

## Product-Service Systems across Life Cycle

# Boundary objects for PSS design

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**Abstract:** In PSS design, hardware and service developers often have different objectives. Lacking to communicate and negotiate them across boundaries might lead to solutions unable to generate market shares and long-term profitability. This paper aims to contribute to the definition of ‘boundary objects’ that facilitate the sharing of knowledge between members of cross-functional teams engaged in PSS conceptual design activities. Empirical data are gathered from three case studies in the Swedish manufacturing industry to reveal how servitization affects early stage design decision-making, and how hardware vs. service trade-offs are negotiated and solved. The analysis of the findings points to four main trends to be considered when designing such objects in the realm of PSS. These are: an underlying model-based logic, the use of metrics based on customer value, the ability to quickly generate and assess scenarios, the use of non linear relationships to map PSS features vs. customer value.

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## 1. Introduction

The aftermarket phase of complex mechanical systems with long operating life is a major source of competitive advantage for companies [1]. New revenue streams may be generated by introducing services [2] to gain a closer relationship with customers [3] and to increase operational performances to a level not reachable by other means [4]. Increased servitization content means for manufacturers to include new objectives into their development projects, stretching and stressing the exiting requirements for the ‘hardware’ [5]. The latter, in turn, determines how revenue streams will be generated [6], how close customer relationships can be established [7] and how services will be planned and delivered to increase performances. For instance, aspects such as maintainability and supportability, which are critical to build profit during the in-service phase [8], are determined by the way the engineering characteristics of the physical system are set in an early phase.

A major problem in this integration is that hardware and service development often have different objectives [9]. For instance, installing a service door behind the engine and battery of a forklift truck may improve the accessibility of

these components for easy disassembly when the truck will be refurbished [5], but it will weaken the steel construction and so the stability of the truck in operation. Often, requirements related to support services - such as user training, customer consultancy, warranties and product upgrading - are considered late in the development cycle [6], as pure add-ons. Similarly, modularity, upgradability or re-manufacturability aspects are introduced when the design space is already constrained. Lacking to communicate and negotiate hardware and service objectives across boundaries can then lead to PSS solutions that are unable to generate value for the customer, and to ensure competitiveness and long-term profitability.

## 2. Objectives

The overall purpose of the research work is to develop decision support for the conceptual phase of PSS design. The objective of this paper is more specifically to explore needs and features for ‘boundary objects’ (BOs) [10] that can facilitate knowledge sharing among hardware and service developers. The paper initially collects objects and models used today to support cross-boundary discussion of problems and possible solutions. It further zooms into the PSS

conceptual design phase and presents empirical findings related to the following research questions:

- How does servitization affect the hardware design process and its outcome?
- How does servitization affect early stage decision-making in design?
- How are hardware vs. service trade-offs negotiated and solved in industry today?

Based on such findings, the paper identifies preferred directions for the development of objects able to increase the designers' awareness of the consequences of their conceptual design choices in the overall business eco-system (composed by products and services).

### 3. Method

Empirical data have been gathered by means of case study research [11], in collaboration with three Swedish manufacturing companies having experience with development and commercialization of PSS offers:

- Company A is a first tier supplier of aero-engine products that proposes different types of PSS-like offers in the military and civil markets.
- Company B is a construction equipment company investing in the development of integrated customer solutions alongside traditional financial contracts.
- Company C is a road construction equipment manufacturer that has experience with different types of bundled product-service offerings.

The primary mode of data collection was semi-structured interviews [11], with questions being modified or added according to the respondents' roles as far as the dialogue proceeded [12]. A total of 20 interviews with practitioners (both managers and designers) were conducted, recorded, transcribed and validated. Coding schemes [13] were used to categorize the empirical data into themes. Excerpts from the transcripts were coded by 'conditions', 'interaction among actors', 'strategies and tactics', and 'consequences', and later analyzed using a 'noting patterns technique' [12].

### 4. Objects to support cross-boundary discussion in PSS design

#### 4.1. Pure products

The requirements for a product are typically generated following product development [14] and Systems Engineering practices [15]. While functional requirements are directly related to the primary capability provided by the system-of-interest, non-functional ones relate to aspects like availability, supportability, security, and training. Service properties refer to the latter and take the form of, for instance, expected planned maintenance intervals on critical components.

