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Designing Value-Driven Solutions: The Evolution of Industrial Product-Service Systems

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Industrial Product-Service Systems (IPS^2) have been increasingly researched and practiced in a variety of fields and sectors. Nevertheless, such solutions are not as significantly implemented as expected by the CIRP keynote in 2010: it is not a dominant business of manufacturing companies today despite their economic and environmental advantages. One reason for this delay is assumed to be that the initial efforts were mainly on business and service when design was an afterthought. The promising digital technologies that have become easily implementable in practice will in the next years facilitate design and implementation of IPS^2 smartly to satisfy users and contribute to sustainability. This keynote analyses literature and practice in the last decade, aiming to propose the main characteristics of IPS^2 of the future and design processes adequate for IPS^2. The design process of both production systems for sustainability and high-value systems for sustainable development goals may need to be supported differently than today. The list of recommendations for future research on IPS^2 design is provided at the end of the paper.

Design, Service, Value creation

1. Introduction

For decades and on a global scale, the manufacturing industry including service providers has been practicing industrial product-service systems (IPS^2) dealing with dynamic interdependencies of products and services [125]. Product-service systems (PSS) have become commonplace in modern society. Fierce competition, higher profitability of services, as well as the need to control a wider range of the product lifecycle to sustain relationships with customers and achieve the better environmental performance, drove practitioners and researchers to study and develop PSS solutions. The initial definitions support the business focus: “a marketable mix of products and services capable of jointly fulfilling customers' needs through innovative design of the value delivery system” [52] or "a mixture of tangible products and intangible services that are co-designed so that they are jointly capable of fulfilling specific customer needs" [206]. In this infant age, service and business model innovation was dominating PSS approaches.

1.1 2010 vision for IPS^2 2020 differs from 2020 reality

In 2010, the CIRP Keynote [125] was the first survey on IPS^2 from both perspectives of industrial practice and academic research and highlighted the add-ons of science and engineering in PSS developments. PSS became popular because of their huge potential in profitability, affordability and environmental sustainability (mainly resource consumption and global warming) in a win-win business for every stakeholder: customers, providers (Original Equipment Manufacturer, directly or through a partnership), product and service modules suppliers, and the society (government, NGOs) with regard to ecological solutions. Based on these potentials, Meier et al. [125] proposed their IPS^2 visions for 5- and 10-year horizons. In 2010, the business was mainly product-functions-oriented and ready to accept lifecycle costs and service management systems. They predicted that, in 2015, the business would be service-advantages-oriented with flexible business models, changed customer requirements and changed OEM abilities. They also expected standards to be available on at least contracting, access to machines, monitoring conditions, and quality assessment and best practices would be shared widely in areas such as knowledge to design, to use machines. As of 2022, we are still far from real-life implementation of these concepts. Even though Meier et al. predicted the following to come true by that very year: “Result-oriented business models evolve as an industry standard. Complex development processes are simplified by automatic configuration by Plug&Play product and service modules. Service will be provided globally by service supply chains based on modularized service processes. Service robots can be used in industrial applications for automated delivery of service processes. Machine tools can communicate over the Internet to exchange data, information or knowledge”. Obviously, IPS^2 is not an industry standard yet.

At the same time, in another CIRP keynote [215], Ueda et al. discussed value creation toward a sustainable society. They claimed that new problems were synthetic and decision-making problems; it was desirable to realize a system in which both the overall purpose and individual demand can be achieved concurrently through dynamic interactions among agents (co-creation). They concluded that co-creation was a promising concept to integrate values in industry and those of consumers. Co-creation is still in its infancy.

However, there are pockets of experience that have been gained, but this has not been shared sufficiently widely. In the last ten years, IPS^2 have seen extensive development in terms of depth and breadth of both research and deployment in industrial environments. In parallel, dramatic developments of efficient IPS^2 (e.g. new value-in-use machine service offers) and innovative B2C (e.g. digital platforms) were good business successes. These have typically been achieved through the digitalization of companies but also due to the awareness of value co-creation by all the stakeholders. Today, the manufacturing industry is facing a transition driven by digital technologies and environmentally-friendly business models. IPS^2 can facilitate circular economy (PSS help closed loops of materials) as well as create and help secure jobs in industry (PSS provide services at least supervised by collaborators). Therefore, economic, ecological, as well as societal evolutions should dominate service and business model innovations to balance the ideal solutions with both customer’s and provider’s values. It combines value of artefact (functionalities, efficiency, low environmental load, etc.) with value in market (fair price, fair trade, stability, etc.) and value for human (happiness, comfortability, safety, security, etc.) [71]. From this, the solutions of the future would be driven by those expected values.

1.2 Underestimated obstacles to designing IPS^2

The paper seeks to contribute to understanding why IPS^2 potentials have not been exploited yet since emblematic successful industrial cases have proven the feasibility and shared good experiences. Is it due to a delay in the world transformation because too much energy is demanded when profit continues with business as usual? Or was there a lack of research on IPS^2 theory [96]? Or is it due to structural reasons that prevent IPS^2 implementation? Two major obstacles can justify the assumptions. First, the complexity of IPS^2 contexts has certainly been underestimated. Current IPS^2 connect products and services loosely, in the form of necessary services around products or products supporting the entire service on their own. Moreover, commercial offers were often under-personalized and did not meet customer's wishes. The multidisciplinary aspect of IPS² was also not seen as a challenge: integration and stakeholder satisfaction are at the core of IPS² success. Second, the activity of designing IPS² is more complicated than expected because while methods and tools to design a product or a service are well mastered, there is a lack of methodology to achieve systems and systems of systems. Globally, there are obstacles to the implementation of IPS² at the right scale, and we need to leverage these obstacles to design the right industrial organizations to deliver the potential of IPS².

1.3 Properties expected for value-driven IPS²

Leadership in use means offering a systemic solution, an integrated offer of IPS² within the societal and industrial systems, with three main properties: relevance, environmental friendliness and innovation. This firstly involves offering optimal service activities spanning the product lifecycle. In terms of engineering methods, it is the continuous improvement of the products, services and the integrated system offer. The industrial target is to propose profitable and affordable offers. Traditionally, this continuous improvement is supported by optimization techniques and the stepwise substitution of subsystems by improved subsystems. Secondly, it involves offering eco-efficient solutions. So far, this was understood by preserving the solution usability by prolonging product lifecycles. This is an important contribution to the implementation of the circular economy, both in terms of environmental impacts and the acceptance of new social behaviours. Once again, engineers have used optimization techniques and substitutions of more relevant sub-solutions to increase asset usability time. Third involves offering the innovation required at any time. Customers' requirements are changing very fast and IPS² should adapt continuously. Even if there seems to be a paradox with prolonging product lifecycles, engineers must continuously contribute to the development of new integrated offers focusing on renewed products and services. This means that design is at the core of IPS² development satisfying customers, society and companies.

1.4 Towards value-driven IPS² solutions design

The core challenge of value-driven IPS² solutions is to give adequate properties by design. The mutual interdependencies of products, services as well as the underlying processes and life cycles require new approaches and processes. The way of designing IPS² is critical because, from a lifecycle perspective, the sustainable performance (i.e., economic, ecologic, and societal) of IPS² largely depends on how they have been designed. While being tremendously facilitated by digital technologies [131], the complexity of integrating products and services in the digital age is growing. Designing IPS² needs a system approach driven by economic, social and environmental objectives, to integrate: 1) the core product (often the legacy machine) complemented with all the sensors and connected devices that support the monitoring of use and going together with the interface that connects the offer to the customer (generally a digital system); 2) the service delivering organization with the design of the value and supply chains (often networks) aligned with the skills expected by both technology and customers and the support products that make it happen; 3) the business model that will assure the offer to be profitable and affordable for manufacturers, as well as their suppliers and customers. The IPS² solution is the right balance of product and service "quantities" to deliver the expected value to every customer. It is therefore time to consider the new dynamics that drive the design and to analyse the shortcomings of current methods to propose improvements or even break-throughs. We cannot afford missing all dimensions of sustainability and therefore we need more adequate ways to consider and emphasize design of IPS².

This keynote investigates the design of value-driven solutions. It leans on the development of IPS² design since 2010, and projects the future development of this field by directing the focus on research challenges derived from demands coming from industry and society. Section 2 points out the key differences between IPS² and product designs in order to facilitate understanding the worthiness of the deeper investigation of the keynote subject. Section 3 details IPS² in current industrial practices based on the authors' own investigations in several industrial sectors and literature survey. Section 4 provides a deeper literature analysis on the development of the state of the art of IPS² design since 2010. Section 5 focusses on how new digital technologies are transforming IPS² design. Finally, section 6 synthesises this keynote paper by elaborating on the key future research orientations.

2. What differentiates PSS design and product design?

2.1 State of knowledge covered by 2010 keynote [125]

The following points raised in the 2010 Keynote are still valid and strong, and those pillars continue to pull PSS and PSS design.

Understanding customer value was pointed out as the key point and a new activity for manufacturers. It includes to design the four phases of value addition: value definition, creation, delivery and capturing [71]. This collection required implementing a knowledge feedback loop.

The high potential of PSS for environmental concerns was the main driver to pushing their wide development. Keys were on eco-efficiency and product's lifecycle prolongation. The PSS promises performance outcomes and raises expectations on sustainability [213] leading to higher legitimacy. They were expected to provide superior environmental performance, meaning that they could contribute to absolute sustainability [61].

Shifting from leadership in technology to leadership in utilization meant changing business models for at least a part of a product-oriented company's business: selling functionality instead of selling products. This change, including mastering the significant risks, is considered the main driver of success.

PSS evoked two conciliated options to improve business. The easiest one with immediate results was to create new services and functionalities leaning on the actual product to meet the increasing customer demands. The second one was to develop new adapted solutions that integrate products and services in a new system that offers more value to the customer. In 2020, the first option solutions are available with their gains but their absolute impact is limited. The second option solutions have just started to be developed based on their greater potential for both customers and manufacturers.

Engineering processes and organizations need to support the interdisciplinary integration as well as their new complexity. Interdisciplinary challenges arise as human values meet high technology density and networked industrial organisations. Engineering and service delivery processes become increasingly complex since the provision of value in use requires the engagement of more stakeholders. Even if new methods and tools (e.g. for business models, sustainability contribution, risk management, knowledge management supporting design, development, delivery and use of IPS²) were initiated and used, they still need to gain robustness and acceptance.

2.2 Specificities of PSS design

Designing PSS is not a mature activity yet. Novelties appeared in this new activity. They were not well analysed initially, or at least, the difficulty of tackling them was under-estimated.

Values of users. Users at both B2B (Business to Business) and B2C (Business to Customer) levels need outcomes, performances, utility of using the products and a good experience in terms of sustainability (economic, environmental, and social). This user need urges a fundamental shift of the design target from product functions to values, as defined in [71,215].

The object to design has changed in nature. Users are provided with an integrated system where products, services, users, service providers, and manufacturers are connected, rather than with a product that they integrate into their life experiences. Consequently, the challenge is to optimize a system rather than an isolated product. Moreover, for solutions to meet the users' (diverse and changing) behaviours and desires, they need to adapt. Finally, design is expected to use both user feed-forward and feedback in terms of data, information and knowledge. Thus, co-design between providers and recipients can be powerful.

Cross-disciplinarity. PSS results from a double integration. First, human and technology must collaborate to deliver value. Second, mechanical, electrical, software, and service components are integrated completely. Trade-off, reconciliation, compromise among the disciplines are keys of success.

More and new stakeholders involved forming a value network [110]. Because of the nature of the design object and the cross-disciplinarity, more stakeholders are involved in design, including those who were not typically involved in traditional product design, as service providers, municipalities, and social organizations.

Evolving system over time. User needs, requirements and expectations evolve over time, and thus any design solution must adapt to the changes [219]. This creates an opportunity for design in the deployment phase. It becomes even more substantial because data are and will be available to anticipate the trends, and services that often leverage data acquisition.

Systems approach. IPS^2 design requires adopting a system approach for effective and efficient design. So, the interplays of the components in the system can be recognized and designed. The lifecycle approach is also required to consider the sustainability impacts effectively. Moreover, designers should manage interconnected models to connect "old" component models with "new" ones at different levels of detail.

Interface design. Many PSS lean on an infrastructure already in use. This infrastructure is public or at least shared, and cannot be changed when designing the solution. It means that designing the interfaces is gaining more relevance. Moreover, this infrastructure is going to evolve to adapt to external decisions that follows a rationale, fully independent of PSS solutions that use it. Providers will have to adapt the interfaces continuously.

3. Industrial practice

Section 3 describes IPS^2 design practice in industry. The sources are scientific literature and, where no citation is given, interviews with practitioners. The interviews were held and documented in 2019 and 2020 by the authors to contextualize the opportunities and challenges relevant to the IPS^2 community and thereby complement the insights reported in the literature. Figure 1 intends to guide the reader to better capture major themes and threads (challenges on the two right columns are closely related to each other and some items appear in both Sections 3.3.1 and 3.3.2).

3.1 Trends and characteristics of PSS offerings in industry

Manufacturing industry faces a trend of servitization [11]: numerous manufacturing companies' business offerings have become a combination or an integration of physical products and services [218]. Many manufacturers are shifting toward service provision while continuing to design and produce products. Some manufacturers earn more than half of their revenue from services (e.g., civil jet engines by Rolls-Royce [165]). Sectors where PSS are offered span from telecom [119], power and automation [151], industrial printers [175], construction machines [10], oil rigs [225], medical equipment [48], automotive [95] to home appliances [182]. A macro-level empirical analysis of the manufacturing sector, for instance, in Sweden [109] also found that services were increasingly characteristic of in-house activity as well as accounted for increasing shares of total sales. Thus, especially in post-industrial economies, service activities are regarded as increasingly important. Common reasons for servitization across sectors, include intense competition from manufacturers selling lower-priced products and increasingly implemented digital technologies. This trend could also be regarded as a general trend that manufacturers' scope of design objects has, in many cases, expanded to larger systems (even a system of systems) [67,98].

IPS^{2}can be characterized by a spectrum of the degree of the provider's commitment to the customer: function-, availability-, and result-oriented businesses [125]. There are many offerings where products are provided with add-on services that are not highly integrated. However, business models are increasingly moving towards availability-based solutions [95]. Associated with this shift, the operational risk is moving from the user to the IPS^2 provider. For instance, Hitachi Rail has moved towards contracts for, e.g., 20+ years where Hitachi Rail manufactures and owns trains and the operators pay a daily usage charge [227]: these contracts are based on availability with associated possible penalties (in case the performance is not reached). Caterpillar shifted to availability-based offerings in construction and mining equipment sectors by guaranteeing costs per operating hour of equipment and including all maintenance and repair activities [227]. In availability-based contracts, IPS^2 providers will be incentivised to tell the customers how to best operate the product. Some result-oriented contracts are also reported; e.g. [180]. While the trend of servitization is clearly observed in the manufacturing industry, at present, it is unclear as to what degree IPS^{2}on the markets will be shifted towards result-oriented business from product and use oriented options.

Integrating products and services with IPS^2 by design can be regarded also as attempts to increase efficiency (and thereby value). Providing services separately from providing the related products, which is traditional in many sectors, is simply demonstrably wasteful [12]. Therefore, providing integrated IPS^2 has a high potential to diminish the inefficiency, and therefore to meet a growing interest in industry to address environmental sustainability (perceived also as value), including circular economy issues [198]. A variety of practices with IPS^2 are reported to contribute positively to the environmental aspects [18]; for instance, an IPS^2 including services effectively using information from machine-to-machine communication networks reduced the need for physical transports and thereby the environmental impacts [92]. Also, a number of companies are moving in to offering sustainability-driven IPS^{2}as reviewed in [220].

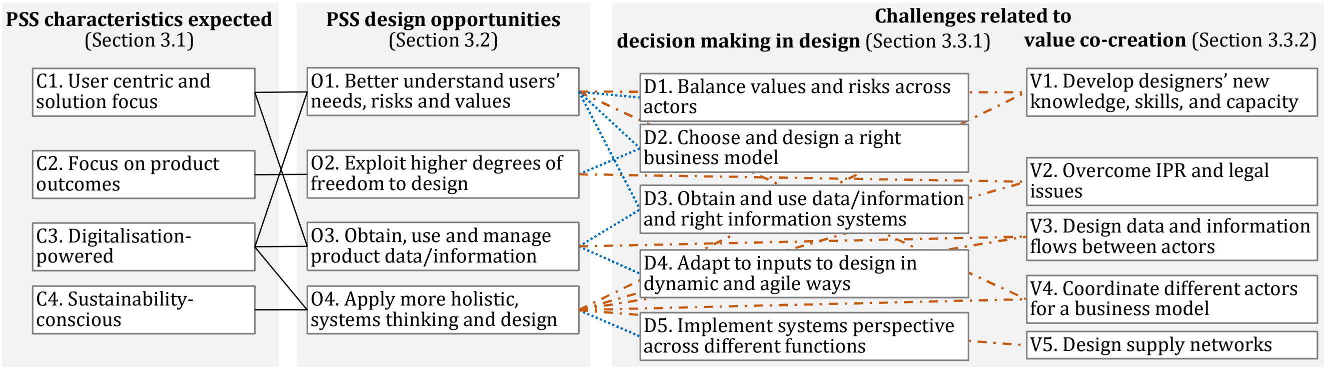

Figure 1: Major themes and threads found in industrial practice of IPS2 design: characteristics expected, opportunities, and challenges.

In the *transport sector*, servitization (toward end users) is a market and business disrupter especially in the automotive domain; see, e.g., car-sharing, mobility-as-a-service and subscription services such as Care by Volvo [23]. This trend focusing on solutions and user value (e.g., convenience) (C1 in Figure 1) has a huge impact on the entire value creation network, by requiring new skills, new revenue models, new partners (in new or existing ecosystems), new services with appropriate products (i.e., means of transport/mobility) and so forth. Mahut et al. [111], based on a review of the transport sector, proposed three requirements for manufacturers adopting PSS: 1) change conceptual models for designing the offerings, 2) manage cross-fertilization across organizations for PSS, and 3) use information from product usage for personalizing offerings. The automotive industry is indeed currently under a massive reorganization from a manufacturing industry towards a value provider focusing on outcomes of products in use through PSS (C2). In the truck domain, the following IPS^2 examples are found on the markets. Scania, a transport solution provider, offers a portfolio of PSS including 1) fleet management including uptime guarantee with a fixed price called *Fleet Care*, 2) tailor-made partnership aiming to maximise the fuel efficiency of the fleet called *Ecolution*, 3) plant optimization giving consultancy service to sites for construction or mining that involve transport by trucks, and 4) a position-based service for automatic vehicle adjustment called *Scania Zone*. These offerings as well as the adopted technologies such as connected vehicles based on digital technologies (C3) are rather new (around 2017-2018). This implies the development and provision of IPS^{2}in this domain is actual and IPS^2 with these features are modern.

The worldwide largest independent privately held automotive R&D company AVL LIST GmbH has been in powertrain engineering services ever since its creation back in 1948. Recently, they have started moving their traditional instrumentation and test systems product offer towards solutions (C1) via IPS^2. Among new key value-adding services are the optimization of test field usage through data analytics based on platform architectures, as well as combined powertrain and testbed engineering services. Other innovative services they are setting up are consulting services for creating seamless data threads from powertrain design over testing to mass production. This includes data/knowledge management over the entire product lifecycle of the components by extending the use of PLM (product lifecycle management) systems, e.g., Dassault ENOVIA and PTC Windchill, to cover the complete IPS^2 lifecycle [9].

In the *energy sector*, IPS^2 with gas turbines are described as an example. Siemens Energy, for instance, provides aftermarket services for gas turbines including; spare part provision, training, upgrades, diagnostics and repair. The service-based solutions (C1) at Siemens Energy providing higher customer value such as uptime, improved output, and hassle-free operation were initiated in the 1980s. As the gas turbines became more critical in operation and were used more extensively, the requirements for maintenance grew. Customer needs have been driving the transition to services. Initially, when services were offered, calendar-based maintenance was the norm with rigid fixed dates set for the maintenance interventions. It was not based on condition-based services originally, but it focused on risk-based analysis [200]. Around 2010, condition-based maintenance (CBM) [27] was introduced, which had a steep learning curve for numerous sites. Introducing CBM contributed to the shift in how risks are passed on to the service provider, and the safety of the customer increasingly became a major driver in contracts. Furthermore, with customers looking increasingly at cost savings, and this is where they are promoting CBM. The customers' reaction to the new service offerings has been very positive. The sources of the revenue can be typically divided into turbines and services with approximately the same portion.

