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Annamalai Vasantha, Gokula Vijayumar and Roy, Rajkumar and Corney, Jonathan Roy (2015) Advances in designing product-service systems. Journal of the Indian Institute of Science, 95 (4). pp. 429-448. ISSN 0970-4140 ,

Advances in Designing Product-Service Systems

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Definition for highlighted terms (in yellow) is provided in a separate document.

Abstract

Product-Service Systems (PSS) have emerged as a class of hybrid business models that have evolved particular relevance to enterprises operating in a resource-efficient, circular economy (environments that places an emphasis on sustainable, collaborative, system-centric perspectives). More than a decade of PSS research has produced some significant contributions, especially in the area of business models, and performance measures associated with delivering successful PSS solutions. This paper reviews recent advances in the existing literature and assesses the essential components required for designing a sustainable PSS. The vital components identified by this analysis of the literature are: PSS ontology, requirements definition, design process support for generating PSS concepts, and the evaluation of PSS concepts. The review highlights the state-of-the-art PSS research in these four areas, and discusses research gaps and directions for future research.

1. Introduction

The academic study of Product Service Systems (PSS) has emerged as a topic in sustainability research where the focus is to find better quid pro quo solutions between production and consumption. The uniqueness of PSS in terms of providing differentiation, establishing long-term relationships with customers, and aiding in better understanding of the customer's needs attracts businesses. Customers benefit from a wider variety of consumption options based on PSS offerings which satisfy their requirements. Put simply, PSS innovate approaches for effective resource use and sharing in businesses and social networks. For example, Jegou and Manzini[1] reported an interactive social community PSS that allowed a neighbourhood to share resources, create mutual assistance, and perform daily practices more easily. It integrated closely the many stakeholders (customers, manufacturers, suppliers, government) involved in the value chain. This collaborative system focused on delivering value-in-use, which aided development of customised solutions to add more value for customers compared to conventional products and services.

Although PSS merits are perceivable, only a few case studies have been reported that focused on how PSS could lead to cost savings (e.g. Power by the Hour[3]). Wang's[4] investigations show that only about 21% of the sampled firms could carry out a service transformation strategy successfully, and most manufacturing enterprises could not gain the expected return and consequently their profits decreased because of the increase in service investment. The analysis of OSIRIS database (that details 10,028 firms, incorporated in 25 different countries) revealed that although sales revenue was larger for sertvitized manufacturing firms, they also generated lower profits as a % of sales[5]. The status quo is similar for environmental impacts (and so it is interesting to note that it is not guaranteed that sertvitizied companies would have less environmental impacts than "normal" companies). In other words unless PSS solutions are specially designed to be eco-friendly, there is no guarantee that they will reduce environmental impacts. Thus the design phase plays a crucial role in developing a sustainable (i.e. business profits, environmental friendly and social merits) PSS.

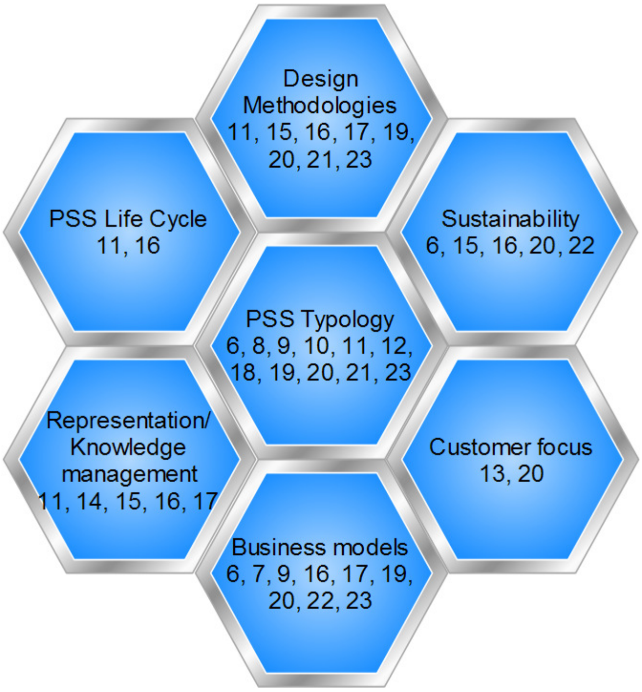

Figure 1. Classification of PSS review papers (referenced by citation number)

The growing importance of the PSS domain over the past decade is reflected in the volume of papers (almost 20) reviewing this research domain. Figure 1 summarizes the wide range of topics covered in these review papers. This review focuses on the literature relating to designing sustainable PSS. The literature identifies the vital components as: PSS ontology; requirements definition; and support of both the processes used to generate PSS concepts; and also the evaluation of PSS concepts. Since the focus is on discussion of the latest advancements, the papers considered for this review were selected on the basis of the authors' assessment of their significance (consequently the comprehensiveness of the review of each topic is not guaranteed). With that caveat the following sections discuss these topics individually and identify both the research advances and gaps.

2. PSS Ontology

Ontology[24] in any domain is of paramount important in establishing communication and shared understanding among/between researchers and practitioners without ambiguity. However, in comparison with other PSS topics (theories, methodologies, tools and techniques), the number of papers published on PSS ontology is relatively modest. Rese et al.[25] developed an ontology of business models for industrial PSS. They described PSS business model ontology in terms of value, organization, risk distribution, revenue streams, and property rights. Kim et al.[26] proposed graph and ontological representations of PSS, consisting of the relationships between values, products and service elements. They defined the difficult term '*value*' with '*ValueNature*' (what the value is) and '*ValueRealizations*' (different subjective interpretations). They also adapted the commonly used product description for defining PSS to be: function, structure, context and environment. Raja et al.[27] defined attributes of '*Value-in-Use*' by adding the following classes: ability to source, access, administration, contract, convenience, cost, delivery, detailed analysis, environment, inventory management, knowledge, price, proactivity, quality of equipment, range of offering, relational dynamic, responsiveness, risk, service orientation, support systems, traceability, understanding customer business and urgency. It is clear from these papers that the concept 'value' is central to any PSS ontology. However, unification of these varying definitions and attributes of 'value' still challenges researchers.

