(a) The full title

Analysing Cognitive Processes of Product/Service-System Design Using Protocol Analysis with a Case Study

Tomohiko Sakao[1], John Gero[2] and Hajime Mizuyama[3]

[1] *Department of Management and Engineering, Linköping University, Sweden*
[2] *Department of Computer Science and School of Architecture, University of North Carolina at Charlotte, NC, USA*
[3] *Department of Industrial and Systems Engineering, Aoyama Gakuin University, Japan*

Corresponding author

Tomohiko Sakao
Department of Management and Engineering, Linköping University, 58183 Linköping, Sweden
tomohiko.sakao@liu.se

Analysing Cognitive Processes of Product/Service-System Design Using Protocol Analysis with a Case Study

Current literature about PSS design lacks an adequate empirical grounding of conceptual designing of Product/Service Systems (PSSs). To fill this gap, this article provides foundations for understanding in the form of hypotheses. The hypotheses are developed based on results from a cognitive case study of a PSS design session using protocol analysis. This study is a part of a larger study comparing PSS design with product design. The results are produced based on the Function-Behaviour-Structure coding scheme. The results show that, in this case study, PSS designers put most of their cognitive design effort into behaviour (61% of all the design issues) and analysis and evaluation (71% of all the design processes). The dominance of design effort on behaviour in PSS design is higher than in product design. The dominant design processes are analysis and evaluation and their dominance is higher than in product design. The ratio of effort spent in the problem space over the solution space is 0.88, which is higher than in product design. Five hypotheses were developed based on the results of this case study concerning where and how designers expend their cognitive design effort. These hypotheses can be used to design experiments that test them and which provide the grounding for a fuller understanding of PSS design.

Key words: design behaviour, design cognition, design process, engineering design, conceptual design

1. Introduction

Today, 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 (2015)). Services here include monitoring, inspection, operation, maintenance, repair, upgrade, overhaul, take-back, training, and consultation. Further, some manufacturers are even strategically shifting from being a "product seller" towards being a "service provider". One reason is that they face intense competition from manufacturers selling lower-priced products. Along with this trend, Product/Service System (PSS) (Morelli, 2003; Roy et al., 2009) is much debated as a promising concept for a design object in academia as well as industry (Eisenbart et al., 2017; Brambila-Macias et al., 2018). Many manufacturers are shifting towards 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 of a PSS, in designing PSSs, services in addition to products are addressed as part of the design object, which has been often dominated by physical products in manufacturing industries. This may impact the PSS design process, as the design of the service may substantially influence the design process (Hubka et al., 1987; Visser, 2009). There are insufficient insights based on empirical research into the conceptual design of a PSS. Only a handful of descriptive studies has been carried out on how PSS design is carried out (Sakao et al., 2011; Bertoni, 2013; Sakao et al., 2014; Shimomura et al., 2015), and there is little literature on an empirically-based understanding of PSS design processes. The processes of PSS design are not sufficiently grounded in scientifically derived data. Currently, it is not possible to answer whether or not designing PSS is different from other designing, and, if so, how it is different based on empirical evidence. Even how to present differences is not available in the literature. Were this information available to PSS design researchers, it could be used to develop PSS design support methods and tools.

Motivated by this gap in our knowledge, the research reported in this article aims to provide foundations to understand the conceptual design processes of a PSS. To do so, the research adopts an exploratory case study methodology. It analyses the design process of a PSS design case in depth using protocol analysis (Ericsson et al., 1993). The major outcome of the research is formalized as a set of hypotheses to be tested by analysis of multiple cases using the methods articulated in this case study.

The remainder of the article is structured as follows: Section 2 presents the knowledge gap in existing research; Section 3 describes the purpose of this article, and the research question; Section 4 describes the research method; Section 5 presents the PSS design case; Section 6 shows the results of the analysis; Section 7 discusses the analysis; and Section 8 concludes the article.

2. Research motivation based on literature analysis

2.1 Overview of 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 a PSS have evolved (Oliva et al., 2003; Baines et al., 2007; Sakao et al., 2013). 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). There creates the opportunity to enhance insights to be utilized in the design of PSSs (ibid.). The rest of Section 2 first analyses the literature on PSSs to derive PSS characteristics, which are substantially different from those of products. It further analyses the literature on PSS design to show the incompleteness of the knowledge of the conceptual design of PSSs.

2.2 Characteristics of PSSs

Characteristics of PSSs that are 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.