The early evaluation of product concepts from a service perspective is often based on expert judgment. For instance,

engineers invite service technicians and aftermarket managers to give feedback on the accessibility of certain critical components on generated CAD models [16]. Service professionals often share with designers the assembly/disassembly times of these components to help defining the overall product architecture [17]. Serviceability aspects are later included in decision matrices, such as Pugh Charts [18] and Quality Function Deployment (QFD) [19], alongside other engineering characteristics to benchmark and down-select concepts.

Failure Mode and Effects Analysis (FMEA) and Failure Mode, Effects and Criticality Analysis (FMECA) [20] are popular techniques to further describe probability, severity and detectability of failure modes for all visible parts of a system. This qualitative information is used to balance hardware and service aspects and refine the product description. FMEA and FMECA are often complemented by more data-intensive methods, such as Fault Trees Analysis, Event Tree Analysis and Reliability Block Diagram [20]. These techniques, which are often described within the Reliability Centered Maintenance [21] or World-Class Maintenance [22] frameworks, model the interplay between serviceability aspects and hardware features. In a more detailed design phase, engineers refine hardware specifications to optimize service intervals. Probability theory and techniques such as Markov chains [23] are used at this stage to obtain the Mean Time Between Failure (MTBF) of critical components.

#### 4.2. Product-oriented PSS

Product-oriented PSS represent a move towards offering extended warranties and maintenance contracts alongside the physical artifact. Several techniques derived from the product domain, such as QFD [24], are used to link service aspects with the product engineering characteristics. Requirements assigned by service managers to hardware developers are emphasized in the process, compared to pure products. For instance, sub-systems may need to be redundant if it is believed that the additional hardware costs will be lower than the expected warranty costs. A main reason is that every unit of hardware repaired, returned or replaced during the warranty period becomes a loss for the manufacturer. Warranty Management Systems [25], showing historical records such as warranty claims on previous components, are used to complement the information captured by traditional decision matrixes. These models are created using statistical analysis, probability theory and simulation techniques [26]. Being data-intensive and requiring constant updates, they are more effectively used for optimization studies in the later phases of the design process [25].

#### 4.3. Use - and Result-oriented PSS

When manufacturers take total responsibility for delivering 'usage' and 'functional result', the requirements definition process becomes more dynamic because needs evolve depending on the customer's own changed environment [27]. Previous contributions show that usage- and hardware-related requirements are virtually impossible to generate

simultaneously [5], because the new service solution may not be yet defined during the early conceptual design phase [28]. The company business model is used as reference object to establish a dialogue between the service and hardware domains. Process modeling techniques, such as Integration DEfinition for Functional modeling (IDEF) [29,30], represent a first attempt to establish a common visual platform for integrating and negotiation objectives. It is only later in the design process that engineers begin estimating the cost of a PSS [31]. Cost modeling tools - such as DMTRADE, PREDICTOR, PREVIEW and MEAROS [32] – are common to support trade-off discussion within the company and with customer and suppliers [28]. Still, they require detailed cost information not typically available during the conceptual design stage. When the offering is more defined, the business solution is engineered applying methodological approaches developed in the area of service engineering [33], while hardware engineers continue with reliability optimization typical of traditional engineering practices. Business process optimization is further obtained using business simulation techniques [34,35].

#### 4.4. Pure service development

Crafting relationships, resources and activities to increase customer value proposition [36] is a major task in the development of ‘pure’ services. First step in this process is the analysis of customer/stakeholder interactions with the system elements, to translate needs and expectations into early requirements for the service. Scenario Based Design [37], and Use Case Diagrams [29] are main enablers to map current interactions, define new service requirements and visualize alternatives. After passing this first screening, scenarios are detailed by means of diagrams showing the flow of activities and their feedback loops/iterations [38]. Techniques such as Service Blueprints [39] are used to keep control of relations between customer activities and supporting activities (the ‘back office’), to make evaluations and to solve trade-offs prior to the testing phases.

These modeling efforts are followed by more analytical assessments informing the choice of the new service layout. Service FMEA provides a first qualitative screening of new service ideas [40]. The principles are the same as traditional FMEA used in mechanical design, but the evaluation also concerns those failures caused by the more intangible nature of the service (e.g., lack of trained personnel). The use of Discrete Event, Systems Dynamics, Agent-Based [35] or Bayesian Networks simulations [41] is further proposed to detect emerging system behaviors and associated service failures.