Vasantha et al.[28,110] proposed an initial structure of a PSS ontology from the design perspective. The notable feature in this work is that thirty international PSS researchers were involved in two cycles of evaluation to refine and agree on the proposed structure. This methodology led to the identification of eight root concepts: Need/Requirement, Stakeholder, Product-Service, Business Model, PSS Life Cycle, PSS-Design, Support System and PSS Outcome. Pagoropoulos et al.[29] also built an ontology of PSS using a maritime case study to elicit classifications and characteristics. They described PSS ontology in terms of three layers: an epistemic layer (to conceptualise the nature and the affinities between products, product life cycle, services, stakeholders, business models, requirements and the transformation process), an offerings layer (an explicit description of existing product/service solutions), and a performance layer (a conceptualisation of the value that products and services entail for all relevant stakeholders). Meier and Massberg[30] differentiated business models by: production responsibilities, supply of operating personnel, service initiative, ownership, supply of maintenance personnel and a service turn model. Baxter et al.[31] depicted an upper level PSS structure that enabled the description of a combined product- and business- system. The central class of life cycle system is comprised of three classes: product, process and resource.

Although PSS ontologies proposed in literature have some converging elements, the core question to be answered is "how commonly are PSS researchers and practitioners using PSS terms in their communications?". To understand consistency in usage of terminologies across research papers, phrases used in 18 PSS review papers (reported in Figure 1) were analysed using Hermetic Word Frequency Counter^{TM} software[92]. The 18 PSS review papers cover more than 400 research papers published in this domain. Analysing phrases from these papers should provide answers for consistency in terminologies usage across research papers. The results suggest that about 40,000 two or three word phrases are referred to at least twice. The 40,000 phrases were manually reviewed to segregate proper phrases (i.e. those which were used at least 5 times). This step included elimination of repetition and meaningless phrases. After segregating, 717 meaningful phrases were generated. Interested readers could download the file containing all phrases from Appendix – 1. The most notable phrases, in the authors' judgement, are listed and categorized in Figure 2.

In Figure 2 the numbers in brackets highlight the most frequent terms used among PSS researchers. The results of this phrase analyses (Figure 2) align reasonably closely with the ontology structure proposed by Vasantha et al.[28] and Pagoropoulos et al.[29]. However, the analysis also reveals that while the literature frequently emphasised 'environmental impact', this aspect is largely ignored in many proposed PSS ontology definitions. The three types of business models proposed by Tukker and Tischner[32] (Product-, Use-, and Result-oriented models) are the most commonly referred architectures in the literature. The emphasis given on creating sustainable solutions through ecological and economic preferences is noted. In the 'life cycle' category, importance is predominantly given to the use phase and maintenance services. So it can be concluded that more common language of other life cycle phases is needed to facilitate communication. The convergence of terms in the important 'customer requirement' category can also be observed. Many authors used 'consumer behaviour', 'consumption patterns' and 'customer value' to define customer requirement. Integrated 'products and services' is strongly emphasized in almost all the papers analysed. But there is a need to depict the characteristics of substitution between products and services. Although 'value chain' is stressed in many papers, emergence of a term equivalent to 'co-creation' is not widely used. Researchers used 'capable of jointly' and 'customer involvement'; however, these terms are not commonly cited by other researchers. It is also noteworthy that the phrase 'system innovation' is used frequently by many authors throughout the cohort of papers reviewed. Importantly, convergence of terms such as 'sustainable consumption' and 'production and consumption' highlights that the core value of PSS domain remains intact. Terms to define 'infrastructure' need to be enriched with reference to applicability of PSS. In summary, while high level PSS terminologies are converging, there is still a greater scope for improvement in the 'life cycle', 'product and service' and 'infrastructure' categories.

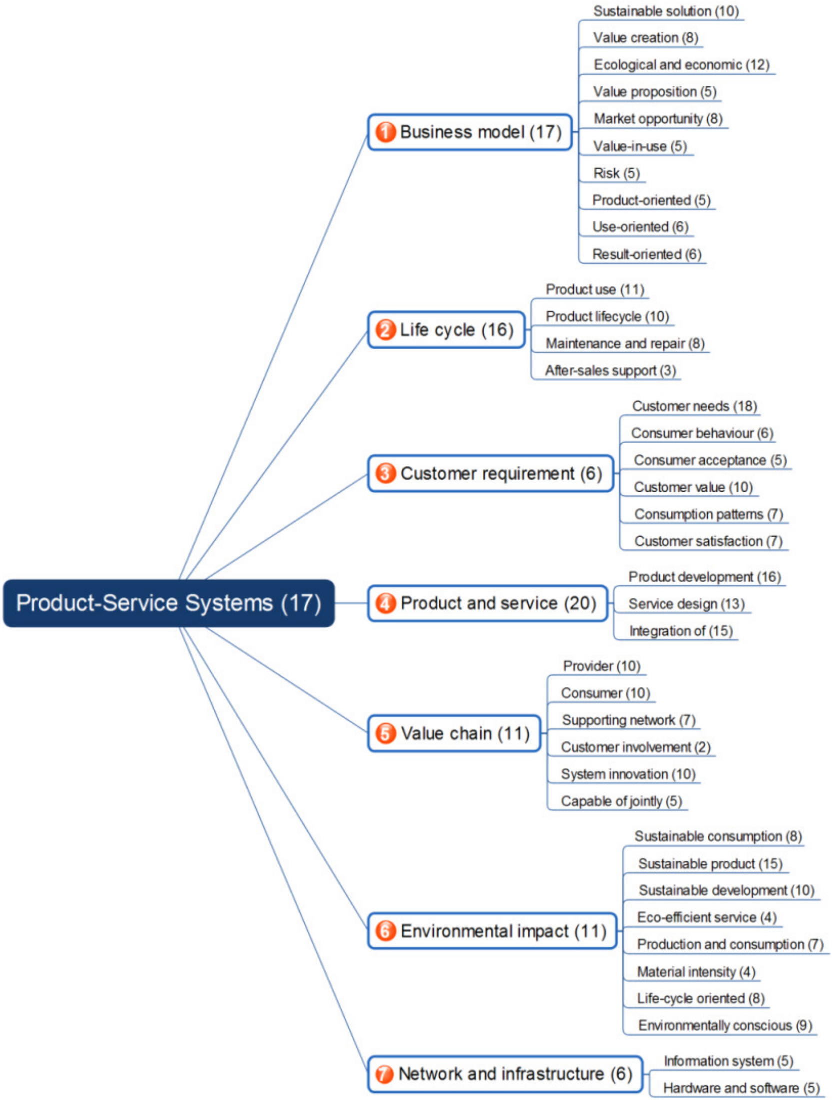

Figure 2. Summary of the most frequently used phrases in the reviewed papers (number in brackets denotes frequency of citation)

3. PSS Requirements

This section considers the question: "how is the PSS design problem defined in the literature?" A good starting point is Tukker[6] and Tukker and Tischner [32] papers on classification of PSS types. These papers aimed to find ways to achieve 'factor 4'[33] sustainability and proposed three main types of PSS which have significant variation in economic and environmental characteristics. Since the types of PSS (proposed by Tukker and Tischner) are commonly accepted in the PSS literature (as discussed in the PSS ontology section), defining the PSS problem has two important interacting variables: economic and environmental. However, most of the PSS literature separated these variables, and considered them individually.

