Artificial Intelligence for Engineering Design, Analysis and Manufacturing

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Research Article

Cite this article: Sakao T, Gero J, Mizuyama H (2020). Analyzing cognitive processes of a product/service-system design session using protocol analysis. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **34**, 515–530. https://doi.org/10.1017/S0890060420000402

Received: 6 May 2019
Revised: 30 August 2020
Accepted: 1 September 2020
First published online: 17 September 2020

Key words:
conceptual design; design behavior; design cognition; design process; product/service systems

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Analyzing cognitive processes of a product/service-system design session using protocol analysis

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Abstract

Product/service systems (PSSs) are increasingly found in markets, and more resources are being invested in PSS design. Despite the substantial research into PSS design, the current literature exhibits an incomplete understanding of it as a cognitive activity. This article demonstrates that the methods used to analyze product designers' cognitive behavior can be used to produce comparable and commensurable results when analyzing PSS designers. It also generates empirical grounding for the development of hypotheses based on a cognitive study of a PSS design session in a laboratory environment using protocol analysis. This study is a part of a larger project comparing PSS design with product design. The results, which are based on the function–behavior–structure coding scheme, show that PSS design, when coded using this scheme, can be quantitatively compared with product design. Five hypotheses were developed based on the results of the study of this design session concerning where and how designers expend their cognitive design effort. These hypotheses can be used to design experiments that test them and provide the grounding for a fuller understanding of PSS design.

Introduction

Manufacturers in developed countries regard service activities as increasingly important (Meier *et al.*, 2010; Baines *et al.*, 2017). Some manufacturers earn more than half of their revenue from services [e.g., aerospace by Rolls-Royce (2019)]. Here, services include monitoring, inspection, operation, maintenance, repair, upgrade, overhaul, take-back, training, and consultation. Furthermore, some manufacturers are even strategically shifting from being a "product seller" toward a "service provider". One reason is that they face intense competition from manufacturers selling lower-priced products. Along with this trend, the product/service system (PSS) (Morelli, 2003; Roy and Baxter, 2009) is much debated as a promising concept for a design object in academia as well as the industry (Eisenbart *et al.*, 2017; Brambila-Macias *et al.*, 2018). Many manufacturers are shifting toward service provision while continuing to design and deliver products. A definition of a PSS is "tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs" (Tischner *et al.*, 2002).

According to the definition above, in designing PSSs, both services and products are addressed as part of the design object, which has been often dominated by physical products in manufacturing industries. Here, the design of the service may substantially impact the PSS design process (Hubka and Eder, 1987; Visser, 2009). Considerable research effort has been expended to understand PSS design (Morelli, 2003; Bertoni, 2013; Sakao and Mizuyama, 2014) and to develop support for designers of PSSs (Alonso-Rasgado *et al.*, 2004; Komoto and Tomiyama, 2008; Medini and Boucher, 2019). There are, however, insufficient insights based on empirical research into how PSS design is carried out, and there is only a handful of descriptive studies of the processes in the conceptual design of a PSS (Sakao *et al.*, 2011; Bertoni, 2013; Sakao and Mizuyama, 2014; Shimomura *et al.*, 2015). Compared to product design (Purcell and Gero, 1998; Kannengiesser and Gero, 2015; Hay *et al.*, 2017), an empirically based understanding of PSS design processes is underdeveloped. Currently, it is not possible to answer whether designing PSSs is different from designing products, and, if so, how it is different based on empirical evidence. Even how to investigate and present differences is not available in the literature.

Motivated by this gap in our knowledge, the research reported in this article aims to demonstrate that the methods used to analyze the cognitive behavior of product designers can be used to produce comparable and commensurable results when analyzing PSS designers. The research adopts the approach of an exploratory case study to do so. It analyzes the design

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Table 1. Key PSS properties and characteristics and their implication on its conceptual design

Property	Characteristic	Implication for conceptual design of PSS
Open process systems	Human activities (Alonso-Rasgado and Thompson, 2006) Heterogeneity (Regan, 1963) Uncertainty (Erkoyuncu *et al.*, 2011) System architecture System components System behavior (INCOSE, 2015) Inputs and outputs Processes and functions	Apply systems thinking (Baines *et al.*, 2007) Integrate the product and service views (Trevisan and Brissaud, 2016) Analyze behavior as a system Consider uncertainty (Erkoyuncu *et al.*, 2011)
Business model	Nature of business Value proposed (Sakao and Shimomura, 2007) Customer orientation (Tukker and Tischner, 2006) Performance of asset (Alonso-Rasgado *et al.*, 2004; Baines *et al.*, 2007) Available resources	Consider business model Analyze customers (Sakao and Shimomura, 2007) Include value proposition (Morelli, 2003; Isaksson *et al.*, 2009) Consider system performance Consider service personnel
Social construct	Actors' roles and scenarios Technological and socio-cultural interactions (Morelli, 2003) Relationship between customer and provider (Baines *et al.*, 2007)	Analyze actors' roles Analyze scenarios Apply co-creation process (Morelli, 2003; Alonso-Rasgado *et al.*, 2004; Baines *et al.*, 2007; Smith, 2013)

Note: The three properties are taken from Durugbo *et al.* (2011), while the characteristics adopt those in Durugbo *et al.* (2011) and others added by the authors with references. The implication for PSS conceptual design comes from the authors' own elaboration.

process of a PSS design case in a laboratory environment in depth using protocol analysis (Ericsson and Simon, 1993). The primary outcome is formalized as a set of hypotheses to be tested by analyzing multiple cases using the methods articulated in this research.

The remainder of the article is structured as follows: Section "Research motivation based on the literature analysis" presents the knowledge gap in existing research by reviewing the key literature; Section "Purpose, goal, and research focus" describes the purpose of this article, the research question, and the research focus; Section "Method" describes the approach and research methods; Section "PSS design case" presents the PSS design case; Section "Results of analyzing the design session" shows the results of the analysis; Section "Discussion" discusses the analysis to produce hypotheses; and Section "Conclusion and future work" concludes the article.

Research motivation based on the literature analysis

Overview of the PSS literature

For more than a decade, interest in the type of offering called a PSS has grown, especially in the manufacturing industry, and, as a result, both theory and practice for the PSS design have evolved (Oliva and Kallenberg, 2003; Baines *et al.*, 2007; Sakao *et al.*, 2013). The existing literature about this integration of products and services suggests classifications, methods, and strategies for PSSs, but they tend to be generic in terms of insights provided (Tukker, 2015). The rest of the section "Research motivation based on the literature analysis" analyzes the literature on PSSs to derive their characteristics, which are substantially different from those of products. It further analyzes the literature on PSS design to show the incompleteness of its conceptual design knowledge.

Characteristics of PSSs

Characteristics of PSSs based on a literature review from the perspective of information flows (Durugbo *et al.*, 2011) are adopted here, and more characteristics are added from the design perspective, as seen in Table 1. There, the characteristics are identified, and their implications for the conceptual design of PSSs are presented.

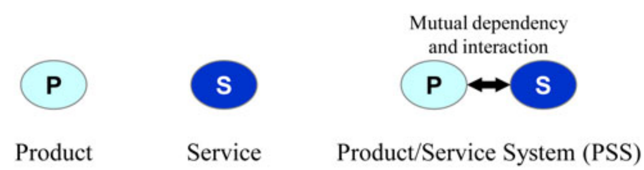

Fig. 1. A PSS depicted with the interdependency between its product and service, in comparison with its product and service parts standing alone.

The first property of a PSS is *open process systems*. This means that the PSS is a system with input and output flows in the following sense. Output flows are determined by processes and functions in the PSS, which involve human activities (Alonso-Rasgado and Thompson, 2006) characterized by heterogeneity inherited from the generic characteristics of pure service (Regan, 1963). The processes in PSSs also involve product behaviors that change over time due to, for example, deterioration. The service heterogeneity and the product change over time are both uncertain (Erkoyuncu *et al.*, 2011). In addition, a PSS's architecture, as seen in Figure 1, is a system characterized by interdependency between product and service components (Meier *et al.*, 2010) and thus the interaction between them (Komoto and Tomiyama, 2008). A more complete description of system behavior can be found in INCOSE (2015).

The next property is *business model*, which takes into account the nature of the businesses involved in the product and service. The business model is often defined to include the value as its crucial construct (Osterwalder *et al.*, 2010; Mason and Spring, 2011). Therefore, the value is proposed as an important characteristic of PSSs (Sakao and Shimomura, 2007). In addition, customer orientation is a PSS characteristic (Tukker and Tischner, 2006). As customer value often lies in the performance of a PSS as well as its products and services instead of the ownership as

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such (Alonso-Rasgado *et al.*, 2004; Baines *et al.*, 2007), the performance of a system is relevant as well. The performance depends on available resources such as service personnel, which are, therefore, a relevant characteristic.

The last PSS property is *social construct*, involving more actors in terms of roles and scenarios than in a pure product. For instance, technological and socio-cultural interactions are relevant (Morelli, 2003). Furthermore, Baines *et al.* (2007) assert that the relationship between the customer and the provider is an important characteristic of relevance.

Characteristics of PSS design and previous research

This section describes PSS design characteristics that are implied from the characteristics of PSSs in Table 1, and key references that show research related to the characteristics of PSS design. The PSS property of open process systems in Table 1 means that the conceptual design of a PSS requires simultaneous and interacting product and service design (Meier *et al.*, 2010) and, therefore, is potentially more complex than that of its product or service parts alone. This implies the need for systems thinking (Baines *et al.*, 2007). For designing a system, behavior as a system needs to be analyzed. The behavior of elements is relevant to design in general (Love, 2000); however, the system property of the PSS makes the behavior as a system especially relevant in the conceptual design of PSSs. Furthermore, the uncertainty mentioned in the section "Characteristics of PSSs" needs to be taken into account in conceptual design.

