expected performances of new configurations in operation (Zhang et al., 2019a). As highlighted by Pirola et al. (2020), having a synchronized digital replica of a physical entity raises awareness about the behavior of the hardware during the utilization phase. In turn, this supports decision-making when it comes to designing new PSS (e.g., providing insights into how products and services are used and how they can be improved), optimizing service operations (e.g., predicting failure and planning intervention accordingly), and improving the quality of services (e.g., using virtualization to support reactive and agile quality improvement processes).

The advancement of the Smart PSS concept in recent years (see: Kuhlenkötter et al., 2017) raises several questions about the application of the DT to support the design of PSS. While the two domains are slowly overlapping, the body of knowledge at this intersection remains scattered. The paper aims to point out the extent to which physical-to-virtual and virtual-to-physical twinning capabilities are exploited in the literature across the PSS life cycle stages. The goal is to shed light on the current application of DT and to elaborate on the ability of DT-related case studies to capture a full value perspective vs. simply attempting to represent hardware and services in the digital realm.

Based on a systematic literature review, the objective of the paper is to address the following questions:

1. What is the state-of-the-art of DT integration in PSS literature? In which stages of the PSS lifecycle are DTs deployed?
2. What is the level of abstraction of the research in this domain? Is this mainly targeting the development of theoretical knowledge or is moving towards the validation of actionable engineering support?
3. What is the level of maturity of the research at the intersection between the PSS design and DT domains, with regard to validation and generalization of the findings?
4. How shall the PSS Digital Twin be defined? What are the themes and research questions ahead for PSS researchers?

The remainder of the paper is structured as following. Section 2 describes goals, features, and characteristics of DTs, linking them to the notion of Smart PSS. Section 3 presents the research methodology applied in the study, which is based upon methods and techniques for systematic literature mapping and analysis. Section 4 aims at quantifying the body of knowledge at the intersection between the DT and PSS realm, by mapping existing contributions along the PSS lifecycle. Section 5 presents the findings from the analysis of the research and contribution facets emerging from the set of papers shortlisted during the study. Section 6 discusses 'what is next' in terms of those research directions that are deemed relevant by the existing literature with regards to future research at the DT vs. PSS intersection. Section 7 discusses the definition for 'PSS Digital Twin' and collects a list of questions that need to be asked to realize its vision and goals. Section 9 concludes the paper, pointing to major research streams in the domain, coupled with reflections for educational development.

2. Theoretical background

2.1. Digital Twins: goals, features and characteristics

As envisioned by Michael Grieves and John Vickers (2017), a DT consists of a physical entity, a virtual representation of that entity, and a bi-directional data connection that couples physical objects and processes to virtual counterparts, feeding data from the physical to the virtual world and vice versa (Glaessgen and Stargel, 2012). As discussed by Jones (2020), a DT is inseparable from its physical counterpart. The latter includes 'vehicles', 'components', 'products', 'systems', and 'artifacts'. Yet, it is not confined to products, but it also includes 'models', 'supply chains', 'systems-of-systems' and more. In symmetry with the physical world, a DT is composed of one or more virtual entities - the 'virtual twins' – each one with a specific purpose. The 'real-world' space in which objects operate is captured too, typically through those parameters deemed to influence the physical
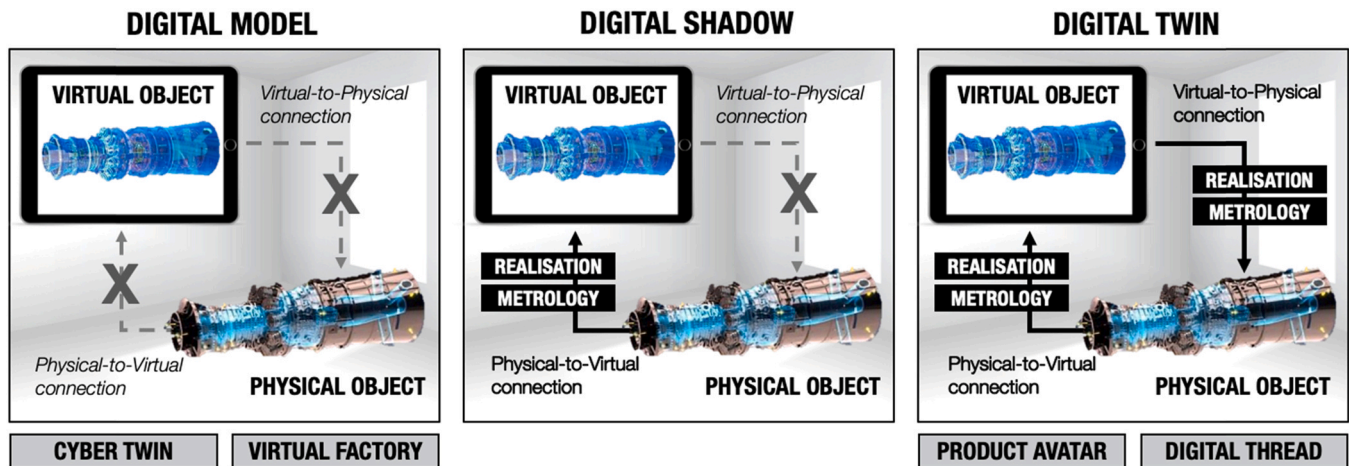
Fig. 1. Digital model vs. shadow vs.twin.
Adapted from Kritzinger et al. (2018).

entity including form, functionality, health, location, process, time, state, and more. This information is also fed to the virtual environment, as a means to ensure the accuracy of the upon which simulations, optimization, and/or decisions are made therein.

Kritzinger et al. (2018) make a clear-cut distinction between so-called 'Digital Models, 'Digital Shadows' and 'Digital Twins' (Fig. 1), by looking at their 'twinning' capabilities. The latter capture the act of synchronizing the virtual and physical states so that they are 'equal', i.e. so that the virtual parameters hold the same value as physical ones. Noticeably, a digital model is characterized by the absence of any form of automated data exchange between the physical and digital entities. Digital models have been observed to be of two main types. Literature in field of Cyber-Physical Systems (CPS) describes those models that purely exists and are merely meaningful within the cyber space as Cyber Twins (Tao et al., 2019). By interconnecting multiple Cyber Twins is then possible to represent CPS with precision. Yet, these twins do not feature those interactions, communication, and collaboration capabilities between physical and cyber space that are proper of the DT. Another type of model that does not need to connect with the real physical system is the Virtual Factory (Jain et al., 2001; Grieves, 2014). The latter does not depend on real-time data to be executed, and it merely offers virtual commissioning capabilities. Its focus lies on performing virtual simulation exercises that - while replicating the real-life scenario – do neither require a physical-to-virtual nor a virtual-to-physical connection.

Developing a DT is primarily a matter of ensuring a *physical-to-virtual* (P2V) connection. This ensures that the state of the physical entity is transferred to, and realized in, the virtual environment. This type of DT is often described as a 'Digital Shadow' (Kritzinger et al., 2018), being characterized by an automated one-way data flow between the state of an existing physical and digital object, but not vice versa. The P2V connection consists of a 'Metrology' phase, in which the state of the physical entity is captured, and a 'Realization' phase, in which the delta between the physical vs. digital entities is determined, so to update the latter accordingly. It is also worth mentioning that literature acknowledges the existence of a special type of 'shadow' named Product Avatar (PA) (Wuest et al., 2014). The PA finds its roots in Product Lifecycle Management (PLM) research and refers to a distributed and decentralized approach to share and manage the relevant item-level information throughout a product's lifecycle.

Both Digital Shadows and Product Avatars do not include a *virtual-to-physical* (V2P) connection. Simply stated, no information is flowing from the virtual to the physical world, and the digital object is not able to automatically trigger a state change on its physical counterpart. The realization of the V2P connection (which also features both a metrology and a realization phase) makes it possible for the digital object to act as a controlling instance of the physical one. Having a V2P connection in conjunction with a P2V one is a defining feature of the DT concept because, in the words of Jones (2020), it is now possible to close the loop between hypotheses generated in the virtual environment and the actual consequences realized in the physical environment.

The combination of the P2V and V2P connections allows for a continuous optimization cycle, as possible physical states are predicted in the virtual environment and optimized for a specific goal. That is, once a virtual optimization process determines an optimal set of virtual parameters, these are propagated through to the physical twin. In turn, the latter responds to the change, and the loop cycle continues. The frequency by which this process repeats is indicated as 'twinning rate', and in an ideal world, this shall be near-instantaneous. The concept of 'Digital Thread' is further used in the literature to describe how to seamlessly manage the stream of data that connects each stage of the 'physical entity' life cycle from design, to build, to in-field usage (Singh and Willcox, 2018). A thread is a matter of realizing data management capabilities mostly along with the P2V connection, with regards to how to store, access, integrate, transform, and analyze data from disparate sources.

2.2. Digital Twins and Smart PSS

Nowadays, designing successful solutions hinges often on the manufacturer's capability to handle data accumulated through the product's lifecycle. As shown by Tao et al. (2019), these include behavior and performance data (e.g., maintenance and failure information, degradation statuses, recycle scheduling records and more) together with data related to the context in which a product is being used (when, where, how, by whom and under what circumstances).

Previous efforts aimed at understanding the interpretation and application of DT in the realm of PSS are concentrated on pure manufacturing issues, while much less is known about the use of DTs for innovation and development purposes. In 2019, only 2 studies were deemed relevant by Zhang et al. (2019b) with regards to how the DT can enhance service offerings. Most of the case studies analyzed at that time were deemed to be out-of-scope from a design standpoint, mainly because they largely focused on some forms of maintenance service for production equipment and large assets. A main limitation of the study, as acknowledged by the authors

themselves, was that of focusing only on the DT concept, while neglecting other forms of digital modeling where at least part of the information flow is automatic.