### 5. Interactions in PSS design: findings from the empirical investigation

#### 5.1. How does servitization affect the hardware design process and its outcome?

One of the most evident changes driven by servitization is related to the new definition of ‘system’. As highlighted by

one of the respondents at Company B, the physical product (i.e., the ‘construction equipment’) is not longer considered as the ‘system’; rather it is an asset within a much larger system, which is the ‘construction site’:

*“It’s a new technology area, for us within [the company] and also for the complete industry... And that is to see machines as units within a production site, within a production cycle.”*

Engineers do not longer design stand-alone machines. Rather, hardware design is approached from the perspective of building an ecosystem, where all machines are connected to each other (e.g., a loader to an excavator) to work as producing units within the complete chain. This adds complexity and asks teams in different functions to work more interdependently. Coordination is challenged by the different life cycles for hardware, software and service. At Company A it might take several years for new technologies to be fully developed, tested in lab, validated and ready to enter into the market. Hardware requirements generated in the beginning of a project quickly become ‘old’ from a software viewpoint. Also, service development focuses on short-term outcomes, measured in weeks and months, while technologies require longer time to mature from simple ideas to complete products. An agile development process for hard and soft products, with shorter development loops, is believed to be critical for the successful integration of hardware and service aspects.

PSS offers also stress the importance of commonality and interoperability between different product platforms, and even with competitor products. Respondents at both Company B and C acknowledge that historically it has being difficult to generate successful solutions across platforms. Commonality means generating gains on certain machines, while losing money on others. Modularity and openness often mean that off-the-shelf solutions shall be preferred, but this exposes the company to the risk of using the same components as competitors use, reducing differentiation. This highlights the importance of taking well-aware make-or-buy decisions. Off-the-shelf parts might also expose shortcomings in the business model. For instance, PSS providers might not be able to fully support machine parts purchased from third parties; hence customers might need to redirect his/her claims directly to the supplier. A related dilemma concerns the opportunity to allow third-party operators to develop additional software features. This is considered both a threat (risk of losing control of how the machine is operated), but also an opportunity to provide additional value to customers by enabling customization.

#### 5.2. How does servitization affect early stage decision-making in design?

Company B showed that concept development for a new ‘system’ that encompasses hardware and soft products can last between 8 to 12 months. Within this timeframe, a number of concepts are iteratively generated and up to 15 ‘events’ are organized to select and de-select design options. Harvesting ideas and opinions across disciplines and roles is critical in these events for successful decision-making. One of the respondents exemplified the importance of the inputs that come from different parts of the organization (e.g., salesmen,

dealers, customer support) pointing to an oil specialist that recognizes the opportunity of introducing a more expensive and performing lubricant as a way to lower the machine total cost of ownership. The same suggestion might come from customer service technicians, who realize that oil replacement is one of the highest costs in service contracts, and thus proposes to stretch service intervals by using oil with higher characteristics. In spite of their power, such networks are found not to be fully deployed today, and knowledge sharing to be impeded by lack of representations able to convey knowledge about the multifaceted aspects of the PSS.

Zooming into these decision-making events, companies acknowledge that the activity of trading-off service requirements against more technical ones is challenged by the unbalanced decisional power between design teams. The technology team is often the one responsible for budget allocation, and takes the final decision in terms of project prioritization and kick-off. In the design process, the performances of the physical hardware often have higher priority compared to aftermarket considerations, which tend to be overlooked when down selecting solutions. In practice, most of the dialogue about new soft products concerns breaking down the service proposition and analyzing its impact on the machine performances and cost together with the technology team. This is explained by looking at the level of maturity of the market for customer solutions. Respondents at company C acknowledged that while some markets are more mature to pay for bundled products and services, others are acquainted with the traditional product-oriented model; hence they perceive services as natural add-ons for a machine. Often customers expect service costs to be already included in machine price tag. This makes it difficult for the manufacturer to prioritize a service-oriented business case, because the return on investment might be limited. Hence, within the design team, a great deal of work is dedicated to internally ‘sell’ ideas related to new soft products, especially when they affect the way hardware is designed.