Table 1. *Key properties and characteristics of PSSs and their implication on the conceptual design of PSSs*

Property	Characteristics	Implication for conceptual design
Open process systems	Human activities (Alonso-Rasgado et al., 2006) Heterogeneity (Regan, 1963) Uncertainty (Erkoyuncu et al., 2011) System architecture System components System behaviour (INCOSE, 2006) [CHANGE to INCOSE 2015 Inputs and outputs Processes and functions	Apply systems thinking (Baines et al., 2007). Analyse behaviour as a system. Consider uncertainty.
Business model	Nature of business Customer orientation (Tukker et al., 2006) Value proposed (Sakao et al., 2007) Performance of asset (Alonso-Rasgado et al., 2004; Baines et al., 2007) Available resources	Consider business model. Analyse customers (Sakao et al., 2007). Include value proposition (Morelli, 2003). Consider performance. Consider service personnel.
Social construct	Actors' roles and scenarios Technological and socio-cultural interactions Relationship between customer and provider (Baines et al., 2007)	Analyse actors' roles. Analyse 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 (ibid) and others added by the authors with references. The implication for conceptual design comes from the authors' own elaboration.

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 in the PSS, which involve human activities. The human activities (Alonso-Rasgado et al., 2006) are characterized by heterogeneity inherited from the generic characteristics of pure service (Regan, 1963). The processes in PSSs also involve product behaviours that change over time due to, e.g., deterioration. The service heterogeneity and the product change over time are both uncertain. In addition, as depicted in Figure 1, a PSS is characterized by interdependency between product and service (Meier et al., 2010) and thus the interaction between them (Komoto et al., 2008). This 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 part alone. This implies the need of systems thinking (Baines et al., 2007). For designing a system, behaviour as a system needs to be analysed. The behaviour of elements is relevant to design in general (Love, 2000), however, the system property of the PSS makes the behaviour as a system especially relevant in the conceptual design of PSSs.

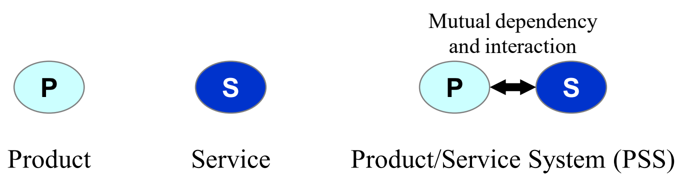

Figure 1. *A PSS depicted with the interdependency between its product and service, in comparison with its product and service parts standing alone*

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 value as its crucial construct (Osterwalder et al., 2010; Mason et al., 2011). Therefore, value is proposed as an important characteristic of PSSs (Sakao et al., 2007). In addition, customer orientation is a PSS characteristic (Tukker et al., 2006). PSS conceptual design involves various actors including customers (Morelli, 2003) and, for value proposition, analysing the actors is crucial (Sakao et al., 2007). As value often lies in the performance of a PSS as well as its products and services instead of the ownership as such (Alonso-Rasgado et al., 2004; Baines et al., 2007), the performance needs to be analysed as well.

Last, the social construct involving more actors in terms of roles than in a pure product is a PSS property.

This implies that more actors and roles are analysed in PSS design. Further, Baines et al. (2007) assert the relationship between the customer and the provider plays a key role in PSS design, which is reported with the case of Rolls–Royce (Smith, 2013). This implies that co-creation between customer and provider may be particularly useful in PSS design.

2.3 Gap in the literature on the PSS design process

Design is crucial in PSSs, as is implied by the definition given in Section 1, and there is a small but growing body of research-based literature on PSS design. The research conducted thus far includes 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 design or service design (e.g. Alonso-Rasgado et al. (2004); Sakao et al. (2009); Kimita et al. (2017)) without focussing on PSS design processes as such. Several articles, on the other hand, report the descriptive study of PSS design processes. Such studies are based on observations of design processes either in laboratory or industrial environments. As an instance of the former, Sakao and colleagues (Sakao et al., 2011; Sakao et al., 2014) carried out protocol analysis of a PSS design and uncovered lifecycle activity is a central notion addressed within the design case. As an example of the latter, 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. The earlier research gives some indication of the characteristics of PSS design processes; however, none of them answers clearly whether or not PSS design is different from other design, and, if so, what are the differences.