Other contributions draw a direct parallelism between the DT and the notion of Cyber-Physical Systems. Zheng et al. (2019) use the two concepts interchangeably, to indicate unique types of enabling technologies for Smart PSS. Here the DT is seen as an enabler for smart PSS solutions, mainly supporting their implementation along the engineering lifecycle. In the words of the authors, this is intended to enable a "design as ordered, manufacturing as built, distribution as located, usage as maintained/reconfigured/re-built, and end-of-life as recycled" paradigm (Zheng et al., 2019, p. 16). Zhang et al. (2019a) further present the Digital Twin for Manufacturing Cells (DTMC) concept and discuss its role in facilitating the application of service-oriented manufacturing in a Smart PSS context. Overall, these contributions emphasize the notion of data-driven design based on the DT and have the merit to spotlight the opportunity for a DT-enabled service innovation process (Zheng et al., 2018).

Karagiannis et al. (2020) further reflect on how the DT shall be considered as an item in the toolbox of the 'digital engineer'. The latter is described as the person with knowledge and skills in the use of engineering and digital technologies to enable major process improvements and performance increases in both physical and business operations. In the context of Smart PSS, a digital engineer is in charge of managing digitalization challenges across multiple levels of smart PSS design, e.g. from innovation context analysis to the evaluation of alternatives.

Watanabe et al. (2020) show that in the current Smart PSS concept, the cyber space is implicitly or explicitly expected to be a 'digital twin' to be able to represent and simulate the states of the corresponding real space precisely for providing better services. Yet, the authors bring forward some major obstacles when it comes to representing all of the PSS physical states the digital world and vice-versa. As major item of concern, it is not practically possible to log human intention and emotions in the same way as this is done for the PSS hardware states. As a result, any digital replica tends to be "smaller" than the corresponding real-life counterpart. Consequently, technological support from the cyber space could be limited or even ineffective, due to incomplete data. At the same time, the dynamic nature of the Smart PSS, which many different actors joining and leaving while new - unexpected - interactions may occur, hinders the possibility to have an exact digital replica of a PSS which is up to date at all times.

3. Research Methodology

This contribution aims to gain insights into the development and application of DT concepts for PSS design by following a hybrid approach in the analysis of the literature. The systematic review is accompanied by a mapping study, a technique mutated from sciences research that emphasizes 'quantity and classification' as opposed to 'state of evidence and practice'. In this spirit, the findings from the review (which are focused on deriving 'best practices' in the field) are complemented by a quantitative, visual mapping of the current body of knowledge ('what is now?') and future research directions ('what is next?') of the research at the DT vs. PSS intersection. A main reason for selecting such a hybrid approach is that the visual appeal of systematic maps has been observed to spark interest and to better summarize a research domain – and hence, helping to transfer the results to practitioners (Petersen et al., 2008). The process followed to gather and analyze the contributions from the literature is shown in Fig. 2.

Initially, the authors worked with the definition of main 'themes' for the generation of the search query, mainly by scanning the available literature under the DT topic – to identify synonyms and

related concepts – as well as by reviewing top-cited contributions to identify relevant keywords under the PSS theme. The initial set of keywords was then compared against other reviews published within the two research fields. After several iterations, the following search query was selected for the study:

TITLE-ABS-KEY ("Digital Twin" OR "Cyber twin" OR "Digital Model" OR "Digital Shadow" OR "Digital Thread" OR "Digital Counterpart" OR "Virtual Twin" OR "Product Avatar" OR "Virtual Factory" AND "product service system*" OR serviti?* OR pss* OR "service engineer*" OR "functional product" OR "through life" OR "total care" OR "total offer" OR "ipss" OR "extended product*").

Previous research dealing with systematic literature reviews in the PSS domain (e.g., Pirola et al., 2020) pointed to the SCOPUS® database as primary source of relevant research contributions. SCOPUS® is indicated to be one of the largest curated abstract and citation databases for quantitative science studies (Baas et al., 2020) and its coverage in the engineering field is comparable to ISI Web of Science (Archambault et al., 2009). The contributions retrieved from the database were initially filtered based on their title and keywords, to render an initial list of papers to be considered in the mapping and review process. Each study was further categorized using publication-based (e.g. author, title, year, peer-review journal, conference proceeding) and content-based meta-data (e.g. study setting, year of publication, proposed intervention). The list of papers shortlisted in the initial stage was scrutinized independently by the 2 authors (to minimize subjectivity) on a full-text basis, rendering a total of 40 papers being shortlisted from the initial search.

3.1. Step 1: PSS cases and the DT

The analysis initially focused on the characteristics of the DT instantiations described in the PSS literature, with the goal of characterizing the P2V and V2P capabilities discussed and/or demonstrated by each paper in relation to the object being twinned. Three main contribution types were defined, as following.

- The first type includes those contributions discussing digital models that are neither able to establish a P2V nor a V2P connection with their physical counterparts.
- The second one collects all those papers discussing a P2V connection.
- The third one gathers case studies and more that discuss and/or demonstrate P2V and V2P capabilities, while also distinguishing between the notions of Digital Twin, Digital Thread and Product Avatar.

Noticeably, the authors have considered Human-in-the-Loop Digital Twin solutions (Al-Yacoubb et al., 2020) belonging to the Digital Shadow category, in line with what described by Jones et al. (2020). A mechanic that is sent to replace a component based on the input of a virtual twin used for predictive maintenance purposes does - in theory - perform the realization process of V2P twinning. Accepting this situation as a 'Digital Twin' is problematic; hence these situations have been considered examples of Digital Shadows instead. Even though the information generated in the virtual environment is acted on in the physical one, such an update of the physical twin 'state' (based on the input of the digital one) is not real-time, but rather much delayed (hours or days). Accepting a Human-in-the-Loop solutions as a type of 'twin' makes it difficult to separate a twin from more traditional multi-physics simulation and modeling approaches.

In a way similar to what described by Liu et al. (2020), the analysis went on to classify each contribution according to the PSS life cycle phase where DT capabilities are proposed, demonstrated or validated. The main reference framework supporting this categorization was the one provided by Wiesner et al. (2015), which builds

PROCESS STEP		AMOUNT OF ENTRIES	OUTCOME
1	Defining research purpose and objective.	Unknown (available literature)	Review scope.
2	Database selection and development of the search query.	Unknown (available literature in the selected database)	Search query for targeted database.
3	Initial search in the selected database.	85 papers	Potentially relevant papers (publication-based filter).
4	Application of publication-based filters.	69 papers	Initial set of relevant papers to be fully investigated. (period considered 2015-2021)
5	Contributions filtered on a title and abstract basis.	45 papers	Unique and potentially relevant papers for the review.
6	Contributions filtered on a full-paper basis.	**40 papers**	Final list of relevant papers (content-based filter).

MAPPING AND REVIEW STEP 1
OBJECT BEING STUDIED vs. PSS LIFE CYCLE STAGES vs. CASE STUDY FOCUS

MAPPING AND REVIEW STEP 2
OBJECT BEING STUDIED vs. CONTRIBUTION FACET vs. RESEARCH FACET

MAPPING AND REVIEW STEP 3
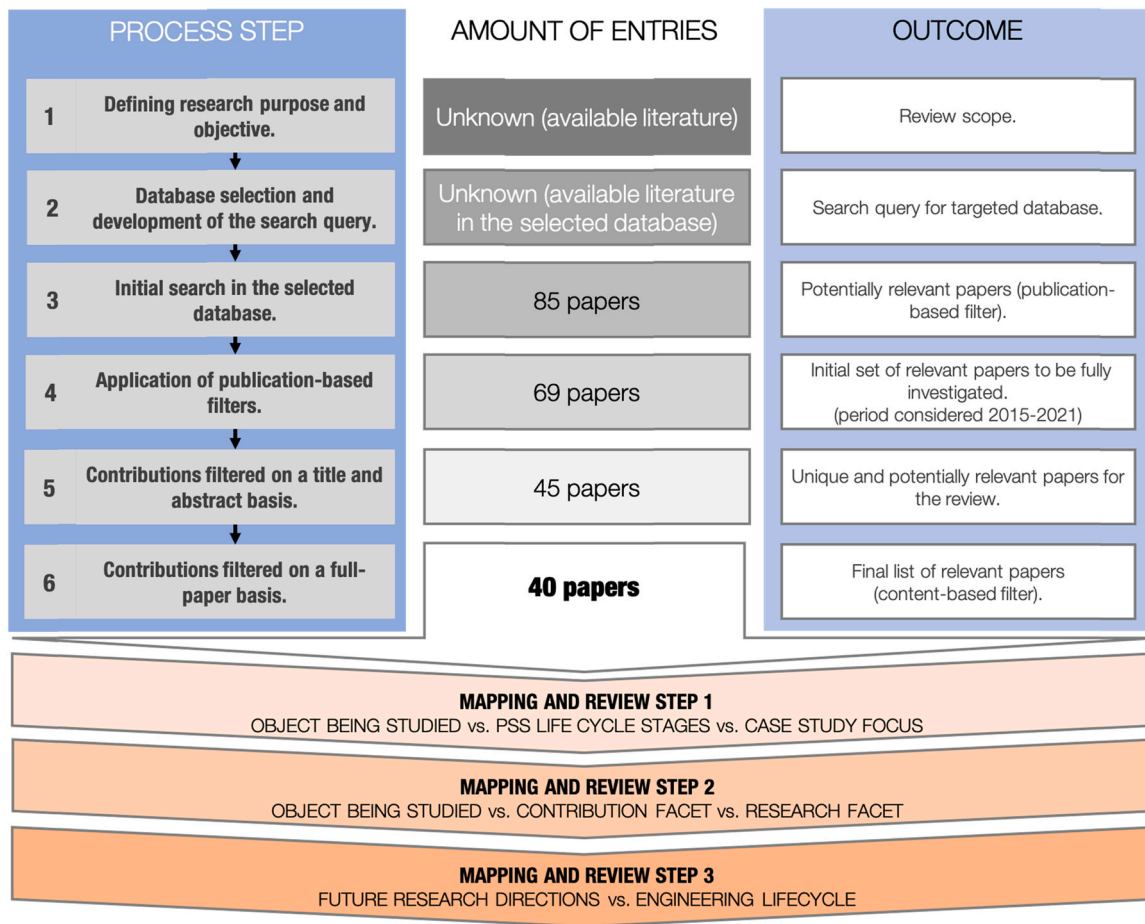FUTURE RESEARCH DIRECTIONS vs. ENGINEERING LIFECYCLE

Fig. 2. Systematic mapping and review process.

upon what was proposed by Stark (2011) in the realm of Product Lifecycle Management. The phases used in the model are: (1) Integrated PSS ideation process, (2) System level requirements, (3) Design (Products and Services), (4) Realization (Product manufacturing and service implementation), (5) PSS deployment to the customers, (6) Support of PSS functionality, and (7) PSS upgrade and decommissioning.