To cope with these characteristics, research modeling PSSs have been reported for developing computer-aided design (CAD) software for PSSs (Sakao *et al.*, 2009) as well as a computer tool for PSS engineering with UML (unified modeling language) (Medini and Boucher, 2019). In particular, functions in design have been researched with comparisons, including PSSs and products (Erden *et al.*, 2008; Eisenbart *et al.*, 2013). A computer tool to analyze the behavior of PSSs has been put forward using life cycle simulation (Komoto and Tomiyama, 2008). In addition, a tool to address uncertainty in cost for the design and delivery of PSSs has been proposed by Erkoyuncu *et al.* (2011). Furthermore, a method to address failures in PSS design has been suggested (Kimita *et al.*, 2018) by extending the failure mode and effect analysis for product design (Stamatis, 1995).

PSS design is expected to consider a business model, as shown in Table 1. More particularly, PSS conceptual design will involve value propositions for various actors, including customers (Morelli, 2003), and thus, analyzing the actors is crucial (Sakao and Shimomura, 2007). Further, the performance of a system and availability of service personnel should be considered.

Research on business model development for PSSs is reviewed in Boehm and Thomas (2013), Lewandowski (2016), and Qu *et al.* (2016), and a design process model for PSSs, including a value proposition, has been proposed by Morelli (2003). The PSS design process proposed by Alonso-Rasgado *et al.* (2004) also incorporates business model aspects such as markets, partnerships, and agreements. In addition, applied research addressing business models on PSS design in the context of sustainability has been reported, for example, in Calabrese *et al.* (2018). Analyzing customers for PSSs using the Persona concept has been proposed by Sakao and Shimomura (2007). Further, a method to appropriately select human resources for PSSs has been proposed by Shimomura *et al.* (2013).

The social construct property means the need to analyze more actors' roles and scenarios and implies that co-creation between customers and a provider may be particularly useful in PSS design. The relevance of co-creation in PSS design is confirmed with the practical case of Rolls-Royce (Smith, 2013)[1]. In general, this implies the importance of addressing the contexts in the industry practice, where the PSS design is performed (Sakao, 2019).

The design object model for PSS by Maussang *et al.* (2009) and the PSS design process model by Morelli (2003) consider the social construct and incorporate interaction between different actors, such as customers and a provider. Co-creation is centered in the integrative PSS design approach consisting of exploration, creation, prototype and testing, and planning implementation by Costa *et al.* (2018). A PSS design framework that includes a context-sensitivity analysis tool that uses feedback from sensors and humans to produce useful information for designers has been proposed (Mourtzis *et al.*, 2018).

The brief review in the section "Characteristics of PSS design and previous research" is organized according to the three major PSS characteristics explained in the section "Characteristics of PSSs" and in line with the five facets of PSS design (Sakao and Neramballi, 2020), which were synthesized from multiple previous review articles. Facet 1, Development and integration of system elements, and Facet 2, Examination of the balance of the integration, are implied by the systems thinking in PSS design; see the implications from the open process systems property in Table 1. Facet 3, Value propositions, and Facet 4, Functionality-oriented designing, are covered in the business model property in Table 1. Facet 5, Identification of relevant actors along the life cycle of PSSs, is implied by the social construct property in Table 1. Therefore, this concise review is considered to cover most of the major PSS design characteristics in the literature.

Gap in the literature on the PSS design process

Previous research can be classified into prescriptive and descriptive studies. The prescriptive models and methods intended to be used for supporting PSS design have been developed largely based on reasoning using existing design theories and methods for product or service design (Alonso-Rasgado *et al.*, 2004; Sakao *et al.*, 2009; Kimita *et al.*, 2018). On the other hand, descriptive studies mostly report insights on PSS design at the macro level, for example, design stages and gates. For example, Morelli (2003) described a PSS design process in an industrial environment as an iterative sequence of phases in which problems generate solutions, which, in turn, redefine new problems. Regarding the micro level, for example, individual designer's actions and information addressed, there is a small but growing body of literature with empirical results of actual PSS design processes in laboratory environments. For instance, Sakao and colleagues (Sakao *et al.*, 2011; Sakao and Mizuyama, 2014) carried out protocol analysis of a PSS design and showed that life cycle activity is a central notion addressed within the design case. A protocol analysis of PSS design sessions was performed to

[1]Smith (2013) provides the results of a longitudinal study of, among other things, how the performance-based contract with aircraft engines was developed, offered, signed, and renewed individually with the US Navy. This co-creation process was supported by improving maintenance quality and performance reliability that met the US Navy's expectations of Rolls-Royce.

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investigate the effects of a specific feature in CAD software (Bertoni, 2013). This earlier research gives some indication of the characteristics of PSS design processes; however, none of them answers whether the PSS design is different from product design at the micro level, and, if so, what are the differences. Even how to investigate and present differences is not available in the literature.

Purpose, goal, and research focus

The purpose of this article is to provide foundations for adding to the understanding of PSS design by generating empirical grounding for the development of hypotheses. The goal is to demonstrate that the methods used to analyze the cognitive behavior of product designers can be used to produce comparable and commensurable results when analyzing PSS designers. The research reported in this article focuses on conceptual redesign in PSS design for the following reasons. First, conceptual design is less well understood than other aspects of design and requires further research. Second, conceptual design in PSS design, where a realization structure for a purpose is not necessarily fixed as a product or service, is peculiar to the PSS design (Sakao and Lindahl, 2015). Once each realization structure is determined as either a product or service, design will then be more like that of a pure product or service, about which more insights are available. Thus, it is more useful to research conceptual design in PSS design. The primary research question is as follows:

Which ontologies and metrics are useful to compare the conceptual design of PSSs with that of products?

Method

Motivation for choice of the approach and method

The research question is abstract, and thus, the approach of an exploratory case study (Yin, 2006) is adopted to ensure a methodological fit. Although the use of case studies does not produce statistically significant results, it provides an opportunity to explore and study an event as it actually occurs (Yin, 2006), and the result is expected to help fill the identified knowledge gap. In addition, a case study is useful in formulating a hypothesis by using such approaches as pattern matching, explanation building, addressing rival explanations, and using a logic model (Teegavarapu *et al.*, 2008). Case studies have been conducted in engineering design research to gain insight into design processes that cannot necessarily be obtained in other ways (Ahmed, 2007; Breslin and Buchanan, 2008).

Adopting an industry case study as the research method for this research may not be satisfactory for PSS design because such a case in the industry is often affected by issues from pragmatic aspect such as non-optimal organizational settings and thereby does not exploit its full potential (Matschewsky *et al.*, 2018). Such circumstances create a critical disadvantage for using an industry case study for this research and, therefore, a laboratory case study was used. This choice reduces multiple confounding variables found in the industrial practice of PSS design (Matschewsky *et al.*, 2018). A design case in a laboratory environment has the potential to directly generate the information we need about PSS design. Interaction with other actors than designers (e.g., customers) is not addressed in this study. However, most of the implications for the conceptual design of a PSS in Table 1 are addressed.

This research adopts protocol analysis as the method to provide empirically based quantitative evidence and rich qualitative information. Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking (Ericsson and Simon, 1993; van Someren *et al.*, 1994). It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers, including exploratory studies (e.g., hypothesis generation) (Atman and Bursic, 1996; Kan *et al.*, 2007; Kan and Gero, 2018) and hypothesis testing (Mc Neill *et al.*, 1998; Christensen and Schunn, 2007; Kannengiesser and Gero, 2015). There have also been recent reviews with insights from protocol studies about methodological aspects (Dinar *et al.*, 2015) and processes in conceptual design (Hay *et al.*, 2017). Using both quantitative and qualitative information is complementary since the interpretation of statistical analyses may be enhanced by a qualitative narrative account (Robson, 2002).

Protocol analysis involves the following activities (Kan and Gero, 2017):

- videoing of participants,
- transcription of verbalizations,
- segmentation and coding of transcription,
- arbitration of coding, and
- statistical analysis of coded protocol.

FBS (function–behavior–structure) ontology

Overview

In carrying out a protocol study, this research makes use of a method for determining and describing design cognition, based on the function–behavior–structure (FBS) ontology (Gero, 1990). This is a design ontology that is independent of the design task, the designer's experience, and the design environment, and hence produces commensurable results from different experiments (Gero, 2010; Jiang, 2012; Gero and Kannengiesser, 2014; Song, 2014; Kan and Gero, 2017). It is, therefore, suitable for use in comparing PSS design with product design. The FBS ontology provides a uniform framework for classifying cognitive design issues and cognitive design processes, as depicted in Figure 2, and includes higher-level semantics in its representation. Higher-level semantics, such as problem space and solution space, can be

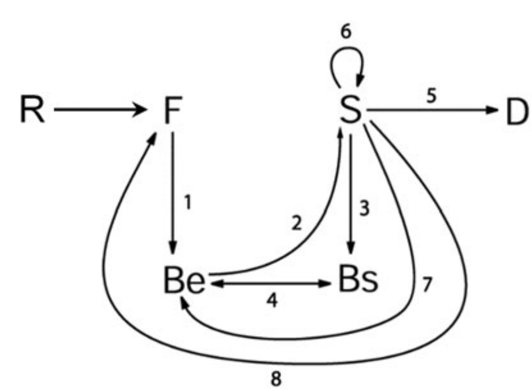

Fig. 2. The FBS ontology with its consequential ontology of design processes, labeled 1 through 8 (Gero, 1990; Gero and Kannengiesser, 2004).

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Table 2. FBS design issues applied in the PSS and product design contexts

FBS design issue	Explanation	PSS design context	Product design context
Requirement (R)	What is required by the client	Needs stated by the client	Needs stated by the client
Function (F)	What it is for	Client's needs as interpreted by the designers and those added by the designers Values	Client's needs as interpreted by the designers and those added by the designers Values
Expected Behavior (Be)	What it is expected to do	Life cycle activities Product's behavior	Product's behavior
Structure (S)	What it is	Core product Peripheral product Actors Contract elements (in documents) Payment model	Product
Structure Behavior (Bs)	What it does	Life cycle activities Product's behavior	Product's behavior
Document (D)	What it is documented as	Contract Sketches Deliverables (e.g., service manual)	Sketches Models

derived directly from the FBS representation. The design issues are *requirements* (R), *function* (F), *expected behavior* (Be), *structure behavior* (Bs), *structure* (S), and *documents* (D). The processes are in the ascending order of the numbers shown in Figure 2: *formulation* (R→F→Be), *synthesis* (Be→S), *analysis* (S→Bs), *evaluation* (Be→ Bs or Bs→ Be), *documentation* (S→D), *reformulation* 1 (S→S), *reformulation* 2 (S→Be), and *reformulation* 3 (S→F). The rationale of the issues and processes are found in Gero (1990).