3. Purpose

The purpose of this article is to provide an empirical foundation for an understanding of the PSS design processes. It is part of a larger study comparing PSS design with product design. The research reported in this article focuses on conceptual design in PSS design, because of 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 PSS design (Sakao et al., 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 pure service, about which more insights are available. Thus, it is more useful to research conceptual design in PSS design. In addition, focus is given to design issues and processes, because design is the activity that decides values for parameters in question (Gero, 1990) and the parameters and deciding values correspond to issues and processes, respectively. Therefore, the research question is:

How is the conceptual design of a PSS carried out in terms of design issues and design processes?

4. Method

4.1 Motivation for choice of the method

The research question stated above is abstract and an exploratory case study approach (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 (ibid.) 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 et al., 2008).

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 et al., 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 behaviour of designers, including exploratory studies (hypothesis generation) and hypothesis testing (Atman et al., 1996; Mc Neill et al., 1998; Purcell et al., 1998; Kavakli et al., 2002; Badke-Schaub et al., 2007; Christensen et al., 2007; McDonnell et al., 2009). 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 because, for example, interpretation of statistical analyses may be enhanced by a qualitative narrative account (Robson, 2002).

4.2 FBS (Function-Behaviour-Structure) ontology

4.2.1 Overview

In carrying out a protocol study, this research makes use of a method for determining and describing design cognition, based on the Function–Behaviour–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 et al., 2014; Kan et al., 2017). It is, therefore, suitable for use in studying PSS design and also for later comparing the results to other studies of design (Kan & Gero, 2017). The FBS ontology provides a uniform framework for classifying cognitive design issues and cognitive design processes and includes higher level semantics in its representation.

4.2.2 Interpretation and use of FBS scheme

A match between the design issues in the FBS scheme and frequently addressed dimensions in PSS design are 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. This matching is used as a basis for the protocol analysis, where the utterances of the designers are segmented and coded using the FBS design issues.

Table 2. *FBS design issues applied in the PSS context*

FBS design issue	Explanation	PSS dimensions
Requirement	What is required by the client	Needs stated by the client
Function	What it is for	Client's needs as interpreted by the designers and those added by the designers Values
Expected Behaviour	What it is expected to do	Lifecycle activities
Structure	What it is	Core product Peripheral product Actors Contract elements (in documents) Payment model
Structure Behaviour	What it does	Lifecycle activities
Document	What it is documented as	Contract Sketches Deliverables (e.g. service manual)

The results from an FBS-coded protocol can be measured in multiple ways to provide foundations for understanding PSS design. This research uses the following quantitative measures.

- Tabular statistics: this produces the statistical distributions of the design issues and the design processes and provides quantitative measurements of where designers' cognitive design effort is expended. This can be visualized with cumulative curves (see Section 4.2.4).
- 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 4.2.5).

4.2.3 System levels in PSSs 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 level or the component level (Gero et al., 1998; Song et al., 2016), PSS design concerns the level of the whole PSS or the level of products or services at a segment in a design episode. These levels are applicable to any design issue in the FBS scheme, as shown in Table 3.

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

System level	Explanation
PSS (Product/Service System)	Mainly concerning the PSS as a whole
Product	Mainly concerning products in the PSS
Service	Mainly concerning services in the PSS

4.2.4 Cumulative occurrences, curves 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 visualisation of the cumulative occurrence of the design issues.

Figure 2 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 $C_y = \sum_{i=1}^{n-1} y_i$, 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).

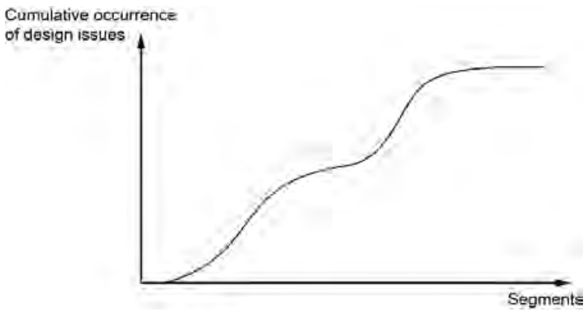

Figure 2. *Graphical representation of the cumulative occurrence of design issues in a design protocol*

4.2.5 Problem-Solution index

The Problem-Solution index (P-S index), whether for issues or processes, is a measurement to characterize the overall cognitive style of design. It is determined by calculating the ratio of the total occurrences of the design issues/processes concerned with the problem space to the sum of those related to the solution space, as shown in Equations (1) and (2). The problem-related processes are formulation C_1, reformulation 2 C_7 *and* reformulation 3 C_8. The solution-related processes are synthesis C_2, analysis C_3, evaluation C_4 and reformulation 1 C_6. The process documentation 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 across 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 problem and 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.