When considering economic aspects, the factor 'value' is predominately used in the literature. Tukker[6] studied economic variables in terms of tangible and intangible value for the user, tangible costs and risk premium for the provider, capital/investment needs, and issues such as the providers' position in the value chain and client relations. Raja et al.[27] investigated customer satisfaction achieved through integrated products and services. They identified seven key attributes of value-in-use for integrated product service combinations: knowledge, access, relational dynamic, range of product and service offerings, delivery, price, and locality. Lindström[34] reviewed literature to identify potential through-lifecycle aspects that needed to be considered during the development and operation of functional products (aka PSS). Among the many dimensions discussed, emphasis was placed on relationships, contract, cost drivers, and risks.

When considering environmental perspectives, the 'use' phase is frequently emphasised over other life cycle stages[35]. Tukker[6] assessed environmental variables by impact reduction mechanisms such as intensive use of capital goods, and inherent incentives for sustainable user and provider behaviour. Analysis performed on a long-term rail contract, for example, reveals that sustainability was emphasised through train's improved performance and energy efficiency, less weight, minimum impact to the infrastructure and minimum maintenance[36]. In this work, Vasantha et al.[36] pointed out that the contract placed substantially higher (80%) emphasis on satisfying the product specification compared to satisfying the service specification (20%). This specification highlights that even in a long-term contract the industrial focus is predominately product-centric. The variation possible in specification from product-centric to PSS is highlighted in a case study of laser system's requirement description[37]. Consequently, the importance placed on the service phase (expressed as a %) needs to be refined. Interestingly initial studies are now emerging to investigate how service requirements are typically evaluated during new product development[38].

Beyond consideration of the economic and environmental variables, researchers have aimed to define PSS holistically. Muller et al.[39] presented a guideline to elicit and analyse requirements of PSS properties and quality. They developed a checklist of criteria in terms of lifecycle activities, values, contracts, business and operation models, structure, behaviour, technical artefacts, service, information, communication and actors. The challenge is to define all these requirements in a different level of abstraction facilitating requirements traceability, and integration of PSS components. Berkovich et al.[40] proposed a requirements data model to facilitate an integrated requirements engineering approach for a PSS described at different levels of abstraction. The proposed RDMod[40] model for the requirements of PSS consists of five levels of abstraction: goal, system, feature, function and component levels. The following paragraphs compared and discussed how well these five levels of abstraction align with the work of other researchers.

At the goal level, Berkovich et al.[40] mentioned business goals for both customers and providers. Although initially customer needs are deemed to be the requirements of products and services, currently customer business goals are commonly agreed in the PSS literature as a first step. Komoto and Tomiyama[41] defined goal(s) and quality as specified by product users as the initial step. Whereas Shimomura et al.[42] specify goals in terms of the state change of the receiver, and Alonso-Rasgado et al.[43] state them in terms of business ambitions of the client. Understanding the customer's business vision and processes revealed the 'need behind the need' of the customer that has to be fulfilled[44]. The environmental and social requirements are not given top level importance. It is important that business, environmental and social changes should be given equal consideration to achieve the aim of PSS sustainability. Even if the first step converges, there are significant variations observed in the subsequent levels.

At the system (i.e. second) level, Berkovich et al.[40] specified customer and stakeholders requirements, business process requirements, environment requirements and provider's requirements. But, the second step of the framework proposed for designing PSS identified existing capabilities and resources of the customer[45]. The research work emphasised that consideration of capabilities that are required during PSS period presented opportunities to provide extra value that could be offered by considering the customer's goals as revealed by their business processes. Also, since PSS is a co-creation between customer and other stakeholders, understanding their capabilities helped to realize value-in-use leading to greater customer satisfaction. Similarly Maussang et al.[46] proposed external functional analysis and use scenarios as the second step in PSS design. It should be emphasised that although defining functionality at the abstract levels is important, all these levels should be well-integrated. Tan et al.[47] emphasised integrated influences between product life cycle, actor network, customer activities and value proposition. In the same way, Sakao et al.[48] proposed cohesive scope, view, scenario and flow models.

At the feature and the function levels, Berkovich et al.[40] specified product- and service-oriented requirements of the system and function structure design. Before specifying product and service requirements, Vasantha et al.[45] emphasised the need to identify the current status of existing products and services. This study helps to identify gaps in existing market and alignment with reference to customer's goals and capabilities. Likewise, Alonso-Rasgado et al.[43] discussed the different combinations of hardware and services available in Total Care products (aka PSS): novel (new) hardware, adapted (from existing) hardware, new service support system, and adapted service support system.

Most of the research work agreed that PSS requirements definition moves from abstract to concrete level, and from system to component level[40,45,46]. However, the levels of abstraction in defining PSS need to be unified across the research outcomes, and also the applicability should be tested with industrial experts. The PSS specification is very specific for matured products such as trains[36]; however, for new products and services it could be incomplete, inconsistent, imprecise and ambiguous. Also, PSS's dynamic characteristics (e.g. a PSS specification needs to incorporate adaptability to a changing environment) need to be studied in-detail using industrial case studies. Also, defining PSS problems at an abstract level (solution-neutral way) is important to explore wider solution spaces adequately (e.g. 'pleasant climate' in offices rather than gas or cooling equipment[6]). However, only a little research work[48] has been reported that emphasised the importance of the value chain in defining PSS; so, there is a need to create awareness about its potential influences on PSS solution, and its influence on coordination of development activities and integration of PSS components. Some of the most frequently observed PSS requirements specification variables in literature (based on the authors' observations) along with related literature are listed in Appendix – 2.