Interpretation and use of the FBS scheme

A match between the design issues in the FBS scheme and frequently addressed dimensions in PSS design is shown in Table 2. There is no commonly agreed-upon set of dimensions for PSS as a design object, so the dimensions by Müller *et al.* (2009) are adopted as a base. The dimensions, which are intended to represent the design rationale, are needs, values, deliverables, life cycle activities, actors, core product, peripheral product, payment model, and contract (Müller *et al.*, 2009). These dimensions are a set of mutually exclusive elements of a design object, and they are suitable as a support when applying the FBS ontology to the PSS design context. Note that they are different in nature from the characteristics and properties used in Table 1 (Durugbo *et al.*, 2011).

This matching is used as a basis for the protocol analysis, where the designers' utterances are segmented and coded using the FBS design issues. For example, as shown in Table 2, an utterance is coded as Expected Behavior (Be) or Structure Behavior (Bs) when it concerns a life cycle activity such as repairing a faulty part of a core product of a PSS in question or behavior of a product such as deterioration of a core product's quality, depending on whether it refers to expectations or performance. Table 2 also shows how the FBS design issues are applied in the product design context. High commonality is found between PSSs and product design, while several items are found only in PSS design. This is a consequence of the enlarged design object in the case of PSS design, as depicted in Figure 1. The results from an FBS-coded protocol can be measured in multiple ways to provide foundations for comparing PSS design with product design. This research uses the following quantitative measures:

- Tabular statistics: this produces the statistical distributions of the system levels (see Section "System levels in PSSs and products for an FBS design issue"), the design issues and the design processes, and thus provides quantitative measurements of where designers' cognitive design effort is expended. This can be visualized with cumulative graphs (see Section "Cumulative occurrences, graphs, and their shapes").
- Problem-solution index: this is a macro measure that describes whether the designers are spending more of their cognitive design effort on the problem or the solution across time during the design session (see Section "Problem-solution index").

System levels in PSSs and products for an FBS design issue

A PSS is a kind of system and is composed of products and services. As system design concerns the system or component levels, PSS design concerns the level of the whole PSS or the level of products or services in a segment in a design episode. A product is also a system, and previous research using protocol analysis adopted the system level for analyzing the cognitive behavior: the levels of a product are differentiated between the whole system and the subsystems of the whole product (Mc Neill *et al.*, 1998; Song *et al.*, 2016). In the case of the PSS, the subsystems are either products or services. These levels are applicable to any design issue in the FBS scheme, as shown in Table 3.

Cumulative occurrences, graphs, and their shapes

The cumulative occurrence (C) of design issue (x) at segment (n) is $C_x = \sum_{i=1}^{n} x_i$, where (x_i) equals 1 if segment (i) is coded as (x) and 0 if segment (i) is not coded as (x). Plotting the results of this equation on a graph with the segments (n) on the horizontal axis and the cumulative occurrence (C) on the vertical axis produces a visualization of the cumulative occurrence of the design issues.

Figure 3 shows a general representation of such a graph, where a curve with its shape shows characteristics of the occurrences over segments ordered by time. Similar to C_x, the cumulative occurrence (C) of syntactic design process (y) is $C_y = \sum_{i=1}^{n-1} y_i$,

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Table 3. Explanation of the system level of a PSS for a design issue

System level of PSS	Explanation	System level of product
PSS (Product/ Service System)	Mainly concerning the PSS as a whole	System: an integral whole
Product	Mainly concerning products in the PSS	Subsystem: details of the subsystem
Service	Mainly concerning services in the PSS	Subsystem: details of the subsystem

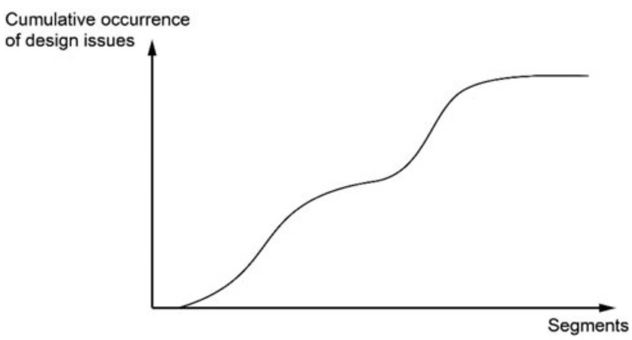

Fig. 3. Graphical representation of the cumulative occurrence of design issues in a design protocol. Note: the *X*-axis refers to the number of segments and not to time, although there is a strong correlation between them (Kan and Gero, 2017).

where (y_i) equals 1 if the transition from segment (i) to segment $(i+1)$ is coded as (y) and 0 if it is not coded as (y).

Problem-solution index

The problem-solution index (P-S index), whether for design issues or design processes, is a measurement that characterizes the overall cognitive style of a designer or design team. It is determined by calculating the ratio of the sum of the occurrences of the design issues or design processes concerned with the problem space to the sum of those related to the solution space, as shown in Eqs. (1) and (2). The cumulative occurrences of the problem-related issues found on the left-hand side of Figure 2 are C_R for Requirement, C_F for Function, and C_{Be} for Expected Behavior. Those of the solution-related issues on the right are C_{Be} for Structure Behavior and C_S for Structure. C_D for Document is not counted here because the D design issue has not been categorized as belonging to either the problem or the solution space. The problem-related processes are formulation (F→Be) referring to C_1, reformulation 2 (S→Be) C_7 and reformulation 3 (S→F) C_8. The solution-related processes are synthesis (Be→S) C_2, analysis (S→Bs) C_3, evaluation (Be – Bs) C_4, and reformulation 1 (S→S) C_6. The process documentation (S→D) C_5 is not coded using information that allows it to be placed into either category and is hence not used in the calculation of the P-S index. P-S indexes with a single value facilitate comparisons across multiple sessions and sessions involving different situations.

$$\text{P-S index (cognitive issues)} = \frac{\sum(\text{Problem-related issues})}{\sum(\text{Solution-related issues})} = \frac{C_R + C_F + C_{Be}}{C_{Bs} + C_S}, \quad (1)$$

$$\text{P-S index (syntactic cognitive processes)} = \frac{\sum(\text{Problem-related syntactic processes})}{\sum(\text{Solution-related syntactic processes})} = \frac{C_1 + C_7 + C_8}{C_2 + C_3 + C_4 + C_6}. \quad (2)$$

When the P-S index = 1, the cognitive design effort is equally divided between the problem and the solution. For values of P-S index <1, more cognitive design effort is expended on the solution than the problem, and for values of P-S index >1, more cognitive design effort is expended on the problem than the solution.

PSS design case

The study's target design was a conceptual redesign, which was chosen from PSSs provided by manufacturers and on the existing market. This selected PSS was provided by a manufacturer that develops, manufactures, and delivers drilling equipment with its related services such as training, spare parts delivery, maintenance, repair, and overhaul, for the construction industry. It could be regarded as a typical PSS provided by manufacturing companies, where such redesign is a more common design activity than designing a completely new product.

The task of this design was to improve, at a conceptual level, the existing PSS provided by the company, and the reason why a conceptual level was set as an endpoint is the research's focus on conceptual design. In addition, the designers were asked to represent the improvement options with the dimensions in Table 1 to describe a PSS (Müller *et al.*, 2009). This task, with information about the current PSS offering, was given to a group of three designers and was required to be conducted within approximately 1 h. More information about the design task and the information provided to the designers can be found in Appendices A and B, respectively.

The three designers were graduate students from a master's course majoring in mechanical engineering. Each had basic knowledge about PSSs in addition to knowledge in mechanical engineering. The language was Japanese, the mother tongue of the three designers. A poster-sized paper with post-its and pens was used to describe and share information. In addition, a whiteboard and pens were used for complementary communication. They were asked to and collaborated in developing improvement options together. The audio and video recording equipment consisted of two video cameras with mobile microphones to provide a suitable sound recording.

The fact that the design session was performed by graduate students in a master's of engineering program might have influenced the results. As Stempfle and Badke-Schaub (2002) point out, although generalizations from student teams to design teams in the industry must be drawn with caution, some insight is expected to be gained into basic thinking processes which are not contaminated by restrictive or unpredictable factors which occur in a field setting. Therefore, the choice of designers is not deemed as a critical problem.

The design session produced nine distinguishable ideas for improving the PSS. These were all effective solutions with respect to the information given to the designers. Thus, the given design session can be regarded as successful.

Table 4. A part of the protocol showing observed implications for the conceptual design of a PSS (1)

Segment number	Designer	Utterance	Design issue	Observed implication on conceptual design
204	RK	…somehow reducing this downtime,	F	Include value proposition
205		and then safety.	F	Include value proposition
206		This one is…Cost and	F	Include value proposition
207	RK	"More drilling time." The red circles here.	Be	Consider performance
208	RK	Besides the red circles, the issues are the safety issue and operators with low skills.	Be	Consider service personnel
209		Those… two issues, can be solved… how to reduce downtimes.	Be	Consider performance
210	RK	How to assure safety. (points) MK: What is safety… I think safety basically involves sudden accidents. RK: Yeah.	Be	Consider uncertainty[a]
211	MK	Therefore, depending on that…well what then? Essentially, breakdowns take up a lot of time. (points)	Bs	Analyze behavior as a system
212	MK	And, if an operator is injured,	Be	Consider service personnel Consider uncertainty
213		The insurance costs are quite high.	Bs	Analyze behavior as a system[b] Analyze scenarios
214	MK	That also means there is a considerable amount of variation involved, so it's only related to reducing costs	Bs	Consider uncertainty
215	MK	Well, using the machinery… the machinery	S	
216		is clearly dangerous.	Bs	Analyze behavior as a system

[a]Sudden accidents are discussed in association with safety, which implies that the uncertainty of future events during the delivery of the PSS is considered.
[b]The thread from Segment 212 concerns uncertainty and analyses its effect, which implies that the designers analyze behavior as a system rather than the propose value.

