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## Digital technologies to support lifecycle management of smart product-service solutions

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The active trend of researches and industrial interests in Digital Servitization Strategies puts forth the recent concept of 'smart PSS'. The large industrial deployment of data management platforms, coupled with the maturity of digital twin, artificial intelligence algorithms or big data solutions, not only increases the functionalities of product-service-systems for the final users, but also demultiplies the opportunities to provide higher added-value at all steps of smart PSS life-cycles. Smartness contributes to enlarge the value delivered by smart PSS towards increased sustainability; smartness facilitates sharing this value among the multiple stakeholders of PSS solutions; smartness increases the strategical capabilities of differentiation for industrial companies. Based on the large literature review developed on the occasion of this Special Issue (Pirola et al., 2020), we do propose this definition attempt for smart PSS: a *“digital-enabled holistic solution, developed and supplied within an ecosystem, which provides economic and sustainable value to a main customer and complementary stakeholders, by integrating into a unique offer connected products together with data-driven services delivered all along the solution lifecycle, supported by physical and digital infrastructures”*. The definition articulates the main dimensions of smartness for industrial companies: the business articulation of the PSS solution with the overall ecosystem; the multi-dimensions and multi-actor characteristics of the value; the life-cycle vision of service delivering and the necessary infrastructures supporting the solutions. This Special Issue intends to address some key international advances on smart PSS. After an extensive literature review, three main sections are developed, linking business strategies at the upper level to the added-value of digital twin at a more technological one: (i) the determinants of data-based smart PSS strategies; (ii) the specificities of smart PSS design; and (iii) lifecycle management solutions through digital twins.

This Special Issue starts with a literature review and a research agenda' developed by the guest editors, “Digital technologies in product-service systems: a literature review and a research agenda” (Pirola et al., 2020). Digital Servitization and smart PSS are exhaustively analyzed as a new dynamic research focus of the community. By analyzing the concept of Smart PSS, the review questions the convergence between digital and service innovations for industrial companies and considers how digital technologies are used to enable decisions along the PSS lifecycle and/or at different decision levels. The outputs of the analysis, emphasizes five main research streams: PSS design, digital servitization, assessing tool for PSS decisions, knowledge management along the lifecycle, sustainability business models. This leads to the definition of a large research agenda on smart PSS and Digital Servitization at 3 levels : (1) Engineering challenges to develop, experiment and validate new engineering capabilities for smart PSS, (2) Managerial issues to support firm's innovation strategies and (3) Conceptual researches to build a theoretical background of research on Digital Servitization. The rest of the special issue is a first contribution to gather international advances facing the challenges of these research roadmap.

After this overall state of the art on the focus of the Special Issue, the next two research works offer interesting advances on the determinants for Data-based smart PSS Strategies. These contributions, addressing some strategical issues of innovation management, provide a high-level vision on smart PSS, before going more in detail within the organization of design activities. In *“Conceptualizing customer value in data-driven services and smart PSS”*, Adrodegari et al. (Italy) intend to help manufacturers of industrial equipment on how services should be designed, depending on the kind of customer-supplier interactions along the data lifecycle (Rapaccini & Adrodegari, 2021). The benefits resulting from smart PSS offerings are directly induced by the decisions taken in terms of design and delivery of data-



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driven services; these design decisions also depend strongly on the value co-creation abilities and mechanisms deployed within the customer-supplier relationships. Analyzing these interdependencies, the conceptual model for value-co-creation proposed by Adrodegari et al. leads to the definition of four generic archetypes of data-driven services, that differ in respect to the kind of customer-supplier interactions along the data lifecycle. The model characterizes how digital service value can be created, depending on alternative opportunities of customer-supplier relationships. Its implications suggest distinct technical options and priorities when implementing operationally each of these archetypes.

Then, the second paper dedicated to Data-based smart PSS Strategies, is proposed by Jaewoong Choi et al. (Korea) on *“Anticipating promising services under technology capability for new product service system strategies: An integrated use of patents and trademarks”* (Choi et al., 2022). One of the ambition, is to bring insights on how to build smart PSS strategies, complementary to more usual customer-centric approaches. Addressing the sector of technological-based firms, the point of view proposed here consists in identifying promising services and PSS, based on technological capabilities already available, so facilitating and accelerating the innovation process. The method uses data treatment algorithms with the objective to identify and predict innovative opportunities of service developments which could be embedded in the lifecycle of targeted products. Based on an initial data input to describe a specific business area as a ‘Business Ecology Network’ (i.e. a mathematically represented network of interrelated product and service nodes), the approach uses a ‘business domain proximity’ indicator to infer new potential innovative relationships between products and services. Then, using a second indicator of ‘technical similarity between product and service’ together with the previous indicator of ‘business domain proximity’, the strategical potential of new services for a given targeted product are analyzed. The quantitative analysis determines those services which are both promising for business development and technically viable because they are based on existing technological capabilities. One of the benefit on this research is to utilize a data-driven approach, thus ensuring an easy reproducibility and applicability of the outputs and decision-aid. This method offers an innovative way for analyzing potential innovation strategies of smart PSS development and could lead to significant implications in practice, with the perspective to develop decision-making tools helping the identification of smart PSS strategy.

Then, the specificities of smart PSS design has been identified as one of the most prominent topic in the initial analysis of the scientific literature and, thus, this topic is also well-represented in the paper selection for this Special Issue. First attempts have been made towards designing Smart PSS, allowing the integration of digital technologies in PSS from the early design stage, delivering intelligent integrated solutions. The next three contributions follow up in this direction with some interesting results, ranging from the role of data for value creation, the classification of the resulting value propositions in patterns, up to supporting efficient service combinations through simulation.