4. PSS Design

This section used a review of reported PSS design methodologies up to the year 2010 conducted by Vasantha et al.[15] as a benchmark reference, against which further development is compared, and future research gaps identified. Integrating business models, products and services together throughout the lifecycle stages, and creating innovative value addition for the system should be the focus of PSS design[15]. Considering multiple aspects involved in PSS design, most of the proposed methodologies used network based interconnected interfaces for conceptual development. In the 'Service CAD with a life cycle simulator' developed by Komoto and Tomiyama[41], networks are modelled using activities, goals, quality, and environment as major elements. For detailing the elements, various other constructs such as service environment, provider, receiver, channel, content, activity, receiver's intention, target, promised goal, realised service, quality and value added are used. Network modelling is used in a Service Explorer developed by Sakao et al.[48] in which a service model consists of four sub-models: 'flow model (who)', 'scope model (what)', 'scenario model (why)' and 'view model (how)'. Welp et al.[49] also used it to describe a modelling approach that defines a 'PSS object (noun)' and 'PSS process (verb)' to represent the system behaviour of the 'PSS artefact' (integrated products and services). Network modelling is widely used to represent to connections between the many components needed in PSS design such as stakeholder modelling, life-cycle modelling, requirement modelling, PSS scenario generation, activity modelling and PSS function modelling[50].

Although network models allow PSS designers to easily model multi-characteristics elements, they quickly become very complex when applied to real problems. Designers need computational support at various levels of developing and managing knowledge to create sustainable PSS solutions. This is a consequence of PSS designers needing to use a broader range of knowledge than that required in product design because both products and services are concurrently included in the design space[51]. Recently Komoto et al.[52] proposed a computational support for abduction[66] in PSS design. It aids the hypothesis formation procedure to help designers' reasoning in analysis, suggestion and transformation of PSS design. The analysis checks *incomplete* nodes due to lack of relations to other concept nodes, *immeasurable* and *unevaluated* quality nodes, and *unjustified* parameter nodes. Then with the help of the collected knowledge base, the computational tool suggests relevant constructs, and finally the PSS network model transforms these, based on the options selected. To reuse PSS design knowledge, Nemoto et al.[53] integrated a design knowledge base and catalogue viewer with the design workspace developed in Service Explorer[42]. Knowledge from existing PSS cases was represented through five elements: core product, need, function, entity, and actor. The authors concluded that by searching the knowledge base, designers were able to generate more ideas than the designers who were not supported. However, the key challenge is to update the knowledge base periodically. Sadek and Theiss[54] proposed a knowledge based assistance tool which helps to deduce PSS concepts from given requirements. They defined a PSS modelling environment by functions, objects and processes. The assistance was developed with knowledge based transformation methods, which depends on an underlying knowledge base in the form of an ontology. The support system aids identification of missing PSS requirements, and checks for correct/missing relations between modelling elements. They proposed to use semantic web technologies (OWL based ontologies) to identify sematic relations, and concluded that efficient PSS modelling requires both declarative and procedural knowledge.

These research works are mainly focused on managing and utilising existing design knowledge in the conceptual phase of PSS design. Future research work should address the need to develop comprehensive schema for developing PSS knowledge bases (focused on reasoning abilities), and aid designers during conceptual design by proposing useful constructs, finding errors in models, and identifying resource redundancy. So, although most of the reported support systems help during the formalised modelling processes, support is also required during the abstract phase. For example, there is a challenge in linking natural language formalisation to PSS ontology to create a useable knowledge base. Syntax (grammatical form of PSS design) and semantics (meaning of PSS ontological words) in PSS design need more rigorous development for common acceptance across practitioners. Automatic acquisition tools are required to develop PSS knowledge from various internal and external sources. PSS research community should also develop a common knowledge base for effective sharing and development.

Another development in the process of conceptual PSS design applies protocol analysis generated from laboratory experiments (which is, traditionally, predominately used to study product development process). Shimomura et al.[55] developed a method for analysing as to how the design process influences the features of design solutions in the conceptual design of PSS. The authors used six categories: customer, value proposition, product-service architecture, actor network, process, and resource, for coding the generated protocols. The protocol analyses revealed that groups spending more time on ‘value’ to be proposed to the customer in the early stage of the design were able to generate the design solutions which were more effective for the targeted customer. They concluded that customer, value proposition, and product-service architecture should be spirally designed, especially at the early stage of PSS design. A similar protocol study was conducted by Sakao et al.[56] using PSS Layer Method[39] constructs: need, value, deliverables, lifecycle activities, actors, core products (technical artefacts), periphery (like IT infrastructure or public transport systems), contract elements, and finance. This study concluded that designers spent the majority of their time on *need* and *value* in the initial stages, and then shifted to focus mainly to lifecycle activities addressing periphery and finance, and closed with a focus on value; it also revealed that PSS design follows a general process of problem solving. Focusing on team interactions, the protocol analysis conducted by Lee et al.[57] revealed that based on individual knowledge and expertise, each team member took leading roles in different design activities in the PSS design process. Although protocol studies are necessary to get deeper insights, it would be necessary to avoid replicating general principles and knowledge generated from many decades of research in product development, since both domains are similar in terms of problem solving. Also, the experiments should involve expert practitioners rather than novice students.

In supporting the PSS implementation phase, Joore and Brezet[58] proposed a multilevel design model to understand the mutual relationship between PSS development and societal change processes. The model integrates a cyclic iterative design approach to describe the design of PSS and complex societal change processes. The model applies a typical design cycle (analysis, synthesis, experience and reflection) on four levels: societal system, socio-technical system, product-service system and product-technology system. The authors assert that further research is necessary to determine the mutual influence between the various system levels and its effect on the design process itself. Song et al.[59] emphasized that successful PSS implementation could guarantee PSS success in the market. They proposed a framework for innovation management of PSS at three different levels (strategy, tactic and support). These three levels aim to manage innovation and how a firm does its business within PSS, how it develops necessary blocks within customer requirement, PSS concept and implementation plan, and how it manages collaboration, resources, reliability and performance. They emphasized that PSS system information in use should be used by the PSS provider for future concept improvement to form an innovative, closed-loop, sustainable process.

Many papers emphasize the importance of novel networks of stakeholders in the co-production of PSS value[60] and to avoid conflicts between them[61]. However, assessment of stakeholders' capabilities is generally the missing elements in PSS design methodologies.