Results of analyzing the design session

Coding

The design session was transcribed and translated into English. Then, the transcription was segmented and coded by two independent coders with experience in design protocol coding. The results of each coder's segmentation and coding were compared and arbitrated. When the two coders were unable to arbitrate to an agreement, a third more experienced coder was consulted for a final decision. The episode resulted in 242 FBS-coded segments. The average of the two coder's agreement with the final arbitrated coding was 83%, which is above the threshold for reliability (75%). We used this measure rather than Cohen's kappa as each coder's agreement was measured against the arbitrated version, not against the other coder.

Narrative description

In the design session, the implications for the conceptual design of a PSS based on the PSS properties and characteristics (shown in the right-hand column of Table 1) were observed. In the part of the protocol shown in Table 4, reducing the machine downtime and the cost of the whole PSS as well as enhancing user safety are raised as purposes of the PSS. This part of the protocol gives relevance to the implications of PSS design derived from the literature analysis, including value proposition (e.g., reducing downtime and cost and enhancing safety), considering performance (e.g., drilling time), considering service personnel (e.g., operators), considering uncertainty (e.g., accidents and varied skill levels of operators), analyzing behavior as a system (e.g., machine breakdowns that will take up much time for the operator and the customer), and analyzing scenarios (e.g., an insurance cost will be incurred should an operator get injured).

In another part of the protocol shown in Table 5, the roles of service personnel and an expected purchase mechanism are discussed, which are related to actors and the business model, and thereby how a deeper understanding of the PSS receiver is obtained. This part of the protocol also gives relevance to the implications of PSS design, that is analyzing customers (e.g., end users), analyzing actors' roles (e.g., the service supplier's support role for the PSS receiver), and analyzing the business model (e.g., rental or purchase). All the conceptual design implications of a PSS in Table 1 were observed except the co-creation process between the customer and the provider, which was beyond the scope of this laboratory setting. The rest of the section "Results of analyzing the design session" shows the quantitative results using the measurement techniques outlined in the sections "System levels in PSSs and products for an FBS design issue", "Cumulative occurrences, graphs, and their shapes", and "Problem-solution index".

Design issue distribution

The distribution of each design issue's occurrence for the entire episode is shown in Table 6. Bs (33.9%) and Be (27.3%) are the two highest occurring issues. The two issues together represent behavior and account for more than 60% of the total cognitive design effort. These are followed by S (14.0%) and F (13.2%). Their differences to Be and Bs are large; S and F each are only

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Table 5. A part of the protocol showing observed implications for the conceptual design of a PSS (2)

Segment number	Designer	Utterance	Design issue	Observed implication on conceptual design
17	KK	Yes. Was it about variation? Somehow, I don't think they were doing that at all. RK: Yes KK: So… RK: That would be one. KK: That's one.	F	Analyze customers
18	KK	Somehow, I think this one is a case peculiar to the site, with [the service supplier].	Bs	Analyze behavior as a system
19	KK	[The PSS receiver]	S	
20		really relies on [the service supplier].	F	Analyze actors' roles
21	KK	Then actually…. One of the things is how can the equipment be purchased…	Be	Analyze business model
22	KK	Uh, was it renting? Renting, hmmm. The premise was a little different, but. RK: Yeah. KK: Well…, so…	Be	Analyze business model

Table 6. Issue distribution (%) and P-S issue index

Requirement (R)	1.7
Function (F)	13.2
Expected Behavior (Be)	27.3
Behavior derived from Structure (Bs)	33.9
Structure (S)	14.0
Description (D)	9.9
P-S issue index	0.88

Table 7. Distributions (%) of the system levels within behavior

	Be	Bs	Be and Bs
PSS	45.5	37.8	41.9
Product	7.6	11.0	9.5
Service	47.0	51.2	48.6
Total	100.0	100.0	100.0

Note: the distributions for "Be and Bs" are the cumulative weighted average of the distributions of Be and Bs.

approximately one-half of Be. These are followed by D (9.9%). The P-S issue index for the entire design session was 0.88, meaning that across the design session more cognitive design effort is expended on the solution than the problem, as explained in the section "Problem-solution index".

The distributions of the system levels based on the section "System levels in PSSs and products for an FBS design issue" for the entire episode for this case are shown in Table 7. Only Behavior is analyzed here because it covers over 60% of all cognitive activity (see Table 6). This shows that different levels are addressed in the design episode. In Behavior as a total (both Be and Bs), Service received the highest distribution (48.6%), followed by PSS (41.9%), while Product received a much smaller portion (9.5%). Interestingly, Be of PSS was discussed (45.5%) more than Bs of PSS (37.8%), while Bs of both Product and Service (11.0% and 51.2%, respectively) were discussed more than Be (7.6% and 47.0%, respectively).

The moving average moves chronologically across the design session of each design issue with a window of 61 segments, corresponding to a quarter of the entire session, as shown in Figure 4. The graph begins and ends with the 30th and 212th segments, respectively, as a moving average is plotted at the mid-point of its window. Figure 4 shows that the cognitive design effort for the design issues varies substantially over time and provides a graphical basis for a qualitative interpretation of the temporal results. Figure 4 shows the high percentages for both Bs and Be can be seen with the transition over segments. More cognitive design effort was expended on Be after the middle of the session than at any other time. The cognitive design effort expended on Bs is more in the earlier and later parts of the design session. S is addressed more in the early and final parts, similar to Bs. F is also addressed in the early and later parts, but this later part occurred earlier than the final part of S.

When examining the source data through its segments, the protocol's cumulative occurrence of design issues is shown graphically in Figure 5. The values of the graphs at segment 242, that is the final points of the episode, correspond to the values in Table 6 and show that Behavior derived from Structure (Bs) occurred in the highest number of segments. The graphs' shapes in Figure 5 provide for a qualitative understanding of the transition of cognitive design effort over time. In each graph, the part with the higher slope indicates that the issue is addressed more frequently. The design issues are different in terms of which parts of the design session the issues are addressed more, as represented by the different shapes and slopes. For instance, the high effort expended on Be found "after the middle" (as described above) of the session in Figure 4 can be seen between the 100th and 165th segments in Figure 4. The reason for the lag between the middle and 100th segment lies in the different ways of measurement; an envelope containing 61 segments is used in Figure 4. In addition, an increase of effort in F followed by that in S can be seen between the 160th and 230th segments in Figure 5.

In order to quantify the shape of each graph, a linear approximation was conducted for each design issue's cumulative effort across the session. Figure 6 shows, as an example, the result for

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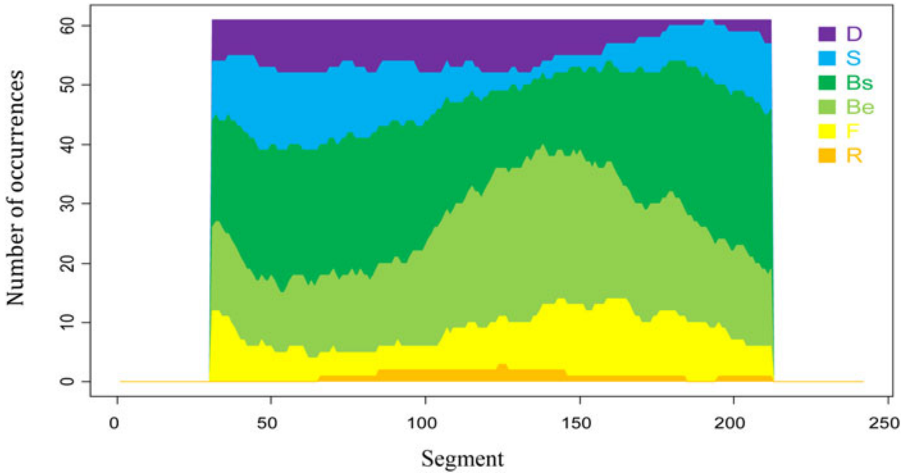

Fig. 4. Moving average of cognitive design effort expended on design issues (window of 61 segments).

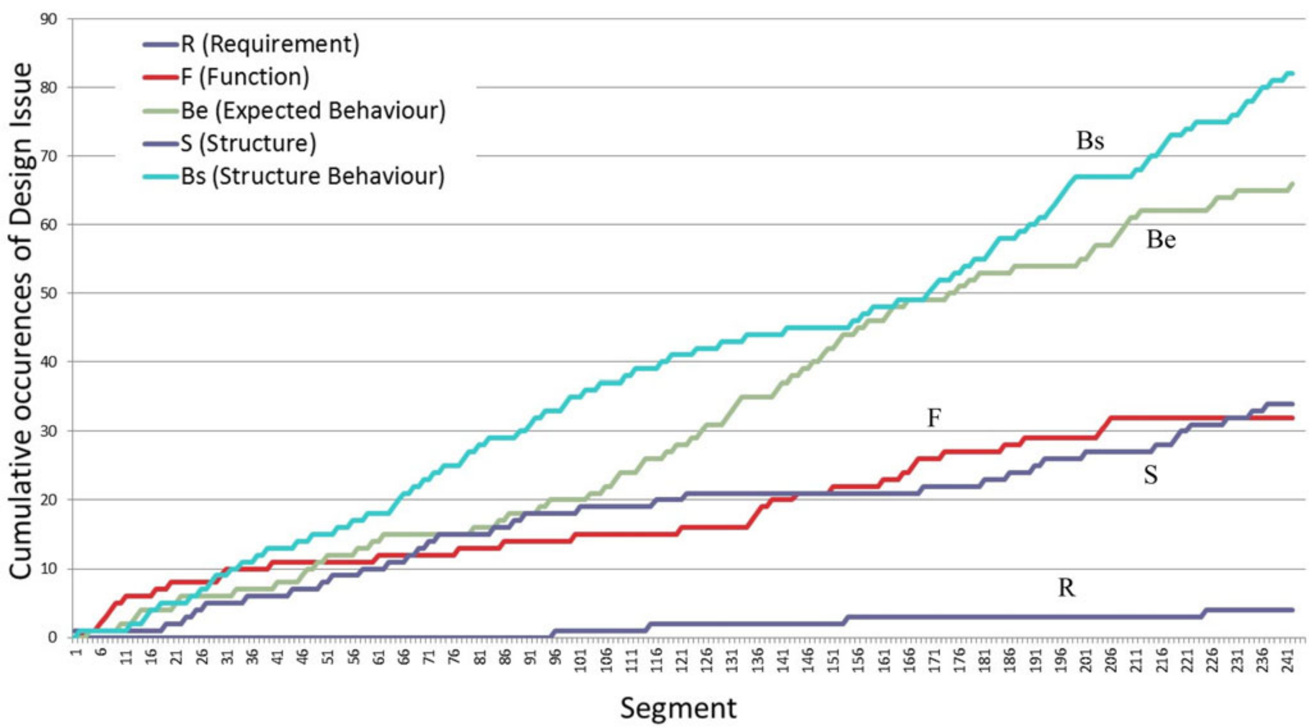

Fig. 5. Cumulative cognitive design effort expended on design issues.