In the *machine tool sector*, products have a long-life span of up to thirty years. In an IPS^2 form of contracts, after OEM's guarantee periods, bespoke service providers often acquire and possibly retrofit the machines and sell, rent or lease them to the customers and provide services based on the product-oriented contract agreement. The current service providers' contract design is, in a typical case, mainly upkeep, not really incentivising to enhance customers' satisfactions. Such upkeep contracts are often based on corrective maintenance using prior experience, resulting in lower quality, higher cost and longer asset downtime for maintenance.

Digitalization with smartness (C3) is a major denominator of enablers for IPS^2, as mentioned above. Chowdhury et al. [30] found three themes that currently drive value creation in industry through smart IPS^2: digital resource driven value systems and business models [78], boundary spanning (i.e., bridging interfaces between parties involved in providing IPS^2) with digital boundary objects, and intelligent dynamic capabilities. They also stated that the applications widely discussed in literature are remote machine monitoring based on embedded sensors and wireless connectivity in line with another review [177,197]. Across 10 industrial case studies covering sectors as diverse as aircraft engines, elevators, white goods, industrial gases, etc., Mittag et al. add to this alerting and X-on-demand [130]. The value lies both in the machine-related data collected, as well as in the on-site control system allowing customers to make better decisions on their machines, and seek provider's help whenever required. Potential, often still unexploited, innovative value propositions enabled through Smart PSS are listed in [245]: for instance, smart production and smart inspection during the manufacturing stage; smart tracing and quality assurance during logistics; smart self- and context-aware, adaptive performance during use; smart sorting and disassembly for a better end-of-life performance. Furthermore, manufacturers are still struggling to articulate value propositions from remote monitoring that would be appealing to customers [64]. This issue hinders also effective business model design: IPS^2 have been analysed primarily in relation to the development of new forms of agreements or revenue models related to asset operation and asset life management [41]. So far, however, there is a clear lack of addressing the evolution of how digital technologies enable advancing towards further stages of the service business or completely new forms of business. Note, that there are a few companies that think beyond these typical applications towards extending their current product-oriented design and business to innovation ecosystems enabled through PSS.

Practices in the *product-oriented service providers* are described here. For instance, according to the authors' interview, Babcock International services aim to improve the capability, reliability and availability of most critical assets within four market sectors of marine, land, aviation, and nuclear, underpinned by a deep understanding of technology integration, unique infrastructure, and specialist training. Babcock is a unique company in that it typically does not manufacture assets but offers service and support solutions. It prides itself in delivering a range of advanced value-added services, among many, which includes different solutions such as engineering support, overhaul and maintenance for most products, and in some it focuses on asset management to obtain maximum utilisation. Often asset management type services are offered at the end of life of the products. The target in the operation stage is typically to offer value added in terms of more asset lifecycle and increased utilisation opportunity (C4). The service is designed and delivered by Babcock. Their position is unique because they typically do not own the design rights, and this creates challenges. Often, they need customer support to acquire the required information. Still, this precondition can have an impact on the total profitability. Babcock has a number of framework agreements with customers, which set a contractual structure to provide services for assets, help to address the IPR challenges, and allow access to asset related sensitive data. Profitability is quite often supported (apart from fixed price contracts) through pain/gain share type agreements.

3.2 Opportunities to improve PSS design

Servitization, in general, requires a better understanding on the needs of customers, users and relevant actors to provide offerings that better fit the needs (O1 in Figure 1). While the first level of rationales for servitization might be in terms of business intelligence and customer relationship management, this will lead with high probability to customer-centric value creation. For instance, in engineering businesses, the customer is typically interested either to improve its process (e.g., faster, lower costs, lower binding of capital or critical resources), or to accelerate the access to knowledge and innovation. Thereby, requirements capture and management based on comprehensive understanding of the scope of design becomes critical to drive the design so that design has been changing. The understanding of the customer needs involves that of risks. IPS^2 providers, in designing, need to better know their responsibilities of managing risks, which substantially influence, for instance, its planning of the service resources. From research with ABB, a global leader in power and automation technologies, a feature to categorizing customers is reported to be whether or not the customers own internal capabilities for operation including maintenance [151]. Better understanding of related risks will lead to better design of contractual elements in IPS^2. Based on a study of a construction equipment manufacturer, not only technical risks but also user behavioural risks and provider competence risks were perceived by the provider, where an appropriate strategy to managing the risks is recommended, e.g., avoidance, reduction, sharing/transfer and retention [160].

A major key to successful PSS design is the degree of freedom given to design (i.e., the size of the design solution space) (O2). A design solution meeting results (i.e., outcomes) irrespective of the means, be it products or services, creates a potential to reaching higher efficiency than services added on to existing products, in line with the analysis of environmental performances [212]. Lindahl et al. [96] found contracts with higher flexibility for designing products and services are an enabler especially for substantial improvement through investigating IPS^2 with e.g. construction equipment. To exploit the higher degree of freedom in design, PSS designers are given a feature of being able to exchange efforts between services and products to improve the overall values of PSS; the feature was called exchangeability between products and services [176], paraphrased also as interoperability [227].

Partly because of the shifted risks, IPS^2 designers need to consider also the capital expenditures (CAPEX) and operating expenses (OPEX) implications according to systems thinking required (O4); manufacturers used to focus on CAPEX, and, as a consequence, not think sufficiently about the OPEX (reducing the lifecycle costs). By not considering this in design, the lifecycle costs are often higher than what they should be. The provision of services will make sense to shift the revenue models from CAPEX to OPEX considering customer values, to bind the customers on longer terms and to improve continuity of revenues to the providers. In the case of Rolls-Royce providing IPS^2 with aero engines, the cost born by the customer was shown substantially lower than in case engines sold with services sold separately when needed [193]. IPS^2 design procedures based on Lifecycle Costing (LCC) were applied to cases in industry; e.g., the application to forklifts showed the user's LCC with IPS^2 was lower than that with separate purchase of forklifts and the services [176]. The application to non-energy-using products showed the provider's LCC and also Lifecycle Analysis (LCA) impacts were lower [72].

The better understanding on the customer needs requires a more holistic coverage of various wants, issues, concerns, and aspects of more actors. This more holistic design (O4) can be facilitated by systemic design, which will enable designers to better understand the addressed values and where these are derived from (and where they are not). It may involve new actors that were not involved in traditional product development. Therefore, systemic design has potential to lower the total costs of design and deployment; for instance, a new actor may do a required job more efficiently in a collaborative setting than in a traditional constellation. In this context, a PSS provider has a significant advantage to become a market leader in product use compared to other actors providing only services or only selling products.

The time dimension of the customer needs is also important, as IPS^2 providers are usually engaged with customers for a longer time (O4). It is possible to change the requirements, which could generate new revenues. The process of capturing requirements has improved, for example, in the naval environment; often moving away from preferences. The customer is requested to be much clearer about their requirements. The requirements capture has improved much more jointly with the customer to understand the value requested from the services and products. Joint workshops tend to be useful for this purpose.

Using digital technologies, designers can get information of the products in use in more precision, within a shorter time and with a higher quantity (O3). Therefore, designers can get better inputs for designing the next generation of products or improving the current products as reported with examples from, e.g., suppliers in the automotive sector [95]. Digitalization technologies are often also useful for providing services over a longer period. Andritz Hydro AG is pioneering digital-twin enabled remote re-configuration and maintenance services of hydropower networks as a global leader in the field. Their concept is focussed on twinning the electronic control network of hydropower plant networks, which not only enables a remote service portfolio, but also a continuous increase of power plant operation knowledge in design departments. Integrated in high-fidelity real-time simulation models enabling, this knowledge enables e.g. the pre-validation of power plant network reconfigurations before actually deploying them.

In the *machine tool sector*, advanced IPS² have not been widely adopted yet as described in Section 3.1. Therefore, major opportunities may be in (related to all O's): 1) designing integrated product and service systems for optimised cost, risk and asset performance, 2) evaluating the lifecycle requirements of complex systems given dynamic risk and uncertainties, 3) minimising the environmental impact of IPS², and 4) developing better information management platforms that are adaptive to different needs, and 5) providing guidelines for reflecting advanced, servitized business models upon the design of the product and service solutions. For instance, DMG Mori, in R&D, is developing functions for exploiting the remaining useful life specified during design and getting alerts proactively by monitoring products based on operation time, temperature and workloads. These functions will be implemented on a system that is shared by DMG Mori and the product users. To realize these functions, sensing, monitoring and analysing data of the products in use are the key activities that may require adapting the products (e.g., adding new sensors) and the services (e.g., introducing new analytics). Providing these functions, once they are developed, will be upgraded during the use phase that enhances value creation (see Figure 2). Concerning design activities of IPS², their current design processes provide opportunities for further adaptation. E.g., how to systematically capture and formalize requirements covering the in-service phase as well as a systematic process of verifying their offerings.

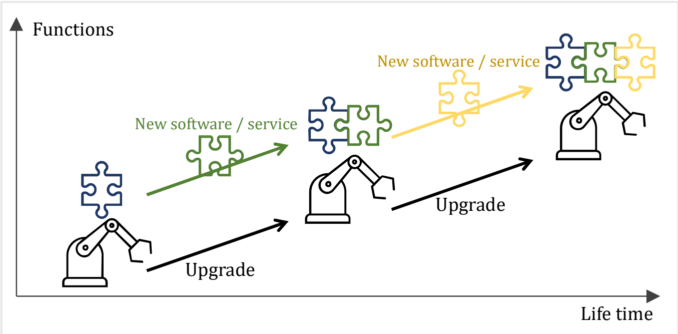

Figure 2: Software / services added to upgrade functions (drawn by the authors based on DMG Mori's brochure in 2017).

The environmental sustainability targets can also influence IPS²design [220]. For instance, it is becoming a target that Siemens Energy has to deliver on alternative sustainability targets for gas turbines (O4). This is promoting much more efficient use of assets, and minimising the number of times that there is part-load Efficiency driven customer service is becoming a necessity. With this type of environmental requirement, manufacturing companies may begin to design IPS² instead of products alone [140] and IPS² providers will further improve their PSS design [75].

3.3 Challenges in carrying out PSS design

3.3.1 Challenges with decision making in design processes

Carrying out PSS design effectively and efficiently challenges different aspects of design; among others, design processes and organizations. However, the customer-centric value creation explained as an opportunity in Section 3.2, may bring adverse side effects, because customized or tailor-made offerings are often costly and could result in inefficiency. This is ironical because the severer competition with a higher cost has led companies to try to distinguish themselves with customization that eventually could result in a higher cost. To avoid this situation termed "vicious circle of diversification" [161], setting the right balance by assigning right values (D1) is an important challenge [174]. To address this challenge, based on a study with an IPS² provider manufacturing professional printing machines [226], it is recommended to accept only a certain amount of customer-provided input and allow charging customers according to the customer provided requirements accepted. Also, modularization was shown to be a potential solution for this issue through application to an IPS² with biomedical devices [48] and service aspects with elevators [181].

In the *machine tool sector*, challenges that need to be tackled are: 1) choosing the right business model based on the three dimensions of sustainability targets (D2), 2) lack of approaches for designing engineering solutions that add value to the customer and deliver profits to the solution provider (D1), 3) ability to measure the environmental impact of IPS² solutions (D5, D3), 4) developing sensor technologies for real-time monitoring, whereby there challenges with deciding the type of sensor, number of sensors, and type of data being monitored and tracked by these sensors (D3), 5) a lack of data architectures to manage the advanced sensor based technologies, which can incur data security and IPR related challenges, too (D3, V2), 6) a need to develop algorithms to accurately predict the failures in the asset and planning for the maintenance (D3), and 7) a lack of methods available to manage the level of risk and uncertainty around the integrated product and service solution (D1). On top of these, proposing that quick and correct service is critical for machine tool users (D4), Mori and Fujishima [132] emphasised the major design challenge as the ability to consider the followings in an integrated manner: remote maintenance and monitoring system, worldwide spare parts supply system, integration of service parts, education system for service engineers, and long-term environmental load reduction.

In the *energy sector*, in the case of Siemens Energy, changes have happened to some extent in the process of transitioning into offering IPS². Gas turbines, similar to other machines, deteriorate more according to increased use. The number of cycles that it is doing will affect the life of the asset. The design process should define what are the robust sensors, and whether they will be able to provide the required value that the customer needs and wants (D3). The accuracy of the sensors or the depth of information needed will vary depending on the supply chain ability to provide, manufacture and distribute the required parts to deliver the availability. As an example, when obsolescence happens, Siemens Energy still has to offer services, and this may have an impact on a number of years in the future. There are many variations of gearboxes, and managing that is complex and costly.

In so-called *total care* contracts, the target is to reduce total lifecycle costs. In more ad-hoc contracts, the focus is on selling parts. These two have two different types of supply chains or value networks. The management of components are different in each of these approaches. Siemens Energy is currently in this transition (D5). Whilst one type of supply chain is focusing on enabling repair, the other one is focusing on selling new units. However, in terms of design, there has been limited changes to account for recognising the lifecycle costs delivered under the *total care* contracts. The transition in design procedures may or may not need to happen depending on the level of service offerings. In general, the design process needs to change more for the use and results oriented scenarios. This is because the reliability of the asset is so high for gas turbines. For example, in oil and gas, the operation process is the most important, not the gas turbine. Current availability is often at 95 % minimum, and improvement to near 100% availability is considered as costly. A major direction is that there will be less maintenance, and there is a need for better prediction of the health.

For availability-based offerings, in design, the serviceability usually concerns minimising the planned downtime. The design process consists of modules addressed by different functions in the organisation taking ownership of different parts of the physical asset (D5). But, the availability is often measured based on planned versus unplanned downtime. Therefore, improving the serviceability of the whole gas turbine is challenging. For part-based contracts, which have been the primary approach until more recently, in design, fixed maintenance intervals are considered, e.g. 32,000 hours.

In line with the dynamic ownership, the customer is passing on the risk to Siemens Energy (D1), and that needs more technology to track the health of parts (D3). More and more sensors are being incorporated. Design transformation will largely come from how sensors are used in design and how they generate data in order to increase the confidence in understanding the health of parts, systems and assets. The change in design for this aspect concerns how it can enable the capability to create a mechanism to understand the health of the asset better, so that the asset life can be better planned. New technologies that enable to capture this type of data will be critical to be able to predict the future health of assets.

Looking at *product-oriented service providers*, organisational changes are observed; for instance, Babcock, in the process of servitization of the whole sector, experienced some organisational changes, which were often due to the evolution in contracts. Customer integrated teams became a new feature to provide adaptive services to meet changing customer demands. When it comes to design processes, for instance, Babcock does not apply a generic design rule across the organisation, where design rules are based on the individual project needs. There is a lack of standardisation in the design processes, which at times causes variation in practices and inefficiencies in design processes. But, it is also considered good not to have a standard approach as every project is different, and requires innovation in the design process on each project. A design model that prompts people to take a comprehensive approach to design is generally missing, and it could be useful, but it needs to enable innovation for each project. Here, the ability to apply robust knowledge management and to transfer knowledge to design is essential (D3). This requires specification decisions that encompass the lifecycle and the implications to be recorded.

3.3.2 Challenges with value co-creation involving other actors

IPS^2 design will significantly influence design organizations. It is expected that a higher agility for business model design (D2), tightly related to skills and competences (V1), will emerge. At AVL LIST GmbH, an organization has grown around its IPS^2 business model, by implementing business units specialized in value delivery in automotive engineering and test. To enable this business, engineering, marketing and sales divisions require high customer intimacy, and AVL has developed a network of R&D centres closely located to each major car manufacturer worldwide. It is expected that ongoing servitization will require yet another transformation within the organization in order to move closer to having specialised product and service capabilities for dedicated businesses.

It should be mentioned that key challenges lie also with clients; focusing on the product availability, an emphasis on diversity in terms of services provided rather than the range of products, and the need for staff to possess both knowledge of the products and relationship management skills (V1), based on the review by Tukker [213] of literature between 2006-2015. Gesing et al. [51] highlight that often customers assume higher risk exposure when buying IPS^2 due to the perception of more dependency on the supplier and fear of losing know-how.

One challenge irrespective of sectors is overcoming legal issues (V2) [73]. One area of high relevance is result-oriented scenarios, where product ownership stays with the provider. Jacobson et al. [69] state that this scenario is not regulated in any legal system, and it is in some cases difficult to establish who is considered to be the product owner: for instance, according to Swedish law, anything of use to the function and usability of a building, and firmly attached to it, will, more often than not, be owned by the owner of the building and not stay in the ownership of the company that installed it. Another area lies with contract periods: a leasing period of a product in the Netherlands must be shorter than 75% of the product lifetime, which is set at eight years for a washing machine [182]. This regulation hinders a PSS provider from making contracts with longer than a six-year leasing term despite the technical and economic feasibility as well as the environmental potential.

In relation to systemic design described in the opportunities in the previous subsection, feedback of information across different phases could be effectively performed (V3). For instance, a design process at an IPS^2 provider in the railway sector includes feedback loops such as one from evaluation to new idea generation [31]. In this sector, Mulder et al. [137] underlined the importance of aligning design and its maintenance service to have effective and efficient maintenance process, focusing on how to design industrial equipment, such as rolling stock, and the associated design of its maintenance service. However, capturing and exploiting useful information and knowledge in a systematic manner can be a challenge: designing a PSS including a complex product can experience design fixation [70] in the level of organizational design activity, thereby not exploiting the full potential [232]. Based on a study with the oil industry [225], a suggested strategy was to translating dynamic knowledge from installation and operation into more static forms of products, and to make the knowledge relevant beyond the original context. In performing this kind of translation, McKay et al. [120] highlighted key challenges related to information requirements and availability, which influence the definition of service elements of PSS and relationships with product elements and service actors.

In the *transport sector*, in the example of *Scania Zone* (shown in Section 3.1), two challenges may be highlighted. *Scania Zone* responds to increased needs by our societies concerning safety and sustainability. It is linked to a public policy (such as "max speed 15 km/h") to a pre-defined zone. When a vehicle enters the zone, it automatically complies with the rule. A policy can be either informative, alerting the driver; or voluntary, which changes the vehicle's behaviour but can be overridden by the driver. Scania says, "many cities in Europe are implementing different kinds of zones in order to improve air quality, safety or traffic congestion". In order to realize this service, different actors need to cooperate including a product provider, a logistic service provider, a logistic service receiver, and a government. Two challenges for design are adaptability (D4) and coping with different scales in time (V4). When this type of system of systems is designed, a result in a project milestone is more difficult to secure compared to a product designed by a single company: unexpected outputs are more often emerged. Therefore, it is necessary for a company to be able to effectively and efficiently adapt its own planned activity after that milestone. In addition, other actors involved in this service work in different areas such as policies [224]. Each of them contributes to the design of the entire system but the required activity differs substantially in terms of needed time: e.g., an actor might just need to change its work manuals, while another develops a certain technology solution. Actors need to cope with this difference of the characteristics of involved parties' business. This instance is a situation emerging from a value network rather than a supply chain; a value network is a spontaneously sensing and responding spatial and temporal structure of largely loosely coupled value proposing social and economic actors interacting through institutions and technology [110].

In relation to systemic design described in Section 3.2, Babcock often has had to develop the supply chain (V5), as whilst the customer used to support the development of the supply chain, nowadays the customer is increasingly expecting the service providers to develop the supply chain. Developing the supply chain has often been achieved by creating new incentives and terms and conditions to work with Babcock to meet the customer requirements. This is more about dynamic access to (smaller number of parts)

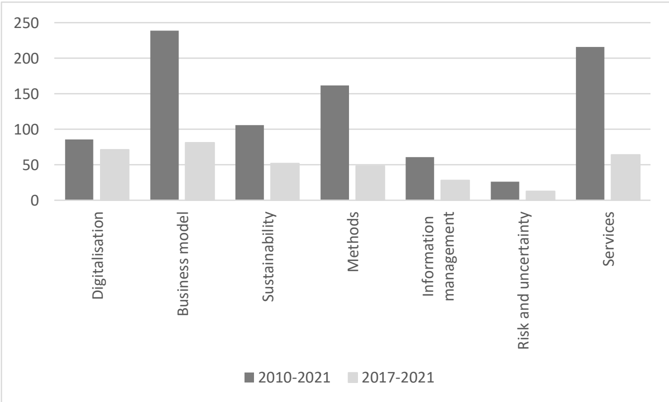

Figure 3: Research publications in IPS² and design between 2010-2021 (dark bar) and between 2017-2021 (light bar)

parts and resources over the lifecycle, rather than the ad-hoc purchases and long wait times.