One notable exception is the capability based PSS design framework proposed by Vasantha et al.[45]. Although many design methodologies are proposed in the literature, demonstrating their critical relevance(s) is missed in most of the work. Dewit et al.[62] used the creativity support index[67] (CSI) as a metric to evaluate the following existing service design tools (modified with a specific PSS focus) in the early stages of PSS design: stakeholders experience journey, context and objectives mapping, research questions, stakeholder interview, persona dimensions, persona template, actors map, design challenge, design requirements and lotus blossom (retrieve important characteristics through inspiring examples). Among these tools, stakeholder interview, design requirements and lotus blossom were highly rated in the CSI. More such studies are required to evaluate the benefits of proposed methodologies. Although the design of smart PSS is a rapidly developing research domain, little work has been reported to date. In one of the few publications to address this area, Valencia et al.[63] outlined seven important characteristics of smart PSS[63]: consumer empowerment, individualization of services, community feeling, service involvement, product ownership, individual/shared experience and continuous growth. Smart PSS could lead to generation of new interactions/partnerships among stakeholders. Enabling smartness is an approach for creating sustainable PSS.

The fundamental questions of "who should design PSS" and "what are their roles" have not yet been clearly answered in the extant PSS literature. A survey conducted by Hinz et al.[64] among PSS researchers concluded that PSS designers are either "people or teams with trans-disciplinary competencies or towards a group of people that together form a collection of competencies". PSS designers' roles vary across the reported methodologies and often represent functions that do not yet exist within industry (like PSS Architect). More studies are required within industries to identify the roles of PSS designers and how they collaborate with multi-disciplinary teams. Another upcoming research area is Lean PSS design. Sassanelli et al.[65] summarized the state-of-the-art, opportunities and challenges in lean PSS design. They argued that a lean product development discipline could support the design and development of PSS. The analysis revealed that most of the methodologies focused on waste reduction, applied Set-Based Concurrent Engineering, and proposed effective knowledge management. Although the majority of the PSS design methodologies have a clear heritage from lean principles, the content is implicit rather than explicit. More research is required in the application of lean principles in PSS design. Another important research area that needs greater focus is inputting information and knowledge collected in PSS life cycle. Hussain et al.[44] proposed a framework to inform PSS conceptual design by using system-in-use data. The framework maps an existing system using service blueprints, and finds gaps between customer requirements and the systems capability. The proposed model is generally applicable to systems where performance needs to be improved. More industrial case studies focused on understanding the knowledge requirements of different phases of PSS design are required. Furthermore, two other aspects mentioned in the PSS design methodologies review[15] are yet to given adequate research attention, namely: influences of business models on integrated solutions, and incorporation of multi-disciplinary approaches.

5. PSS Evaluation

Evaluation plays a vital role in developing viable and sustainable PSS. However a PSS evaluation process is a complex activity due to involvement of many variables at various stages of PSS development. The complexity increases from considering the behaviour of individual product to the whole life cycle network of products and services, and stakeholders and the infrastructure system. Figure 3 presents the stage gate evaluation processes of the whole PSS life cycle. PSS evaluation domain is not matured enough to cover all these stages, especially the feedback loops between stages which are frequently ignored. The PSS evaluation literature mainly focused on the following stages: PSS requirements (customer needs, and product/service requirements), PSS solutions, PSS implementation, and PSS performances (particularly on life cycle costing and sustainability). The following sub-sections review these topics individually.

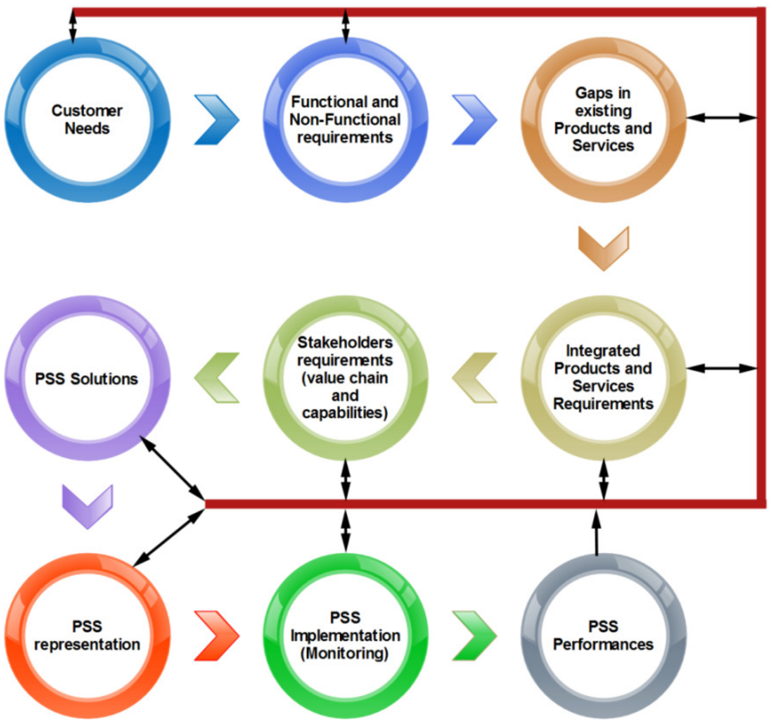

Figure 3. The Stage Gate Evaluation Processes of Whole PSS Life Cycle

Requirements

Evaluation of PSS requirements is not a highly developed domain and only two prominent research works have exclusively focused on requirements evaluation. The important challenge in defining PSS customer requirements is to take into account subjectively, uncertainty, and vagueness. Song et al.[68] argued for use of customer activity cycle to elicit PSS requirements, and proposed the rough analytic hierarchy process (AHP) set approach for evaluating (prioritizing) vague customer PSS requirements at the earliest stage. Notably, the work has taken into account the merging of varying opinions of different experts. However, the following drawbacks are noted in this work: *(i)* it only considers *fuzziness* in requirements definition, leaving out *heterogeneity*, *incompleteness* and *fluctuation*; *(ii)* Satisfying consistency test (part of the judgements' adjustment process) is a challenging part considering the variations possible among experts, and lastly *(iii)* the possibility of interdependencies among customer requirements are not adequately modelled.

Geng et al.[69] focused the evaluation on PSS planning, which starts by mapping Customer Requirements (CRs) to Engineering Characteristics (ECs) (which includes product-related and service-related ECs). The proposed PSS requirements evaluation process was structured in the following phases: first a fuzzy pairwise comparison is used in Analytic

Network Process (ANP) approach in QFD, and then a Data Envelopment Analysis (DEA) approach was employed to identify the initial and final weights of ECs respectively (considering customer and manufacturer's requirements); and then a categorized of the ECs into different Kano attribute classes using fuzzy Kano's questionnaire (FKQ) was done. They argued that using ANP approach in QFD supports the modelling of asymmetry relationships between customer's requirements and ECs. The limitation of the proposed approach however, is that handling a large number of pair-wise comparisons (dependency relationships) using ANP is a complex process.