The first paper on *“Data-driven Value Creation in Smart Product-service System Design: State-of-the-art and Research Directions”* from Machchhar et al. (Sweden) addresses the topic of using operational data from the use, maintenance or reconfiguration phase of PSS for value creation (Machchhar et al., 2022). Through a systematic literature review of 60 representative studies, a classification of potentially useful data in the four dimensions of product, service, environment and human with overall ten classes could be achieved. The application of these data for value creation is discussed along five themes for data collection and the underlying functional or non-functional requirements to see how data in different approaches are leveraged for value creation. Gaps identified include a lack of methods to trade-off the investment in data capturing and the revenue generated for a Smart PSS, as well as a lack of methods capable of simulating dynamically changing service configurations and their impact.

In line with the first gap, Ebel et al. (Germany) present a new method for Smart PSS design in *“Smart already at Design Time - Pattern-Based Smart Service Innovation in Manufacturing”* in the second contribution (Ebel et al., 2022). The paper aims to support product-centric companies in customer-centric smart service innovation with a pattern-based service design approach, which addresses the challenge to assess the potential of digital technologies for creating new business opportunities, while transforming from transactional product sales towards relationship oriented solutions already in the design phase. A Delphi study delivered 116 descriptions of smart service offerings that the authors combined into 12 value proposition patterns, such as ‘analysis of data’ or ‘personalisation of solutions’. These patterns are integrated in a Pattern-Based Smart Service Innovation (PBSSI) method, supporting exploration and ideation in systematic smart service innovation. Evaluation in three industrial test cases shows stronger customer-orientation and questioning of previous product-oriented approaches.

The third paper in the area of Smart PSS Design, from Chen and Chuang (Taiwan), deals addresses the second gap with *“Digital Servitization of Symbiotic Service Composition in Product-Service Systems”* (Chuang & Chen, 2022). Cloud manufacturing combines the aspect of servitization from PSS with the Cyber-Physical Systems (CPS) concept, with physical manufacturing resources as the physical space, and the cloud as the cyber space. It requires selecting



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appropriate services from available manufacturing cloud resources to complete the manufacturing tasks and fulfil customer requirements as a service composition and optimization selection (SCOS) problem. The authors have applied symbiotic simulations with algorithms from operations research or machine learning to achieve efficient service combinations in cloud manufacturing. This approach was implemented in a multi-agent-based symbiotic simulation platform and evaluated in two experiments. While the first experiment verifies the stability of the approach regarding resource availability and response time, the second experiment validates scalability to a larger service scenario, altogether showing a reduction in resource usage and waiting times.

The third section of the Special Issue addresses Digital Twinning. As emerged in the state of the art, one of the most promising research area in the smart PSS life cycle management field is related to the concept of digital twin since it could potentially provide benefits in all the different lifecycle phases, supporting decision-making from the design phase, through service operations to end of life phases.

In the first paper in this area is *“Designing solutions with the Product-Service Systems Digital Twin: what is now and what is next?”*, in which Bertoni M. and Bertoni A. (Sweden) carried out a systematic literature review combined with a mapping study to understand how digital twins are applied today across the PSS lifecycle (beginning of life, middle of life and end of life), in terms of types, capabilities, research facets, and contribution facets (Bertoni & Bertoni, 2022). The results show that research on the concept of ‘Product-Service System Digital Twin’ is still in its infancy with contributions mostly proposing frameworks and methods, while scarce contributions are related to models and tools, as well as evaluation and validation of digital twins. This raises nine research questions that still need to be answered concerning the development of the PSS DT as a support tool for engineering designers and five recommendations for practitioners. While research questions focus on understanding how PSS DT should be designed, manipulated and used to (i) support needs and expectations analysis, (ii) to generate and select PSS design concepts, and (iii) to test and validate PSS solutions, recommendations for practitioners mainly go in the direction of cost-benefit trade-off, complexity reduction, and accessibility and user-friendliness goals.

The second paper of Karagiannis et al. (Austria) *“The OMILAB Digital Innovation environment: Agile conceptual models to bridge business value with Digital and Physical Twins for Product-Service Systems development”* goes into more detail on digital twin proposing the OMILAB Digital Innovation environment which comprises several toolkits and workspaces, designed to support Product-Service Systems (PSS) prototyping (Karagiannis et al., 2022). Focusing on the notion of Agile Digital Twin, this innovation environment aims at bridging the gap between business (i.e., value creation) and engineering (i.e., proof of concepts) perspectives, proposing a solution that drill down business ideas and PSS value propositions down to the level of feasibility experiments, benefitting from a middle knowledge layer that can be agilely customized with metamodeling means and model interoperability adapters. To this purpose, the proposed environment orchestrates, across three abstraction layers, methods such as Design Thinking, Agile Modeling Method Engineering and Model-driven Engineering to turn Ideation into smart Product-Service Systems experiments, in a laboratory setting. Furthermore, Karagiannis et al. report some evidence discussing a couple of case-based applications developed in the scope of research and students projects.

The last paper dedicated to Smart PSS Lifecycle Management supported by Digital Twinning focuses on the challenge of data integration between the manufacturing and the usage phases of the lifecycle, as an essential way to develop PSS. In this context, Woitsch et al. (Austria) in the paper *“Model-Based Data Integration along the Product & Service Life Cycle supported by Digital Twinning”* propose a model-based approach, including digital twinning, showing how data can be integrated along the product & service lifecycle leading to closer integration of products and services (Woitsch et al., 2022). To depict how this integration could be eased and guided in manufacturing, the authors discuss the development of the digital twin of a paint production pilot and the results of a physical experiment created to raise awareness of the challenges of digitization and servitization. In particular, process simulation and reliability monitoring are presented as promising innovation scenarios to further improve the data integration along the product & service lifecycle.

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