Respondents pointed out that this phenomenon is also related to the way performances are measured within the organization. While the service development team is measured against the revenue generated on the aftermarket, the hardware development team is measured against cost saves. Engineering the PSS means radical changes in the way the machine is designed: in turn, this means more engineering hours and likely more costly features. Even if PSS gives a sense of generating revenues in the aftermarket, projects might be stopped because being over the threshold for what concerns development costs.

### 5.3. How are hardware vs. service trade-offs negotiated and solved?

Observations show that a list of generic product and service requirements is used as input to trade-off discussion meetings, together with textual documents complemented with diagrams and pictures. This material contains a short description of the overall idea, of the market situation and of the business case. Only in a later phase it evolves into a more structured and mature document detailing the business opportunity. Still,

service and product descriptions are often captured by separate documents. In the next maturation stage, service roadmaps and blueprints are detailed and used as main reference in the work.

Demonstrators follow these textual descriptions to allow potential stakeholders to have a more ‘touch and feel’ experience with soft products. This helps in growing a common understanding on what the proposal is about, and in realizing the trade-off between the value added to the customer process (e.g., achieving a 10% increase in productivity) and the effort/cost needed for the development of the required solution. A main reason for using demonstrators is that service development is approached in a more trial and error mode compared to the design of a new technology. This is because quantifying achievements and setting objectives for service provision is not as straightforward as in mechanical engineering (where, for instance, a 5% higher torque or 2% lower fuel consumption can be directly measured). To understand the benefit of a new soft product, engineers have to test them in scaled down scenario and use the feedback from the exercise to elaborate arguments on why and how it should be launched.

Respondents at Company C exemplified this problem looking at how engines are designed to ensure serviceability. In order to minimize hardware costs, critical components might need to be installed very deep into the engine architecture. This might significantly reduce the availability of the machine: the engine will need to be completely disassembled every time inspection and maintenance activities are needed, an operation that takes several days and requires skilled operators. The installation of an easy access mechanism would significantly reduce service time, but brings with it additional hardware costs, which are reflected in the final product price. In order to solve such trade-off, engineers need information about what customers value most in this context, and how they rank-weight ‘hardware cost’ in comparison with ‘serviceability’. Some customer segments might be appealed by the latter, others might prefer the first option because more sensitive towards the price tag.

Resources allocated to install the easy access mechanism might also be used to improve serviceability in other areas of the machine, and it is not at all intuitive to assess which is the optimal direction to go. To solve such trade-offs, it is necessary to look back at those criteria that reflect what customers value in a solution, defining appropriate metrics that reflect activities in the customer process. The empirical study further shows that setting such metrics is far from being an intuitive task, mainly due to the problem of showing number and ‘hard facts’ related to the performances of soft products, as explained by a respondent at Company A:

*“If you do not have a trade factor between two things, then it is my experience that the one with a number on wins... If we cannot set a quantitative measurement for something during conceptual design, it simply goes away. When talking about qualitative measurements there is a tendency to ignore them.”*

## 6. Reflections on building BOs for PSS design

Many objects and models have been found to stretch from the pure product/service domains into the PSS one (Figure 1).

However, coming from opposite ends, they are not likely to be perceived as a ‘shared space’ by practitioners, reducing their effectiveness as BOs [10].

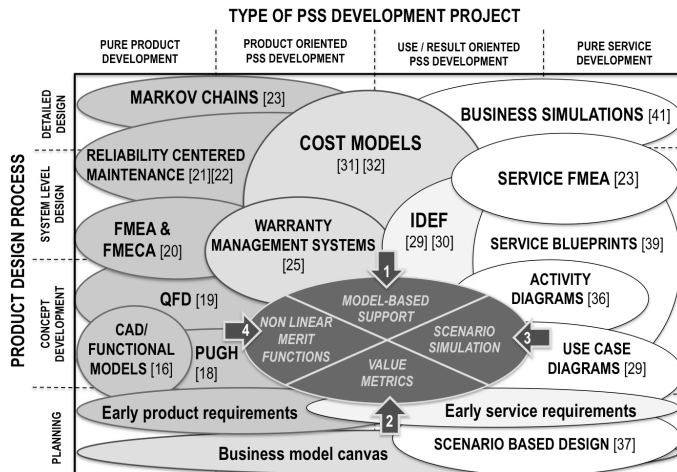


Fig. 1. Objects supporting cross-boundary discussion in PSS design.