5. PSS design case

The target case, which is the input for the protocol study, was selected from a laboratory environment instead of an industrial one. This is motivated by the fact that for the industrial practice of PSS design there are multiple confounding variables that cannot be controlled for (Matschewsky et al., 2018). A design case in a laboratory environment reduces confounding variables and has the potential to directly generate the information we need about PSS design.

The task of this design was to improve at a conceptual level for an existing PSS provided by a company 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. 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 generic dimensions 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 one hour.

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 did collaborate with each other in developing improvement options together. The equipment used for both audio and video recording consisted of two video cameras with mobile microphones to provide 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 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 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 effective.

6. Results of case study

6.1 Coding

The design session was transcribed and translated into English. Then, the transcription was segmented and coded by two independent coders. 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 coder was consulted for a final decision. The episode eventually consisted of 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. 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.

6.2 Narrative description

In the design session, the implications for conceptual design of a PSS based on the PSS properties and characteristics (shown in the right-hand column of Table 1) were observed: in a part of the protocol shown in Table 4, reducing the machine downtime and the cost of the whole PSS as well as enhancing the 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), analysing behaviour as a system (e.g. machine breakdowns that will take up a lot of time for the operator and the customer), considering service personnel (e.g. operators), and analysing scenarios (e.g. 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 analysing customers (e.g. end users), analysing actors' roles (e.g. the service supplier's support role for the PSS receiver), and analysing the business model (e.g. rental or purchase). All the implications of the conceptual design of a PSS in Table 1 were observed except the co-creation process between the customer and the provider, which was not possible in this laboratory setting. The rest of Section 6 shows quantitative results using the measurement techniques outlined in Sections 4.2.3, 4.2.4 and 4.2.5.

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
211	MK	Therefore, depending on that...well what then? Essentially, breakdowns take up a lot of time. (points)	Bs	Analyse behaviour 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	Analyse behaviour as a system Analyse 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	Analyse behaviour as a system

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	Analyse customers
18	KK	Somehow, I think this one is a case peculiar to the site, with [the service supplier].	Bs	Analyse behaviour as a system
19	KK	[The PSS receiver]	S	
20		really relies on [the service supplier].	F	Analyse actors' roles
21	KK	Then actually…. One of the things is how can the equipment be purchased…	Be	Analyse business model
22	KK	Uh, was it renting? Renting, hmmm. The premise was a little different, but. RK:/ Yeah. KK:/ Well..., so…	Be	Analyse business model

6.3 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 behaviour 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 are large; S and F each are only approximately one half of Be. These are followed by D (9.9%). The P-S Issue Index for the entire design session was calculated to be 0.88, meaning that across the design session more cognitive design effort is expended on the solution than the problem, but the difference between this value and an equal distribution is relatively small.

Table 6. *Issue distribution [%] and P-S Issue Index*

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

The distributions of the system levels based on Section 4.2.3 for the entire episode are shown in Table 7. Only Behaviours are targeted here because they received higher distributions (see Table 6). This shows that different levels are addressed in the design episode. In Behaviour 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).

Table 7. *Distributions [%] of the system levels within Behaviour*

	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

Figure 3 shows the moving averages chronologically across the design session of each design issue with a window of 61 segments, corresponding to a quarter of the entire session. 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 3 shows that the cognitive design effort for the design issues vary substantially over time and provides a graphical basis for a qualitative interpretation of the results. From Figure 3, 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 part, but this later part of F occurred earlier than the final part of S.

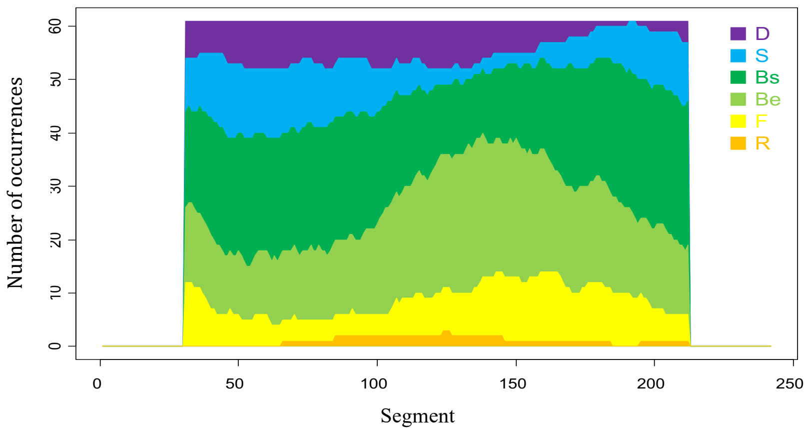

Figure 3. *Moving average of cognitive design effort expended on design issues (window of 61 segments)*