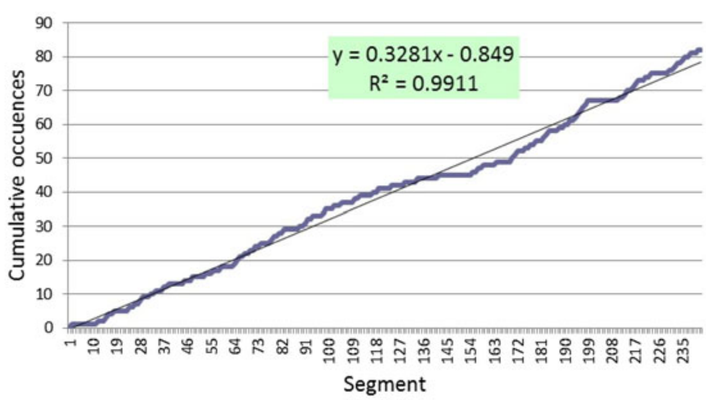

Fig. 6. Result of linear approximation of the cumulation of design issue Bs.

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Table 8. Coefficients of determination from linear approximations of the cumulative occurrences of each design issue

Requirement (R)	0.9057
Function (F)	0.9649
Expected Behavior (Be)	0.9832
Behavior derived from Structure (Bs)	0.9911
Structure (S)	0.9462
Description (D)	0.9472

design issue Bs. The coefficient of determination was calculated as 0.9911 in this case and indicates a high linearity. The coefficients for the design issues are shown in Table 8. The linearity of Bs, Be, and F is sufficiently high, with the threshold for linearity for R^2 being 0.95. Those for D and S are very close to the threshold for linearity. Only R clearly fails to meet the threshold for linearity. This means that the design issues Bs, Be, and F can be regarded as being constantly focused on during the design session.

Syntactic design process distribution

The distribution of each syntactic process, aggregated for the entire episode, is shown in Table 9. The percentage of each process is a ratio of its occurrence over those of the eight processes, with the sum of all the eight percentages being 100%. Note that "Be – Bs" (4. Evaluation) is a bidirectional process unlike the others, which are uni-directional as indicated by "→".

Evaluation, referring to the comparison process between Be and Bs, occurred with by far the highest frequency (45.5%) of all the processes. Since Be and Bs sit in the problem space and solution space, respectively, this shows the high frequency of transition between these two spaces. Considering this, one could infer that evaluation is a characterizing process of PSS design based on this design session's result.

The second highest frequency is that of analysis, referring to the process from S to Bs (25.7%). The total of the frequencies of these top two, evaluation and analysis, is 71.2%, and one can say that these are the dominant processes. Analysis is followed by formulation, referring to the process from F to Be (12.9%). The top three distributions of evaluation, analysis, and formulation indicate that behavior is the dominant design issue within the syntactic processes and that the behavior is at the end point of the processes rather than the starting point.

Figure 7 shows the moving averages of each syntactic process, with a window of 61 segments. The reason why the total number of occurrences per each window is not always 61 is that these eight syntactic processes are not collectively exhaustive. For instance, the transitions from F to S occurred but are not counted as a formal syntactic design process. The F to S process is based on learning through experience rather than design reasoning (Kannengiesser and Gero, 2019).

The majority of syntactic processes change over time, and the whole session could be divided into four phases across time, shown by three dotted lines in Figure 7. From the beginning to approximately the 90th segment, the major syntactic processes are F→Be (Formulation), Be→S (Synthesis), S→Bs (Analysis), and Be – Bs (Evaluation). After this and up to approximately the 120th segment, Be – Bs (Evaluation) and S→Bs (Analysis) are dominant. Then, up to the 160th segment, Be – Bs (Evaluation) and F→Be (Formulation) are dominant. In the last phase, the dominant processes are Be – Bs (Evaluation) and S→Bs (Analysis).

Table 9. Syntactic process distribution (%) and P-S process index

1: Formulation (F→Be)	12.9
2: Synthesis (Be→S)	7.9
3: Analysis (S→Bs)	25.7
4: Evaluation (Be – Bs)	45.5
5: Documentation (S→D)	1.0
6: Reformulation 1 (S→S)	1.0
7: Reformulation 2 (S→Be)	5.0
8: Reformulation 3 (S→F)	1.0
P-S Process Index	0.24

Interestingly, Be – Bs (Evaluation) occurred substantially throughout the session, though the second and third phases include more occurrences. Except for Be – Bs (Evaluation), the whole session could be understood in this way: The first phase is occupied with F→Be (Formulation), Be→S (Synthesis), and S→Bs (Analysis); the second with S→Bs (Analysis); the third with F→Be (Formulation); and the fourth with Be→Be (Evaluation) and S→Bs (Analysis).

Shifting to a more microscopic view of syntactic processes' occurrences, Figure 8 shows the cumulative occurrences of each syntactic process on the vertical axis. The values of the graphs at segment 241 correspond to Table 9, showing, for example, that Be – Bs occurred with the highest number. From the shapes of the graphs the following steeper slopes are observed: Be – Bs (Evaluation) from the 92nd to 145th and from the 155th to 178th; S → Bs (Analysis) from the 50th to 75th and from the 220th to 240th; F→Be (Formulation) from the 140th to 165th; and Be→S (Synthesis) from the 45th to 65th. These observations are a set of the processes' most frequent occurrences within narrower windows and give a different view from that in Figure 7 because of the difference in granularity.

Problem-solution index series

The Problem-solution issue index for the entire session is 0.88, as shown in Table 6. The P-S issue indexes from session deciles are found to vary over time, as shown in Figure 9. The maximum is 4.25 in the sixth decile, while the minimum is 0.22 in the tenth decile. The deciles with the index greater than 1 are the first, fifth, sixth, and seventh deciles. This means that the problem space is focused on more than the solution space in those deciles.

The sixth decile has by far the highest P-S index, as indicated in Figure 9. This corresponds to a window right after the middle in Figure 4, where Be has its peak and F is also discussed. In addition, it coincides with the third phase in Figure 7, where F→Be and Be – Bs are dominant syntactic processes. Also, the index increases from the third to the sixth decile, while it decreases from the sixth to the eighth decile. It means that in this design session, the space addressed shifts from the solution to the problem toward the sixth decile and then shifts back to the solution.

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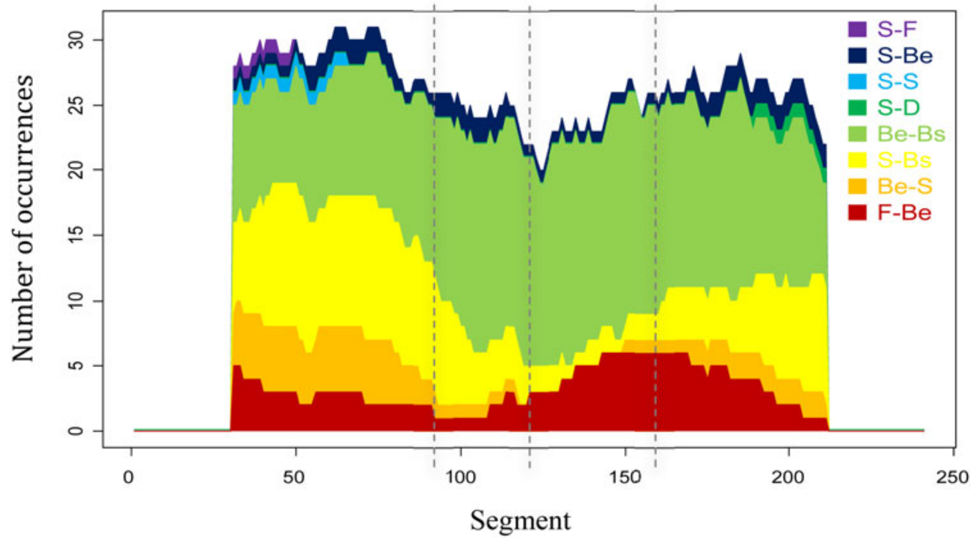

Fig. 7. Moving average of cognitive design effort expended on syntactic processes (window of 61 segments).