3.4 Conclusions from reviewing the IPS² practices

Although IPS² are prevalent across sectors and companies, the gaps between the 2010 vision and the 2020 reality (as stated in Section 1.1) are shown with concrete cases in industry in Sections 3.1 to 3.3. The gaps could be explained by the numerous challenges in designing IPS² described in Section 3.3. and call for more design research. Firstly, there is still a need for evidence-based scientific understanding that PSS design can add value to industry (a.o., designers) and other stakeholders and how it is performed [173]; insufficient knowledge of these issues is observed in industrial practice partly because of insufficient verification and validation of prescriptive design methods. Secondly, PSS design in practice has yet to exploit full potential of design in terms of the lifecycle phases and thereby contribute to much needed patterns for sustainable consumption and production. To do so, implementing design methods and dynamic deployment supported by available data and data science thanks to the digitalization megatrend can be helpful [118]. Thirdly, we must not forget the importance that people play in the design and delivery of IPS², which requires adequate attention towards organizations and skills.

4. Literature review: Design for IPS²

This section explains the literature review that the authors have conducted related to design for IPS². It has been structured to provide the evolution of the topic since 2010, and to draw out key emerging themes with the ambition to capture key research directions currently and moving into the future.

4.1 History since 2010

Meier et al. [125] were fundamental in shaping the research direction in IPS², as they highlighted that IPS² deals with evolving interdependencies of products and services. Whilst in Section 2.1, we outlined the main contributions of the paper; it is worth highlighting that this paper raised awareness of how IPS² offers a paradigm shift towards integrated products and services. They also suggested that this could potentially increase the sustainable competitiveness of mechanical engineering and plant design. Overall, the interest in IPS² research has grown since 2010 in terms of the number of publications (Sciencedirect – Search term: "industrial product service system" and design). Since 2010, the key focus areas of research have spread across: 1) designing business models, 2) managing sustainability, 3) developing new design methods, 4) delivering integrated services, and 5) digitalisation. The three primary interests up to date have been in designing business models, developing design methods, and delivering services. However, between 2017-2021, research in digitalisation has increased more than any other key topic related to IPS². This is captured as we compare the dark (publications since 2010), and light coloured (publications since 2017) lines in Figure 3. The research in this theme includes digital transformation, digital twins, blockchains, and virtual and augmented reality (VR/AR) among other topics, and sets the major direction for future research. It is also worth noting the IPS²Conference series ended in 2019 and since then the number of publications in the topic area have declined.

An initial overview of literature across these key themes is presented next based on various example papers:

Digitalisation and information management: Tomiyama et al. [207] highlight the growing importance of smart products, which are software-intensive, data-driven, and service-conscious, their development clearly needs new capabilities underpinned by advanced tools, methods, and models. Freitag et al. [50] focus on developing an agile approach of a PSS design in the furniture industry with the help of VR/AR technology. The use case enables employees to select their new office furniture. Zhang et al. [240] promote the need for further research in the use of Digital Twin technology in the context of IPS² and suggests various applications for a closed loop product life-cycle.

Business models and services: Leitão et al. [90] present a roadmap for new business models. This consists of a set of tools that cover each stage from business model design to its evaluation. Kondoh et al. [79] developed a model of sustainable business. This was achieved through a survey to study business models, in particular sustainable ones (e.g., eco-innovations, sustainable innovations). Dombrowski and Engel [36] focus on the automotive aftermarket and offer an approach to reconsider existing service strategies and to modify them as needed. Schuh et al. [190] develop a modular sensor platform for service-oriented cyber-physical systems for an injection moulding tool. Uhlmann et al. [217] present an approach that allows IPS² providers to respond to changing requirements by managing functionality and evaluating the impact on the IPS² network partners. Aurich et al. [10] present that the integration of products and services enable companies to improve competitiveness and to achieve economic success.

Design methods: Kimita and Shimomura [77] review the existing design methods for PSS based on the Proceedings of the CIRP International Conference on IPS², 2009–2013. They consider six design perspectives: customer requirements, value proposition, product-service architecture, process, resource, and actor network. As an example, in terms of customer requirements, they highlight customers' barriers may occur if customers are not enthusiastic about ownerless consumption, as opposed to owning a product. Vasantha et al. [223], after reviewing literature, offer an understanding of PSS design in terms of eight state-of-the-art methodologies so as to identify common needs in future research. As examples, Sakao and Lindahl [175] present a value driven design method. The approach evaluates the importance of customer value and each offerings' contribution to the value delivered as well as the customer's budget.

4.2 Design methodologies for IPS²

Qu et al. [158] outlines the state-of-the-art in PSS design, evaluation, and operation methodologies (PSS-DEOM) based on their insights gained from reviewing up to 258 publications. Figure 4 summarizes their results, and adds further references that we found in our research. Tran and Park [209] take an alternative approach by proposing eight groups of twenty-nine scoring criteria aimed at assisting designers and practitioners to compare and select an appropriate methodology for a certain design needs for PSS.

Tran and Park [208] propose a new generic design methodology for different types of PSS. An alternative view was shared by

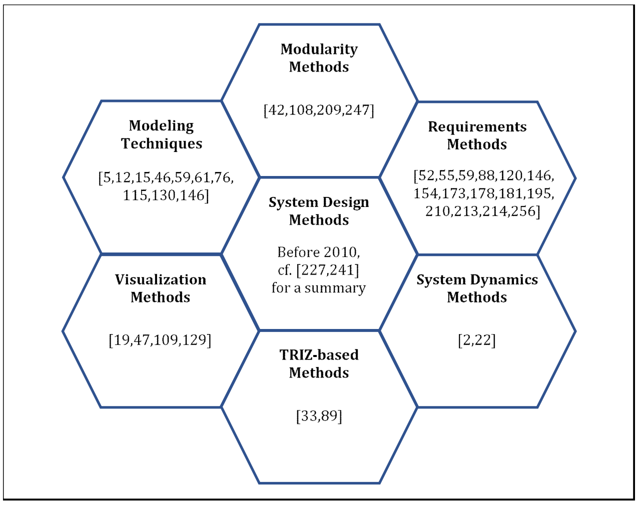

Figure 4: Design methodologies

Scherer et al. [187] as they proposed a methodology that integrates design thinking and business analytics in PSS design with the ambition to achieve profitable and lasting PSS. Design thinking is presented as a means to deeply understand customer needs and satisfy their emotional requirements in light of the providers' resources and constraints. Mourtzis et al. [135] propose a methodology for improving the leanness of PSS design, by combining real-time KPI monitoring with lean principles and practices. The paper develops the Total Leanness Index (TLI), which relies on correlating the typical wastes with the metrics used in the calculation of KPIs. This can automatically identify trade-off values for TLI, whereby lean rules are extracted to improve the performance of PSS lifecycle phases. The proposed methodology is validated through a case study in a mould-making company. Numata et al. [141] develop an approach to design actor network of PSS by visualizing state changes within the design process. This includes how tasks change with state transitions. Lindahl et al. [97] consider the Integrated Product Service Offering (IPSO) actors and system maps in order to identify and access IPSO-related requirements. Their focus is on identifying and analysing how IPSO-related requirements are managed and integrated into product-related design aspects. Sakao [172] presents results of applying a PSS design method to two cases in industry – from the manufacturing and service industries. The method is a structured and comprehensive design method that the authors' group has developed and is now called SPIPS. The method is shown to be effective in supporting designers with deriving relevant improvement solutions. Marilungo et al. [115] present an integrated methodology to support the PSS design process into a virtual enterprise. It involves different stages, from idea management to global network definition. Furthermore, the business model items can be defined in parallel along the design process and benefit the design itself by supporting decision-making, according to a concurrent engineering approach. Chen and Jiao [28] present an eco-innovative design method within the context of developing eco-leasing type PSS by using the TRIZ method. Their proposed approach aims to help the designer to find systematically creative solutions for eco-leasing. Hara [59] uses the grey-box modelling approach integrating a model-based PSS design with data-driven improvement and proposes an extension of the quality table in the quality function deployment methodology. Various papers have focused on the design methods that put emphasis on data and information management. Meier et al. [123] came from the angle of information that is provided by the partners and the supplied resources are managed by a software system. They developed an architecture and a conceptual design for such a system, called IPS^2-Execution System. Roy et al. [168] focuses on the context of predicting the remaining life of component and proposes ways to reuse the knowledge and feedback to design and manufacturing.

4.3 Key Research Topics around IPS^2

4.3.1 Conceptual design

Conceptual design has largely focused on early decision making, new methodologies, and the role of people. There have been various approaches developed that particularly focus on value in PSS. Bertoni et al. apply a systematic literature review and map existing contributions on metrics for PSS value in early design. They highlight the lack of a common taxonomy to define what PSS value is. Meuris et al. [127] focus on single developers as well as development teams and offers a value-oriented design process that integrates different methodological IPS^2 design approaches. Finally, the most promising approach is model-based system engineering (MBSE) that supports modelling the whole value creation [199].

Various philosophies, and logical approaches have been developed to assist with conceptual design. Sassanelli et al. [185] outlines the aspects of lean thinking that have already been applied in PSS development. Nemoto et al. [139] presents an educational business game for accustoming users to the philosophy of PSS and changing their mindset. There has also been interest in the role requirements capture has on design. Nemoto et al. [139] propose a framework, which focuses on classifying viewpoints from key information extracted related to context. This also includes an approach to analyse context-based requirements.

From a strategic design perspective, Grandjean et al. [53] proposes a multilevel approach to identify and plan the amount and kind of adaptability needed over time. Taisch et al. [204] developed a design approach to define effective performance indicators related to an enterprises' goals. Orellano et al. [143] focus on the early stage of the process of value co-creation and establishes the strategic positioning of stakeholders. This involves a comprehensive conceptual framework integrating both strategic and operational perspectives of a business model.

Song and Sakao [196] focus on supporting PSS customization in the early design phase. They developed a design framework, involving modules and offered flexibility based on the user needs. Mitake et al. [129] developed a context modelling based method, which identified the factors causing information asymmetry in PSS design. Akasaka et al. [2] proposed methods for supporting PSS ideas generation and evaluation. A case-based knowledge is applied to creating new design solutions by offering maximized customer satisfaction under resource constraints.

4.3.2 Detailed design

Detailed design approaches often go into much more detail from a data perspective. Dorka et al. [37] highlight that for lifecycle design, different types of data are required and have to be collected from the different partners involved in the lifecycle of IPS^2. They describe which data types are needed to efficiently and effectively organize the IPS^2 delivery. Hosono and Shimomura [62] focus on increasing the reusability of data developed in the past, and proposes a method to identify suitable assets from service repositories with set-based synthesis of both designers' and operators' intentions. Belkadi et al. [13] present a design platform tool focusing on the management of the whole PSS lifecycle as part of the ICP4Life European platform. This aims to encapsulate a collection of feasible solutions as the knowledge fragment, which is able to deliver a product–service offering meeting a set of requirements.

There are also various approaches that have been developed from the perspective of the human involvement. Wiesner et al [237] come from the perspective of how knowledge is exchanged between domains, including tacit knowledge and sentiment in order to develop integrated design of products and services.

From a detailed design perspective, there are numerous proposals outlining step-by-step processes to apply detailed design. Muto et al. [138] propose a PSS design guideline which is based on Software Engineering Methods and Theory (SEMAT). The proposed guideline provides designers with a PSS design perspective with milestones throughout the design process, enabling an effective approach to manage the design process.

The detailed approaches to value driven design have also attracted numerous studies. Bertoni et al. [16] focus on gaps and opportunities for integrating value driven design (VDD) and PSS. They develop optimization models derived from VDD in the PSS design process. Andriankaja et al. [6] propose an extension of the functional analysis approach (NF X 50-100) with the ability to integrate smoothly the whole PSS design process, including product-service design and the network configuration. In a similar context, Boucher et al. [19] targets the challenge of a lack of integration among the diversity of methods, tools and concepts available for PSS design. For this they develop a model and an associated tool, which allows a higher level of integration, starting with a first level of conceptual integration. Medini and Boucher [122] develop a methodological framework enabled by modelling and simulation to evaluate the performance of different configurations of the value network, and the impact of different input parameters across scenarios. Bertoni et al. [16] also take a modelling and simulation-based approach using a Discrete Event approach to support cross-disciplinary decision making in PSS design, facilitating the identification of the most valuable hardware configuration for a given business model. Khan and Wuest [74] highlight that design methodologies on the upgradability of PSS are limited. They identify key upgrade-enabling design features with a specific focus on their adoption towards an upgradable PSS design framework.

4.3.3 Value Co-creation

Value co-creation in IPS² is a fundamental driver of design thinking and has attracted significant amount of interest. Widmer et al. [235] define value co-creation for multiple stakeholders and use the example of mobility as a service to illustrate the importance of system and life cycle thinking to prevent rebound-effects and recognise the trade-offs of a circular PSS. Liu et al. [107] highlight that value co-creation can fulfil customer needs, enhance the organisational core competitiveness, lower environmental impacts and generate positive network externalities of platform business model. The article proposed a value co-creation-oriented framework for smart PSS. Harms et al. [60] pointed at the potential for high added value that can be achieved through services along the life cycle stages of production facilities. Lindström et al. [99] added that the overall functional products' lifecycle is governed by a sustainable win-win situation between the provider and customer sides, whilst needing a balance regarding the perceived value for both parties. Schweitzer and Aurich [191] put emphasis on how IPS² are realised by the members of a value creation network with the customer highly integrated. They highlighted that the network requires an organizational and operational structure to achieve its targets. Also, Kowalkowski [81], the shift to service-dominant logic is broader than merely an increased emphasis on services as it evolves the purpose of the firm and its role in value co-creation. Sandin [184] explores value perceptions among buyers of industrial service solutions developed for aviation products. The results showed that customers were satisfied with the partnership, even if the learning process was painful.

4.3.4 Business models, servitization and services

There have been numerous papers published focusing on the design of the IPS² management approach. As an example, Dorka et al. [38] develop a process to manage the information exchange between the partners. The paper links the information exchange to different management perspectives of IPS² and their interplay. In terms of performance management, Morlock and Meier [133] represent an adaptation of the Value Stream Mapping for services and shows how it can offer improvements.

There has also been significant interest in the design of contracts and business models. Richter et al. [162] come from the perspective of controlling customer-supplier relationships, which are challenged by the long-term horizon and the associated uncertainties. These often create incentive problems and inefficiencies. They evaluate how re-allocating property rights in use-oriented business models can lead to distributing incentives and risks more uniformly. Liu et al. [104] present an initial approach to apply the Prospect Theory on a use-oriented PSS - car sharing service. Zine et al. [246] propose a hybrid PSS business model that enables value co-creation through customization and personalization. This integrates co-design, co-production and co-delivery, leading to the personalization of solutions. For PSS customization, a review has been performed, among others, in terms of what to design for service characteristics and how to design them [59]. Lagemann et al. [85] develop an agent-based simulation approach for strategic IPS² evaluation of business model-specific objectives, constraints and parameters. The approach builds a link between different business models and the IPS² functions and physical modules, and the types, times and frequency of services, which need to be delivered. Orellano et al. [144] review 33 papers between 2010 and 2017, with the intent of proposing a conceptual framework for designing business models for PSS solutions. This takes a lifecycle perspective illustrated by an example inspired by a real company case.

A significant amount of research has investigated the concept servitization and the transformation of business models. Sjödin et al. [167] focus on the transition process from traditional transaction-oriented roles to future co-creation roles within provider–customer relationships. This study presents the dynamics in provider and customer relationships during the PSS co-creation process. Exner et al. [47] promote the need for data-driven value creation to be part of smart contracts. They highlight that this requires consideration of core processes, resources, abilities and partners to enable the individual customer solution. Elfving et al. [42] explores Ericsson's journey from a product provider to a PSS provider. The paper highlights future challenges and opportunities in terms of business models, trends and product design.

Numerous papers have considered the link between PSS design and commercial factors such as cost, affordability and profitability. Salado and Nilchiani [183] focus on achieving system affordability and propose a mathematical model to requirements elicitation. Sakao and Lindahl [176] present a method and a new toolkit for the design of integrated product-service offerings by employing life cycle cost analysis. Bertoni and Bertoni [15] focus on the concept design stage and describe a model-based approach to estimate the life cycle cost of a PSS hardware. Sydor et al. [203] evaluate the role that design processes have on reducing whole life cost within the aerospace industry.

In terms of the organisational behaviours, Dubruc et al. [41] evaluate the transition of the corporate culture during servitization through changes in practical, behavioural and intellectual habits. Bertoni and Bertoni [15] focus on PSS changeability whilst moving towards result-oriented offers. They base their approach on systems engineering principles and offer the definition of the changeability criteria.

4.3.5 Sustainability

Numerous papers have put sustainability at the centre of the design methods proposed. Somers et al. [194] focus on the link between PSS design and the sharing economy. The link was established through the different kinds of stakeholders through five operable levels: product-service characteristics (0), the users (1), the ecosystem (2), the organization (3) and society (4). Pieroni et al. [153] analysed nine existing process models and the associated perspectives of practitioners about considering sustainability issues when designing PSS. They concluded that only few examples existed that propose activities, methods or tools to support a sustainable PSS design. Medini and Boucher [121] offer a critical evaluation of engineering methods to develop and implement sustainable PSS in different and complementary dimensions.

Mert et al. [127] evaluated sustainability in terms of increasing the resource efficiency of a machine tool with different services. Kondoh and Mishima [81] propose a method to formulate a wide variety of causalities in our society design and plan sustainable businesses. Lelah et al. [92] propose adopting a 'scenarios'-based approach to move towards sustainable PSS. Allais and Gobert [4] develop a multidisciplinary method for sustainability assessment, which integrates social sciences with environmental and engineering. Erkoyuncu et al. [46] present an innovative uncertainty-based framework for increased sustainability within the context of IPS^2. The developed framework focuses on sustainability improvements whilst transforming to the delivery of advanced services.

4.3.6 Risk and uncertainty management

The role of risk and uncertainty has been well documented within the IPS^2 literature. Primarily risk and uncertainty cause the difference between the actual and predicted outcomes. Reim et al. [159] proposed ten prioritised risks that can negatively affect operations in areas including: contractual, technical and organizational structure. They developed risk categories in business models, value creation, value delivery and value capture. Rodrigues et al. [24] propose that an integrated approach needs to be taken by incorporating the value proposition with uncertainties to make complex decisions. Their approach to this is to apply scenarios with real options considering the most suitable financial performance indicators. Durugbo and Erkoyuncu [40] explored information flows across the service supply chain based on five major companies in aerospace. Masood et al. [116] come from the angle of how uncertainty influences design for services. The paper defines the design attributes, the associated knowledge requirements and the uncertainties experienced. Estebanez et al. [45] explored the role of service requirements in reducing Life Cycle Cost (LCC). In order to capture the impact of uncertainty on reliability they applied the Weibull distribution and Monte Carlo principle. Farsi and Erkoyuncu [49] focus on quantifying uncertainty in cost and benefit estimates of PSS contracts. This takes a bottom-up approach for costing using the agent-based simulation technique to capture the stochastic nature of costs. The novelty in their approach is in the aggregation of uncertainty in terms of service costs, service lead-times, and their occurrences.

Overall, the topic of risk and uncertainty has attracted significant interest as they critically impact the ability to achieve the desired outcomes of IPS^2. The more we can build visibility of outcomes early on and present an understanding of the confidence attached to decisions, the more design methodologies will make an impact. However, there are significant challenges with the methods applied to identifying and quantifying risk and uncertainty, as we often rely on subjective opinions, which are hard to justify.