A third dimension used in the analysis refers to Focus Facet (see: Paternoster et al., 2014), which refers to the specific characteristics of the case study(ies) described by the different contributions. Only a subset of the papers, in fact, is able to describe the tangible application of Digital Twins in the context of the PSS DT, with many contributions struggling to move past the traditional product/service view when demonstrating DT capabilities. The framework proposed by Gaiardelli et al. (2021) was used as the main guidance in this work. This identifies a progression in the way value is delivered communicated, and acknowledged by the customer, in a way to distinguish 4 different PSS types, as described in Table 1.

3.2. Step 2: Research and contribution facets for the PSS DT

The content analysis is focused on the *Contribution Facets* and *Research Facets* of each paper. The notion of *Contribution Facet*, which is adapted from Petersen (2008), aims at providing information on the type of contribution brought forward in a publication, with regards to a specific domain of study. This can be explained simply by the type of 'deliverable(s)' and/or 'prescriptive result(s)' emerging from the research work. A total of 6 facets are defined and used in study, as shown in Table 2.

The notion of *Research Facet* reflects the research approach used in a contribution, and does not depend from a specific focus area, case study, or application. Adopting again the classification initially described by Wieringa et al. (2006) and later reused by Petersen et al. (2008), the analysis considered six main facets, as shown in Table 3.

As discussed by Petersen et al. (2008), papers can span more than one category, although some combinations are unlikely. It is quite possible to write a paper proposing a new technique and presenting a sound validation of the technique, ending with a discussion in which the author airs his or her opinion about what other researchers should do.

3.3. Step 3: Future research directions along the Engineering Cycle framework

The first level of analysis with regards to the 'what is next?' question foresaw the collection of the main challenges being discussed in the papers as items for future work at the intersection of the PSS and DT domain. These were then categorized into 'topics', grouped into families of 'issues', and further mapped against the Engineering Cycle (EC) framework proposed by Wieringa (2014). The framework recognizes a 'progression' in the development of a solution - the PSS Digital Twin in this case – and was deemed suitable by the authors to discern between 'directions' at different levels of maturity and granularity. The EC builds on the premise that, to justify that a proposed solution (in this case, the PSS Digital Twin) solves a problem, the developer (of the PSS DT) should first investigate the problem itself. After that, to justify the selection of one solution rather than another, the developer should refer to their

Table 1
Focus Facets (adapted from Gaiardelli et al., 2021).

Category	Description
Product or service	*These value offerings are either based on a trade between a customer and a manufacturer - which is concluded with the customer ownership of a tangible artefact (the product) - or on a transaction, between the customer and the service provider, which is concluded with the temporal customer accessibility to the (service) benefit.*
Product + after-sales services	*These value offerings are based on an initial transaction of a good and its ownership by the customer, followed up by value-added complimentary service benefits (e.g., a product warranty).*
Product-Service System	*These value offerings are designed and delivered as a product-service bundle composed of tangible products and intangible services that, combined, fulfil specific customer needs that include a wide range from ownership to accessibility to result-oriented benefits.*
Full value solution	*These value offerings are completely oriented to the satisfaction of the customer's needs through a mix of product and service elements that appear indistinguishable in their ability to deliver value from the customer/ user view. The customer/user only perceives the final value (result) associated with experiencing the solution.*

different properties as uncovered by solution validations. Furthermore, to justify an implementation, the developer should refer to the solution design that had been chosen, and so on. In line with this, the papers were categorized in the 6 'tasks' of the EC, which are: (1) Problem investigation, (2) Solution design, (3) Solution validation, (4) Solution selection, (5) Solution implementation, and (6) Implementation evaluation.

4. What is now? Experiences with the DT across the PSS lifecycle

Fig. 3 plots the 40 contributions down selected from the literature along 3 axes. The vertical one focuses on the type of digital models described by these papers and features 3 'layers', as described in Section 3.1. From the top to the bottom of this axis, the authors progressively collect those manuscripts that discuss both P2V and V2P connections (in the form of Digital Twins, Digital Shadows and Product Avatars), those that do merely address the P2V one, and those that do not demonstrate or elaborate on the need/ benefit for such connections while developing digital models for the PSS. The axis on the left-end side of Fig. 3 categorizes the proposed twins, shadows, and models along the PSS lifecycle, while the axis on the right-end side spotlights the Focus Facets addressed in the papers.

The results reveal a scattered landscape with regards to the application and demonstration of the PSS DT. The 'hotspots' receiving most of the attention in later years are unsurprisingly gathered along the MoL phase (e.g., using digital replicas to monitor and optimize the PSS during the realization and operational phases). Less attention is paid to issues related to innovation, design (both in the BoL phase), upgrade, and decommissioning (in the EoL phase).

Fig. 3 also shows a 'misalignment' in the way the Digital Twin 'word' is used (or misused) in literature. Several contributions, while referring to the DT as their main object of investigation, present findings and lessons learned merely concerning the flow of information that goes from the physical world to the digital one, and not vice versa. It is also noticeable how much of the literature describes the DT without demonstrating, applying or reflecting neither on the P2V/V2P connectivity nor on real-time synchronization, hence merely describing the implementation of digital models of the PSS.

Fig. 3 shows that not all the papers feature a case study or example. Hence, several contributions have been excluded from the map, while those featuring more than one case have been featured twice or more. Noticeably, the number of papers describing an application with a relevant service component is relatively low. Most of the case studies tend to exemplify frameworks, tools and more focus either on a value offer based on an ownership transaction (of a tangible artifact, the good), or on a trade of an intangible and perishable artifact (the service). None of the contributions is found to exemplify the application of the DT from the point of view of value offerings completely oriented to the satisfaction of the customer's needs (i.e., a full-value solution as discussed by Gaiardelli et al., 2021).

4.1. Beginning-of-Life (BoL) stage – ideation and requirements definition

As previously observed by Tao et al. (2019), comparably few papers discuss how the DT can lead to a more informed, expedited, and innovative PSS design process that benefits from the communication, synergy, and coevolution between physical and digital objects. Several publications discuss the DT as an enabler for a more integrated ideation process; nevertheless, the focus often lies often on pure products (or, conversely, on pure services) rather than on PSS as a holistic solution. No contribution is seen to explore how the DT can be used to guide the definition of the system-level requirements for the PSS, while more research is available later, at the PSS design stage – yet with little emphasis on the product-service integration.

Wuest and colleagues (2015) are among the firsts to touch upon the concept of Product Avatar and to discuss how and why a P2V and (with less emphasis) a V2P connection are deemed to be beneficial for the PSS ideation process. The contribution shows how usage data (e.g., from a boat) can be called up by designers and manufacturers - via the Avatar - to define new business models based on the provision of up-to-date information from the customer.

Vrabic et al. (2018) is one of the few contributions clearly showing how P2V and V2P connection capabilities can support the engineering design process. However, the example described in the paper is mostly product-based (a mobile robot). Similarly, Zheng and Lim (2020) has recently raised the issue of DT-driven product family optimization, where the data obtained from the user's in-context operational information can be used to optimize the design of a solution, typically a product. At the same time, the DT can be leveraged to model the ambient information in the virtual

Table 2
Research type Facets (adapted from Petersen et al., 2008).

Category	Description
Knowledge	*The theoretical or practical understanding of a subject, including contextualized information and lessons learned acquired through experience or education.*
Framework	*A basic conceptional structure including a particular set of rules, ideas, or beliefs used to deal with a specific problem/issue or to decide what to do.*
Method	*A systematic procedure for accomplishing a particular goal or approaching something, especially a systematic or established one.*
Model	*An abstract view of a complex reality, a simplified representation of all the notable features which characterize a product, service or system.*
Tool	*A software application and/or supporting services that are used for the conceptualization, definition, and refinement of a design.*
Algorithm	*A process or set of rules to be followed in calculations or other problem-solving operations.*

Table 3

Research type Facets (Wieringa et al., 2006; Petersen et al., 2008).