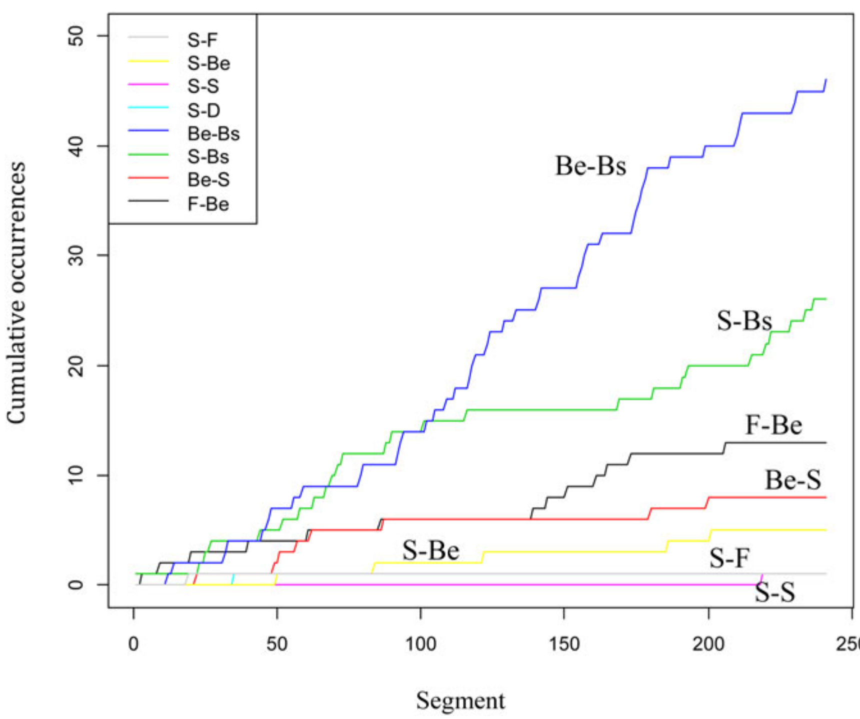

Fig. 8. Cumulative cognitive design effort expended on processes.

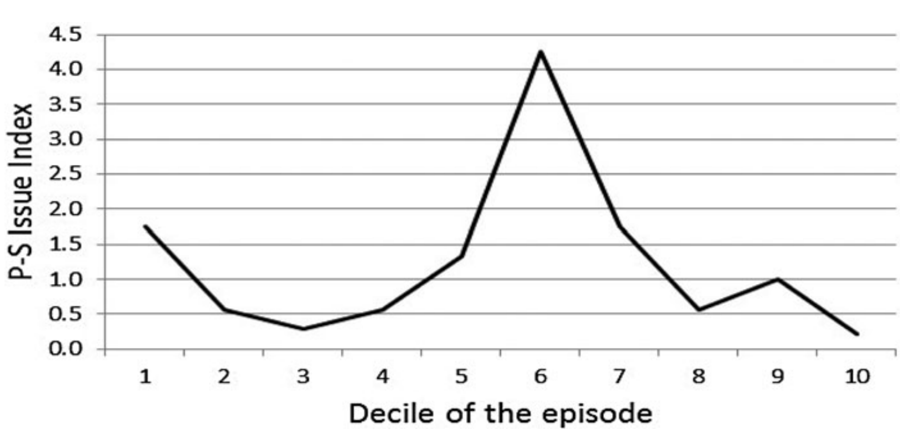

Fig. 9. P-S index in deciles over the design session.

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Table 10. Design issue distributions (%) from multiple studies of product design as compared to this study (of PSS design)

Study	Ref.	R	F	Be	Bs	S	D
Conceptual PSS design by mechanical engineering major	This study	1.7	13.2	27.3	33.9	14.0	9.9
Conceptual product design by mechanical design major	(Jiang *et al.*, 2014)	1.1	12.1	15.6	19.8	31.2	20.1
Product design by mechanical design major	(Jiang *et al.*, 2014)	1.8	11.4	13.5	28.3	28.0	16.9

Discussion

Comparability and commensurability of PSS and product design

The results obtained from analyzing these PSS designers in the sections "Design issue distribution", "Syntactic design process distribution", and "Problem-solution index series" show that the methods used to analyze the cognitive behavior of product designers can be used to produce comparable and commensurable results between PSS and product design. The methods adopt the FBS ontology and the metrics such as design issue distributions and design process distributions, answering the research question in the positive. The comparability is based on the method described in the section "Method", including the matching between PSS and product design, as shown by Tables 2 and 3. The commensurability is demonstrated further in the sections "Design issues" and "Design processes".

Design issues

Design issues are investigated based on results from the PSS design episode (Sections "Narrative description" and "Design issue distribution") and from analyzing characteristics of PSSs and PSS design (Sections "Characteristics of PSSs" and "Characteristics of PSS design and previous research") to demonstrate the commensurability and formulate hypotheses. From Table 6, the dominance of behavior (Be and Bs) is in contrast to the dominance of Structure in studies of designing products (Yu *et al.*, 2015). The percentage of Be and Bs in total is calculated based on Table 6 as follows:

$$\text{Be} + \text{Bs} = 27.3 + 33.9 = 61.2.$$

This means Behavior was addressed for 61.2% of all the design issues. This originates partly from the discussion of behavior as a system and performance of products and services (as shown in the section "Narrative description" with observation of the partial protocol of Tables 4 and 5). In addition, the high linearity of the cumulative occurrence of Bs (with an $R^2 = 0.9911$ in Figure 6) and that of Be (with an $R^2 = 0.9832$ in Table 8) indicates that behavior was discussed constantly during the entire process. Other design issues, such as S (14.0%) and F (13.2%), received some, but much less, cognitive design effort. This means that the designers were not uniquely focused on behavior but a mixture of behavior, structure, and function, with behavior dominating.

The results of the analysis in the sections "Characteristics of PSSs" and "Characteristics of PSS design and previous research", Table 1, theoretically show the relevance of *behavior* as a design issue in the conceptual design of a PSS: *behavior* as a system with various types of uncertainty is expected to be analyzed substantially due to the PSS's property of being an open process system. In addition, the performance of products and services is expected to be analyzed due to the PSS's property of being a business model. Therefore, cognitive effort spent on behavior in a PSS design was expected.

The reasoning shown above, based on the analysis of this design session and the literature on PSS, leads to the following hypothesis, Hypothesis 1 (H1):

H1. In the conceptual design of a PSS, the behavior of the design is the dominant design issue.

The degree of dominance of behavior found in this PSS design episode is uncommon in product design. PSS design and product design are compared in Table 10 utilizing the same FBS coding scheme (Jiang *et al.*, 2014), which resulted from a conceptual product design by mechanical design majors and product design by industrial design majors. Be and Bs in total in product design received 35.4% (15.6% + 19.8%) and 41.8% (13.5% + 28.3%) in the two studies shown in Table 10. They are substantially lower than the 61.2% in this PSS design session.

The cognitive effort spent on S (14.0%) in this PSS design session is substantially lower than in product design. In addition, the analysis of characteristics of PSSs and PSS design (Sections "Characteristics of PSSs" and "Characteristics of PSS design and previous research") does not sufficiently explain the difference specifically for the structure. Based on the reasoning above, the following hypothesis, Hypothesis 2 (H2) is formulated:

H2. More effort is spent on behavior in the design of PSSs than in the design of products alone.

Examining the results in Table 7, the system level (the PSS as a whole) and the component level (products or services within the PSS) are both addressed substantially in Behavior: 41.9% for the system level and 48.1% for the component level (Be and Bs in total). This accords with the literature analysis in Table 1, which indicates that systems thinking is expected to be applied in PSS design. In this study, analysis in terms of the levels was performed only for Behavior, and this leads to the following hypothesis, Hypothesis 3 (H3):

H3. In the conceptual design of a PSS, substantial effort is spent on the behavior of the PSS as a system as well as its products and its services.

Using the Problem-solution issue index in the FBS scheme, design issues are discussed further here. As described in the section "Problem-solution index", where this index is greater than 1, the problem space is focussed on more than the solution space, and the reverse applies when the index is less than 1. The P-S index from the entire episode is 0.88, as shown in Table 6. However, looking at the temporal distribution of the P-S index, Figure 9, at four of the ten deciles of the episode, the P-S issue index exceeds 1 in this design session.

In product design, the P-S issue index is substantially lower than that in PSS design found by this study, according to Jiang

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Table 11. Syntactic process distribution (%) from multiple studies of product design as compared to this study (of PSS design)

Study	Ref.	F→Be	Be→S	S→Bs	Be – Bs	S→D	S→S	S→Be	S→F
Conceptual PSS design by mechanical engineering major	This study	12.9	7.9	25.7	45.5	1.0	1.0	5.0	1.0
Conceptual product design by mechanical design major	(Jiang *et al.*, 2014)	6.2	6.1	15.4	15.1	20.6	17.9	2.4	10.5
Product design by mechanical design major	(Jiang *et al.*, 2014)	5.9	6.3	15.0	10.5	20.3	27.3	3.4	6.7

et al. (2014). From Table 10, the P-S index for the two studies of product design is calculated as follows:

$$\frac{1.1 + 12.1 + 15.6}{19.8 + 31.2} = \frac{28.8}{51.0} = 0.56$$

and

$$\frac{1.8 + 11.4 + 13.5}{28.3 + 28.0} = \frac{26.7}{56.3} = 0.47.$$

The problem space is expected to be discussed in PSS design partly due to its business model property (see Table 1): a customer is to be analyzed to define the value proposed. Further, according to Alonso-Rasgado *et al.* (2004), a PSS customer aims to obtain a functional performance to be expected in the customer's own settings, that is the customer's purposes and does not necessarily appreciate the hardware as such (i.e., a partial solution). The literature points out the importance of addressing purposes and expectations rather than only solutions. These support how PSS design tends to spend more cognitive design effort on purposes and expectations, which are closely linked to value. The literature referred to in this paragraph states that the problem space becomes more relevant in the conceptual design of a PSS, as compared to that of product design. This is borne out in the results of this PSS design session.

In sum, the PSS design case exhibited parts with a higher P-S issue index, where the expected roles of service personnel, the expected scenarios of product usage, and the purpose of the PSS receiver were discussed. This discussion is expected to occur more frequently according to the PSS design theory as compared to product design and is, therefore, considered reproducible in other PSS design. This reasoning leads to the following hypothesis, Hypothesis 4 (H4):

H4. The conceptual design of a PSS produces a higher Problem-solution index than that for product design.