4.3.7 Digitalisation

Digitalisation is offering, numerous business models to be implemented in an effective way. As an example, Through-life Engineering Services (TES) is a particular business model within the context of IPS^2 that relies on digitalisation within the B2B context. TES is a specific branch of IPS^2 as it puts emphasis on deriving commercial gains across the life-cycle from high value and complex engineered assets such as planes. As described in PAS 280 [22], there are three main ways of applying digitalisation in TES to derive value: avoid, contain, and recover. *Avoid*, aims to minimise the need for support interventions, maximise the likely effectiveness of TES interventions and minimize the likely cost of TES by considering the optimum through-life value and cost solution at the outset. As an example, Saito et al. [171] propose a method to identify common parts and/or differences among his/her recognition, and then, to enable a consensus to the structure of service failure factors. Wits et al. [239] offer insights on how Maintenance, Repair and Overhaul (MRO) strategies can be optimized for end-users using Additive Manufacturing (AM). *Contain* optimizes major asset value and cost by selecting the ideal support intervention timing and scope, based on knowledge of when a major asset has failed (completely or partially), when it approaches the point of failure, or the current risk of future failure. As an example, Teixeira et al. [205] investigate how Prognostics and Health Management can enhance delivery of PSS contracts. In parallel, Lee et al. [87] explore how manufacturing service transformation can be achieved in a big data environment. The *recover* value stream enables a sub-assembly or component within the major asset, which has insufficient residual useful functionality to be restored to a condition where it can once again meet its functional requirement, to a level of confidence, and at an agreed cost and period of operation. As an example, Uhlmann et al. [216] applies an ICT-based approach for human-machine-interaction to trigger test routines on the machine, which enables to receive information about the condition of the machine and plan responses proactively. Lagemann et al. [86] focus on introducing flexibility by systematically exploiting IPS^2-specific planning and finding close-to-optimum planning solutions.

4.3.8 Evaluation of the literature review

The following presents an evaluation of the results from the literature review:

Design methods: a vast number of approaches have been developed for both conceptual and detailed considerations. However, there is still a lack of convergence and guidance on when to use which approach, as well as on how we can connect the suitable methodologies across the different phases of design, particularly when considering the asset life cycle. We further need new *systemic design* and *science-based* methodologies to deal with the dynamic nature of IPS^2, which copes with the changes in demand and supply requirements over time.

Value co-creation: as there have been challenges with defining and measuring value in IPS^2 solutions, there is a growing need from industry to formalise the benefits that customers can attain. This not only can help to measure success in IPS^2 contracts, but it can also be a significant means to derive competitive advantage. Moving forward value creation is going to become even more critical for IPS^2 solutions. There is a need to position *value centric design* methodologies as the core means to create value and offer continuous fulfilment of targets across the supply network.

Business models, servitization and services: Whilst there is a growing list of business model examples considered for use and result oriented solutions, we still require more guidance on how to choose the appropriate business model for alternative contexts. Furthermore, we need a clear link between the selected business

Table 1: Research overview in design for IPS^2

	Conceptual design	Detailed design	Value co-creation	Business models, servitization and services	Sustainability	Risk and uncertainty	Digitalisation
Challenges	Enlarged design space with a system of systems [199] Avoiding fixations [232] Developing sustainable businesses [78] Defining the right balance of integration of products and services [10] Early decision-making focus and the role of people [17] Reaching a consensus among stakeholders [129]	Need for data from multi-source [37] [62] Coordinating multiple disciplines involved [1] Agile approaches required [50] Measuring customer value and budget trade-off [175] Integration of the whole design process [19] Eco-efficient design [28] Upgradability of PSS [74]	Focus on value co-creation networks [16] [81] [191] Customers' barriers to derive value [75] [184] System and life cycle thinking [235] Dealing with uncertainty for value creation [114] Value co-creation-oriented framework [107] Life cycle thinking [235]	Determining service strategy [36] [82] Ensuring market positions and achieving economic success [10]. Role dynamics in provider and customer relationships [167] Estimating the costs of life cycle contracts [35]	Measuring environmental impact [127] Optimising sustainability across commercial, environmental and societal targets [194] Design methods considering sustainability [154] [122] [212] Design considerations for uncertainty over the IPS^2 life cycle [46] Inefficiencies in supply chains [26] [149]	Inherent uncertainty of services [116] Ability to estimate life-cycle costs [82] Knowledge management, communication and decision-making processes [229] Understanding risks and addressing uncertainties [157]	Data-driven, and service-conscious design [205] Managing data with different levels of maturity [60] Interoperability across technologies [148] Need for life cycle integration [169] Mapping digitalisation to performance outcomes [123]
Solutions	Cause effect relationships [78]. Scenarios-based approach [89]. Multi-disciplinary method for sustainability assessment [4]. Integration of different design approaches [127]. Lean methods [136] [185]. Training game-based method [139] Lean thinking methodology [185]. Educational business game [139]. Goal Modelling [143][204] PSS customization design method [196] Model based system engineering [199] Context based requirements capture [140] [197] [130] [2] Design method for integrated adaptability [53]. Integrating Open Innovation method with IT solutions [114]	Set-based synthesis [62] VR/AR technology [50] Value driven design [175] Design improvement solutions for design using SPIPS [172] Software Engineering Methods and Theory [138] Modelling and simulation [16] Discrete Event simulation [16] TRIZ method [28] Multi-views modelling framework [6] [208] Knowledge based design methodology [14] [239]	Value co-creation-oriented framework for smart PSS [107] Engineering value assessment method [155] [103] Additive manufacturing technologies [239] Condition monitoring and fault diagnostic [192] [18] Value driven design [16] Design of sustainable PSS [153] [99] Context modelling based method [129] Value creation networks [191] Service dominant logic [60] [81]	Evaluating existing service strategy [36] Shift to service-dominant logic [81] [155] [188] Value Stream Mapping for services [133] Prospect Theory [101] [104] Servitization [39] Changeability [14] Information exchange [38] Incentivisation [162] New business models [56] [101], Customising & personalization [59] [246] Agent-based simulation [85] Life cycle cost [15] [35] [84] [175] [203]	Linking PSS design and the sharing economy or sustainability [18] [194] Design method for sustainability as a value driver [153] PSS "multi-views" modelling framework [210] Modelling causalities in or society design and plan sustainable businesses [80] 'Scenarios'-based approach to sustainability [91] multidisciplinary method inc. social sciences, environment and engineering [4] Life cycle analysis [236] PSS "multi-views" modelling framework [210] Optimising resource efficiency [126]	Uncertainty-based framework PSS sustainability analysis [44] Cost estimation [35] [49] [176] Remaining useful life prediction [140] Hybrid fuzzy methodology [227] Risk prioritisation [157] Weibull distribution and Monte Carlo principle [45] [45] Agent-based simulation technique to capture the uncertainty in costs [49] Information flows [40] Design for services [117]	Smart products and digital transformation [205], Blockchains and smart predictive informatics tools [87] ICT-based approach [213] XR technology [50] Cloud integration [240] Digital twin technology [93] Big data analytics [87] [142] [178] [231] Image and text mining [171] Additive manufacturing [239] Prognostics and Health Management [55] [192] [205] Optimisation methods [86]
Research gaps	Adaptability in design and uncertainty in decision making [120] [196] Linking PSS design and sharing economy [17,194] Capturing context-based requirements [2] [129] [139]	Decoupled design of product and services and the lack of operational solutions [6] Lack of guidance on when to use what design method [75] Need for detailed life cycle data [38]	Lack of a common taxonomy to define what PSS value is [17] Upgradability of PSS [74] Lack of design methodologies that offer value as an outcome [127]	Methods to optimise the PSS business model selection [125] New business models that offer win-win scenarios for commercial and environmental sustainability [21,167]	Methods to trade-off value and sustainability [126] Methods to quantify the monetary value of sustainability [18] Methods to design sustainability into long life assets [44] [194]	Defining and quantifying relationships between information and knowledge with uncertainty [116] Earlier visibility of outcomes given the impact of risk and uncertainty [44]	Strategic methods for digitalisation [50] Ability to link commercial models and digital technologies [184] Digitally enabled servitization [152] Evaluation of digital technologies [205]
Lessons learnt	A vast number of approaches have been developed. However, there is still a lack of convergence and guidance on when to use which approach, as well as on how we can connect the suitable methodologies across the different phases of design, particularly when considering the asset life cycle. We further need new systemic design methodologies to deal with the dynamic nature of IPS^2, which means that the demand and supply requirements can change over time.	Numerous new methods have been developed to assist with detailed design. There is a lack of view on how to bring together these methods. There are also challenges with different software and methodologies being built in siloes with a lack of consideration for integration. Further research is also needed to allow value driven outcomes to meet targets across the IPS^2 delivery networks in a sustainable manner.	As there have been challenges with defining and measuring value in IPS^2 solutions, there is a growing need from industry to formalise the customer benefits. It helps to measure success in IPS^2 contracts and derive competitive advantage. Moving forward value creation is going to become even more critical for IPS^2 solutions. There is a need to position value centric design as the core means to create value and offer continuous fulfilment of targets across the supply network.	Whilst there is a growing list of business model examples considered for use and result oriented solutions, we still require more guidance on how to choose the appropriate business model for alternative contexts. Furthermore, we need a clear link between the selected business model and the design implications through new context aware design methods. We also require further empirical examples on the sustainability impact of IPS^2 business models.	Sustainability related research often relies on information technologies and analytics to enhance the predictive capability to realise potential asset/component failures. Moving forward better links between the design methodologies, and service requirements and delivery will promote more efficient and effective IPS^2 solutions, which will lead to sustainable outcomes. Flexibility in design methods is critical to allow a balance between demand and supply in IPS^2 solutions in a sustainable manner.	There is a need to integrate risk and uncertainty related analysis into future dynamic design methodologies, so that we are proactively considering their impact, and are able to offer flexible means to deal with their impact. Further research also needs to embed resilience related thinking in design methodologies, so that we can achieve sustainability targets.	As an emerging research field, digitalisation has been the fastest area of growth in IPS^2 since 2017. The research has been relatively broad considering a vast range of digital applications and approaches. However, existing design methodologies need to improve by taking account of the context, value offering, systemic elements, and the dynamic behaviour of complex systems in order to meet the full potential. Section 5 focuses on this significant evolution of this theme.

model and the design implications through new context aware design methods. We also require further empirical examples on the sustainability impact of IPS^2 business models.

Sustainability: there is a growing range of approaches that are focusing on developing sustainable means to deliver IPS^2. These often rely on information technologies and analytics to enhance the predictive capability to realise potential asset/component failures. Moving forward better links between the design methodologies, and service requirements and delivery will promote more efficient and effective IPS^2 solutions, which will lead to sustainable outcomes. We also need better understanding of what IPS^{2}demand means particularly with respect to the chosen business model and sustainability targets. The *context-aware design* methodologies give the frame of the design. The *dynamic design methodologies* to emerge need to allow flexible means to balance the demand with the approach to supply solutions in a sustainable manner.

Risk and uncertainty management: whilst IPS^2 projects are increasingly aiming to achieve sustainability outcomes, this can only be achieved by suitable mechanisms to predict and manage risk and uncertainty. There is a need to integrate risk and uncertainty related analysis into future *dynamic design methodologies*, so that we are proactively considering their impact, and are able to offer flexible means to deal with their impact. Further research also needs to embed resilience related thinking in design methodologies, so that we can achieve sustainability targets.

Digitalisation: as an emerging research field, digitalisation has been the fastest area of growth in IPS^2 since 2017. The research has been relatively broad considering a vast range of digital applications and approaches. However, existing design methodologies need to improve by taking account of the digital technologies with respect to IPS^{2}context, value offering, systemic elements, and the dynamic behaviour of complex systems in order to meet their full potential.

4.4 Conclusion

Overall, design methodologies play a critical role in generating value in IPS^2. Whilst, there have been a significant number of new design methodologies proposed since 2010, this section has illustrated numerous emerging trends for future research. Table 1 synthetizes the main findings against the research topics. As the industrial adoption of IPS^2 continues to grow, there are still several challenges whether it be technical or soft in nature that need solutions, and *science-based design* is centrally positioned to answer many if not most of these. The key lessons learnt from the literature review are summarized in Table 1 against the main aspects of IPS^2 design. The literature review has demonstrated the need for integrated holistic approaches, which bring together both technical and soft perspectives. It is important to define the requirements and mechanisms for IPS^2 delivery holistically so that the design of the solution can be efficient and effective at the same time. It is also critical to build flexibility, and adaptability in to design to be able to respond to emerging risks and uncertainties. Section 5 focuses on this significant evolution of this theme.

5. New technologies for new value creation through IPS^2

5.1 Relevance of new technologies for IPS^2

As elaborated exhaustively in [207] by Tomiyama, linking digital systems with physical products creates opportunities for PSS packages both in B2C and B2B environments. In [95], Lerch and Gotsch analysed opportunities and potential transition paths for manufacturing firms towards digitalized PSS based on numerous related contributions in this domain. Most notably, they argue that a more developed service orientation with more complex service offerings leads to a greater need for digital solutions, while at the same time, the integration of embedded ICT systems into products opens up new avenues for providing innovative services. From a design process perspective, this implies that the design of embedded electronics and software needs to be increasingly integrated into the PSS design process, including the related business model design. This leads to digital architectures that are enablers for smart PSS features, data analytics, cloud integration, as well as modern technology trends such as the Industrial Internet of Things (IIoT) and distributed ledgers. We will elaborate on each of those in this section, based on their current coverage in engineering literature. As our own literature analysis summarized in section 4 as well as the systematic literature review and research agenda on digitalized PSS presented in [150] confirm, publications have focussed on the role of few digital technologies only, in particular the IIoT. Another important finding is that despite the fact that several themes have been associated with the digital servitization concept ('smartness', new business models, value co-creation, sustainability, etc.), a fragmented view on them prevails. Furthermore, they identified that new specific types of benefits of servitization compared to traditionally acknowledged ones have been associated with digital servitization, with little detail on how they can be achieved. Given that their study is very recent, this proves that there is a need for a more profound and holistic investigation on the consequences that digitalized PSS imply on their design process and related practices.

Emerging digital technologies form a large part of the opportunity to take advantage moving forward in the PSS theme, along with thinking about culture, business models, skills and legislation among other areas. Research related to digital has touched on numerous angles such as data, modelling and visualisation. Whilst numerous technological opportunities have emerged, a clear strategy to choose among these options is still expected. As an initial example, Schenkl et al. [186] present an approach that uses a layer model for PSS including goals on the upper level, PSS elements at medium level and technologies at the bottom. Paschou et al. [149] focus on how knowledge about digital technologies enhances servitization and promotes the need to understand better the links between digital and service transformation. Pirola et al. [154] highlight the need for further convergence between digital and service orientations and elaborates on ways to use digital technologies along the PSS lifecycle and at different planning levels. They highlighted five main research streams: PSS design, digital servitization, assessing tools for PSS decisions, knowledge management along the lifecycle, sustainability and business models.

In the following key literature on IPS^2 and digital technologies are analysed taking a focus on different digital technologies in each subsection. Although we did not choose particular criteria to order these technologies, we did apply a method to select them: first, in section 5.2, we analyse in greater detail the specific challenges that the predominant—as stated above—design objective *smartness* brings along, and which technologies are required and already used to meet them. Based on this analysis, we will investigate more specific research challenges related to the above-cited streams in section 6.

5.2 IPS^2 and smart products and services

With the ubiquity of Internet, computational intelligence and network technologies, smart product-service systems (SPSS) have become an important research area and a source for potential innovative value propositions [29]. In the original definition proposed by Valencia et al., SPSS were defined as "the integration of smart products and e-services into single solutions delivered to the market to satisfy the needs of individual consumers" [222]. Huge research effort has been devoted to propose conceptual frameworks for capturing the aspect of the systematic co-digitalization of products and services [88,244]. In [83], Kuhlenkötter et al. analyse the specific challenges of SPSS design to exiting engineering methodologies. Keys are intrinsically high levels of *complexity* through *horizontal interconnectedness* of many components and disciplines, as well as *closed-loop engineering* design activities having to cover the entire SPSS life cycle, including the business model. As of [32], these key requirements lead to the three specific design characteristics *IT-driven value co-creation*, *closed-loop design* and *context-awareness*. Cong et al. [32] attempt to map existing design methods to these three characteristics, with the net result that a fundamental design methodology for SPSS is still missing. In particular, existing design frameworks do not cover design-level adaptations according to the specific context.

Based on their analysis of the *hybrid concerns* of value co-creation by design, Zheng et al. [245] propose a generic system architecture for Smart PSS that follows the DIKW (data-information-knowledge-wisdom) model [8]. While this architecture reflects the needs of hybrid design [63] on a macro-level, it helps point out the needs for a re-thinking of existing design methods on a micro-level [245]. Hou et al. propose a formal closed-loop framework of data-informed inverse design based on complementing the classic forward-design problem by the inverse problem including a feedback loop. Unlike the forward or direct problem, the latter begins by evaluating results (typically measured by sensors) before calculating the causes. This inverse problem in engineering is analogous to the regularization problem of parameter estimation in distributed systems, that is, to determine unknown parameters in the functional form of the governing model of the phenomenon, from the observed data [63]. At an industrial scale, this inevitably produces Big Data, both in terms of volumes and variety of data. Moreover, the transformation from product usage data to design information is a complex process, for which a single data processing and analysis method alone can hardly be capable to solve the problem effectively [63]. To address these challenges in an incremental rather than disruptive approach, several works have focussed on specific value propositions that can be leveraged through the adoption of a SPSS design mind set rather than a purely product-focused one. Examples are reconfigurability and upgradeability, e.g. [20,74,152]. Others such as [5,26,66] take a more user-centric approach to focus and prioritize SPSS design efforts. Key is the systematic analysis of service value through the integration of user experience evaluation in the design process, as well as the feedback of in-use data to foster learning for future design iterations.

The required co-design of products and services, as well as the increasing integration of digital design elements, leads to a more complex process of requirements elicitation [230], specification, interaction [195], evolution, analysis [57,58,106] and validation [46], as well as management throughout the design process [243]. The digital dominance in the design of SPSS brings along specific challenges with respect to functional safety and cybersecurity [100,163,164], as well as reliability [76].

5.3 IPS² and data analytics and visualization

There are significant opportunities in the perspective of enhancing value generated from data. Huang et al. [65] evaluate the role of product tracking and tracing with triggering and delivering service. They highlight potentials with blockchain and offer an initial application in the context of IPS². As a benefit, they indicate that blockchain inherently creates a synchronized database of all transaction at each node while smart contracts allow for responsive action. Rondini et al. [166] focus on the early design phases and propose a method that combines two existing approaches: The Engineering Value Assessment and Provider Value Evaluation methods. This is composed of two steps, the first pursuing the identification of valuable concepts from the customer and provider perspectives; the second pursuing an individual analysis of the components available for use in the concept selected. Abramovici et al. [1] develop a new approach for data management for interdisciplinary, globally distributed and continuous reconfiguration of smart products.

Integrated IPS² design requires closing the design loop by feeding system-in-use data into the design process, starting from the conceptual design phase [66,241]. One of the key technical and business challenges in this process is the data aggregation over several products and service providers [145,233]. Due to multi-layered and interdependent stakeholder involvement in both IPS² design and delivery, challenges related to data ownership and data privacy are increasingly coming up in the form of design requirements or constraints to the products, services, as well as the underlying business models [128,189] and in particular data-driven business models [47]. A similar tendency can be observed for the subject of human-data interaction [156].

From a more technical perspective, data orchestration from the edge level to the IT cloud is of vital importance to provide the fundamental basis to collect and aggregate data [105]. At the lowest design level, design decision aid is required to determine which data needs to be collected, at what quality level, and derive from this information the sensors to select and the location to integrate them [112,113]. Designers also need specifications related to the ways data, once collected, shall be analysed and used to control and design IPS² and their design process [66,108,177].

There has also been interest in the role that visualisation can have with enhanced decision making. Mourtzis et al. [134] focus on enabling the remote cooperation between the on-spot technician and the manufacturer and develops a cloud-based service-oriented system that uses Augmented Reality (AR) for remote maintenance. The AR platform records the malfunction by the end user, provides instructions by the expert, and the cloud-based platform allows communication and exchange of information. Palmarini et al. [146] apply a systematic literature review on AR in maintenance and offer insights to the most relevant technical limitations. They point to the high fragmentation among hardware, software and AR solutions. This was noted as a major reason for challenges with selecting and developing AR systems

More generally, the rapidly growing use of data in design, as well as the fact that design needs to increasingly consider data generation, collection, and processing during the IPS² life cycle, leads to *data-enabled* or *data-driven* design, terms used in the automation domain, and re-used in the context of smart product design [207]. We consider *data-enabled* design more appropriate in the context of IPS², since design shall be *value-driven*, and data are just a means to achieve that. Service life cycle data enable feedback of real and actual service use patterns to the design of the underlying products, processes, and infrastructure.