Examining the source data through its segments, Figure 4 presents a graphical representation of the cumulative occurrence of design issues in the protocol. The values of the graphs at segment 242, i.e., the final points of the episode, correspond to the values in Table 6 and show that Behaviour derived from Structure (Bs) occurred in the highest number of segments. The graphs' shapes in Figure 4 give an intuitive understanding of the transition of cognitive design effort over time. In each graph the part with the higher slope, the issue is more frequently addressed. The design issues are different in terms of which parts of the entire design session the issues are addressed more in, as represented by the different shapes and slopes. For instance, the high effort received by Be found "after the middle" (as described above) of the session in Figure 3 can be seen between the 100th and 165th segments in Figure 4. The reason for the lag between the middle and the 100th segment lies in the different ways of measurement; an envelope containing 61 segments is used in Figure 3. In addition, an increase of effort in F followed by that in S can be seen between the 160th and 230th segments in **Figure 4**.

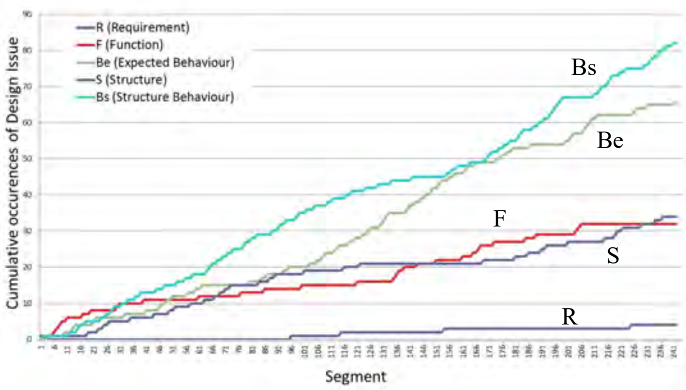

Figure 4. *Cumulative cognitive design effort expended on design issues*

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 5 shows, as an example, the result for 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.

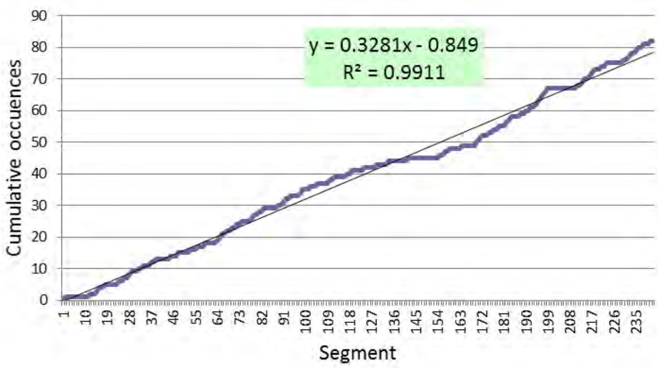

Figure 5. *Result of linear approximation of the cumulation of design issue Bs*

__Table 8.__ Coefficients of determination from linear approximation of the transition

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

6.4 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 this PSS design.

__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

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 these two 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 behaviour is the dominant design issue within the syntactic processes as well as that the behaviour is at the end point of the processes rather than the starting point.

Figure 6 shows 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.

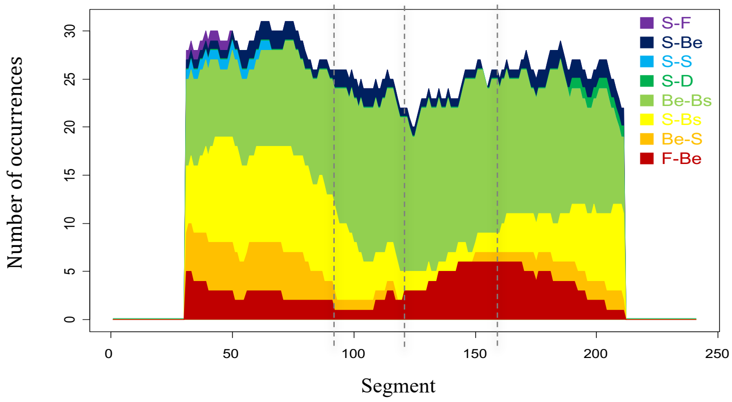

Figure 6. *Moving average of cognitive design effort expended on syntactic processes (window of 61 segments)*

The majority of syntactic processes change over time, and the whole session could be divided into four phases, shown by three dotted lines in Figure 6. 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, they are dominated by Be – Bs (Evaluation) and F→Be (Formulation). In the last phase, they are Be – Bs (Evaluation), F→Be (Formulation), and S→Bs (Analysis).