Apart from the limitations mentioned in the above work, the following points summarise the areas where further investigation is needed into requirements evaluation:

- Eliciting customer requirements is not adequately modelled in the current literature. This is particularly true if customers are unaware about the PSS concepts, and perhaps may be focusing solely on product aspects.
- PSS design could fail if any of the customer requirements are missed in the modelling process. Consequently, support is needed to help PSS designers identify missing requirements.
- The dynamics involved in prioritizing customer requirements (in the context of long-term contracts) needs to be modelled.
- Modelling and prioritizing method for integrated value chain requirements (involving customer, provider and supplier) are needed.

Overall PSS solutions

Commonly, customer satisfaction is given priority importance in PSS solutions assessment[70]. From the business perspective, Neely et al.[71] argued that performance is defined by effectiveness (the extent to which customer requirements are met) and efficiency (how economically the resources are utilised). However, PSS evaluation of solutions should take into account economic, environmental and social factors[72]. But the difficulty of considering all these factors during an assessment process limits the evaluating overall PSS solutions. Chou et al.[73] defined sustainable product-service efficiency as Product-service value (Perceptions) divided by sustainability impact. Perceptions are measured by customer perceptions (tangibles, interaction, sustainability, prices) and employee perceptions (commitment). Likewise impact is measured in terms of cost, lives, consumption and working conditions. The important observations in this work are (i) it considers both environmental and socio-economic issues for PSS sustainability assessment; and (ii) the assessment gives importance to employee perceptions. The limitations of this research are (i) the assessment was carried out using 1-5 Likert scale because it was considered simple and understandable for companies and decision makers. However the scale is subjective and could vary with other assessors; (ii) the hierarchical structure of the multiple criteria used needs to be unified for the presentation of indicators across different sustainability dimensions- economy, environment, and society (the scope of each indicator could vary with different scales).

Lee et al.[74] defined the functional dynamics of PSS as the "functional performance of PSS over time, depicting how the PSS functions and changes over time". The proposed five-step analytic scheme of PSS functional dynamics is structured as: identifying the functional structure of PSS; identifying intensifying and weakening factors of each function; specifying key policy issues; analyzing the functional dynamics of PSS; and assessing functionality of PSS and setting the goals and strategy of a firm. The highlight of this work is that it emphasised heterogeneous elements such as tangibles, intangibles, actors and uncertainties of uncontrollable factors in measuring functional performances. The limitations of this work are in the assumptions employed, which limit the validity of the results, and only economic trends in functional performance of PSS are considered (ignoring socio and environmental issues).

The challenges of assessing overall PSS solutions are:

- A more comprehensive definition of PSS efficiency is needed that considering multiple aspects and stakeholders.
- Incorporating the rebound effect (changes in customer's behaviour) is difficult considering the dynamics involved in the usage phase.
- Fluctuations in qualitative measures of customer's satisfaction and its changes over time are difficult to incorporate in current assessment models.
- Assumptions in defining the evaluation parameters of PSS solutions limit the accuracy and validity of results.

PSS Implementation - Operation models

PSS performances largely rely on operation models to deliver/generate the needed content at the right location. Many operational evaluation models are proposed in literature, particularly car/bike sharing use-oriented models which are frequently used as examples of the proposed model. Alfian et al.[75] developed a discrete event simulation tool based on fuzzy classification to evaluate the performance of service models in a car sharing system. The highest income for service providers (average profit per day, car utilization ratio) and the best service for customers (reservation acceptance ratio) were considered as objectives. Based on the combination of return time (specified / unspecified) and destination service (round-trip, one-way and undeclared destination), six options of relocation scenarios were developed and evaluated. They demonstrated that the option '*static shortest time relocation*' was the best relocation technique; providing the highest profit, the highest percentage utilization ratio and highest acceptance ratio. The limitations of this work are that it used approximate information for input data, did not compare with existing transportation modes, and other options such as dynamic pricing and clustering of customers that could be included in the evaluation.

Maisenbacher et al.[76] discussed the applicability of Agent-Based Modelling (ABM) for supporting PSS development, using (once again) the e-bike sharing system as an example. They modelled the environment with the number of houses, and their arbitrarily chosen coordinates as input parameters. The satisfaction gain/loss and the total number of people and bikes were modelled as actuating variables. The merits highlighted for using ABM were that autonomous decision-making entities help the system to develop adaptive strategies based on situations which could lead to development of unanticipated behaviours. The limitations of this work are that it used a linear model to calculate customer satisfaction, acknowledged difficulty in modelling complex mathematical functions with the ABM model, and the additional work required to model complex, directed, people movements (process sequences and iterations).

Yoon et al.[77] proposed an evaluation method stressing objective, quantitative analysis for designing a new PSS, and demonstrated using the inevitable car-sharing service case study as to how the perspectives of service providers and customers could be combined. The authors emphasised the importance of the risk of failure in grasping customer needs, ascertaining technological and economic feasibility, knowing stakeholders' requirements, and anticipating other players' action. Location, investment cost, market size, and growth analysis were the factors included in studying economic feasibility. The simulation results highlighted that an increase in the number of customers of the car-sharing service reduced the number of private cars. The merits of this work are that not only did the model emphasised feedback loops to improve the systems, but also real-time field test were conducted, and compared with other modes of transport. The authors also highlighted difficulty in modelling competitors' action based on the implemented PSS model.

The major comparative observations from these three studies are the following:

- Objective functions focused on only a few parameters, but evaluation requires a broader coverage of domains (economic, environmental and social).
- There is no consensus on the methodology for considering separation, integration and incorporation of quantitative and qualitative parameters.
- The high variability in the selected parameters, illustrating complexity in PSS operational models.

The challenges in operational models are:

- Modelling dynamics of information flows between stakeholders while a PSS operational model is in execution, and its consequences on PSS performances.
- ABM, system dynamics and discrete event simulation are randomly used in predicting operational scenarios. The merits and limitations of these techniques need to be clearly established with reference to PSS modelling.
- Common operational elements involved in all the three types of PSS business models need to be mapped. This would facilitate easy comparison between different models and avoids missing critical factors.
- Support in technological road map development is needed to understand possible competitive scenarios.