5.4 IPS² and the cloud

Cloud-service based IPS² development incites taking a user-centric value design approach [26], in that by the very architecture of the cloud, it enforces the designer's thinking in terms of perceivable value-providing, individualized front-end IPS² components and enabling, re-usable back-end units. Platform approaches to back-end designs (e.g. [145]) have obvious technical and economic advantages in all life cycle stages [25]. Lindström et al. [102] highlight the potential use of cloud services in functional products and their application to enhance availability using modelling and simulation.

While cloud-based IPS² architectures allow to clearly separate responsibilities for the design of front-end and back-end units, this separation is less evident from a function-oriented perspective: in general, service function cross front-end and back-end boundaries several times, implying change of responsibilities for the correct functioning of the invoked IPS² units. Providers use cloud services themselves, and need to rely on the Quality of Service (QoS) provided. In environments where IPS² providers implement and operate the back-end units in the cloud themselves, this aspect is not critical. However, this is not the general case, since the idea of the cloud is to aggregate and encapsulate data and functionality for multiple users. Hence, QoS becomes a major design challenge in

IPS² driven by the cloud, as does the aspect of very clear interface definitions and integration strategies and validation procedures.

Cloud environments, therefore, have become Infrastructure as a Service, (IaaS) enabling both added-value services as smart products [207]. They provide data and functionality at various levels of quality and trust, which themselves power higher-level PSS. Responsibilities for design, deployment, operation, decommissioning need to be very clearly defined, as do any liability matters. Therefore, while designing based on cloud environments and services reduces technical efforts for IPS² design teams (due to re-use of existing functionality in the cloud), it increases the number and breadth of interfaces, shared responsibilities, and by consequence the need for appropriate business models. Furthermore, it confronts validation processes and methods with new challenges [46].

5.5 IPS² and the IoT

The IoT market can be segmented into B2C (connecting people and devices), B2B (connecting industries for business), as well as B2B2C (interconnecting industries, people and devices, such as smart cities). Interconnected products shed a new light on the classical view on the value chain and on value creation [157]. The IoT fosters thinking in terms of highly interconnected business ecosystems [34] comprising a community of interacting companies and individuals along with their socio-economic environment, where the companies are competing and collaborating by utilising a common set of core assets related to the interconnection of the physical world of things with the virtual world of Internet [238]. Exploiting all the value creation opportunities through PSS and enabling business models is a long way full of strategic implications and transformation risks. As summarized from a recent exhaustive literature review in [170], few things have been published about how such IIoT-enabled ecosystems can be created successfully. Instead, the potentials of value creation through the exploitation of data collected have widely been analysed, in particular in the context of asset monitoring and control applications. Another review points out the lack of research addressing feedback of data acquired via IIoT to IPS² design, which could be realized by PLM software [179].

In the logistics domain, providing smart logistics services based on the IoT gradually leads to the implementation of the Physical Internet (PI). The PI is a concrete, pragmatic paradigm of a collaborative and coopetitive logistics system. The term was coined in 2010 to emphasise the essence of full interconnectivity, intelligence, and interoperability for resource sharing based on modularisation and standardisation of tools, facilities, and business processes [147]. As shown in [147], PSS in combination with the IoT leads towards the realization of smart PI-containers, PI-hubs, as well as PI-information tools and services, which are altogether aggregated in a global logistics cloud to make an interconnected global logistics system enabling seamless asset sharing and flow consolidation real in the next 10 to 20 years to come. This includes fostering the implementation of Circular Economy [7].

From the engineering design perspective, some works have been investigating PSS reference architectures [3,25], mostly on the basis of more established IIoT architecture frameworks, most notably Reference Architecture Model Industry 4.0 (RAMI 4.0), the Industrial Internet Reference Architecture (IIRA) and the Internet of Things Architecture (IoT-A).

The bottom line of our investigations regarding the role of (I)IoT for future IPS² evolution and design is mainly as a fundamental enabler of the business ecosystems that foster the adoption of IPS² at a large scale. Furthermore, from an IPS² design perspective, the IIoT serves as an enabler for data-centric design and consequently the IPS² adaptive capabilities.

5.6 IPS² and the Digital Twin

While there is broad consensus that the Digital Twin [27] is an enabler of new value propositions through IPS² [234], published ways of exploiting these potentials systematically are rare. Meierhofer et al. propose a holistic and actionable concept for modelling industrial service ecosystems [124]. Their key proposal is to switch from the classical Goods Dominant Logic driven to a Service Dominant Logic (SDL) driven design process. This process starts by modelling the ecosystem of IPS² stakeholders, typically in the form of graphs which nodes represent stakeholders and edges the value flows. Next, these actors' problems are described using service design tools, and the moments of truth (MoT) for decision support identified based on hybrid simulation-based models (like physical modelling, System Dynamics Modelling, Discrete Event Simulation, or Agent Based Simulation). These allow determining the simulation elements that provide most value and factors and impacts are analysed. Based on this, the digital twins of the service ecosystem "family members" are built in an iterative way in order to be able to simulate IPS² operation. Although their contribution is only conceptual at this stage, it has the potential of making the IPS² design process evolve fundamentally towards value-based service design, where the actual product design process is driven from a higher-level perspective on value proposition.

West et al. [234] investigated ten diverse industrial use cases, each of them exceeding the initial proof-of-concept stage of the design process, in which digital twins enable a significant shift and extension of value propositions. Leng et al. demonstrated digital-twin based real-time warehouse optimization, where a digital twin-driven joint optimisation model allows quickly optimising stacked packing and storage assignment in warehouse operations [94] and a digital twin-driven approach for rapid reconfiguration of automated manufacturing systems from the semi-physical simulation that maps data of the system followed by optimization [93]. From a design perspective, a key enabler for reconfiguration and control through the digital twin is their open architecture for machine tools.

Schuh et al. [189] focus on maintenance, repair and overhaul (MRO) services for machine manufacturers. They cover a wide scope with the order processing as a service, mapping the MRO services and their single elements through a case study. They also offer a data model for the digital shadow of MRO services that entails a comprehensive representation of the associated processes. Digital twins have also received numerous interests as a means to offer federated modelling capability, which enhances the ability to represent complex systems. Stark et al. [199] investigate methodological, technological, operative, and business aspects of developing and operating Digital Twins. Erkoyuncu et al. [43] develop an

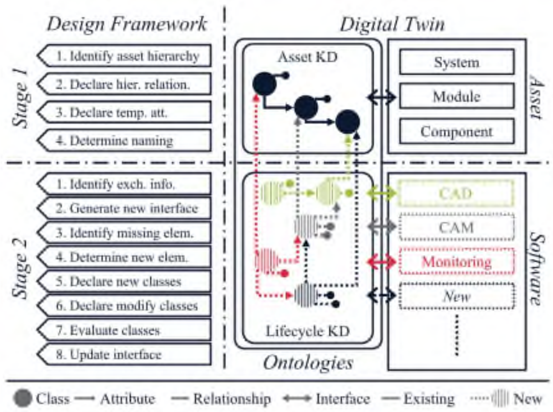

Figure 5: Ontology Design Framework (from [43])

ontology-based digital twin design framework for adaptive industrial assets. The digital twins' adaptive capabilities are leveraged by including the capture of key data required to track asset life in the asset's design (Figure 5).

While the reported potential applications of Digital Twins as powerful simulation environments used during the design and validation process are countless, the amount of published use cases of Digital Twins in IPS^2 contexts are still rare. As pointed out earlier in this paper, predictive maintenance seems to be the most prominent applications for time being. Even for design processes, tools and methods, supporting designers to leverage the seamless up to real-time link with operations for realizing the key IPS^2 design challenges related with context-awareness and adaptability.

5.7 IPS^2 and distributed ledger technologies

Since PSS are intrinsically decentralized, linking several organisations and stakeholder together in day-to-day operations and transactions, distributed ledger technologies such as blockchain lend themselves for enabling peer-to-peer transactions that are anonymous while at the same time visible to everybody in the chain. This provides novel ways to improve traceability and transparency throughout the product lifecycle [65]. In their critical review and analysis of the use of blockchain in IPS^2, Huang et al. [65] conclude that although blockchain is highly promising for making IPS^2 adoption in industry progress, much research still needs to be done to unlock its full potential. Major research challenges include: How can right data input be ensured? How can members in the chain be protected from data waste? How can competition be ensured in the value chain? How can both peers be protected in low trust business environments?

Initial applications have been coming up recently in IPS^2 supply chains [228]. Key challenges are linked to trust and governance rather than to technical design [240]. The potential the blockchain and other distributed ledgers have for the design and deployment of ever more complex and far-reaching IPS^2 does not seem to be captured in any publication found so far. The core concept of "upgrading" any data transferred via the internet to a secured transaction of a value object enables associating any data transmission and use to a monetary transfer. This allows services to be provided and used without any explicit payment procedures of any stakeholders in the IPS^2 value chain (e.g. "e-wallet" solutions). Smart contracts define relationships between both legal and technical entities. From a design perspective, this also implies that the engineering design will no longer be separated from the business model design. In Distributed Ledger Technology (DLT) and blockchain terms, the underlying infrastructure is often called the *Internet of Value* [202], where in this context, the notion of value is associated with a layer on top of the Internet that allows monetary transactions without the need for a third party.

5.8 IPS^2 and design organisations in the digital age

Very little has been published about the required organizational changes that have to go along with the commercial exploitation of smart technologies enabling applications such as remote monitoring [54,55]. Yet, apart from technological challenges, companies adopting digitalized PSS and servitization are confronted with organizational challenges. In their recent study, Tronvoll et al. [211] found that key transformational shifts concern the company's identity shift from a purely planning-based approach to discovery (in data, during service deployment), from data scarcity to abundance, as well as from hierarchy to collaboration and multi-actor partnerships. Managerial impacts include changing employee structures, engaging internal and external stakeholders, cultivating agile ways of working, establishing digital service centres, focusing on customer value, as well as developing new business models. Multi-actor multi-company collaboration models lead to ecosystems that are ruled by laws of organisational ecology [214]. Turunen et al. [201] investigate the impact of an enterprise's or industry sector's endogenous and exogenous environments on its capability of moving towards servitization, as well as on the ways of doing so successfully. They identified multiple influencing factors and proposed a conceptual framework for managerial decision-making.

Increasingly distributed IPS^2 systems imply increasingly distributed organisations, both during design and deployment. This, in turn, leads to a higher amount of parties and stakeholders involved in service provision, as well as interfaces in between them. The governance of such distributed organisations is a challenge, as are the skill needs of individuals. While highly specialized qualifications are required more than ever to master technology challenges, transversal, interdisciplinary skills have become indispensable for countless roles in the design process to understand and solve IPS^2 design challenges. Another particular organizational difficulty is implied by the fact that an increasing amount of evolving IPS^2 ecosystems span across several industry sectors, which differ not only in qualifications and cultures, but also in regulations, standards and legal requirement and constraints. All these factors particularly challenge Conway's law saying that design solutions always reflect their underlying design organisations [33].

6. Synthesis and recommendations

This section summarises the main findings to draw what are the main challenges in the design of IPS^2 of the future (6.1), taking the mobility case as an example to show the complexity and the main changes for designers (6.2). Then a framework for the design of IPS^2 is proposed (6.3). Finally, recommendations are drawn to contribute to future research in design methodologies (6.4).

6.1 Synthesis after sections 3, 4 and 5

Sections 3 and 4 analysed the current situation in industry and literature respectively, regarding both IPS^2 and its development process. Section 5 highlighted the on-going and potential evolutions of IPS^2 from digital applications 4.0. A first global conclusion is that both industry and academia emphasized the urgent need for convergence and guidance tools and methods to help designers to be coherent and efficient, and pointed out the increasing importance of interdisciplinarity and digital technologies. It is important to notice that this starting conclusion from IPS^2 perspective is very similar to the Design Society's visionary report [68] recently published regarding product development in 2040. This section merges the findings of our study in a global view that help clarify the next ten years. It is assumed that politicians (section 1), industrialists (section 3), scientists (section 4), and people (section 5) came to a consensus to share a vision that we propose in 5 points (6.1.1-6.1.5).

6.1.1 Design is the core means to create value in the long term

It is claimed that design and manufacturing are back at the forefront to (re)shape the future we desire, both for society and industry. Manufacturing industries are responsible for designing for a shared goal, for something that makes sense for the customer, the collaborator and the society and secures environmental, social and economic sustainability for future generations. PSS has great capabilities to implement responsible consumption and production (SDG 12), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9) [221].

The first point concludes that designing IPS^2 needs to support the understanding of the context of the new developments and consider values as core, whether customers or industrial collaborators.

6.1.2 The solutions of the future

In this perspective, value creation solutions call for new design and engineering processes and systems. Customized products and services enable those high quality and sustainable solutions to meet end-user satisfaction and manufacturing outcomes. Products within IPS^2 will be more connected, shared, servitized, and intangible. They will involve much greater integration between mechanical parts, software and human interfaces. Highly personalized and complex products and services are already common practice in most of sectors but scale-up is expected.

The second point highlights that the systemic nature of the IPS^2 design process stays its main characteristic, the system embedding more various stakeholders than before.

6.1.3 IPS^2, innovation and the industry transformation

Two kinds of PSS will cover most of the design activities. First, they are production systems-oriented and enable responsible and personalized manufacturing. Second, they are high value systems-oriented and support the sustainability of the main development goals such as health, mobility and energy. Service innovation will be one of the main drivers to develop such systems. This transformation is possible because of the initial excellence of the manufacturing industry that enables it to be the leader in manufacturing technologies, the new-comer in digital technologies and the manager of complexity at the same time. It is also due to the great capacity of PSS to put manufacturing at the forefront of environmental and social challenges such as circular economy, decent work practices and resource efficiency.

As a third point, it is claimed that innovation is more and more central to designing IPS^2 and for that, understanding the whole context and the world evolution is crucial.

6.1.4 IPS^2 and value creation ecosystems

While the term "industrial product-service-system" will undoubtedly remain relevant, it will probably no longer reflect sufficiently well the ongoing ever more profound interweaving of products, services, and industries. It also does not explicitly reflect the strong need for orientation towards sustainability and collaborative and digitalized eco-systems. It is evident that in such digitally enabled hyper-connected ecosystems, the traditional supply chains will be transformed into complex supply networks, within which secured data related to the provenance, authenticity, and traceability of any parts and components will be available. These can contribute to the fidelity and transparency of life cycles, their environmental and social impacts, as well as associated revenue models. Moreover, many PSS are implemented using existing infrastructures or assets from which the designer has no influence. The border of the system to design is part of the design process. It is proposed that the notion of *value creation ecosystems* (VCE) can integrate IPS^2 of the future.

The fourth point focuses on innovative and digitalized IPS^2 that are very dynamic while the eco-system continuously evolves. Workers and customers are fully part of the evolving ecosystem calling for a value-centric design approach.

6.1.5 Digitalized design processes

Let us remind that, how promising new technology may be, it is only useful when it makes sense with the business and if we know how to design and integrate technology into innovative working products and solutions. Smart technologies can adapt to users (and differently to every user), and assist people including workers while respecting privacy. It is expected to have complementarity between humans and technology in achieving modern manufacturing and the ways of designing are evolving dramatically to meet the new nature of design problems. Consequently, models, tools and methods to aid designers will be partly different, envisioned as more digital and driven by modelling and simulation of behaviours, covering the whole set of lifecycles. Designing PSS comes to be the dominant activity of design. A second property of the design of the future is its human-centric approach. Users and employees co-design. Human knowledge and skills drive smart solutions and interaction with technologies are common manners. Simulations embed behaviours explored and validated with end users. Very new work practices are being designed. The Design Society report [68] insists on the new emerging technologies such as digitalization, analytics, rapid manufacturing and quantum computing for engineers to work in interdisciplinary teams, including data scientists.

The last point is to recall that IPS^2 design still needs science to lean on for decision makings due to its various disciplines and the complex network of interactions among them that influence design decisions.

6.2 Proposed framework for the design of IPS^2

Based on literature review and industrial feedback, the authors have developed a common framework to design for IPS^2 (Figure 6). Its aim is to offer a comprehensive illustration of the different ingredients to optimize the design for IPS^2. This ultimately will lead to the optimization of value, cost, environmental impact and social outcomes. In the context of IPS^2, this refers to keeping assets working better, for longer, more economically. Its main features include: it is value-driven in each phase of the life cycle; it offers the ability to balance dynamic demand and supply by good planning; it considers the role of all stakeholders across the supply chain. It consists of five main dimensions: Strategic IPS^2 targets setting (figure item 0 and based on Sections 3.1, 4.1 and 5.1); operational IPS^2 targets definition for product and service life-cycle (figure item 1 and based on Sections 3.2, 4.2 and 5.2); life cycle resources and constraint identification (figure item 2 and based on Sections 3.3, 4.2 and 5.3); design methods specification (figure item 3 and based on Sections 4.3 and 5.4-5.7); and design methods execution for optimized value outcomes (figure item 4 and based on Sections 4.3 and 5.7).

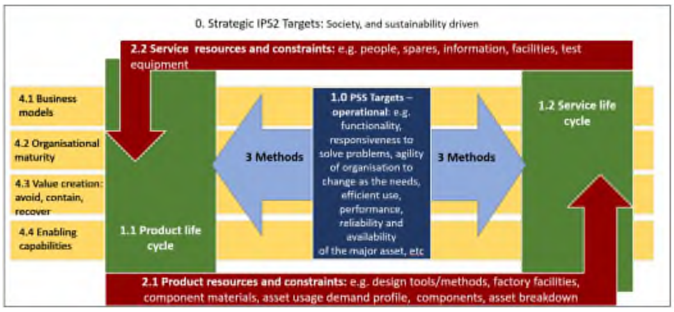

Figure 6: A common framework for integrated design in IPS^2

Strategic IPS^2 targets setting: this is a fundamental step that focuses on defining strategic targets and requirements that may comprise commercial, societal, and sustainability-driven outcomes among others (Sections 3.4 and 4.2). At this point, it is essential to identify realistic and achievable targets that will enable continuity in the IPS^2 outcomes in the long term in collaboration with value network stakeholders (Section 3.3.2).

Operational IPS^2 targets definition for product and service lifecycle: this focuses on translating the strategic targets into operational objectives, which are actionable in terms of clear requirements set out across the product and service lifecycles (Sections 3.3). Depending on the type of IPS² solution, the requirements will vary, which will promote product or service centricity or integrated product-service oriented design methods (Section 4.2). These targets may be driven by various factors such as product functionality, reliability, agility in response, and availability type requirements among other factors (Section 4.2.3).

Life cycle resources and constraint identification: each organization across the supply network operates under certain available resources and wider constraints that govern the ability to design, deliver, and terminate IPS² solutions (Section 3.1). It is critical to fully comprehend these, as it will enable to select and apply the most suitable design methods to achieve the required value creating IPS² solutions (Sections 4.2 and 5.2).

Design methods specification: this considers design methods in a holistic manner to facilitate better decision making in an agile manner across the value network and the asset' life cycle (Section 3.3.2). It should not only consider appropriate selection of individual design methods (Section 4.3), but it also requires consideration of ever-growing challenges in interoperability across design methods and associated software platforms (Section 5.1).

Design methods execution for optimised value outcomes: there are numerous key decisions that are needed whether it be commercially or technically driven to enable continuous value creation in IPS² solutions (Sections 3.1 and 4.1). Here, the focus is on applying the prescribed design methods to bring numerous decisional guidance together rather than taking an isolated approach (Sections 3.3, 4.2 and 5.2). Accordingly, four main areas to implement design methods are proposed: 1) business models, which require suitable methods to identify the commercial models that are available (Sections 3.1 and 4.2.2), and to select the most appropriate for the IPS² context; 2) organizational maturity, which requires the organization (Section 4.2.2) and the associated supply network (Section 4.3.2) to design the best means to improve its organizational maturity in the delivery of IPS² solutions (Section 4.3.3); 3) value creation, which requires design methods to define the value creation opportunities (Sections 3.2 and 4.3.1), and to continuously enable their delivery over the life-cycle (Section 4.2.3); and 4) enabling capabilities, which are focusing on applying design methods to enable the continuous availability of the best processes, skills, and technologies across the supply network to meet the requirements of the IPS² design and delivery (Sections 4.2.3 and 5.3-5.7).