| Category	Description
Experience paper	*These papers explain what and how something has been done in practice. These are intended to present and discuss the personal experience and lessons learned of the author(s).*
Opinion paper	*These papers express the personal opinion of somebody (the authors, a practitioner, etc.) whether a certain technique is good or bad, or how things should be done. They do not rely on related work and research methodologies.*
Philosophical paper	*These papers sketch a new way of looking at existing things by structuring the field in form of a taxonomy or conceptual framework.*
Solution proposal	*These papers propose a solution for a problem, which can be either novel or a significant extension of an existing technique. The potential benefits and the applicability of the solution are shown by a small example or a good line of argumentation.*
Evaluation research	*These papers describe how a solution (e.g., a method or a technique) is implemented in practice (solution implementation) and what are the consequences of the implementation in terms of benefits and drawbacks (implementation evaluation).*
Validation research	*These papers aim at validating new solutions (e.g., experimenting with a method or a technique), typically when these are novel and have not yet been implemented in practice.*
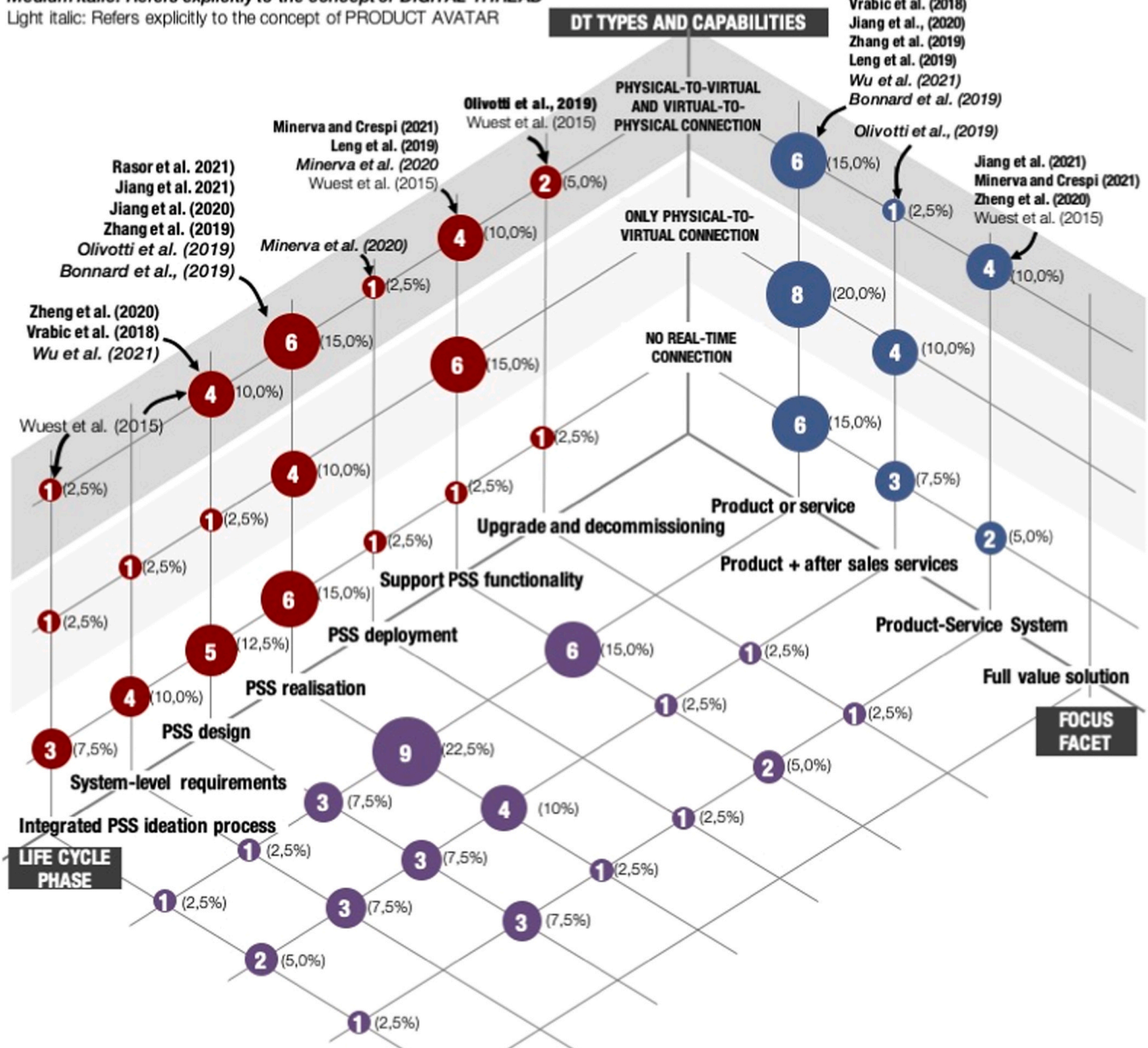
Fig. 3. Experiences with Digital Twins in PSS research.

environment, where product family design can be performed in a more user-friendly and visualized manner for idea generation. The availability of a high-fidelity virtual environment is intended to stimulate designers in creating their own designs with functional constraints embedded. Yes, the need for a seamless, real-time entanglement is far from being evident in this approach.

Wu et al. (2021) is an even more recent example of the application of the Digital Thread concept in the conceptual design stage of Smart PSS solution. The paper proposes a five-dimensional framework that is applied to analyze the correlations among elements in both the physical and digital spaces. While a physical entity (PE) collects operational and environmental data, a virtual entity (VE) replicates the structure, function, and environment of the PE to search for optimization and to control the state of the PE itself. Here, a Digital Twin data model is used to merge and combine sensory data and inform the optimization process, while a connection model is used to enable real-time interactive communication between the physical and the virtual world. What makes this framework more unique for PSS design is the service model. The latter includes the business services for users and the functional services required to support the DT and features a bi-directional interaction with the users to realize personalized services.

More lessons learned, best practices, and solutions related to the application of the DT for PSS innovation and design are identified in the BoL stage. Yet, they do not provide a tangible evidence for the need for real-time V2P connectivity. One example is Wang et al. (2021), who discuss the DT as a tool for designers to correctly interpret precise contexts in the virtual space, so to pre-identify customer requirements, quality metrics, or design parameters ahead based on the accumulated product interaction data. Meierhofer et al. (2020) further point out the opportunity to use the DT as a means to understand the business system and the problem of (all) its actors (e.g., people, things, and processes) during the initial ideation stage of the PSS. The twin is considered here as a means to define a value proposition for the PSS; with a focus on 'gain creators' and 'pain relievers'. Yet, the twins addressed in both works do behave as a 'shadow', as they collect direct customer input and feedback but lack to close the loop through real-time metrology and realization in the V2P connection.

Similarly, Donoghue et al. (2018) elaborate on how the DT can help the engineering team in planning how services are used and integrated into customer PSS. Later, Li et al. (2021) interpret the DT as a means for gathering, storing, transmitting, and analyzing massive data to support the collection and update of smart PSS requirements with an outlook to sustainable production. There are more contributions where the discussion is shifted towards the use of the 'twin' as an 'information layer' to make experts aware of the multi-dimensional factors and their coupling relationship that affect the determination of the PSS overall layout (Li and Li, 2020). Yet, these papers lack to demonstrate how real-time V2P connectivity can raise awareness on how the PSS shall be addressed holistically early in the innovation process. Similarly, the DT-aided life cycle assessment exercise performed by Kaewunruen et al. (2020) does not feature real-time data exchange between the physical and the virtual entity. For this reason, this is considered to be more an example of how a digital model (or a Cyber Twin, not a DT) can be applied to the task of requirement definition.

4.2. Beginning-of-Life (BoL) phase - design

Older literature (Peruzzini et al., 2016) sees the application of digital replicas for the creation of Digital Mock-Ups (DMUs) and virtual prototypes able to represent the PSS in all its main features. In later papers, such as in Donoghue et al. (2018), the idea of using such replicas to get customer insight faster - and at lower cost - starts to gain ground mainly as a means to replace time-consuming

activities linked to physical product testing. Zheng et al. (2019) further propose a DT-enabled design approach for Smart PSS service innovation composed of 4 stages: (1) Platform development, (2) Data acquisition (pre-processing), (3) Data analytics for service innovation, and (4) DT-enabled service innovation. The last step foresees a process where the digitalized and physical products can communicate, evolve and sync with each other in real-time. In the example provided, a modularized face mask is virtualized in the cyber space, it is linked to a product configuration system. This it is then connected to cloud-based 3D printers, in a way that the customized order fulfilment is offered as a service to the users. Yet, while the contribution describes the P2V connection in detail, very little is said about the need and function of the V2P connection, even though the paper claims that the virtual model is used to impact the physical object by generating new services.

Zhang et al. (2019b) further reflect on the main benefits of a DT-driven PSS design process. They consider the main function of DT technology that of helping customers in tracking the emergence of a design, enabling them to implement and test modifications and changes in the digital model that can be directly communicated to the provider company. Wang et al. (2021) further spotlight how the DT can help PSS designers in acquiring a deeper understanding of the product 'context', mainly by integrating user interaction data with environmental ones to raise awareness about customer behavior and choice decision logics. Hence, DT is envisioned as a virtual testing tool, able to uncover and resolve all kinds of product defects virtually, significantly reducing the time to market for new concepts. The data uploaded in the virtual space shall be used to simulate expected usage scenarios, through which designers can quickly identify implicit demands and resolve potential risks in advance.

The DT is also interpreted as a product competitiveness model, which is as a means to gather online customer review data to predict market trends, existing rivalry, and emerging customer requirements. Another main benefit linked to the DT open platform is found in the creation of a realistic user environment where all stakeholders can participate in the customization process for a solution to know more about unknown user scenarios. Yet, these contributions are strongly product-centered and do not consider servitization aspects with much detail. Furthermore, they neither put forward a strong case for why a real-time connection between the physical and virtual object is needed, nor describe examples or lessons learned from the DT implementation.

4.3. Middle-of-Life (MoL) phase – realization, deployment and support

In the PSS MoL stage, the DT is often seen as an opportunity to simulate and optimize the production system linked to the PSS hardware (including its logistical aspects), visualizing the manufacturing process in detail from single components up to the whole assembly.

Zhang et al. (2019a), for instance, describe how a virtual model can be used to visualize the motions of a manufacturing robot according to the position parameters published by the physical model. By collecting the robot's performances in real time, is then possible for the engineers to predict and optimize its performances. Contributions from Olivotti et al. (2019) and Bonnard et al. (2019) provide further insights on how such a 'Digital Thread' in manufacturing can be realized.