PSS Life Cycle Costings

Life cycle costing (LCC) is a critical parameter for deeper consideration of PSS concepts from the customer perspective. LCC largely depends on strategy decisions on products (e.g. maintenance schedule, end-of-life options) and services characteristics (e.g. delivery time and performance). Datta and Roy[78] discussed various cost estimation techniques and suggested that combinations of existing cost estimation techniques could be used at different life cycle stages. Komoto et al.[79] proposed a method to analyse the capability of original equipment manufacturers (OEMs) to reconfigure their supply chain and end-of-life operations to achieve performance targets, which were defined in terms of environmental impacts and life cycle costs. A highlight of this work was it consideration of multiple factors that considered stochastic characteristics: Product model (modularity, demand fluctuation of products, physical deterioration, functional obsolescence); process network (end-of-life operations, postponing the decisions at end-of-life operations, delay in component delivery); and performance indicators (costs, environmental impacts, market fulfilment). The life cycle simulation (LCS) results demonstrated that the product reuse scenario gives the best result in terms of the average performance. The drawbacks of this system are that the implemented method does not guarantee the detection of all Pareto optima, and the difficulties of obtaining the industrial information required for simulation models.

Sakao and Lindahl[80] used life cycle cost (LCC) analysis to improve PSS offerings. They presented a method, implemented using a spreadsheet (integrated with Matlab software), to conduct LCC analysis both from the provider and customer perspectives, and compares results with other PSS offerings. The two unique steps proposed in addition to general LCC method are the development of function structure and improvement analysis steps. The outcomes were (a) ranking of activities and components' contribution to an offering's LCC; (b) ranking of offerings; (c) ranking of factors influencing sensitivity; and (d) ranking of PSS improvement efficiency. The first three outcomes are not unique, while the last one is unique with the proposed method. Future work suggested were: (i) investigation of the LCC analysis process such as data allocation specific to the context of PSS, and (ii) handling more complex cases such as analysis of a customer's multiple contracts.

Settanni et al.[81] attempted to answer the question: "To what extent are the current approaches to LCC methodologically appropriate for costing the provision of advanced services, particularly availability, through a PSS?" The challenges of PSS cost assessment with regard to 'what?' (cost object), 'why/to what extent?' (scope and boundaries),and 'how?' (computations) are discussed. They highlighted the following three propositions which are largely overlooked in the current PSS LCC:

"Proposition 1: A reductionist approach that focuses on one cost object at a time is not appropriate for a PSS. A PSS is a system potentially involving multiple, interconnected and interacting cost objects simultaneously.

Proposition 2: If the purpose of a PSS is to exploit strategic alliances on a continuous basis, its scope should cover interlinked activities performed within and across the organisational boundaries. Its scope should be also inter-temporal, since the impact of decisions on the state of the PSS at subsequent times has to be considered.

Proposition 3: Costing an advanced service delivered through a PSS is a problem of attributing the value of means to the economic activities carried out for the ends to be achieved. Cost results from the interplay between monetary and non-monetary metrics, and uncertainties thereof."

Marten and Gatzen[82] developed a lifecycle cost model to investigate holistic trade-off decisions at the conceptual design stage considering service reliability and reducing operational cost. The model emphasized the need for early involvement of all stakeholders to input expert knowledge (for both current CAPEX (Capital) and OPEX (Operating expenditures) to the LCC model. The importance of lean, reliable, and standardized processes to gather detailed, reliable, and accessible data to evaluate an objective LCC model is emphasized. They reiterated the importance of bottom-up costing approach for early result utilization and extension of the model applicable to add life cycle aspects. Wong et al.[83] collected data from Physics-based life predictions to feed into discrete event simulation tool to calculate maintenance costs based on predicted component unit costs and component deterioration. The authors argued that the proposed approach enables designing products and services in parallel, considering life cycle performances and predicting the total life cycle costs.

Rese et al.[84] attempted to quantify PSS value for an individual customer over its life cycle through a combination of the Net Present Value (NPV) approach and the Real Options approach. NPV is a decision making tool which helps the customer to decide on the better options (higher NPV is better). NPV is calculated using investment, revenue, expenses and weighted average costs of capital of the customer. The authors argued that only these combined approaches enable a reliable estimation of a PSS's true value. The limitation is that economic aspects from other stakeholders also need to be taken into account. Garetti et al.[85] conducted a state-of-the-art review of existing solutions implementing LCS, in order to identify common characteristics and prioritize next steps to be done for a comprehensive implementation. They noted that activities and events should be modelled in a stochastic way due to lack of resources, faulty events, and random occurrences of unconstrained activities. They advocated not using single software application for complete LCC, and suggested that software should assist modelling many different situations and use different data types.

The challenges involved in LCC are:

- Difficulty in quantifying the relationship between costs and value as perceived by customers and service providers.
- Costs are committed in the decisions taken by various stakeholders involved in the PSS development. Early support system is necessary to keep respective stakeholders aware of cost committed due to each decision.
- A method is needed to calculate LCC considering social changes that occurred due to a PSS implementation.
- Previous experiences play a vital role in the LCC estimation process. Capturing and storing expert knowledge in appropriate format will greatly support the process. The challenge is for new PSS development processes where previous experience (data) is unavailable. More sophisticated techniques should be developed to mature Bottom-up modelling as equivalent to parametric cost models (where cost relationships to be established in the beginning itself).
- A complexity management system is needed while expanding the scope of the boundary (e.g. complete supplier network).
- Quantification of time and effort needed in each costing technique should be established to help engineers to plan their scope accordingly.
- Sensitivity analysis needs further sophistication to handle LCC risks due to complex relationships across products and services.

PSS Sustainability (Environmental)

PSS architects are responsible for sustainable efficiency where decisions taken at the early stages play a critical role. Meier et al.[16] stressed that PSS solutions should be optimized from a life cycle perspective in relation to customer value. However, developing sustainable products and services concurrently is a challenge. Unless PSS solutions are designed to reduce environmental impacts, it cannot be taken for granted. PSS life-cycle sustainability assessment moved from no research effort reported till 2007[86] to qualitative to currently with few quantitative studies. Much of the earlier research is qualitative, and not detailed enough to help compare impacts among various solutions. This section reviews some of the latest methodologies proposed to assess PSS solutions for sustainability.

Lindahl et al.[87] quantified PSS environmental and economic benefits from a life cycle perspective and compared with product-sales type business as a reference. They concluded that PSS had environmental and economic advantages in comparison with the product-sales type business due to the contributing life cycle activities of recycling, remanufacturing, reuse, maintenance, and holistic planning and operation. The enablers were found to be of high flexibility for realizing products and services, and had close relationships with relevant actors. Designers need help to choose and define sustainability criteria. Chen et al.[88] adopted a zigzag mapping process to obtain criteria from the customer domain (economic, environmental and social aspects) to function domain. They used the TOPSIS method and Information Axiom to handle fuzziness and randomness variables respectively. They argued that the proposed method could reflect the judgements of decision makers. However, the limitations are that it did not address the co-evolution of criteria in the generation and evaluation processes, needed substantial amounts of history data, and had difficulty in identifying uncoupled criteria.