6.3 Recommendations to research on future IPS² design

6.3.1 IPS² challenges in value creation ecosystems

Figure 7 attempts to illustrate some key challenges implied in IPS² design, based on the MaaS (Mobility as a Service) case investigated in [207] that provides a showcase example of the various interlinked and interdisciplinary challenges the design of modern IPS² is confronted with. The horizontal layers symbolize different industry sectors, each made up of domains of products (e.g. the transport sector in the second layer from the bottom is made up of domains like passenger cars, trucks, busses, trains, etc.). PSS in this sector are directly used by End Users, who are visualized in the lowest layer of the figure. Value-adding use cases demanding specific means of transport are defined on this bottom-most level, on which the actual user-perceived value is created. E.g. the shopping use-case illustrated by a dark red line could necessitate a public means of transport like a car (i.e., devices in the IoT terminology) provided by a car-sharing service. The car-sharing access infrastructure is an IPS² that is enabled by infrastructures providing energy and internet. Rooting the design activities in the very use cases rather than the product functions/features implies

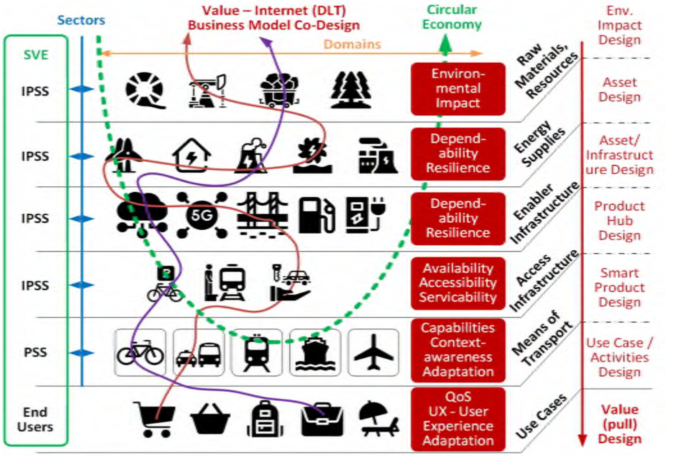

Figure 7: IPS² challenges in Value Creation Ecosystems (Case of mobility)

considering the requirements all along the service provision chain, up to the raw material extraction (or re-use). Each layer has specific design focus challenges, as indicated in the red boxes on the right-hand side of each layer. This "value-pull" design approach requires design and collaboration systematics different from those we know from the traditional "product-push" approach.

6.3.2 Research requirements for future IPS² design

The main result that should guide research orientations on future IPS² is the evolving nature of IPS² design problems (Table 2). Following the conclusions drawn in section 6.1, five main domains of IPS² designing that need further research are highlighted. Two of them (science-based, systemic) have already developed tools and methodologies since 2010 and should deepen their knowledge to support the wider IPS² dimensions. The three others (value-centric, context-aware, dynamic) have to be developed because they become more and more central to IPS² development and need to be supported and structured as their own. 13 action plans (for example, link data science and engineering design) are associated with the domains to highlight the scientific direction due. They relate to the findings in the different sections of the paper. Finally, for each action plan, there is a list of potential research projects, more or less concrete. It is not an exhaustive list but based on the authors' views.

Science-based design (from conclusion 6.1.5): the highest robustness of the solution is fundamental to support the offer quality. In IPS² solutions, technology is embedded in smart products connected to assist high-level decision functions. Main new scientific knowledge is asked for linking data science and engineering design; aligning models and current situations to control the offer through digital twins; enhancing the scientific understanding of IPS² design, verification and validation.

Systemic design (from conclusion 6.1.2): In nature, PSS is a system of systems and its design needs a holistic perspective. The main new focus is on the design implications of every relationship among the contributors to the system. It asks for developing inclusive methods and interconnected models; consolidating model-based system engineering (MBSE); aligning organisations and design activities.

Value-centric design (from conclusions 6.1.1 and 6.1.4): user satisfaction is the main driver of the design process. The consumption and production modes that prevailed so far are severely challenged. It takes use-cases as starting points of the design process, not forgetting the sustainable development goals and resource-constrained world. Tacit aspects should be clarified. New scientific directions are to develop science to consider user satisfaction throughout design; investigate the complementarity of human

Table 2: Recommendations for IPS² research

DOMAINS	ACTIONS PLAN	LIST OF POTENTIAL RESEARCH PROJECTS
Science-based design (Section 4.3.8, Table 1 – columns 1 & 2)	Link data science and engineering design (Sections 3.4, 5.3, 5.5)	Elicitation and management of the critical parameters to monitor the solutions to improve quality and reliability
		Global optimization method of the quality of service on the long-term perspective
		Models of joint work of human beings and smart products
	Align models and current situations to control the offer through digital twins (Sections 4.2, 5.6)	Revisited lifecycle engineering methods based on operating and reusing concerns
		Digital twin design methods
	Enhance the scientific understanding of IPS² design, verification and validation (Sections 3.4, 5.2,)	Documentation and characterization of PSS designing and validating at the levels of individual designers and organizations (more transparent)
		Measurement and analysis of the effects of PSS design and validation methods to compare design methods
Systemic design (Section 4.3.8, Table 1 – columns 1 & 2)	Develop inclusive methods and interconnected models (Section 5.1)	Development of inclusive methods of design to merge different disciplines within decision-making meetings and performance indicators
		Meta-model of interconnection of models for their safe and correct exploitation (variety of disciplines, different levels of details, coherent connection)
	Consolidate model-based system engineering (Section 4.2.1)	Adapt MBSE to IPS²
	Align organizations and design activities (Sections 3.4, 5.8)	Development of a transfer design method from provider A to provider B (should be outspoken and researched)
		Influences between design activities and organizations, in particular the interlinked stakeholder relationships all along the lifecycle
Value-centric design (Section 4.3.8, Table 1 – column 3)	Develop science to consider user satisfaction throughout designing (Section 4.3)	Methods and models to support rigorous human factor process, including integration of user experience
		User-centered design and design for usability renewed and supported
		Making explicit user behavior and link to user satisfaction and provider behavior partly enabled by services from user behavior
		Mechanisms for feedback from the customer and better in-formation flow back in to design
	Investigate the complementarity of human knowledge and technology (Sections 5.1, 5.2)	Human skills complemented by artificial intelligence solutions
		Interaction of Human with AI, robot, digital twin, VR/AR to achieve the performance in manufacturing
	Design new work organization and workplaces (Section 3.4)	Design work organization among all the IPS² stakeholders
		Design of the IPS² design studio
Context-aware design (Section 4.3.8, Table 1 – column 5)	Develop methods for innovation in services (Sections 4.2, 5.4)	Impact on product design of innovations in service, including privacy and cybersecurity
		Design of data collection and exploitation in an IPS² context
		Personalization of service and optimization of the quality of the individualized service rendered
		Multi-layer cybersecurity, multi-domain standards and legal requirements for IPS²
	Enable new consumption and production patterns - SDG 12 (Section 3.4)	Innovative production systems due by engineers to society
		Social sustainability of IPS²
	Model all the interactions among design problem perspectives and solution spaces (Section 4.2)	Modelling of the contexts within the problem space for services and products under design
		Digitalization of the problem space to better inform designers
Dynamic design (Section 4.3.8, Table 1 – columns 5 & 6)	Follow user experience (Sections 3.4, 5.2)	Design for capabilities, design of solutions patterns, design method to balance functions between automation and do-it-yourself perspectives for personalized solutions
		Design of frequently evolving and flexible contracts
		Co-evolution of IPS² design with user experience, with product technology and with competence value chain
	Design in a fuzzy system border and negotiate the border (Section 4.3.6)	Design methods to define and negotiate the border of the IPS² system under study
		New methods to incorporate continuous requirement engineering with strong uncertainties
	Design the most desired future (every section)	Method to follow user's demand and technology emergence
		Design IPS² on living infrastructures (new road, 5G standard, etc.)

knowledge and technology; design new work organization and workplaces.

Context-aware design (from conclusions 6.1.1 and 6.1.3): IPS² are shaped in ecosystems that influence their design and implementation. Ecosystems themselves are shaped by the values that companies and society target. Engineering support has to develop for that and should develop methods for innovation in services; focus on solutions that enable new consumption and production patterns (SDG 12); model all the interactions among design problem perspectives and solution spaces.

Dynamic design (from conclusion 6.1.4): the resulting design is only for short term since solutions evolve and adapt continuously due to customer wishes, the value chain reorganization or external decisions. New methods are needed to integer new viewpoints in design. The objective is to follow user experiences of both customers and value partners; design in a fuzzy system border, including decisions. New methods are needed to integer new viewpoints in design. The objective is to follow user experiences of both customers and value partners; design in a fuzzy system border, including negotiate the border; design the most desired future.

Research should also focus on new soft skills of designers and organisational issues:

Innovative conflict resolution. PSS designers are, thanks to their enlarged design spaces, given opportunities to make innovative solutions that are impossible solely by product design or service design. Trade-off management, including conflict identification, is the basis for many decision makings, which may lead to innovative conflict resolution in PSS design. Trade-offs can be observed with high-level functions that structure the PSS offer (Table 1, column 1): balance of human centred and optimized/intelligent functions within the PSS; choice of differentiating and standardized items within PSS offer; antagonism between value sharing within the value chain and profit for companies and environmental impacts.

Transformed soft skills of designers. Designers are expected to see the world differently and make it happen much more than before guiding by their essence in thinking business and value for the customer. Designers must accept ambiguity and room of manoeuvre. As engineers used to be rigorous humans mastering uncertainties (Table 1, column 6), the change in mind mood is very significant when now they must accept not to know at a critical moment. Strong digital and data analytics skills are expected for designers and engineers.

An agile organisation of the design team. Due to the structuring decision that occurs during the design process, and not at the beginning, the team composed of M-shaped skills, will evolve continuously and needs a kind of "self-organize altogether" for their collective work and for their trans-sectorial interactions as well (Table 1, columns 2, 4).

7 Concluding remarks

This paper presents a discussion of designing value-driven solutions for a sustainable society, focusing on the design of industrial product-service systems (IPS^2). Product-service systems have a great potential for aligning economy, social and environmental objectives together. For this reason, there are already good successes in industry and lots of academic literature. The CIRP community was very active and published the first keynote on IPS^2 in 2010 [125], two keynotes in 2009 and 2018 on value creation mechanisms [71,215] and a keynote on smart products in 2019 [207]. This keynote builds on this initial work to understand the state of the art in the design of value-driven solutions and draw recommendations from them. To conclude, we want to highlight the following particular points:

(1) In 2022, we are still far from the forecasts made in the 2010 keynote. We can say that the overall progress is much slower than expected and that there are no specific outstanding lines of R&I that turned out to meeting a dead-end. From our perspective, the main reason for this is that design objects, and appropriate design processes, are complex and heavily depend on contexts. Therefore, the standardization forecasted is very hard to achieve.

(2) The literature review provides many context-specific cases, and the generalization is still to be made. It is the main weakness of PSS design research so far.

(3) At present, there are huge expectations in the ongoing digitalization of industry to leverage PSS. We observe that this has indeed been happening for PSS offers, however much less for PSS design methods and processes.

Finally, we would like to emphasize the main future perspective drawn in our work: as today, industry suffers from a lack of knowledge support when facing design challenges with value cocreation ecosystems, we call for *establishing a design theory for value cocreation ecosystems*.

Design theory is based on domains of knowledge that relate together in a structured way. It started with the assumption of quasi-independence of the domains, only weakly connected to neighbouring domains. Those loose connections could be addressed by local solutions. Then, these interconnections have got increasingly strong. This was addressed by axioms and systematic considerations (in particular, priorities). In the new era of PSS, the nature of domains has grown multiple and various. Consequently, it is now complicated to consider domains and interactions. Instead, a new theory that *puts domain interactions and interconnections at the core* should be established. We consider that this theory should follow the many PSS design considerations and cases that have been brought up both in research and industry contexts. We hope that this paper will help address this important need. Relaunching a conference dedicated to PSS design would also make it possible to bring together ideas and proposals on how to tackle this interdisciplinary challenge.

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References

[1] M. Abramovici, J.C. Göbel, H.B. Dang, Semantic data management for the development and continuous reconfiguration of smart products and systems, CIRP Annals - Manufacturing Technology. 65 (2016) 185–188.
[2] F. Akasaka, Y. Nemoto, K. Kimita, Y. Shimomura, Development of a knowledge-based design support system for Product-Service Systems, Computers in Industry. 63 (2012) 309–318.
[3] K. Alexopoulos, S. Koukas, N. Boli, D. Mourtzis, Architecture and development of an Industrial Internet of Things framework for realizing services in Industrial Product Service Systems, in: Procedia CIRP, Elsevier B.V., 2018: pp. 880–885.
[4] R. Allais, J. Gobert, A multidisciplinary method for sustainability assessment of PSS: Challenges and developments, CIRP Journal of Manufacturing Science and Technology. 15 (2016) 56–64.
[5] J. Amaya, A. Lelah, P. Zwolinski, Design for intensified use in product–service systems using life-cycle analysis, Journal of Engineering Design. 25 (2014) 280–302.
[6] H. Andriankaja, X. Boucher, K. Medini, H. Vaillant, A Framework to Design Integrated Product-Service Systems Based on the Extended Functional Analysis Approach, Procedia CIRP. 47 (2016) 323–328.
[7] M. Antikainen, T. Uusitalo, P. Kivikytö-Reponen, Digitalisation as an Enabler of Circular Economy, in: Procedia CIRP, Elsevier B.V., 2018: pp. 45–49.
[8] M. Ardolino, M. Rapaccini, N. Saccani, P. Gaiardelli, G. Crespi, C. Ruggeri, The role of digital technologies for the service transformation of industrial companies, International Journal of Production Research. 56 (2018) 2116–2132.
[9] E. Armengaud, C. Sams, G. von Falck, G. List, C. Kreiner, A. Riel, Industry 4.0 as Digitalization over the Entire Product Lifecycle: Opportunities in the Automotive Domain, in: J. Stolfa, S. Stolfa, R. v O'Connor, R. Messnarz (Eds.), Systems, Software and Services Process Improvement, Springer International Publishing, Cham, 2017: pp. 334–351.
[10] J.C. Aurich, C. Mannweiler, E. Schweitzer, How to design and offer services successfully, CIRP Journal of Manufacturing Science and Technology. 2 (2010) 136–143.
[11] T.S. Baines, A.Z. Bigdeli, O.F. Bustinza, K. Ridgway, Servitization: Revisiting the State-of-the-art and Research Priorities, International Journal of Operations & Production Management. 37 (2017) 256–278.
[12] L. Batista, S. Davis-Poynter, I. Ng, R. Maull, Servitization through outcome-based contract – A systems perspective from the defence industry, International Journal of Production Economics. 192 (2017) 133–143.
[13] F. Belkadi, N. Boli, L. Usatorre, E. Maleki, K. Alexopoulos, A. Bernard, D. Mourtzis, A knowledge-based collaborative platform for PSS design and production, CIRP Journal of Manufacturing Science and Technology. 29 (2020) 220–231.
[14] A. Bertoni, M. Bertoni, Modeling 'ilities' in early Product-Service Systems design, Procedia CIRP. 83 (2019) 230–235.
[15] A. Bertoni, M. Bertoni, PSS cost engineering: A model-based approach for concept design, CIRP Journal of Manufacturing Science and Technology. 29 (2020) 176–190.
[16] A. Bertoni, M. Bertoni, M. Panarotto, C. Johansson, T.C. Larsson, Value-driven product service systems development: Methods and industrial applications, CIRP Journal of Manufacturing Science and Technology. 15 (2016) 42–55.
[17] M. Bertoni, A. Rondini, G. Pezzotta, A Systematic Review of Value Metrics for PSS Design, Procedia CIRP. 64 (2017) 289–294.
[18] T. Blüher, T. Riedelsheimer, S. Gogineni, A. Klemichen, R. Stark, Systematic Literature Review—Effects of PSS on Sustainability Based on Use Case Assessments, Sustainability. 12 (2020) 6989.
[19] X. Boucher, K. Medini, H. Vaillant, PS3M: Integrative Modelling Environment to support PSS design, in: Procedia CIRP, Elsevier B.V., 2018: pp. 73–78.
[20] S. Brad, M. Murar, Employing smart units and servitization towards reconfigurability of manufacturing processes, in: Procedia CIRP, Elsevier B.V., 2015: pp. 498–503.
[21] S.A. Brambila-Macias, T. Sakao, C. Kowalkowski, Bridging the gap between engineering design and marketing: Insights for research and practice in product/service system design, Design Science. 4 (2018) 1–61.
[22] British Standards Institution, Innovate UK, Through-life engineering services: adding business value through a common framework: guide., PAS 280:2018, BSI, 2018.
[23] V. Car, Care by Volvo - The all-inclusive car subscription from Volvo, (2021).
[24] K.F. de Castro Rodrigues, V. Nappi, H. Rozenfeld, A proposal to support the value proposition in product-oriented service business model of product service systems, in: Procedia CIRP, Elsevier, 2014: pp. 211–216.
[25] J. Cenamor, D. Rönnberg Sjödin, V. Parida, Adopting a platform approach in servitization: Leveraging the value of digitalization, International Journal of Production Economics. 192 (2017) 54–65.
[26] D. Chang, Z. Gu, F. Li, R. Jiang, A user-centric smart product-service system development approach: A case study on medication management for the elderly, Advanced Engineering Informatics. 42 (2019) 100979.
[27] S. Chatti, L. Laperrière, G. Reinhart, T. Tolio, CIRP Encyclopedia of Production Engineering, Springer Berlin Heidelberg, Berlin, Heidelberg, 2019.
[28] J.L. Chen, W.-S. Jiao, TRIZ Innovative Design Method for Eco-leasing Type Product Service Systems, Procedia CIRP. 15 (2014) 391–394.
[29] Z. Chen, M. Lu, X. Ming, X. Zhang, T. Zhou, Explore and evaluate innovative value propositions for smart product service system: A novel graphics-based rough-fuzzy DEMATEL method, Journal of Cleaner Production. 243 (2020).