Another prototypical example is provided by Kampker et al. (2019) in relation to the harvesting process in agriculture. In this case, a physical object mimicking a potato being harvested is equipped with sensors, and the data accumulated by such a device are sent back to a machine operator to optimize the process in real-time. Yet, since the V2P connection, in this case, is of type Human-in-the-Loop, this contribution is mainly displaying Digital Shadow
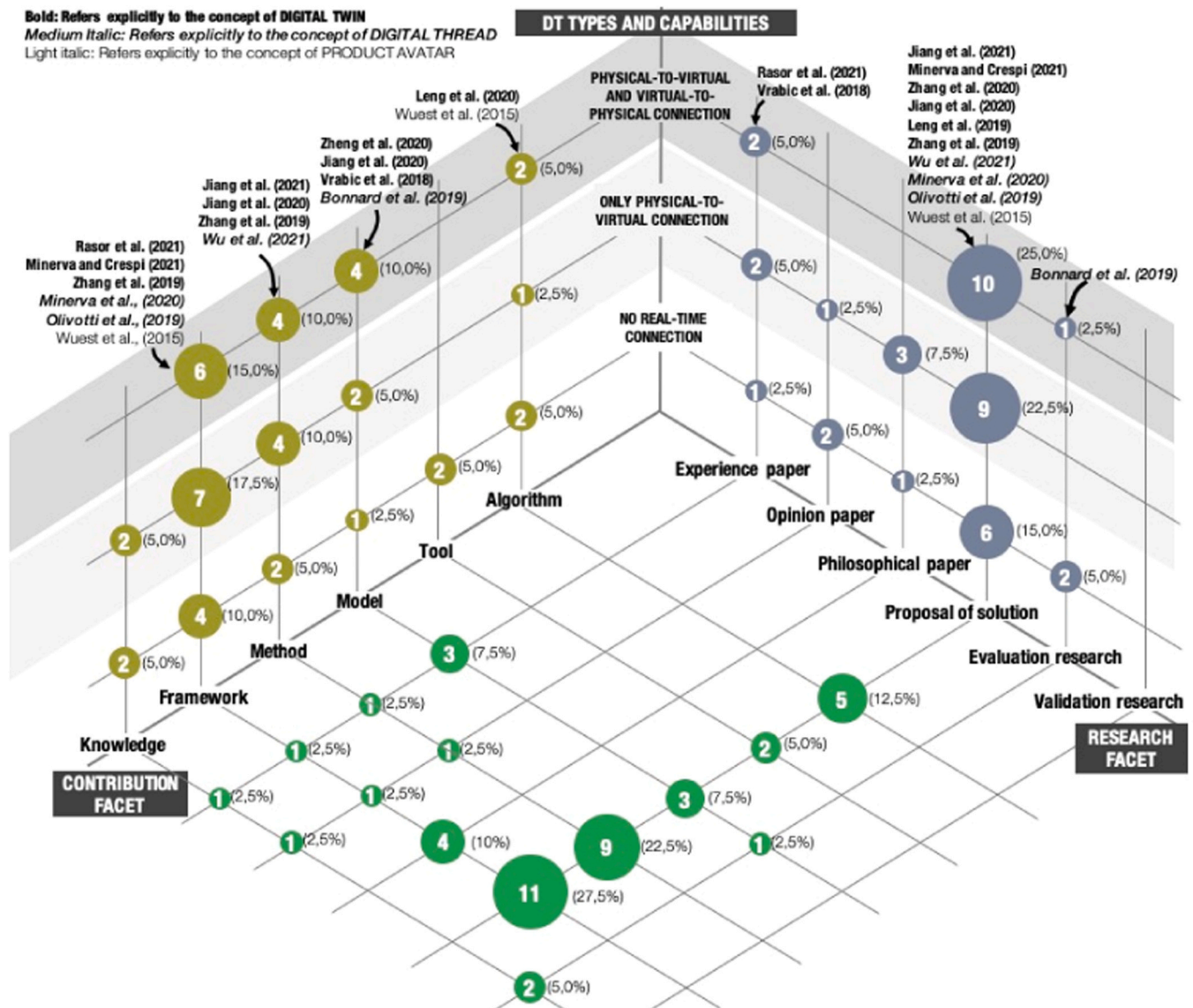
Fig. 4. Research and Contribution Facets at the intersection of the DT and PSS domains.

capabilities. In some cases, DTs in manufacturing are associated with the notion of gamification, such as in Loizou et al. (2019).

The issue of real-time monitoring is covered by authors such as Zhang et al. (2019b), who describe how the DT can provide such capabilities in manufacturing, and Bagozi et al. (2017), who propose an architecture for the twin composed of several services implemented on top of the collected data. These are named: (1) State detection, (2) Data summarization, (3) Data relevance, and (4) Data exploration. Similarly, Vichare et al. (2018), exploits the DT concept to gather through-life maintenance data of a machine tool for maintenance and service application. Noticeably, data collection and analysis activities are not always happening in real-time. For instance, a clustering procedure is applied every Δt seconds as in Bagozi et al. (2017), and cannot be classified as pure DT.

Noticeably, most of the examples in the MoL phase do not follow up the description of how the DT is used to simulate the physical item and its environment with a reflection on how to include in the models value-added complimentary service benefits. None of the contributions describe the application of the DT to model product-service bundles that, combined, fulfil specific customer needs.

4.4. End-of-Life (EoL) phase

Several papers discuss the DT as an enabler for improving maintenance delivery and the management of spare parts, dealing with the topics of remote prognostic and health management, product conditions monitoring, and reliability assessment. The use of the DT for degradation prediction of service-relevant components is described by Ströer et al. (2018), D'Amico et al. (2019) and Grijalvo Martín et al. (2021). More authors elaborate on the needed data functionalities and support to enable the creation of digital shadows for maintenance, repair, and overhaul services of machine manufacturers, including Abramovici et al. (2018) and Schuh et al. (2018).

Minerva et al. (2020) discuss several examples of DT application for functionality support, from sensors to patients, from Cultural Heritage to the Digital City. The latter gets close to the realm of PSS, since the emphasis lies on continuous monitoring and programmability of services for citizens and their applications. Yet, while the description spotlights some of the challenges related to the development of Digital Threads, the PSS focus remains quite vague, and it is mainly implicitly infused in the example. Minerva and Crespi (2021) has since then refined their Digital City example, elaborating on the business implication of the DT concept, from a more generic
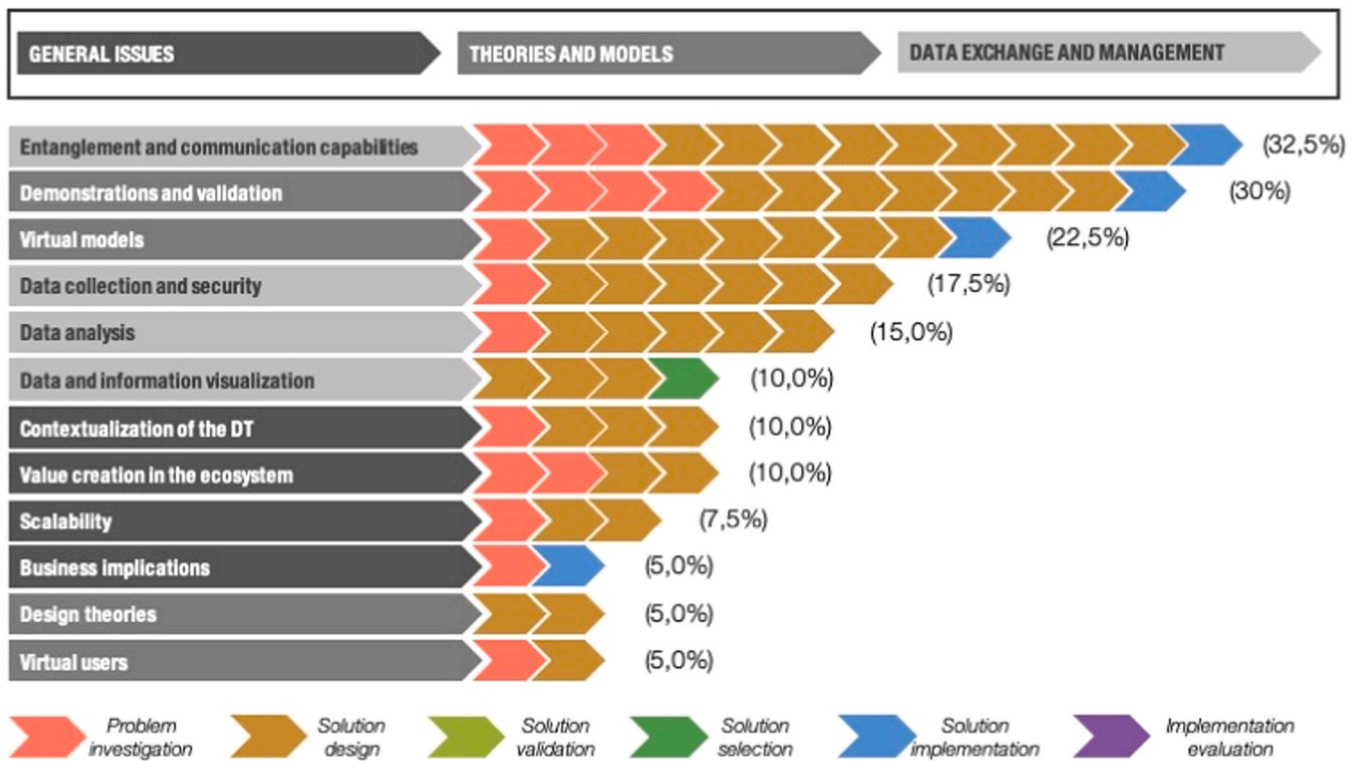
Fig. 5. Directions from future research identified in the literature.

'product' perspective. The main benefit of a DT representation is that of predicting malfunctions in the city before they occur, to mitigate their impact.

Leng et al. (2019) describe a different application example there the DT is used to maximize the utilization and efficiency of large-scale automated high-rise warehouses. Based on the data received data from the physical warehouse PSS, periodical optimal decisions can be obtained via the optimization engine of the DT, which are fed back to a semi-physical simulation of the warehouse to verify their effect.

Fig. 3 also shows that few contributions discuss the application of DT to explicitly support PSS upgrading and decommissioning. Wuest et al. (2015) are among the firsts to point out that the information gathered in the previous life cycle phases can be applied to make recommendations about upgrading and refurbishing existing products and solutions based on real usage data. Zhang et al. (2019b) further propose the DT as a way to follow the recycling path of a product, to ensure that this is not only produced sustainably, but also recycled and disposed properly. Here, the DT can communicate the current state of a product in real time to the customers, until the very end of its lifecycle. Yet, no examples or implementations are proposed, and the available evidence in literature mainly consists of systems where the product status is manually updated in discrete time intervals.