Design processes

Distributions of the syntactic processes of the FBS scheme from this session are shown in Table 9. The distributions of analysis and evaluation from the entire episode were calculated as 25.7% and 45.5%, respectively, that is about 70% for both. Examples of analysis and evaluation are shown in Table 4, where they are concerned with the system as a whole. PSS design and product design are compared in Table 11 (Jiang, 2012; Jiang *et al.*, 2014). Analysis and evaluation in total in product design received 30.5% (15.4% + 15.1%) and 25.5% (15.0% + 10.5%) in the two studies shown in Table 11, which are substantially lower than in the PSS design. On the other hand, documentation (S→D), reformulation 1 (S→S), and reformulation 3 (S→F) in the PSS design received substantially lower distributions than in the two studies of product design.

In the literature on the PSS design processes, analysis as a system, performance, and customers are raised as important issues, as shown in Table 1. In design, in general, analysis of a design solution is regularly followed by evaluation. Evaluation is carried out against the expectation for a solution and is thus an activity to reason about a design solution and a design problem to be solved (Pahl and Beitz, 1996). Reasoning between the solution and problem spaces, which corresponds to evaluation, is also implied to be substantial in PSS design by Morelli (2003): he asserted the importance of an iteration between problems and solutions. Komoto and Tomiyama (2008) stated that PSS design involves finding a mapping between activities in a service environment and a value. From this and the results of this explorative case study, hypothesis 5 (H5) is generated:

H5. In the conceptual design of a PSS, analysis and evaluation are the dominant processes.

Conclusion and future work

PSSs have received steadily increasing interest by practitioners, especially among manufacturing companies integrating services with products to combat low-priced product manufacturers. After analyzing the literature about PSSs, their characteristics and properties as compared to physical products were derived, and their implications for PSS conceptual design were derived. Descriptive knowledge about differences between designing PSSs and products at the micro level is, however, underdeveloped: even how to investigate and present the differences is not available in the literature. Motivated by this gap and the need for insights for the differences between PSS and product design, this article aims to provide foundations for adding to the understanding of PSS conceptual design. A PSS design case in a controlled environment was analyzed and compared with product design using the same coding scheme to meet this aim, and five hypotheses were created.

Attention should be paid to several conditions for this PSS design case analyzed: the task was performed in a controlled environment without interacting actors other than designers. In addition, the designers were students majoring in mechanical engineering. Since the results are based on a single case, these conditions might have influenced the results. However, the product design used as a reference was performed with the same conditions in order to produce commensurability. Driven by the five hypotheses developed from the results of this study, further research to analyze more PSS design sessions and compare them with product design is needed to generalize the insights into PSS design obtained in this study.

The measurement and calculation techniques adopted in this research are shown to effectively produce quantitative results about PSS design in a commensurable way with product design.

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This article has demonstrated the successful use of a method for determining and describing design cognition, based on protocol analysis utilizing the FBS coding scheme for PSS design. The techniques and the method can be re-used for further research addressing a larger number of design cases to derive statistically significant knowledge.

A number of promising future works are envisioned, building upon this research. First, analyzing more PSS design sessions, as stated above, is needed to enable statistical significance for generalizing insights. Second, different types of PSS design are of interest to be researched: for example, new design involving use-oriented or result-oriented service (Tukker, 2004). Third, analyzing design sessions by different types of designers, such as experienced practitioners, is needed. Fourth, different compositions of a designing group are important to be analyzed: for example, a heterogeneous setting where individual designers of the provider possess different expertise or roles as well as one with both the customer and the provider potentially involving co-creation processes. Fifth, an evaluation of the effects of PSS design methods and tools on PSS design processes is needed. Comparisons with an earlier work on product design (Kannengiesser and Gero, 2017) would be valuable.

Acknowledgments. The company that provided this research with the PSS case and the three anonymous reviewers are much appreciated.

Financial support. This research is supported in part by grants from the US National Science Foundation (J.G. Grant Nos. EEC-1463873 and CMMI-1762415). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This research is also supported in part by the Mistra REES (Resource-Efficient and Effective Solutions) program funded by Mistra (The Swedish Foundation for Strategic Environmental Research) (T.S. Grant No. DIA 2014/16).

References

Ahmed S (2007) An industrial case study: identification of competencies of design engineers. *Journal of Mechanical Design* **129**, 709–716.

Alonso-Rasgado T and Thompson G (2006) A rapid design process for total care product creation. *Journal of Engineering Design* **17**, 509–531.

Alonso-Rasgado T, Thompson G and Elfstrom B (2004) The design of functional (total care) products. *Journal of Engineering Design* **15**, 515–540.

Atman CJ and Bursic KM (1996) Teaching engineering design: can reading a textbook make a difference? *Research in Engineering Design* **8**, 240–250.

Baines TS, Lightfoot HW, Evans S, Neely A, Greenough R, Peppard J, Roy R, Shehab E, Braganza A, Tiwari A, Alcock JR, Angus JP, Bastl M, Cousens A, Irving P, Johnson M, Kingston J, Lockett H, Martinez V, Michele P, Tranfield D, Walton IM and Wilson H (2007) State-of-the-art in product-service systems. *Proceedings of the Institution of Mechanical Engineers, Part B* **221**, 1543–1552.

Baines TS, Bigdeli AZ, Bustinza OF and Ridgway K (2017) Servitization: revisiting the state-of-the-art and research priorities. *International Journal of Operations & Production Management* **37**, 256–278.

Bertoni A (2013) Analyzing product-service systems conceptual design: the effect of colorcoded 3D representation. *Design Studies* **34**, 763–793.

Boehm M and Thomas O (2013) Looking beyond the rim of one's teacup: a multidisciplinary literature review of product-service systems in information systems, business management, and engineering & design. *Journal of Cleaner Production* **51**, 245–260.

Brambila-Macias S, Sakao T and Kowalkowski C (2018) Bridging the gap between engineering design and marketing: insights for research and practice in product/service system design. *Design Science* **4**, e7, 1–61.

Breslin M and Buchanan R (2008) On the case study method of research. *Design Issues* **24**, 36–40.

Calabrese A, Forte G and Chiron NL (2018) Fostering sustainability-oriented service innovation (SOSI) through business model renewal: the SOSI tool. *Journal of Cleaner Production* **201**, 783–791.

Christensen BT and Schunn CD (2007) The relationship of analogical distance to analogical function and preinventive structure: the case of engineering design. *Memory & Cognition* **35**, 29–38.

Costa N, Patrício L, Morelli N and Magee CL (2018) Bringing service design to manufacturing companies: integrating PSS and service design approaches. *Design Studies* **55**, 112–145.

Dinar M, Shah JJ, Cagan J, Leifer L, Linsey J, Smith SM and Vargas Hernandez N (2015) Empirical studies of designer thinking: past, present, and future. *Journal of Mechanical Design* **137**, 1–13.

Durugbo C, Tiwari A and Alcock JR (2011) A review of information flow diagrammatic models for product–service systems. *The International Journal of Advanced Manufacturing Technolgy* **52**, 1193–1208.

Eisenbart B, Gericke K and Blessing LTM (2013) An analysis of functional modeling approaches across disciplines. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **27**, 281–289.

Eisenbart B, Gericke K and Blessing LTM (2017) Taking a look at the utilisation of function models in interdisciplinary design: insights from ten engineering companies. *Research in Engineering Design* **28**, 299–331.

Erden MS, Komoto H, van Beek TJ, D'Amelio V, Echavarria E and Tomiyama T (2008) A review of function modeling: approaches and applications. *Artificial Intelligence for Engineering Design Analysis and Manufacturing* **22**, 147–169.

Ericsson KA and Simon HA (1993) *Protocol Analysis Verbal Reports as Data*. Cambridge, MA: MIT Press.

Erkoyuncu JA, Durugbo C, Shehab E, Roy R, Parker R, Gath A and Howell D (2011) Uncertainty driven service cost estimation for decision support at the bidding stage. *International Journal of Production Research* **51**, 5771–5788.

Gero JS (1990) Design prototypes: a knowledge representation schema for design. *AI Magazine* **11**, 26–36.

Gero JS (2010) Generalizing design cognition research. DTRS8: Interpreting Design Thinking, DAB documents, Sydney.

Gero JS and Kannengiesser U (2004) The situated function-behaviour-structure framework. *Design Studies* **25**, 373–391.

Gero JS and Kannengiesser U (2014) The function-behaviour-structure ontology of design. In Chakrabarti A and Blessing L (eds), *An Anthology of Theories and Models of Design*. Springer, London, pp. 263–283.

Hay L, Duffy AHB, McTeague C, Pidgeon LM, Vuletic T and Grealy M (2017) A systematic review of protocol studies on conceptual design cognition: design as search and exploration. *Design Science* **3**, 1–36.

Hubka V and Eder WE (1987) A scientific approach to engineering design. *Design Studies* **8**, 123–137.

INCOSE (2015) *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. International Council on Systems Engineering, Wiley, Hoboken, NJ, USA.

Isaksson O, Larsson TC and Öhrwall Rönnbäck A (2009) Development of product-service systems: challenges and opportunities for the manufacturing firm. *Journal of Engineering Design* **20**, 329–348.

Jiang H (2012) *Understanding Senior Design Students' Product Conceptual Design Activities* (PhD thesis). National University of Singapore, Singapore.

Jiang H, Gero JS and Yen CC (2014) Exploring designing styles using problem-solution indexes. In Gero JS (ed.), *Design Computing and Cognition'12*. Springer, Dordrecht, Netherlands, pp. 85–101.

Kan WT and Gero JS (2017) *Quantitative Methods for Studying Design Protocols*. Dordrecht: Springer.

Kan JWT and Gero JS (2018) Characterizing innovative processes in design spaces through measuring the information entropy of empirical data from protocol studies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **32**, 32–43.

Kan JWT, Bilda Z and Gero JS (2007) Comparing entropy measures of idea links in design protocols: linkography entropy measurement and analysis of differently conditioned design sessions. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **21**, 367–377.