[30] S. Chowdhury, D. Haftor, N. Pashkevich, Smart Product-Service Systems (Smart PSS) in Industrial Firms: A Literature Review, in: Procedia CIRP, Elsevier B.V., 2018: pp. 26–31.
[31] R.J. Clayton, C.J. Backhouse, S. Dani, Evaluating existing approaches to product-service system design: A comparison with industrial practice, Journal of Manufacturing Technology Management. 23 (2012) 272–298.
[32] J. Cong, C.-H. Chen, P. Zheng, X. Li, Z. Wang, A holistic relook at engineering design methodologies for smart product-service systems development, Journal of Cleaner Production. 272 (2020) 122737.
[33] M.E. Conway, How do committees invent?, Datamation. 14 (1968) 28–31.
[34] F. daCosta, Rethinking the Internet of Things, APress, 2013.
[35] P.P. Datta, R. Roy, Cost modelling techniques for availability type service support contracts: A literature review and empirical study, CIRP Journal of Manufacturing Science and Technology. 3 (2010) 142–157.
[36] U. Dombrowski, C. Engel, Impact of electric mobility on the after sales service in the automotive industry, in: Procedia CIRP, Elsevier, 2014: pp. 152–157.
[37] T.M. Dorka, H.B. Dang, H. Meier, M. Abramovici, Interaction within dynamic IPS2 networks - A proposal of an IPS2 Lifecycle Management and IPS2 delivery management architecture, in: Procedia CIRP, Elsevier, 2014: pp. 146–151.
[38] T. Dorka, F. Morlock, H. Meier, Data interfaces of IPS2-Execution Systems - Connecting virtual organization units for the delivery management of IPS2, in: Procedia CIRP, Elsevier, 2014: pp. 373–378.
[39] N. Dubruc, S. Peillon, A. Farah, The impact of servitization on corporate culture, in: Procedia CIRP, Elsevier, 2014: pp. 289–294.
[40] C. Durugbo, J.A. Erkoyuncu, Managing integrated information flow for industrial service partnerships: A case study of aerospace firms, in: Procedia CIRP, Elsevier, 2014: pp. 338–343.
[41] B. Eisenbart, K. Gericke, L.T.M. Blessing, Taking a look at the utilisation of function models in interdisciplinary design: insights from ten engineering companies, Research in Engineering Design. 28 (2017) 299–331.
[42] S.W. Elfving, M. Lindahl, E. Sundin, Ericsson - The history from product to solution provider and challenges and opportunities in an evolving environment, in: Procedia CIRP, Elsevier B.V., 2015: pp. 239–244.
[43] J.A. Erkoyuncu, I.F. del Amo, D. Ariansyah, D. Bulka, R. Vrabič, R. Roy, A design framework for adaptive digital twins, CIRP Annals. 69 (2020) 145–148.
[44] J.A. Erkoyuncu, R. Roy, E. Shehab, C. Durugbo, S. Khan, P. Datta, An effective uncertainty based framework for sustainable industrial product-service system transformation, Journal of Cleaner Production. 208 (2019) 160–177.
[45] L.R. Estebanez, E. Shehab, P. Sydor, T. MacKley, P. John, A. Harrison, Enhancing service requirements of technical product-service systems, in: Procedia CIRP, Elsevier B.V., 2015: pp. 7–11.
[46] K. Exner, K. Lindow, C. Buchholz, R. Stark, Validation of Product-Service Systems – A Prototyping Approach, Procedia CIRP. 16 (2014) 68–73.
[47] K. Exner, R. Stark, J.Y. Kim, R. Stark, Data-driven business model a methodology to develop smart services, in: 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC), 2017: pp. 146–154.
[48] M. Fargnoli, N. Haber, T. Sakao, PSS modularisation: a customer-driven integrated approach, International Journal of Production Research. 57 (2019) 4061–4077.
[49] M. Farsi, J.A. Erkoyuncu, An agent-based approach to quantify the uncertainty in Product-Service System contract decisions: A case study in the machine tool industry, International Journal of Production Economics. 233 (2021) 108014.
[50] M. Freitag, P. Westner, C. Schiller, M.J. Nunez, F. Gigante, S. Berbegal, Agile Product-Service Design with VR-technology: A use case in the furniture industry, in: Procedia CIRP, Elsevier B.V., 2018: pp. 114–119.
[51] J. Gesing, K. Maiwald, J. Wieseke, R. Sturm, Are IPS2 always a solution? Obstacles towards buying industrial product service systems, in: Procedia CIRP, Elsevier, 2014: pp. 265–270.
[52] M. Goedkoop, C. van Halen, H. te Riele, P. Rommes, Product Service Systems, in: Ecological and Economic Basis, 1999: p. 36.
[53] L. Grandjean, S. Alevifard, M. Steven, Strategic adaptability of industrial product-service-systems - Dynamic effective IPS2, in: Procedia CIRP, Elsevier, 2014: pp. 314–319.
[54] T. Grubic, Servitization and remote monitoring technology: A literature review and research agenda, Journal of Manufacturing Technology Management. 25 (2014) 100–124.
[55] T. Grubic, Remote monitoring technology and servitization: Exploring the relationship, Computers in Industry. 100 (2018) 148–158.
[56] T. Guidat, A.P. Barquet, H. Widera, H. Rozenfeld, G. Seliger, Guidelines for the definition of innovative industrial product-service systems (PSS) business models for remanufacturing, in: Procedia CIRP, Elsevier, 2014: pp. 193–198.
[57] N. Haber, M. Fargnoli, T. Sakao, Integrating QFD for product-service systems with the Kano model and fuzzy AHP, Total Quality Management and Business Excellence. 31 (2020) 929–954.
[58] T. Hara, Integrating usage information into quality function deployment for further PSS development, Procedia CIRP. 73 (2018) 21–25.
[59] T. Hara, T. Sakao, R. Fukushima, Customization of product, service, and product/service system: what and how to design, Mechanical Engineering Reviews. 6 (2019) 18-00184-18–00184.
[60] R. Harms, T. Fleschutz, G. Seliger, Life cycle management of production facilities using semantic web technologies, CIRP Annals - Manufacturing Technology. 59 (2010) 45–48.
[61] M.Z. Hauschild, S. Kara, I. Røpke, Absolute sustainability: Challenges to life cycle engineering, CIRP Annals. 69 (2020) 533–553.
[62] S. Hosono, Y. Shimomura, Asset-based Service Production under Uncertainty, Procedia CIRP. 16 (2014) 247–252.
[63] L. Hou, R.J. Jiao, Data-informed inverse design by product usage information: a review, framework and outlook, Journal of Intelligent Manufacturing. 31 (2020) 529–552.
[64] J. Huang, S. Li, M. Thürer, On the use of blockchain in industrial product service systems: A critical review and analysis, in: Procedia CIRP, Elsevier B.V., 2019: pp. 552–556.
[65] J. Huang, S. Li, M. Thürer, On the use of blockchain in industrial product service systems: A critical review and analysis, in: Procedia CIRP, Elsevier B.V., 2019: pp. 552–556.
[66] R. Hussain, H. Lockett, G.V. Annamalai Vasantha, A framework to inform PSS Conceptual Design by using system-in-use data, Computers in Industry. 63 (2012) 319–327.
[67] INCOSE, Systems Engineering Handbook, International Council on Systems Engineering, 2006.
[68] O. Isaksson, C. Eckert, Product Development 2040, 2020.
[69] H. Jacobson, A. Carlson, M. Lindahl, Legal, environmental and economic issues with functional sales – A case of indoor lighting, Journal of Cleaner Production. 298 (2021) 126713.
[70] D.G. Jansson, S.M. Smith, Design fixation, Des Stud. 12 (1991) 3–11.
[71] T. Kaihara, N. Nishino, K. Ueda, M. Tseng, J. Váncza, P. Schönsleben, R. Teti, T. Takenaka, Value creation in production: Reconsideration from interdisciplinary approaches, CIRP Annals. 67 (2018) 791–813.
[72] M.L. Kambanou, T. Sakao, Using life cycle costing (LCC) to select circular measures: a discussion and practical approach, Resources, Conservation and Recycling. 155 (2020).
[73] O. Karlsson, J. Kellgren, "The Bottom Calling the Top" — The Selling of Function (PSS) as a Business Model for Sustainability, in Need of Some Assistance from the Legislator, Florida Tax Review. (2020) 825–844.
[74] M.A. Khan, S. Mittal, S. West, T. Wuest, Review on upgradability – A product lifetime extension strategy in the context of product service systems, Journal of Cleaner Production. 204 (2018) 1154–1168.
[75] K. Kimita, S.A. Brambila-Macias, T. Sakao, A.-M. Tillman, Failure Analysis Method for Enhancing Circularity through Systems Perspective, Journal of Industrial Ecology. (2020).
[76] K. Kimita, T. Sakao, Y. Shimomura, A failure analysis method for designing highly reliable product-service systems, Research in Engineering Design. 29 (2018) 143–160.
[77] K. Kimita, Y. Shimomura, Development of the Design Guideline for Product-service Systems, Procedia CIRP. 16 (2014) 344–349.
[78] L.L. Kjaer, D.C.A. Pigosso, M. Niero, N.M. Bech, T.C. McAloone, Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?, Journal of Industrial Ecology. 23 (2019) 22–35.
[79] S. Kondoh, H. Komoto, Y. Kishita, S. Fukushige, Toward a sustainable business design: A survey, in: Procedia CIRP, Elsevier B.V., 2014: pp. 367–372.
[80] S. Kondoh, N. Mishima, Proposal of cause-effect pattern library for realizing sustainable businesses, CIRP Annals - Manufacturing Technology. 60 (2011) 33–36.
[81] C. Kowalkowski, What does a service-dominant logic really mean for manufacturing firms?, CIRP Journal of Manufacturing Science and Technology. 3 (2010) 285–292.
[82] P. Krenz, S. Basmer, S. Buxbaum-Conradi, T. Redlich, J.P. Wulfsberg, Knowledge management in value creation networks: Establishing a new business model through the role of a knowledge-intermediary, in: Procedia CIRP, Elsevier, 2014: pp. 38–43.
[83] B. Kuhlenkötter, U. Wilkens, M. Herzog, K. Lenkenhoff, A. Hypki, B. Bender, T. Süße, M. Abramovici, J. Göbel, New Perspectives for Generating Smart PSS Solutions - Life Cycle, Methodologies and Transformation, Procedia CIRP. 64 (2017).
[84] P. Kyösti, S. Reed, Prediction of service support costs for functional products, Simulation Modelling Practice and Theory. 59 (2015) 52–70.
[85] H. Lagemann, M. Boßlau, H. Meier, The influence of dynamic business models on IPS2 network planning - An agent-based simulation approach, in: Procedia CIRP, Elsevier B.V., 2015: pp. 102–107.
[86] H. Lagemann, T. Dorka, H. Meier, Evaluation of an IPS2 delivery planning approach in industry - Limitations and necessary adaptations, in: Procedia CIRP, Elsevier, 2014: pp. 187–192.
[87] B.D. Lee, C.J.J. Paredis, A conceptual framework for value-driven design and systems engineering, in: Procedia CIRP, Elsevier B.V., 2014: pp. 10–17.
[88] C.-H. Lee, C.-H. Chen, A.J.C. Trappey, A structural service innovation approach for designing smart product service systems: Case study of smart beauty service, Advanced Engineering Informatics. 40 (2019) 154–167.
[89] J. Lee, H. Davari, J. Singh, V. Pandhare, Industrial Artificial Intelligence for industry 4.0-based manufacturing systems, Manufacturing Letters. 18 (2018) 20–23.
[90] A. Leitão, P. Cunha, F. Valente, P. Marques, Roadmap for business models definition in manufacturing companies, in: Procedia CIRP, Elsevier B.V., 2013: pp. 383–388.
[91] A. Lelah, X. Boucher, V. Moreau, P. Zwolinski, Scenarios as a tool for transition towards sustainable PSS, in: Procedia CIRP, Elsevier, 2014: pp. 122–127.
[92] A. Lelah, F. Mathieux, D. Brissaud, L. Vincent, A Collaborative Network with SMEs Providing a Backbone for Urban PSS: A Model and Initial Sustainability, Planning Production & Control. 23 (2012) 299–314.
[93] J. Leng, Q. Liu, S. Ye, J. Jing, Y. Wang, C. Zhang, D. Zhang, X. Chen, Digital twin-driven rapid reconfiguration of the automated manufacturing system via an open architecture model, Robotics and Computer-Integrated Manufacturing. 63 (2020) 101895.

[94] J. Leng, D. Yan, Q. Liu, H. Zhang, G. Zhao, L. Wei, D. Zhang, A. Yu, X. Chen, Digital twin-driven joint optimisation of packing and storage assignment in large-scale automated high-rise warehouse product-service system, International Journal of Computer Integrated Manufacturing. 34 (2021) 783–800.
[95] C. Lerch, M. Gotsch, Digitalized product-service systems in manufacturing firms: A case study analysis, Research Technology Management. 58 (2015) 45–52.
[96] A.Q. Li, M. Kumar, B. Claes, P. Found, The state-of-the-art of the theory on Product-Service Systems, International Journal of Production Economics. 222 (2020) 107491.
[97] M. Lindahl, E. Sundin, T. Sakao, Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases, Journal of Cleaner Production. 64 (2014) 288–296.
[98] U. Lindemann, Systems Engineering versus Design Methodology, in: H. Birkhofer (Ed.), The Future of Design Methodology, Springer, London, 2011: pp. 157–167.
[99] J. Lindström, A. Dagman, M. Karlberg, Functional Products Lifecycle: Governed by sustainable Win-Win Situations, Procedia CIRP. 22 (2014) 163–168.
[100] J. Lindström, J. Eliasson, A. Hermansson, F. Blomstedt, P. Kyösti, Cybersecurity level in IPS^2: A case study of two industrial internet-based SME offerings, Procedia CIRP. 73 (2018) 222–227.
[101] J. Lindström, M. Karlberg, Outlining an overall Functional Product lifecycle – Combining and coordinating its economic and technical perspectives, CIRP Journal of Manufacturing Science and Technology. 17 (2017) 1–9.
[102] J. Lindström, M. Löfstrand, S. Reed, A. Alzghoul, Use of Cloud Services in Functional Products: Availability Implications, Procedia CIRP. 16 (2014) 368–372.
[103] S. Lingegård, N. Svensson, Scenarios for resource efficient rail infrastructure-Applying Integrated Product Service Offerings, in: Procedia CIRP, Elsevier, 2014: pp. 134–139.
[104] A. Liu, T. Wuest, W. Wei, S. Lu, Application of prospect theory on car sharing product service system, in: Procedia CIRP, Elsevier, 2014: pp. 350–355.
[105] B. Liu, Y. Zhang, G. Zhang, P. Zheng, Edge-cloud orchestration driven industrial smart product-service systems solution design based on CPS and IIoT, Advanced Engineering Informatics. 42 (2019).
[106] Z. Liu, X. Ming, S. Qiu, Y. Qu, X. Zhang, A framework with hybrid approach to analyse system requirements of smart PSS toward customer needs and co-creative value propositions, Computers and Industrial Engineering. 139 (2020).
[107] Z. Liu, X. Ming, W. Song, S. Qiu, Y. Qu, A perspective on value co-creation-oriented framework for smart product-service system, in: Procedia CIRP, Elsevier B.V., 2018: pp. 155–160.
[108] X. Li, Z. Wang, C.-H. Chen, P. Zheng, A data-driven reversible framework for achieving Sustainable Smart product-service systems, Journal of Cleaner Production. 279 (2021).
[109] M. Lodefalk, Servicification of manufacturing – evidence from Sweden, International Journal of Economics and Business Research. 6 (2013) 87–113.
[110] R.F. Lusch, S.L. Vargo, M. Tanniru, Service, value networks and learning, J Acad Mark Sci. 38 (2010) 19–31.
[111] F. Mahut, J. Daaboul, M. Bricogne, B. Eynard, Product-Service Systems for servitization of the automotive industry: a literature review, International Journal of Production Research. 55 (2017) 2102–2120.
[112] E. Maleki, F. Belkadi, A. Bernard, Industrial Product-Service System modelling base on Systems Engineering: Application of sensor integration to support smart services, IFAC-PapersOnLine. 51 (2018).
[113] E. Maleki, F. Belkadi, A. Bernard, A Meta-model for Product-Service System based on Systems Engineering approach, Procedia CIRP. 73 (2018) 39–44.
[114] E. Marilungo, E. Coscia, A. Quaglia, M. Peruzzini, M. Germani, Open Innovation for Ideating and Designing New Product Service Systems, Procedia CIRP. 47 (2016) 305–310.
[115] E. Marilungo, M. Peruzzini, M. Germani, An Integrated Method to Support PSS Design within the Virtual Enterprise, Procedia CIRP. 30 (2015) 54–59.
[116] T. Masood, J.A. Erkoyuncu, R. Roy, A. Harrison, Integrating design attributes, knowledge and uncertainty in aerospace sector, CIRP Journal of Manufacturing Science and Technology. 7 (2014) 83–96.
[117] T. Masood, R. Roy, A. Harrison, Y. Xu, S. Gregson, C. Reeve, Integrating through-life engineering service knowledge with product design and manufacture, International Journal of Computer Integrated Manufacturing. 28 (2015) 59–74.
[118] J. Matschewsky, M.L. Kambanou, T. Sakao, Designing and providing integrated productservice systems – challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies, International Journal of Production Research. 56 (2018) 2150–2168.
[119] J. Matschewsky, M. Lindahl, T. Sakao, Capturing and enhancing provider value in product-service systems throughout the lifecycle: A systematic approach, CIRP Journal of Manufacturing Science and Technology. (2018).
[120] A. McKay, S. Kundu, A representation scheme for digital product service system definitions, in: Advanced Engineering Informatics, Elsevier Ltd, 2014: pp. 479–498.
[121] K. Medini, X. Boucher, Configuration of Product-Service Systems value networks – Evidence from an innovative sector for sludge treatment, CIRP Journal of Manufacturing Science and Technology. 12 (2016) 14–24.
[122] K. Medini, X. Boucher, Specifying a modelling language for PSS Engineering – A development method and an operational tool, Computers in Industry. 108 (2019).
[123] H. Meier, H. Lagemann, F. Morlock, C. Rathmann, Key performance indicators for assessing the planning and delivery of industrial services, in: Procedia CIRP, Elsevier B.V., 2013: pp. 99–104.
[124] J. Meierhofer, S. West, M. Rapaccini, C. Barbieri, The Digital Twin as a Service Enabler: From the Service Ecosystem to the Simulation Model, in: M. and K.N. Nóvoa Henriqueta and Drăgoicea (Ed.), Exploring Service Science, Springer International Publishing, Cham, 2020: pp. 347–359.
[125] H. Meier, R. Roy, G. Seliger, Industrial Product-Service systems-IPS2, CIRP Annals - Manufacturing Technology. 59 (2010) 607–627.
[126] G. Mert, C. Bohr, S. Waltemode, J.C. Aurich, Increasing the resource efficiency of machine tools by life cycle-oriented services, in: Procedia CIRP, Elsevier B.V., 2014: pp. 176–181.
[127] D. Meuris, M. Herzog, B. Bender, T. Sadek, IT support in the fuzzy front end of Industrial Product Service design, in: Procedia CIRP, Elsevier, 2014: pp. 379–384.
[128] A. Michalik, F. Möller, M. Henke, B. Otto, Towards utilizing Customer Data for Business Model Innovation: The Case of a German Manufacturer, in: Procedia CIRP, Elsevier B.V., 2018: pp. 310–316.
[129] Y. Mitake, T. Yusuke, Y. Shimomura, A context asymmetry analysis method for successful PSS design, in: Procedia CIRP, Elsevier B.V., 2019: pp. 369–374.
[130] T. Mittag, M. Rabe, T. Gradert, A. Kühn, R. Dumitrescu, Building blocks for planning and implementation of smart services based on existing products, in: Procedia CIRP, Elsevier B.V., 2018: pp. 102–107.
[131] L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, K. Ueda, Cyber-physical systems in manufacturing, CIRP Annals. 65 (2016) 621–641.
[132] M. Mori, M. Fujishima, Sustainable service system for machine tools, in: Procedia CIRP, Elsevier B.V., 2013: pp. 8–14.
[133] F. Morlock, H. Meier, Service Value Stream Mapping in industrial product-service system Performance Management, in: Procedia CIRP, Elsevier B.V., 2015: pp. 457–461.
[134] D. Mourtzis, J. Angelopoulos, N. Boli, Maintenance assistance application of Engineering to Order manufacturing equipment: A Product Service System (PSS) approach, IFAC-PapersOnLine. 51 (2018) 217–222.
[135] D. Mourtzis, S. Fotia, E. Vlachou, Lean rules extraction methodology for lean PSS design via key performance indicators monitoring, Journal of Manufacturing Systems. 42 (2017) 233–243.
[136] D. Mourtzis, S. Fotia, E. Vlachou, A. Koutoupes, A Lean PSS design and evaluation framework supported by KPI monitoring and context sensitivity tools, International Journal of Advanced Manufacturing Technology. 94 (2018) 1623–1637.
[137] W. Mulder, R.J.I. Basten, J.M. Jauregui Becker, L.A.M. van Dongen, Work in progress: Developing tools that support the design of easily maintainable rolling stock, in: Procedia CIRP, Elsevier B.V., 2013: pp. 204–206.
[138] K. Muto, K. Kimita, Y. Shimomura, A Guideline for Product-Service-Systems Design Process, Procedia CIRP. 30 (2015) 60–65.
[139] Y. Nemoto, K. Uei, K. Sato, Y. Shimomura, A context-based requirements analysis method for PSS design, in: Procedia CIRP, Elsevier B.V., 2015: pp. 42–47.
[140] A. Neramballi, T. Sakao, S. Willskytt, A.-M. Tillman, A design navigator to guide the transition towards environmentally benign product/service systems based on LCA results, Journal of Cleaner Production. 277 (2020) 124074.
[141] E. Numata, S. Hosono, H. Sakaki, S. Izukura, K. Kimita, Y. Shimomura, Disciplines for Designing PSS Actor Network, Procedia CIRP. 30 (2015) 408–414.
[142] C. Okoh, R. Roy, J. Mehnen, L. Redding, Overview of Remaining Useful Life prediction techniques in Through-life Engineering Services, in: Procedia CIRP, Elsevier, 2014: pp. 158–163.
[143] M. Orellano, C. Lambey-Checchin, K. Medini, G. Neubert, Towards an integration of lifecycle thinking into PSS business models, Procedia CIRP. 73 (2018) 291–296.
[144] M. Orellano, K. Medini, C. Lambey-Checchin, G. Neubert, A system modelling approach to collaborative PSS design, Procedia CIRP. 83 (2019) 218–223.
[145] M. Paiola, H. Gebauer, Internet of things technologies, digital servitization and business model innovation in BtoB manufacturing firms, Industrial Marketing Management. 89 (2020) 245–264.
[146] R. Palmarini, J.A. Erkoyuncu, R. Roy, H. Torabmostaedi, A systematic review of augmented reality applications in maintenance, Robotics and Computer-Integrated Manufacturing. 49 (2018) 215–228.
[147] S. Pan, R.Y. Zhong, T. Qu, Smart product-service systems in interoperable logistics: Design and implementation prospects, Advanced Engineering Informatics. 42 (2019) 100996.
[148] V. Parida, D. Rönnberg-Sjödin, J. Wincet, H. Ylinenpää, Win-win collaboration, functional product challenges and value-chain delivery: A case study approach, in: Procedia CIRP, Elsevier B.V., 2013: pp. 86–91.
[149] T. Paschou, F. Adrodegari, M. Rapaccini, N. Saccani, M. Perona, Towards Service 4.0: A new framework and research priorities, in: Procedia CIRP, Elsevier B.V., 2018: pp. 148–154.
[150] T. Paschou, M. Rapaccini, F. Adrodegari, N. Saccani, Digital servitization in manufacturing: A systematic literature review and research agenda, Industrial Marketing Management. 89 (2020) 278–292.
[151] G. Pezzotta, F. Pirola, A. Rondini, R. Pinto, M.-Z. Ouertani, Towards a methodology to engineer industrial product-service system – Evidence from power and automation industry, CIRP Journal of Manufacturing Science and Technology. 15 (2016) 19–32.
[152] O. Pialot, D. Millet, J. Bisiaux, “Upgradable PSS”: Clarifying a new concept of sustainable consumption/production based on upgradablility, Journal of Cleaner Production. 141 (2017) 538–550.
[153] M.D.P. Pieroni, C.A.N. Marques, R.N. Moraes, H. Rozenfeld, A.R. Ometto, PSS Design Process Models: Are They Sustainability-oriented?, in: Procedia CIRP, Elsevier B.V., 2017: pp. 67–72.