5. What is now? Contribution and research facets

The level of maturity and progression of the PSS DT research was investigated by mapping DT types and capabilities against the Contribution Facet and the Research Facet of each paper. The results of these studies are presented in the bubble plot in Fig. 4.

5.1. Contribution facets

The analysis of the Contribution Facets reveals that current research is gathered around the description of *methods* and *frameworks*. One example is provided by Wang and colleagues (2021), who have proposed an example of the latter for the smart customization of PSS offering driven by the data collected during the usage phase. Similarly, Abramovici et al. (2018) describes a framework for smart product reconfiguration to capitalize on the data collected during the usage phase of the PSS. More frameworks are presented to enable value creation through data in service delivery (see for instance Meierhofer et al., 2020), to support the development of DTs for manufacturing focusing, for instance, on the management system (Olivotti et al., 2019), or on the cyber twin of manufacturing cells (Zhang et al., 2019a). With regards to sustainable manufacturing, Li et al. (2021) discuss a framework supporting sustainable smart PSS contextualizing, exemplifying it in the case of a smart 3D printer. Also aiming to achieve better sustainability performance goals, Grijalvo Martin et al. (2021) describe the opportunities that DTs create in the field of predictive maintenance, but with a focus on advanced business models based on servitization.

In parallel with the development of frameworks, a consistent amount of literature discusses more specific methods for the implementation of DTs in the realm of PSS. Noticeably, most of these solution proposals are developed ad-hoc for a specific application or case study. Among these, Lin et al. (2021) present a method for efficient container virtualization, Barata et al. (2020) describe a DT application for a product biography information system, and Kaewunruen et al. (2020) present a method for vulnerability audit of subway stations.

Less emphasis is observed with regards to the proposal of *models*, and even less work is available with regards to specific *tools* needed for the development, realization, and management of the PSS DT. No contribution is further observed to propose implementation guidelines and/or lessons learned related to prototyping and deploying

the PSS DT in an industrial context. Such gap is not necessarily unexpected, considering that Digital Twins are a relatively novel research topic, and that the research community is still largely focusing on defining their potential benefits and implementation challenges, rather than on validating applications of the concept in a real environment.

Only a handful contributions presents *algorithms* to support the analysis of the available data in the physical and virtual environments. These are proposed for improving the servitization potential in the boat manufacturing industries by using Product Avatars (Wuest et al., 2015), for estimating the tool wear in a smart factory setting (Bagozi et al., 2017), for optimizing the packaging and storage assignments in a large warehouse (Leng et al., 2019), and for optimizing the selection of PSS in the case of an air purifier (Li and Li, 2020). In general, there is a lack of generalizable knowledge with regard to how algorithms should be applied, or developed, in the PSS context to support the development and deployment of DT.

5.2. Research facets

The vast majority (25 of the 40) papers are classified in the *proposal of solution* category, as they deal with the description of a solution (either novel or a significant extension of an existing technique) for a given problem. The potential benefits and the applicability of such solutions are typically demonstrated by small examples or a good line of argumentation. A total of 4 contributions are further classified as *philosophical papers*. This category includes contributions dedicated to the definition of taxonomies or conceptual frameworks, for with regards to DTs as service enablers for the PSS (Meierhofer et al., 2020) for new business models in the field of servitization to reach sustainable development objectives (Grijalvo Martin et al., 2021), or for reaching smart customization (Wang et al., 2021). Six papers are categorized as based on *personal experience*, i.e. reporting the lessons learned from the application of previously proposed solutions in new contexts or domains. These all discuss case study applications that deal, for instance, with potato harvesting (Kampker et al., 2019), with the development of a mobile robot (Vrabič et al., 2018), and with the development of an industrial valve (Schroeder et al., 2016). Few papers were classified as *opinion papers*, because either containing the authors' opinions about specific aspects of DT implementation in PSS, or because of their provocative argumentation likely to raise discussion in the research community.

Much less common are *evaluation papers*, which focus on the evaluation of a given technique – namely those from Bonnard et al. (2019), Zhang et al. (2019a), and Donoghue et al. (2018). At last, no paper is found to deal with *research validation*. The lack of contributions in these last two categories can be seen as a reflection of the novelty of the research area, but also highlights the need to provide solid and scientifically validated examples of successful application of DT in PSS in a real industrial environment.

6. What is next? Research directions from the literature

Fig. 5 provides a snapshot of those research directions for the PSS DT that are deemed to be important by the existing literature to be investigated in the near and far future. Noticeably, these 'directions' (which have been further grouped into 3 'topics') refer to all the PSS lifecycle stages, and do not merely target PSS design and development issues. Their distribution along the Engineering Cycle is also spotlighted, to show the type of study these questions originate from.

Looking at the Engineering Cycle, the vast majority of the papers are found to propose an improvement to the current situation, hence they have been classified as belonging to the *Solution design* category. The remaining contributions are mostly dealing with the *Problem investigation* task, which is they undertake the analysis from a 'problem' standpoint, analyzing the current situation, working modes, and ways of doing things. A few contributions have been observed to cover *Solution implementation* issues, for instance discussing the implications of introducing a new DT model in an organization. Only one contribution is dealing with *Solution Selection* and no contributions are observed to deal with *Implementation evaluation* and *Solution Validation* domains.

6.1. General issues

The topic of 'contextualization' is touched upon by a few researchers (e.g., Minerva et al., 2020), who highlight the need to develop the ability of the DT to be 'context-aware' as a means to support its effective development and implementation in different situations. In this spirit, Zheng and Lim (2020), when looking at the evolution of a DT-enabled approach to enhance product family design in a PSS context, point to the need of developing self-adaptable approaches and/or algorithms for design with context awareness. The latter is exemplified in relation to the design of a smart tower crane product family that is capable of adapting to different types of building scenarios. Similarly, Li et al. (2021) are mostly concerned with the need to update existing data analytics tools with, for instance, natural language processing to give more meaning to the data collected across the lifecycle of a solution. While attempting to propose a DT architecture for effective product lifecycle cost estimation, Farsi et al. (2021) further pinpoint that a main area of investigation for the future of DT in PSS design is that of tracing 'causalities', which is to identify those causes of costs which are often difficult to capture and visualize.

Another issue being brought forward is 'scalability'. While most of the examples presented in literature concern the development of a single-object DT, future research shall aim at demonstrating the ability to scale up the notion of DT to a small set of objects, and ideally up to thousands of objects, to be able to realistically capture the behavior of complex systems (such as PSS) in a multitude of scenarios (Minerva et al., 2020). Very recently, Minerva and Crespi (2021, p.54) further reflected that "the complexity and technical challenges associated with the creation of scalable, secure DT frameworks are such that the construction of a viable platform remains to be proven in-the-large".

Donoghue et al. (2018) are among the firsts to address the issue of 'benefit' created by the DT over the complete lifecycle of the product. More recently, other researchers have pinpointed the need to further investigate DTs from an ecosystem perspective (e.g., Minerva and Crespi, 2021), for instance by detailing relevant factors to transform data into value inside the ecosystem (Martin et al., 2021). There is an opportunity with the DT, which lies, according to Barata et al. (2020) in the impact of organizations and their products/services on societal challenges. Paraphrasing the authors, the ability to memorize product/service information from the different stages of the lifecycle can support the design and deployment of energy reduction practices, as well as reduce environmental impact.

Another aspect of interest for future research concerns the cost-effectiveness of DT applications for PSS. Zheng et al. (2018) claim that the DT may not be applicable or cost-effective in many cases, for instance due to the time, effort, and technologies needed to implement a real-time control over the entire solution. Kampker et al. (2019) explain that further research is needed to better understand the particularities of the business model for the PSS DT, and put the finger on how to communicate the value of subscription-based and pay-per-x business models enabled by the DT.

6.2. Theories and models

A topic attracting much attention is the development of the DT models, for both products and services. One of the underlying dilemmas for the development of future DT applications, as highlighted by Minerva and colleagues (2020), refers to the development of specialized DTs vs. a generic one representing the entire system-of-interest. The temporal dimension of DT development is another frequently discussed aspect for future research in the literature. Barata et al. (2020) reflect on the need to understand how to represent the product biography for the DT, and how to trace back a new DT to its previous generations. At the same time, Kaewunruen et al. (2020) do question about how to modify and re-update the DT automatically as a project change – so that the project has an elective model to manage risk dynamics throughout its life cycle. More reflections on the need to research how to support the reconfiguration of the DT architecture are presented by Abramovici et al. (2018). The issue of investigating how to assist the reusability of previous customization efforts, e.g., by designing and developing advanced querying and recommendations/matching capabilities during the ideation phase, is further touched upon by Loizou et al. (2019). More case-specific research directions on the topic of virtual models are presented by Ströer et al. (2018) and Leng et al. (2019). Noticeably, the literature also highlights the need of developing service-related 'avatars'. Wuest and colleagues (2015) pinpoint that the research community shall strive to understand how all the service life cycle data and information shall be connected transparently in the same fashion as the product avatar does.

Another aspect of interest is the Virtual User, which is defined by Minerva and Crespi (2021) as the counterpart of the physical user. How to create, represent, update and exploit 'users' are seen to be important emerging questions for the PSS DT. The servitization of generally used goods and products will inevitably reveal specific people's behavioral usage patterns in a deeper way than what is already possible. It might be even possible to influence, control, govern, or manipulate their behavior, hence triggering the need to include more ethical aspects in DT research (Minerva et al., 2020). A few authors, such as Zheng et al. (2018) and Zheng and Lim (2020) also spotlight the need to dedicate time for the development of design theories at the intersection of PSS and smart connected environments, with an eye on both human factors and technical aspects affecting servitization concept generation.

Almost one-third of the contributions point to 'demonstration and validation' as the main topic related to the future development of DT in the realm of PSS. As claimed by Minerva et al. (2020), more experiments, demonstrations, and deployments are needed to fully grasp the cost, complexity, and viability of the DT concept. Several authors, starting from Wuest et al. (2015) to more recent contributions (Zhang et al., 2019b; Minerva and Crespi, 2021) claim that DT approaches need validation before being widely accepted and used. Comprehensive evaluations via more applications need to be explored, and the development of prototype applications is often mentioned as a way forward for the PSS DT (e.g., Bagozi et al., 2017; Vichare et al., 2018; Grethler et al., 2020). The application of a multiple-case study methodology is advocated to be critical to develop further knowledge at the PSS-DT intersection (e.g., in Meierhofer et al., 2020; Stoll et al., 2020).