Effective BOs use a shared syntax to facilitate a process where individuals transform their knowledge and learn about dependencies (and specify differences) across the organizational boundaries [42]. Existing representations stick rather to their own domain-specific syntax: this suggests that one group (e.g., service designers) feels more at home than the counterpart, which might find it difficult to engage in the discussion. To become a “good communicative device across” [10] and serve as basis for conversation and knowledge sharing, PSS representations shall not demarcate any real territory but rather “sit in the middle”. Furthermore, ‘true’ BOs change into infrastructure and methodological standards as they move back-and-forth between cooperating groups [10]. It should then be possible for individuals to adjust them to their own needs, and translate these inputs into a description that can support work that is not interdisciplinary. Looking at existing support, functional models and decision matrixes vs. scenario descriptors and blueprints, room for improvement exists in the creation of design support able to leverage cross-boundary negotiation in early stages of the PSS design process. Four main development trends can be synthesized from the empirical study findings (Figure 1).

- 1) Model-based support: industrial observations show the importance of model-based thinking for successful decision-making. A clear trend is also seen towards frontloading engineering design activities with both physical and virtual models. However, a gap is observed in the way engineering models today are closely coupled to the knowledge for solving specific problems (e.g., in the hardware domain they are bound to geometry modeling). From a collaboration point of view, engineers struggle to exploit the results of their models outside their specific discipline, and this translates in decision makers being often unable to get the big picture of how a design can contribute in satisfying customer and stakeholders needs.
- 2) Value-based metrics: previous research [43] identified ‘perception of value’ as one of the 6 boundary conditions for PSS design, pointing to the need for the development

task to come much closer to understanding value perception that a traditional product context. The creation of an overarching cross-system value-based metrics, which captures customer activities and business concerns, becomes appealing for the development team to elaborate on the impact of solution options beyond technical performances and cost aspects. The empirical study shows that the introduction of such metrics addresses two issues. Firstly, it provides a common denominator for value, creating an entity that can be dispatched to concerned stakeholders. Also, it addresses the problem of progressive opacity of intent and rationale behind the requirements description, which manifests as far as the system is detailed in its sub-systems and components. This is advocated to raise designers’ awareness of the consequences of their choices during the design synthesis stage, when critical decisions are made, and hence to support more explorative design activities.

- 3) Scenario simulation: value scales change over time and are dependent from the specific environmental conditions experienced by customers. Hence, early stage models shall account for such change and illustrate the dynamic of value provision. Scenario simulations can be used then to assess the ability of a solution to deliver value along the lifecycle of a system. Learning is critical aspect in this activity. Aggregation of unpredictable design information in an early stage may give a false impression of precision; hence the real purpose of the simulation shall be to get to know the behavior of the system, rather than to ‘engineer’ it. Therefore, the object shared between the cross disciplinary team shall support quick what-if analysis of scenarios to identify emerging behaviors and trends.
- 4) Non-linear merit functions: different types of matrices can be used to map PSS features against value generation, in the different scenarios. In PSS these relationships are likely to be more complex than in pure product/service design. While nowadays most of the existing mapping approaches exploit linear relations, such as in the House of Quality, dependencies between hardware/service combinations and customer value are found to be less straightforward. The Service Engineering domain has recently proposed ‘Receiver State Parameter’ [44] and ‘Satisfaction-Attribute Function’ [45] to capture the relationship between quality and customer satisfaction. A main feature of these constructs is that they do not apply a linear logic in the mapping. This suggests expanding QFD mathematics with concave and convex functions to both incorporate a Kano logic [46] and to better communicate the complexity of trade-off activities and the rationale for value provision.

## 7. Conclusions

BOs serve multiple purposes in PSS design. By facilitating cross-boundary discussions they improve service and hardware designers’ ability to contribute with innovative content to the definition of total solutions. Also, they reduce the amount of re-work that originates from misinterpretations

of requirements (both related to hardware and service) and sub-optimal designs. This paper contributes to the definition of meaningful BOs for PSS design. It highlights 4 main trends that shall be considered when creating support to be used across boundaries to improve early stage decision-making dealing with the development of total offers.

Current and future work concerns the application of these models in the early phases of PSS design to gather lessons learned about their ability to facilitate cross-boundary discussion. This phase also features the development of an experimental approach (experimental setup, metrics for assessment and related coding scheme for evaluation) for assessing the effects of using value models in the analysis and synthesis phase of conceptual PSS design [47].

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