Kannengiesser U and Gero JS (2015) Is designing independent of domain? Comparing models of engineering, software and service design. *Research in Engineering Design* **26**, 253–275.

https://doi.org/10.1017/S0890060420000402 Published online by Cambridge University Press

Kannengiesser U and Gero JS (2017) Can Pahl and Beitz' systematic approach be a predictive model of designing? *Design Science* **3**, e24.
Kannengiesser U and Gero JS (2019) Design thinking, fast and slow: a framework for Kahneman's dual-system theory in design. *Design Science* **5**, e10.
Kimita K, Sakao T and Shimomura Y (2018) A failure analysis method for designing highly reliable product-service systems. *Research in Engineering Design* **29**, 143–160.
Komoto H and Tomiyama T (2008) Integration of a service CAD and a life cycle simulator. *CIRP Annals - Manufacturing Technology* **57**, 9–12.
Lewandowski M (2016) Designing the business models for circular economy-towards the conceptual framework. *Sustainability* **8**, 43, 1–28.
Love T (2000) Philosophy of design: a metatheoretical structure for design theory. *Design Studies* **21**, 293–313.
Mason K and Spring M (2011) The sites and practices of business models. *Industrial Marketing Management* **40**, 1032–1041.
Matschewsky J, Kambanou ML and Sakao T (2018) Designing and providing integrated product service systems – challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies. *International Journal of Production Research* **56**, 2150–2168.
Maussang N, Zwolinski P and Brissaud D (2009) Product-service system design methodology: from the PSS architecture design to the products specifications. *Journal of Engineering Design* **20**, 349–366.
Mc Neill T, Gero JS and Warren J (1998) Understanding conceptual electronic design using protocol analysis. *Research in Engineering Design* **10**, 129–140.
Medini K and Boucher X (2019) Specifying a modelling language for PSS engineering – a development method and an operational tool. *Computers in Industry* **57**, 787–796.
Meier H, Roy R and Seliger G (2010) Industrial product-service systems - IPS2. *CIRP Annals - Manufacturing Technology* **59**, 607–627.
Morelli N (2003) Product-service systems, a perspective shift for designers: a case study: the design of a telecentre. *Design Studies* **24**, 73–99.
Mourtzis D, Fotia S, Vlachou E and Koutoupes A (2018) A lean PSS design and evaluation framework supported by KPI monitoring and context sensitivity tools. *International Journal of Advanced Manufacturing Technology* **94**, 1623–1637.
Müller P, Kebir N, Stark R and Blessing L (2009) PSS layer method - application to microenergy systems. In Sakao T and Lindahl M (eds), *Introduction to Product/Service-System Design*. London: Springer, pp. 3–30.
Oliva R and Kallenberg R (2003) Managing the transition from products to services. *International Journal of Service Industry Management* **14**, 160–172.
Osterwalder A, Pigneur Y and Smith A (2010) *Business Model Generation*. Hoboken, NJ: John Wiley & Sons, Inc.
Pahl G and Beitz W (1996) *Engineering Design: A Systematic Approach*. London: Springer-Verlag.
Purcell T and Gero JS (1998) Drawings and the design process: a review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies* **19**, 389–430.
Qu M, Yu S, Chen D, Chu J and Tian B (2016) State-of-the-art of design, evaluation, and operation methodologies in product service systems. *Computers in Industry* **77**, 1–14.
Regan WJ (1963) The service revolution. *Journal of Marketing* **47**, 57–62.
Robson C (2002) *Real World Research - A Resource for Social Scientists and Practitioner-Researchers*. Malden, MA: Blackwell.
Rolls-Royce (2019) *Rolls-Royce Holdings PLC Annual Report 2018*. London: Rolls-Royce.
Roy R and Baxter D (2009) Special issue - product-service systems. *Journal of Engineering Design* **20**, 327–431.
Sakao T (2019) Research series review for transdisciplinarity assessment—validation with sustainable consumption and production research. *Sustainability* **11**, 5250, 1–22.
Sakao T and Lindahl M (2015) A method to improve integrated product service offerings based on life cycle costing. *CIRP Annals - Manufacturing Technology* **64**, 33–36.
Sakao T and Mizuyama H (2014) Understanding of a product/service system design: a holistic approach to support design for remanufacturing. *Journal of Remanufacturing* **4**, 1–24.
Sakao T and Neramballi A (2020) A product/service-system design schema: application to big data analytics. *Sustainability* **12**, 3484, 1–22.
Sakao T and Shimomura Y (2007) Service engineering: a novel engineering discipline for producers to increase value combining service and product. *Journal of Cleaner Production* **15**, 590–604.
Sakao T, Shimomura Y, Sundin E and Comstock M (2009) Modeling design objects in CAD system for service/product engineering. *Computer-Aided Design* **41**, 197–213.
Sakao T, Paulsson S and Mizuyama H (2011) *Inside a PSS Design Process: Insights through Protocol Analysis*. International Conference on Engineering Design, Copenhagen.
Sakao T, Öhrwall Rönnbäck A and Ölundh Sandström G (2013) Uncovering benefits and risks of integrated product service offerings – using a case of technology encapsulation. *Journal of Systems Science and Systems Engineering* **22**, 421–439.
Shimomura Y, Kimita K, Tateyama T, Akasaka F and Nemoto Y (2013) A method for human resource evaluation to realise high-quality PSSs. *CIRP Annals - Manufacturing Technology* **62**, 471–474.
Shimomura Y, Nemoto Y and Kimita K (2015) A method for analysing conceptual design process of product-service systems. *CIRP Annals - Manufacturing Technology* **64**, 145–148.
Smith DJ (2013) Power-by-the-hour: the role of technology in reshaping business strategy at Rolls-Royce. *Technology Analysis & Strategic Management* **25**, 987–1007.
Song T (2014) *Expert Vs. Novice: Problem Decomposition/Recomposition in Engineering Design* (PhD thesis). Utah State University, Logan, UT, USA.
Song T, Becker K, Gero J, DeBerard S, Lawanto O and Reeve E (2016) Problem decomposition and recomposition in engineering design: a comparison of design behavior between professional engineers, engineering seniors, and engineering freshmen. *Journal of Technology Education* **27**, 37–56.
Stamatis DH (1995) *Failure Mode and Effect Analysis: fMEA From Theory to Execution*. Milwaukee, WI: ASQC Quality Press.
Stempfle J and Badke-Schaub P (2002) Thinking in design teams - an analysis of team communication. *Design Studies* **23**, 473–496.
Teegavarapu S, Summers JD and Mocko GM (2008) *Case study method for design research: a justification*. ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, New York: ASME.
Tischner U, Verkuijl M and Tukker A (2002) First Draft PSS Review. Cologne, Econcept.
Trevisan L and Brissaud D (2016) Engineering models to support product–service system integrated design. *CIRP Journal of Manufacturing Science & Technology* **15**, 3–18.
Tukker A (2004) Eight types of product-service system: eight ways to sustainability? Experiences from suspronet. *Business Strategy and the Environment* **13**, 246–260.
Tukker A (2015) Product services for a resource-efficient and circular economy - a review. *Journal of Cleaner Production* **97**, 76–91.
Tukker A and Tischner U (eds) (2006) *New Business for Old Europe*. Sheffield: Greenleaf Publishing.
van Someren MW, Bardard YF and Sandberh JAC (1994) *The Think Aloud Method: a Practical Guide to Modelling Cognitive Processes*. London: Academic Press.
Visser W (2009) Design: one, but in different forms. *Design Studies* **30**, 187–223.
Yin RK (2006) *Case Study Methods. Handbook of Complementary Methods in Education and Research*. Mahwah, NJ: Erlbaum.
Yu R, Gu N, Ostwald M and Gero JS (2015) Empirical support for problem–solution coevolution in a parametric design environment. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **29**, 33–44.

Appendix A. Design brief for the PSS design session

Concerned company

This design is carried out for the company who develops, manufactures, and delivers drilling equipment for, for example, the construction business. The firm is named Company Alpha based in Sweden. Training, spare parts delivery and MRO (maintenance, repair, and overhaul) are part of the company's service portfolio.

https://doi.org/10.1017/S0890060420000402 Published online by Cambridge University Press

Client

The PSS receiver is a general construction company named Company Beta who makes tunnels for roads in mountains is the client of Company Alpha. Beta's client is the government (Ministry of Land, Infrastructure, Transport, and Tourism) in Japan. Beta's suppliers include two service suppliers, Company Gamma and Company Delta, providing construction services at the tunnel site.

Design background

In much of the manufacturing industry today, numerous companies' business offerings are a combination of physical products and services. Service here includes operation, maintenance, repair, upgrade, take-back, and consultation. Manufacturers especially in developed countries today regard services as crucial. The motivation of Company Alpha to provide PSSs is to create higher value for its customers/users. Company Alpha sees potential to improve their PSSs.

Design object

The object addressed was one of the major PSSs (Product/Service Systems: a marketable set of products and services capable of jointly fulfilling a user's needs) and provided by Company Alpha. Instead of selling a physical product alone, that is a drilling machine, Company Alpha also delivers warranty of quality, original spare parts in time, early information on the next MRO activity, grease and oil of adequate quality, cleaning equipment, and a service binder. Life cycle activities are early fault detection, MRO prognostics and execution including scheduling, transport of spares to the field, and take-back of rotatable and broken parts.

Design task and deliverable

A redesign task of the existing PSS by Company Alpha was to be completed in a group working in a cooperative manner. The deliverable was requested in a form of rational improvement options of this PSS and represent them on the provided PSS dimensions.

Benchmark

No information was given to the designers.

Budget

No constraint was given to the designers.

Appendix B. Information provided to designers prior to the session

The designers were provided opportunities to study the existing PSS through materials such as brochures from Company Alpha explaining the overall information about the products and services and by visiting a real tunnel construction site located in Japan. This site was observed by the designers, where the same core product, Figure B1, and some of the services (spare parts delivery as shown in Figure B2) of the PSS were provided by Company Alpha. Staffs of Company Alpha gave additional information about the products and services to the designers at the site.

Fig. B1. The drilling machine in use at a tunnel construction site.

Fig. B2. The spare parts at a tunnel construction site.

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https://doi.org/10.1017/S0890060420000402 Published online by Cambridge University Press