6.3. Data exchange and management

Entanglement is advocated by several researchers (Minerva et al., 2020; Zhang et al., 2020), to be the main area of investigation for the PSS DT of the future, stressing the importance of effective, reliable communication between the physical objects and their virtual counterpart. Minerva and Crespi (2021), for instance, stress the importance of making sure that the DT and the physical object are constantly connected, so that the DT can instantaneously register any relevant changes in status in the time period consistent with the requirements of applications. Closely related 'entanglement' is the notion of 'integration'. Ideally, the DT shall be offered and made accessible to other departments and functions of the enterprise to make it a realistic representation of a physical world object (Schuh et al., 2018). Here, transdisciplinary domain knowledge shall be merged into a common knowledge base, to enable a more solid logical inference and achieve higher autonomy in the development process (Li et al., 2021). Vrabič et al. (2018) envision the opportunity of reducing the effort needed to parametrize the models and define their interconnections. Ideally, each model should only be connected to the common model space, while a learning mechanism would be able to automatically discern how the model is connected to others through observation of the behavior of the physical counterpart. This topic is often linked to the need of developing the structure of new DT frameworks, as well as of the communication protocols and libraries to speed up and ensure the correct circulation of information across models (D'Amico et al., 2019), of the necessary computational methodologies and data fusion methods (Wang et al., 2021), and of cloud deployment protocols (Lin et al., 2021). The need of developing ad-hoc standards to enable such communication and exchange is also touched upon in Bonnard et al. (2019), Jiang et al. (2021) and Zheng and Lim (2020).

With regards to the topic of data collection and security, Schuh et al. (2018) pinpoint how further studies on digital shadows need to consider that customers might not be willing to grant access to their data without having a benefit and guaranteed data security. Minerva et al. (2020) further ask themselves if the servitization capability enabled by the DT might be accepted by users and customers, so to transform the latter into a 'virtual customer'. Wang et al. (2021) reflect on the fact that product manufacturers should carefully determine the system boundary of the DT between multiple participants, with consideration of what types of data can be shared within the organization. For this reason, Lin et al. (2021) conclude by stating that security problems of DT-based simulation for multi-tenants should be studied and strengthened.

Some authors reflect on the future research directions concerning the application of data analytics and artificial intelligence approaches. Li and Li (2020) propose to investigate the introduction of "few-shot machine learning methods and incentive mechanisms" as a way to cope with the "cold start" issue for a newly developed sustainable Smart PSS. In addition, Barata et al. (2020) elaborate on the need to develop artificial intelligence techniques in biographical data, to suggest product changes or anticipate transformations in the product lifecycle stage. On the same page, (Niu et al., 2021) Niu et al. (2021) reflect on how to exploit Big Data Analytics and Artificial Intelligence capabilities to enhance the simulation models embedded in DTs for design purposes, looking mainly at how to optimize product performances, the productivity of the system, and user experience.

The topic of data exploration and information visualization is also addressed in detail. One aspect of interest is related to the further development of virtual prototyping technologies to support PSS design (Peruzzini et al., 2016). Li et al. (2021) also indicate the need to exploit computer vision techniques to leverage the understanding of the different sorts and types of data generated in the development process of smart PSS. Loizou et al. (2019) point to augmented and virtual reality as a way forward to augment the decision makers' ability to analyze and take action on data. The development of advanced user interfaces specifically meant for big data exploration is also on the future research agenda of Bagozi et al. (2017).
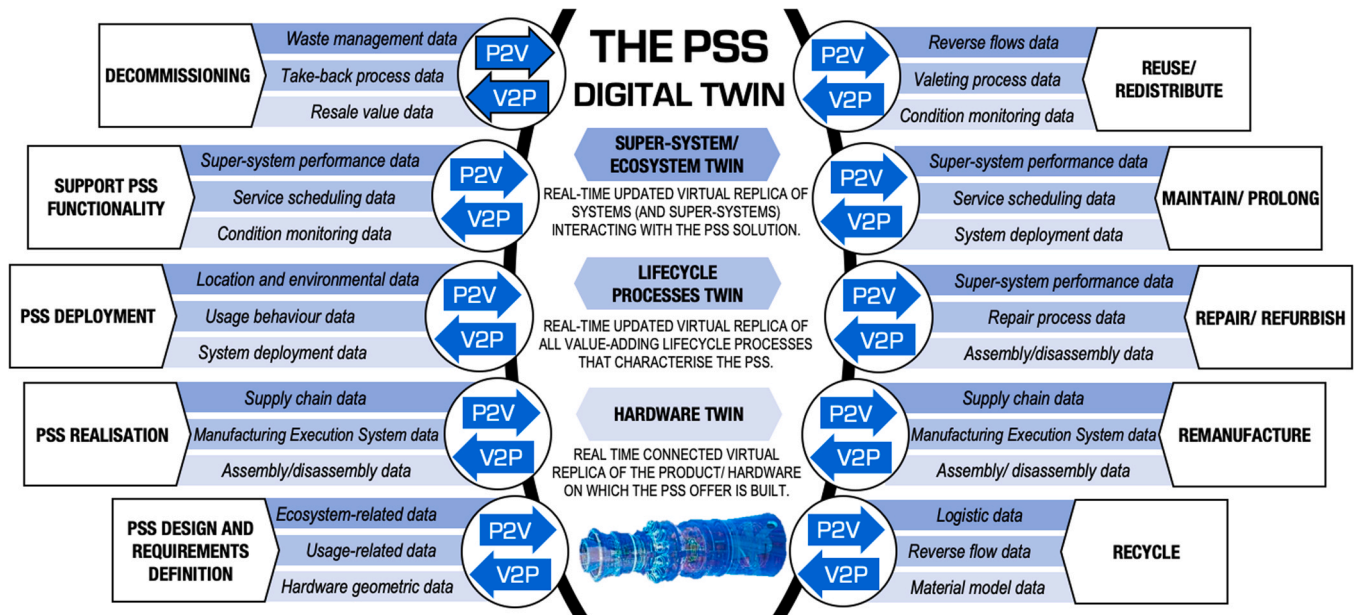
Fig. 6. A pictorial representation of the PSS Digital Twin across its 3 layers of 'twinning'.

7. Discussion

7.1. Towards a specialized definition of the PSS Digital Twin

The concept of DT has been approached and interpreted from different standpoints in the PSS community. As for any research effort aimed at integrating new technologies in established contexts, the available contributions have so far been focusing on 'designing' solutions across a broad spectrum of applications, rather than on evaluating and validating their short- and long-term effects. Yet, common to most of the research at the intersection between PSS design and DT development is a vision for the PSS Digital Twins to become a commodity in the engineering toolbox, helping the design team in mitigating the challenges and ambiguities that characterize early stage development activities of the PSS. A successful implementation of the PSS DT in design is also commonly envisioned as one that can raise awareness and understanding of expectations, needs, and requirements for integrated product/service solutions and systems. From the analysis of the literature, a specialized definition of the PSS Digital Twin, based on 3 main layers, is proposed, as shown in Fig. 6.

The framework considers, on the left end side, the generic PSS lifecycle process, adapting the classification proposed by Wiesner et al. (2015), while on the right-end side it features the circular economy system strategies described by MacArthur (2013). Data are gathered at each layer to support the definition of relevant simulation models able to represent the contribution of a PSS design from a value perspective. Several examples of possible data sources at each layer have been identified and mapped in the framework for illustration purposes. These includes sensor data (e.g., collected from production processes and or by the PSS hardware during its lifecycle) as well as more qualitative data (e.g., gathered through sentiment analysis to know more of the subjective perception of the customer).

The PSS DT shall be composed of several layers, expanding on the seminal vision of Grieves (2014) to incorporate the digital counterpart for more abstract entities, from processes to human behaviors to more intangible assets (see Dietz and Pernul, 2020). Hence, the PSS DT must necessarily provide simulation capabilities that go behind the State-of-the-Art for pure products, in a way to represent (and control) the entire range of lifecycle processes (from manufacturing to delivery, from maintenance to decommissioning and recycling) that influence value provision for customers and stakeholders.

Yet, this might not simply be enough to capture all aspects of value for PSS solutions, mainly with regards to all those more 'intangible' value creation aspects which are related, for instance, to the human dimensions and/or to the impact of new solutions on the society and on the environment. For this reason, a third layer of 'simulation capabilities' is envisioned for the PSS DT, which is related to the ability to understand the effects a proposed PSS solution might have at the super-system level, on its ecosystem.

7.2. Research questions that need to be answered

The analysis of the literature has revealed how the definition of DTs able support the process of PSS design presents numerous challenges, not merely related to the issue of realizing real-time communication between the physical and virtual entity. This section aims to reflects on the research ahead with regards to the development of the PSS DT as a support tool for engineering designers, by defining 9 main 'questions' that need to be answered.

7.2.1. Knowing more about expectations and needs for the PSS

The correct identification of expectations and needs, including those that are not explicitly perceived and communicated by the customers, is a recognized successful criterion for the design and delivery of any product or service. The same logic applies to PSS offering, and here the DT can support the collection of data and experiences from many people in different locations, all 'experiencing' the virtual PSS at the same time. An interesting aspect to be investigated is how quantitative (e.g. the PSS hardware sensors) and qualitative ones (e.g., from interviews and observations) shall be captured by the DT to know more about the Voice of the Customer (VoC) for PSS solutions, leading to RQ1:

RQ1. *How shall the PSS DT be designed to enhance engineers' awareness of tacit/implicit customer and stakeholder expectations?*

As a corollary to RQ1, it is worth investigating how to support designers in exploiting the DT to create immersive environments where the digital replica of future solutions can be accessed anytime and anywhere by all the potential stakeholders (internal and external to the provider organization). The ability to create such a

'virtual' PSS experience is seen by the authors as a way to speed the collection of feedback from a large customer and statehooder base. RQ2captures then the opportunity to realize the vision of data-driven PSS design, modularizing design solutions, and tuning them for specific customers and markets.