[154] F. Pirola, X. Boucher, S. Wiesner, G. Pezzotta, Digital technologies in product-service systems: a literature review and a research agenda, Computers in Industry. 123 (2020) 103301.
[155] F. Pirola, G. Pezzotta, A. Rondini, Early-stage assessment of PSS concepts: a case study in automation industry, Procedia CIRP. 83 (2019) 236–241.
[156] G. Pogrebna, Servitization through Human-Data Interaction: A Behavioural Approach, in: Proceedings of the Spring Servitization Conference (SSC2015), 2015.
[157] M. Porter, J.E. Heppelmann, How Smart, Connected Products Are Transforming Companies, Harvard Business Review. (2015) 1510.
[158] M. Qu, S. Yu, D. Chen, J. Chu, B. Tian, State-of-the-art of design, evaluation, and operation methodologies in product service systems, Computers in Industry. 77 (2016) 1–14.
[159] W. Reim, V. Parida, J. Lindström, Risks for Functional Products – Empirical Insights from Two Swedish Manufacturing Companies, Procedia CIRP. 11 (2013) 340–345.
[160] W. Reim, V. Parida, D. Rönnberg Sjödin, Risk management for product-service system operation, International Journal of Operations & Production Management. 36 (2016) 665–686.
[161] C. Rennpferdt, D. Krause, TOWARDS A FRAMEWORK FOR THE DESIGN OF VARIETY-ORIENTED PRODUCT-SERVICE SYSTEMS, Proceedings of the Design Society: DESIGN Conference. 1 (2020) 1345–1354.
[162] A. Richter, T. Sadek, M. Steven, Flexibility in industrial product-service systems and use-oriented business models, CIRP Journal of Manufacturing Science and Technology. 3 (2010) 128–134.
[163] A. Riel, C. Kreiner, G. Macher, R. Messnarz, Integrated design for tackling safety and security challenges of smart products and digital manufacturing, CIRP Annals. 66 (2017) 177–180.
[164] A. Riel, C. Kreiner, R. Messnarz, A. Much, An architectural approach to the integration of safety and security requirements in smart products and systems design, CIRP Annals. 67 (2018) 173–176.
[165] Rolls-Royce, Rolls-Royce Holdings PLC Annual Report 2018, Rolls-Royce, London, 2019.
[166] A. Rondini, J. Matschewsky, G. Pezzotta, M. Bertoni, A simplified approach towards customer and provider value in PSS for small and medium-sized enterprises, Procedia CIRP. 73 (2018) 61–66.
[167] D. Rönnberg Sjödin, V. Parida, J. Wincent, Value co-creation process of integrated product-services: Effect of role ambiguities and relational coping strategies, Industrial Marketing Management. 56 (2016) 108–119.
[168] R. Roy, J. Mehnen, S. Addepalli, L. Redding, L. Tinsley, C. Okoh, Service knowledge capture and reuse, in: Procedia CIRP, Elsevier, 2014: pp. 9–14.
[169] R. Roy, R. Stark, K. Tracht, S. Takata, M. Mori, Continuous maintenance and the future – Foundations and technological challenges, CIRP Annals - Manufacturing Technology. 65 (2016) 667–688.
[170] A. Rymaszewska, P. Helo, A. Gunasekaran, IoT powered servitization of manufacturing – an exploratory case study, International Journal of Production Economics. 192 (2017) 92–105.
[171] J. Saito, Y. Kurita, K. Kimita, Y. Shimomura, A Method for Analyzing Service Failure Factors based on Multiple Perspectives, Procedia CIRP. 16 (2014) 235–240.
[172] T. Sakao, What is PSS design? – Explained with two industrial cases, Procedia - Social and Behavioral Sciences. 25 (2011) 403–407.
[173] T. Sakao, J. Gero, H. Mizuyama, Analyzing cognitive processes of a product/service-system design session using protocol analysis, Artificial Intelligence for Engineering Design, Analysis and Manufacturing. 34 (2020) 515–530.
[174] T. Sakao, T. Hara, R. Fukushima, Using product/service-system family design for efficient customization with lean principles: Model, method, and tool, Applied Sciences (Switzerland). 12 (2020) 1–25.
[175] T. Sakao, M. Lindahl, A value-based evaluation method for Product/Service System using design information, CIRP Annals - Manufacturing Technology. 61 (2012) 51–54.
[176] T. Sakao, M. Lindahl, A method to improve integrated product service offerings based on life cycle costing, CIRP Annals - Manufacturing Technology. 64 (2015) 33–36.
[177] T. Sakao, A. Neramballi, A Product/Service System Design Schema: Application to Big Data Analytics, Sustainability. 12 (2020) 3484.
[178] T. Sakao, A. Neramballi, A Product/Service System Design Schema: Application to Big Data Analytics, Sustainability. 12 (2020) 3484.
[179] T. Sakao, A.K. Nordholm, Requirements for a Product Lifecycle Management System Using Internet of Things and Big Data Analytics for Product-as-a-Service, Frontiers in Sustainability. 2 (2021).
[180] T. Sakao, A. Öhrwall Rönnbäck, G. Ölundh Sandström, Uncovering benefits and risks of integrated product service offerings - Using a case of technology encapsulation, Journal of Systems Science and Systems Engineering. 22 (2013) 421–439.
[181] T. Sakao, W. Song, J. Matschewsky, Creating service modules for customising product/service systems by extending DSM, CIRP Annals - Manufacturing Technology. 66 (2017) 21–24.
[182] T. Sakao, R. Wasserbaur, F. Mathieux, A methodological approach for manufacturers to enhance value-in-use of service-based offerings considering three dimensions of sustainability, CIRP Annals. 68 (2019) 33–36.
[183] A. Salado, R. Nilchiani, Increasing the Probability of Developing Affordable Systems by Maximizing and Adapting the Solution Space, Procedia Computer Science. 28 (2014) 547–554.
[184] J. Sandin, Procuring industrial service solutions, exploring enablers for co-creating value, in: Procedia CIRP, Elsevier B.V., 2015: pp. 7–12.
[185] C. Sassanelli, G. Pezzotta, M. Rossi, S. Terzi, S. Cavalieri, Towards a Lean Product Service Systems (PSS) Design: State of the Art, Opportunities and Challenges, Procedia CIRP. 30 (2015) 191–196.
[186] S.A. Schenkl, R.M. Sauer, M. Mörtl, A technology-centered framework for Product-Service Systems, in: Procedia CIRP, Elsevier, 2014: pp. 295–300.
[187] J.O. Scherer, A.P. Kloeckner, J.L.D. Ribeiro, G. Pezzotta, F. Pirola, Product-Service System (PSS) design: Using Design Thinking and Business Analytics to improve PSS Design, Procedia CIRP. 47 (2016) 341–346.
[188] P. Schönsleben, Tangible services and intangible products in industrial product service systems, in: Procedia CIRP, Elsevier B.V., 2019: pp. 28–31.
[189] G. Schuh, P. Jussen, T. Harland, The Digital Shadow of Services: A Reference Model for Comprehensive Data Collection in MRO Services of Machine Manufacturers, in: Procedia CIRP, Elsevier B.V., 2018: pp. 271–277.
[190] G. Schuh, M. Pitsch, S. Rudolf, W. Karmann, M. Sommer, Modular sensor platform for service-oriented cyber-physical systems in the european tool making industry, in: Procedia CIRP, Elsevier B.V., 2014: pp. 374–379.
[191] E. Schweitzer, J.C. Aurich, Continuous improvement of industrial product-service systems, CIRP Journal of Manufacturing Science and Technology. 3 (2010) 158–164.
[192] L. Selak, P. Butala, A. Sluga, Condition monitoring and fault diagnostics for hydropower plants, Computers in Industry. 65 (2014) 924–936.
[193] D.J. Smith, Power-by-the-hour: the role of technology in reshaping business strategy at Rolls-Royce, Technology Analysis & Strategic Management. 25 (2013) 987–1007.
[194] L. Somers, I. Dewit, C. Baelus, Understanding product-service systems in a sharing economy context - A literature review, in: Procedia CIRP, Elsevier B.V., 2018: pp. 173–178.
[195] W. Song, J. Cao, A rough DEMATEL-based approach for evaluating interaction between requirements of product-service system, Computers and Industrial Engineering. 110 (2017).
[196] W. Song, T. Sakao, A customization-oriented framework for design of sustainable product/service system, Journal of Cleaner Production. 140 (2017) 1672–1685.
[197] T.T. Sousa-Zomer, P.A.C. Miguel, A QFD-based approach to support sustainable product-service systems conceptual design, International Journal of Advanced Manufacturing Technology. 88 (2017) 701–717.
[198] W.R. Stahel, Circular economy, Nature. 531 (2016) 435–438.
[199] R. Stark, C. Fresemann, K. Lindow, Development and operation of Digital Twins for technical systems and services, CIRP Annals. 68 (2019) 129–132.
[200] M. Stewart, R.E. Melchers, Probabilistic Risk Assessment of Engineering Systems, Springer, London, 1997.
[201] T. Süße, Improvisation as a prerequisite for the dynamic interplay of production and service in PSS: Insights of an organizational design principle and a game-based learning approach, in: Procedia CIRP, Elsevier B.V., 2015: pp. 366–371.
[202] M. Swan, Blockchain: blueprint for a new economy, First Edition, O'Reilly Media, Inc, Sebastopol, 2015.
[203] P. Sydor, E. Shehab, T. Mackley, P. John, A. Harrison, Improvement of system design process: Towards whole life cost reduction, in: Procedia CIRP, Elsevier B.V., 2014: pp. 293–297.
[204] M. Taisch, M. Heydari, A. Carosi, C. Zanetti, Service Performance Monitoring and Control Toolset, Procedia CIRP. 16 (2014) 62–67.
[205] E.L.S. Teixeira, B. Tjahjono, S.C.A. Alfaro, A novel framework to link Prognostics and Health Management and Product-Service Systems using online simulation, Computers in Industry. 63 (2012) 669–679.
[206] U. Tischner, M. Verkuijl, A. Tukker, SUSPRONET Report: First draft report of PSS review, Report No. Available from: Econcept, Cologne, Germany. (2002).
[207] T. Tomiyama, E. Lutters, R. Stark, M. Abramovici, Development capabilities for smart products, CIRP Annals. 68 (2019) 727–750.
[208] T.A. Tran, J.Y. Park, Development of integrated design methodology for various types of product — service systems, Journal of Computational Design and Engineering. 1 (2014) 37–47.
[209] T. Tran, J.Y. Park, Development of a novel set of criteria to select methodology for designing product service systems, Journal of Computational Design and Engineering. 3 (2016) 112–120.
[210] L. Trevisan, D. Brissaud, Engineering models to support product–service system integrated design, CIRP Journal of Manufacturing Science and Technology. 15 (2016) 3–18.
[211] B. Tronvoll, A. Sklyar, D. Sörhammar, C. Kowalkowski, Transformational shifts through digital servitization, Industrial Marketing Management. 89 (2020) 293–305.
[212] A. Tukker, Eight Types of Product-Service System: Eight Ways to Sustainability? Experiences from Suspronet, Business Strategy and the Environment. 13 (2004) 246 – 260.
[213] A. Tukker, Product services for a resource-efficient and circular economy - a review, Journal of Cleaner Production. 97 (2015) 76–91.
[214] T. Turunen, M. Finne, The organisational environment's impact on the servitization of manufacturers, European Management Journal. 32 (2014) 603–615.
[215] K. Ueda, T. Takenaka, J. Váncza, L. Monostori, Value creation and decision-making in sustainable society, CIRP Annals. 58 (2009) 681–700.
[216] E. Uhlmann, C. Geisert, N. Raue, C. Gabriel, Situation Adapted Field Service Support Using Business Process Models and ICT Based Human-Machine-Interaction, in: Procedia CIRP, Elsevier B.V., 2016: pp. 240–245.
[217] E. Uhlmann, N. Raue, C. Gabriel, Flexible implementation of IPS2 through a service-based automation approach, in: Procedia CIRP, Elsevier B.V., 2013: pp. 108–113.

[218] W. Ulaga, W.J. Reinartz, Hybrid Offerings: How Manufacturing Firms Combine Goods and Services Successfully, Journal of Marketing. 75 (2011) 5–23.
[219] Y. Umeda, S. Kondoh, Y. Shimomura, T. Tomiyama, Development of design methodology for upgradable products based on function–behavior–state modeling, AI EDAM - Artificial Intelligence for Engineering Design Analysis and Manufacturing. 19 (2005) 161–182.
[220] Y. Umeda, S. Takata, F. Kimura, T. Tomiyama, J.W. Sutherland, S. Kara, C. Herrmann, J.R. Duflou, Toward integrated product and process life cycle planning - An environmental perspective, CIRP Annals - Manufacturing Technology. 61 (2012) 681–702.
[221] United Nations, Transforming Our World: The 2030 Agenda for Sustainable Development, 2015.
[222] A. Valencia, R. Mugge, J.P.L. Schoormans, R. Schifferstein, The Design of Smart Product-Service Systems (PSSs): An Exploration of Design Characteristics Chronic disease prevention through real-life monitoring and intervention design View project Food experience View project, 2015.
[223] G.V.A. Vasantha, R. Roy, A. Lelah, D. Brissaud, A review of product–service systems design methodologies, Journal of Engineering Design. 23 (2012) 635–659.
[224] C. Vezzoli, F. Ceschin, J.C. Diehl, C. Kohtala, New design challenges to widely implement 'Sustainable Product–Service Systems,' Journal of Cleaner Production. 97 (2015) 1–12.
[225] G. Vianello, S. Ahmed, Transfer of knowledge from the service phase: a case study from the oil industry, Research in Engineering Design. 23 (2012) 125–139.
[226] F. Visintin, Providing integrated solutions in the professional printing industry: The case of Océ, Computers in Industry. 63 (2012) 379–388.
[227] I. Visnjic, M. Jovanovic, A. Neely, M. Engwall, What brings the value to outcome-based contract providers? Value drivers in outcome business models, International Journal of Production Economics. 192 (2017) 169–181.
[228] B. Wang, W. Luo, A. Zhang, Z. Tian, Z. Li, Blockchain-enabled circular supply chain management: A system architecture for fast fashion, Computers in Industry. 123 (2020) 103324.
[229] X. Wang, C. Durugbo, Analysing network uncertainty for industrial product-service delivery: A hybrid fuzzy approach, Expert Systems with Applications. 40 (2013) 4621–4636.
[230] Z. Wang, C.-H. Chen, P. Zheng, X. Li, L.P. Khoo, A novel data-driven graph-based requirement elicitation framework in the smart product-service system context, Advanced Engineering Informatics. 42 (2019) 100983.
[231] S. Wan, D. Li, J. Gao, R. Roy, Y. Tong, Process and knowledge management in a collaborative maintenance planning system for high value machine tools, Computers in Industry. 84 (2017) 14–24.
[232] R. Wasserbaur, T. Sakao, Conceptualising Design Fixation and Design Limitation and Quantifying Their Impacts on Resource Use and Carbon Emissions, Sustainability. 12 (2020) 8104.
[233] S. West, P. Gaiardelli, B. Resta, D. Kujawski, Co-creation of value in Product-Service Systems through transforming data into knowledge, IFAC-PapersOnLine. 51 (2018).
[234] S. West, J. Meierhofer, O. Stoll, L. Schweiger, Value propositions enabled by digital twins in the context of servitization, in: Proceedings of the Spring Servitization Conference: Advanced Services for Sustainability and Growth, 2020: pp. 152–160.
[235] T. Widmer, B. Tjahjono, M. Bourlakis, Defining value creation in the context of circular PSS, in: Procedia CIRP, Elsevier B.V., 2018: pp. 142–147.
[236] S. Wiesner, M. Freitag, I. Westphal, K.D. Thoben, Interactions between service and product lifecycle management, in: Procedia CIRP, Elsevier B.V., 2015: pp. 36–41.
[237] S. Wiesner, F. Lampathaki, E. Biliri, K.D. Thoben, Requirements for Cross-domain Knowledge Sharing in Collaborative Product-Service System Design, in: Procedia CIRP, Elsevier B.V., 2016: pp. 108–113.
[238] I. and H.M. and T.K.-D. Wiesner Stefan and Westphal, Manufacturing Service Ecosystems, in: M. and K.D. Emmanouilidis Christos and Taisch (Ed.), Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013: pp. 305–312.
[239] W.W. Wits, J.R.R. García, J.M.J. Becker, How Additive Manufacturing Enables more Sustainable End-user Maintenance, Repair and Overhaul (MRO) Strategies, in: Procedia CIRP, Elsevier B.V., 2016: pp. 693–698.
[240] M. Zachariadis, G. Hileman, S. v. Scott, Governance and control in distributed ledgers: Understanding the challenges facing blockchain technology in financial services, Information and Organization. 29 (2019) 105–117.
[241] M. Zambetti, R. Pinto, G. Pezzotta, Industry 4.0 Data-Related Technologies and Servitization: A Systematic Literature Review, in: IFIP Advances in Information and Communication Technology, Springer, 2020: pp. 347–360.
[242] H. Zhang, L. Ma, J. Sun, H. Lin, M. Thürer, Digital Twin in Services and Industrial Product Service Systems, Procedia CIRP. 83 (2019) 57–60.
[243] P. Zheng, C.-H. Chen, S. Shang, Towards an automatic engineering change management in smart product-service systems – A DSM-based learning approach, Advanced Engineering Informatics. 39 (2019) 203–213.
[244] P. Zheng, T.J. Lin, C.H. Chen, X. Xu, A systematic design approach for service innovation of smart product-service systems, Journal of Cleaner Production. 201 (2018) 657–667.
[245] P. Zheng, Z. Wang, C.-H. Chen, L. Pheng Khoo, A survey of smart product-service systems: Key aspects, challenges and future perspectives, Advanced Engineering Informatics. 42 (2019) 100973.
[246] P.U. Zine, M.S. Kulkarni, R. Chawla, A.K. Ray, A framework for value co-creation through customization and personalization in the context of machine tool PSS, in: Procedia CIRP, Elsevier, 2014: pp. 32–37.

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