Amaya et al.[89] used a bicycle sharing to demonstrate how PSS environmental assessment using LCA can be incorporated into the design process. The functional units were defined using the following elements: service provision time, availability, and conditions of use. Stand-by stage, use and maintenance were the three stages considered in the use phase. A comparison with different PSS strategies shows that the scenario of combining bicycle robustness, redistribution and maintenance leads to less environmental impact. The merit is that the approach linked the PSS life-cycle parameters to PSS design characteristics facilitating the decision making process. However, the proposed approach is static, and many assumptions were made on an average use behaviour. Lelah et al.[90] used a Machine-to-Machine (M2M) enhanced PSS example (bring-in waste glass collection) to test a proposed methodology for LCA. The study highlighted the impact of PSS infrastructure on the environment and data exchanges. Unavailability of data sources, and not including the full inventory of the equipment used in the telecom structures and the pick-up trucks are the major drawbacks.

Table 1. PSS Examples and their environment impacts

PSS examples	**Environmental impact**	**Reasons**
Shared utilization of a clothes washing service[91]	Achieved a factor 10 reduction in water consumption by 2025	Efficiencies of scale and availability of skilled operators
Efficient wastage truck loading[90]	84% reduction in the category of global warming	Replaced materials (truck and fuel) and real-time information
Core plugs for paper mills[87]	Achieve a factor 10 reduction (90% decrease in Eco-indicator points)	Material change, and reuse and recycle options
Cleaning of building exteriors[87]	More than a factor of 10 reduction	Decrease in drying time due to new method which does not allow moisture to penetrate deep into the exterior wall
Soil compactors[87]	26% Eco-indicator points decrease	Material change and remanufacturing of parts
Bicycle sharing[89]	Difference of 78% comparative Eco-indicator points between use of a 'personal bicycle' and the combined scenario	Due to increase in bicycle robustness, maintenance, and bicycle redistribution

Although research into PSS assessment is gaining momentum, more concrete industrial case studies are required to gain more insight in this domain. Carbon emissions, energy consumption, resource depreciation rate, resources consumption, and Ecosystem quality system are some of the factors considered widely in PSS sustainability assessment.

The challenges in sustainability assessment are the following:

- Many research studies use sub-optimized solutions without covering the whole life cycle stages and involvement of multiple stakeholders. PSS assessment should be considered as multi-criteria decision-making (MCDM) problems to avoid sub-optimization.

- PSS solutions are assessed to understand environmental issues. However, support is required to make design alternatives that are environmentally friendly.
- Developing sustainable solution is an iterative process. Methodologies are needed to develop systems that are flexible enough to adapt to changes without major requiring updates.
- Most of the demonstrated sustainability assessments have limitations in terms of defining system boundaries. There are exclusions of important features which could have changed the assessment results. A system needs to be established to test validity of the sustainability results.
- Sustainability analysis, comparing the different stands/views taken by various stakeholders, is needed.
- A better support system is needed for defining and managing multiple variable types, especially uncertain variables.
- Although Table 1 demonstrates that all the purpose built environmentally friendly PSS strategies led to less environmental impacts, they were limited by the lack of completeness of the life cycle considered. There is a need to define a complete PSS life-cycle model.
- The quality relies on the availability of data. However, availability of data is a greater challenge in the PSS sustainability assessment.

6. Conclusions

This paper reviewed advancement in the following components required for designing PSS: PSS ontology, requirements definition, design process support for generating PSS concepts, and evaluation of PSS concepts. A phrases analysis among the PSS review papers revealed that although high level PSS terminologies are converging among researchers, there is a greater scope for improvement in the ‘life cycle’, ‘product and service’ and ‘infrastructure’ categories. Importantly, definitions and attributes of the term ‘value’ need to be unified. In most cases, PSS requirements definition disintegrates economic and environmental aspects. Currently, holistic PSS requirements definition by classification into various layers is a source of disagreements between researchers. The industrial environment is still giving priority to product requirements over service requirements. Integrated and substituting attributes between products and services are not adequately defined in requirements.

PSS design is a complex process where designers require much greater knowledge support. Although many knowledge assistance tools are proposed in the literature, the knowledge schemas used across researches are different. The differences are barriers to creating a unified knowledge PSS portal which could support learning from multi-disciplinary PSS examples, and facilitate easier knowledge update. This common schema could help in automatic acquisition required to develop PSS knowledge from various internal and external sources. The support system should equally focus on declarative and procedural PSS knowledge. PSS design methodologies should demonstrate innovative value creation in the system.

The protocol studies conducted required experts participations from various stakeholders involved in various layers of the value chain. These could clearly depict the roles and responsibilities of various stakeholders. Similarly PSS design methodologies should emphasise incorporation of societal change processes. Better support frameworks are required to transfer information and knowledge from PSS life cycle to PSS conceptual design. This will enable stronger collaboration, efficient resources management, increased reliability and performance. The emerging research areas such as developing smart and lean PSS need more impetus.

Although PSS domain emerged from the sustainability field, its development is not matured. This review provided an opportunity to develop stage gate evaluation processes of the whole PSS life cycle. The PSS evaluation domain need specific focus on feedback loops between stages. Incorporating *subjectively, uncertainty, vagueness, fuzziness, heterogeneity, incompleteness* and *fluctuation* in the requirements definition remains a challenge. Although various complex evaluation methods are proposed, their applicability to industrial practices needs to be established. Importantly, PSS efficiency needs to be defined and accepted across the PSS researcher community. Indeed most of the evaluation methods are limited by assumptions that had to be made due to unavailability of data, missing different scenarios, and dynamics involved in the PSS life cycle. The evaluations largely ignored influences of dynamics of information flows between stakeholders on PSS performances. The evaluation methods also need mechanisms to detect sub-optimized solutions in the offerings. Addressing the identified limitations will mature the PSS domain to achieve the intended aim to develop resource-efficient, sustainable, collaborative systems.

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Appendices Web link:

Appendix – 1 : https://goo.gl/0EUocj

Appendix – 2: https://goo.gl/eoMLu2