RQ2. *How shall the PSS DT be manipulated to enable heterogeneous/ distributed customers and stakeholders to 'experience' PSS design concepts already during the early design phase?*

RQ2 can possibly open up a new stream of research with regards to how the DT shall be communicated and prototyped in the virtual realm so that novel concepts and ideas can be 'played' instantly, and modifications of the original design can be embodied and tested without delay in different scenarios. Recent research looking at the 'gamification' of the engineering design process (see for instance Leclercq et al., 2017) suggests that, rather than testing design concepts against a fixed set of requirements derived from worst-case scenarios, their behavior can be explored directly through simulation in real use scenarios derived from usage data, hence leading to the following research question (RQ3):

RQ3. *How shall the PSS DT be prototyped virtually to enable the "gamification" of the PSS design process?*

7.2.2. Generating and selecting PSS design concepts

The availability of 'immersive' twins has the potential to support designers in knowing more about the qualitative and quantitative aspects of the value of a proposed solution. Typical evaluation methods like QFD or Pugh matrixes are affected by the high level of uncertainty that is ingrained in qualitative evaluation. At the same time, research in engineering design (e.g. Isaksson et al., 2015) has highlighted the need for decision support capable of enabling the screening of potential solution candidates in a matter of hours, with limited effort. RQ4 captures then the opportunity to assess PSS embryos using real-time connected virtual replicas that are also informed by the experience accumulated from previous initiatives, or by the analysis of future scenarios.

RQ4. *How shall historical information be merged with real-time data from the DT to generate new concepts, and to down select them during early design?*

Noticeably, the DT shall not become a fully automated black-box solution that removes humans from the design decision making process. It shall rather be intended as a support tool, as a means to improve collaboration and knowledge sharing within the PSS cross-functional design team. The latter includes individuals from a variety of disciplines that do not necessarily share the same expertise, understanding, and terminology. This is an important aspect to consider when looking at how to define the PSS DT, as the ability to take 'rational decisions' in PSS design is found to be limited by the inability to leverage informal and unstructured knowledge, contextualize information, leverage networks of connections, and support collective creation and maintenance of knowledge assets (see: Chirumalla, 2013). RQ5 spotlights the need to research how the DT can work as a 'boundary object' (see: Bertoni et al., 2016) in the multi-disciplinary decision-making context that is typical of PSS design:

RQ5. *How shall DT be designed and implemented to function as 'boundary objects' for the cross-functional PSS design team?*

7.2.3. Testing and validating PSS solutions

As explained by Grieves and Vickers (2017), a main function of the DT is to support engineering design in discovering unpredictable and undesirable emergent behavior in complex systems. A main limitation of the current virtual prototyping environments is that they lack to represent emerging behaviors, as everything is by nature pre-coded in the application. These unpredictable behaviors may be beneficial or detrimental for value creation, hence an interesting aspect for future research concerns how the DT can be used to determine all the unwanted and unexpected behaviors early in the product lifecycle, eventually helping to correct them (RQ6):

RQ6. *How can the DT be used in prototyping and testing to know more about the emerging behaviors of PSS embryos?*

Early detection requires the ability to verify and test digital replicas in many more situations and conditions than traditional physical prototypes can do. A breakthrough for the PSS DT would be then to be able to seamlessly plug in and connect it to other (interacting) twins to answer higher-order questions. For instance, a bike-sharing twin could be connected to the DT of a city, to simulate with more rigor and precision system-of-system effects and behaviors. RQ7 and RQ8 capture the need to investigate how the PSS DT can be connected to such higher-order twins to 'find the unexpected' with regards to their real monetary value as well as to their environmental performances.

RQ7. *How can the PSS DT be connected with higher-order twins (i.e., system-of-system twins) to improve the resolutions and reduce the uncertainty of the lifecycle monetary value created by a proposed solution?*

RQ8. *How can the PSS DT be connected with higher-order twins (i.e., system-of-system twins) to provide evidence of the environmental and sustainability impacts that a proposed solution will have all along its lifecycle?*

The DT can make it possible to align the goals of PSS design with the concept of circularity, so that designers can explore, in an early phase, how a hardware will behave if intended to be used in multiple lives, recycled, refurbished, and reconstructed. The DT will make it possible to test circularity scenarios, ideally having customers to step in and interact with the twin, for instance, to assess the benefit vs. effort linked to take-back mechanisms for the different parts of the PSS hardware. At the same time, the DT will allow engineers to play with scenarios, for instance to stress-tests for a hardware and investigate its survivability in a Product-as-a-Service business model. Such application of the DT would need a number of research questions to be explored in the near future, which are summarized in RQ9.

RQ9. *How can the PSS DT shall be used to verify the survivability of a hardware in alternative circular business models?*

7.3. Recommendations for practitioners

The aim of this section is to distil from the analyzed literature - and building upon the previously listed research questions- five recommendations for practitioners dealing with the development of the PSS DT – as a means to stimulate the discussion on common research themes for industry-academia collaboration.

R1). *Evaluate the cost-benefit trade-off of developing DT solutions for the PSS.*

At present, very few contributions are focusing on evaluation and validation matters. While several solution proposals are brought forward, the cost-benefit trade-off linked to the development and implementation of the DT for PSS design is far from being totally clear. Industrial practitioners shall then reflect if and when it does pay off in PSS design to invest time and money to develop exact digital replicas that feature a 2-way synchronization with the physical world. More research is needed to pinpoint suitable strategies

for the implementation, validation, and evaluation of DT in the PSS design process, from the perspective of 'is the DT worth it?'.

R2). *Balance the complexity of any digital solution with the objective that a specific application wants to achieve.*

Even if DTs are much 'hyped' today, they are also predicted by the Hype Cycle for Emerging Technologies to fall into a *Through of Disillusionment* before reaching their *Plateau of Productivity*. More instances of how the technology can benefit the enterprise need to crystallize and become more widely understood, to avoid interest to wane as experiments and implementations fail to deliver. Noticeably, the analysis has shown that Digital Shadows (with no V2P entanglement) can be as effective as a full DT implementation in addressing a variety of challenges related to the design of PSS offers. A corollary recommendation is then to carefully consider how the Key Performance Indicators (KPI) of the design process are expected to be affected by the ability to establish a P2V connection together with a V2P one.

R3). *Plan for more than one PSS DT in order not to kill radical innovation.*

The PSS DT shall not be intended as a static entity, but rather as a collection of increasingly refined Beta prototypes, never reaching a 'final solutions'. It shall be envisioned as a 'living thing', since the accumulation of data from the physical entity will make it possible to update the virtual models almost in real time, generating yet another 'version' of the PSS DT. Furthermore, it will be important for the design team to run several 'twins' in parallel, each one incorporating, for instance, radical changes in the PSS hardware. This is seen important not to fall into the trap of exploiting the DT to merely achieve incremental improvements of the PSS offer. Rather, industrial implementations shall target the development of twins that make possible to observe if a radical redesign of the original PSS concept will become more value-adding in the future, for both the provider and its customers, considering investments, switching costs, risks and more in the equation.

R4). *Make the DT accessible and "user-friendly" for the decision-makers.*

Nowadays, the selection of PSS embryos in the early design phase is still dominated by qualitative methods, mainly due to the need of involving cross-functional capabilities in the discussion and negotiation of the PSS features. Simply stated, the concept selection process is often a matter of applying Multi-Criteria Decision Making (MCDM) models that, as a bottom line, rely on the gut feelings and intuitions of the decision-makers. The DT can improve the use of such tools in two ways. Firstly, the twin will make possible to know more about the value creation factors and metrics for the PSS in its specific context. At the same time, the DT will raise awareness about the connections between customer need/expectations with specific PSS functionalities, reducing biases when populating MCDM tools.

R5). *Make the DT accessible and "user-friendly" for the customers.*

Knowing about 'what to design' in an early design phase is a matter of 'empathizing' with clients, users, and other stakeholders in the process of gathering their Voice-of-the-Customers (VoC). An important skill for PSS designers is that to put themselves in other people's shoes and connect with how they might be feeling about their problem, circumstance, or situation. Allowing all these stakeholders to 'walk-through' PSS solutions concepts through the DT can be a very valuable instrument to reduce uncertainties and deliver added value. A major aspect of interest in this respect is the opportunity to use the DT to know more about the most intangible and subjective aspects of the customers' experience, by having them to virtually testing the PSS. Future potential customers might be able to step into an ultra-realistic environment to assess the PSS (not only the product but also the service and software aspects) before this is even implemented. This will allow to know more about functions and affordances and to analyze hard and soft values.

8. Conclusions

The research on the concept of 'Product-Service System Digital Twin' is still in its infancy. While several examples lack a clear PSS foundation, others are not able to demonstrate DT capabilities, e.g. why and how a V2P connection shall be established in a particular lifecycle stage, with most of the contributions found to be focused on the development of specific, standalone applications that match with the requirements of their particular case study. Among those contributions that do address the notion of PSS DT with more precision and detail, it is noticeable how most of them gravitate towards the conceptualizations of 'frameworks' and 'methods' for the PSS DT, from a hardware viewpoint. At the same time, the work reveals how a few hotspots catalyze a large share of the attention in the research community, mainly linked to the 'realization' and 'support functionality' life cycle stages of the PSS. More research aiming to evaluate the 'goodness' of the PSS DT, looking at its benefit vs. cost mainly in the early innovation and design stages, is expected in the near future. Together with this, more validation research is expected to assess the level to which the different DT architecture, implementations, and solutions hold up to their promises.

More research on how a DT-enabled design process is also needed to 'connect the dots' and make clear how current processes for PSS design shall make the best out of the DT opportunity. 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 shall not be underestimated in this respect.

CRediT authorship contribution statement

Marco Bertoni: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Alessandro Bertoni**: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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