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 F→Be (Formulation) and S→Bs (Analysis).

Shifting to a more microscopic view of syntactic processes' occurrences, Figure 7 shows cumulative occurrences of each syntactic process on the vertical axis. The values of the graphs at segment 241 correspond to Table 9, showing, e.g., 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 92th 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 6 because of the difference in granularity.

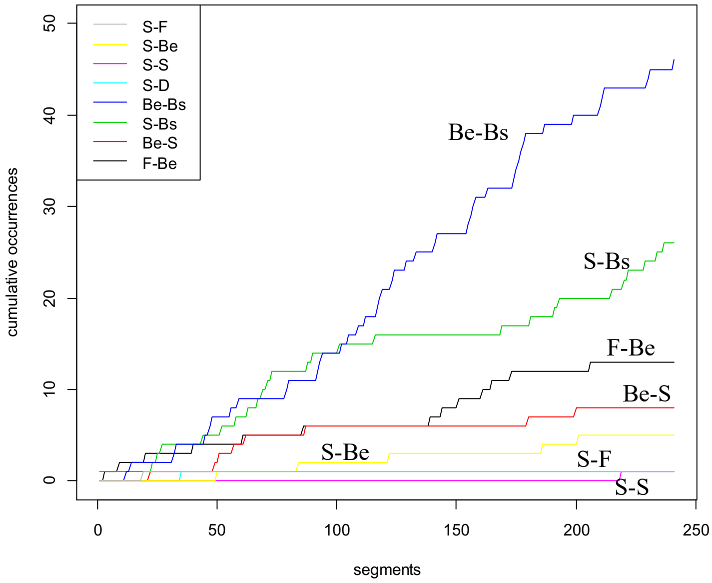

Figure 7. Cumulative cognitive design effort expended on processes

6.5 Problem-Solution index series

The Problem-Solution issue index for the entire session is 0.88, as is shown in Table 6. The P-S issue Indexes from session deciles are found to vary over time, as shown in Figure 8. The maximum is 4.25 of the sixth, while the minimum is 0.22 of the tenth. The deciles with the index greater than 1 are the first, fifth, sixth, and seventh deciles. It means that the problem space is focused on more than the solution space in those deciles.

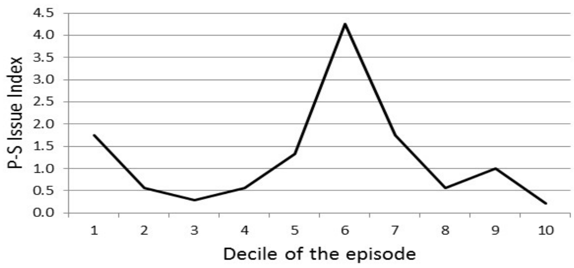

Figure 8. *P-S Index in deciles over the design session*

Interestingly, from the graph's shape it can be seen that the sixth decile has by far the highest P-S Index. This corresponds to a window right after the middle in Figure 3, where Be has its peak and F is also discussed substantially. In addition, it coincides with the third phase discussed with Figure 6, 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 the space addressed shifts from the solution to the problem towards the six decile and then shifts back to the solution.

7. Discussion

7.1 Design issues

Following the research question, design issues are investigated based on results from the PSS design episode (Sections 6.2, 6.3 and 6.5) and from analysing literature on PSSs (Section 2.2). From Table 6, the dominance of behaviour (Be and Bs) is in contrast to the dominance of Structure in studies of designing products (Yu, et al., 2015). The ratio (%) of Be and Bs in total is calculated based on Table 6 as follows:

Be + Bs = 27.3 + 33.9 = 61.2.

This means Behaviour was addressed for 61.2% of all the design issues. This originates partly from the discussion of behaviour as a system and performance of products and services (as shown in Section 6.2 with observation of the partial protocol of Tables 4 and 5

Table 5). In addition, the high linearity of the cumulative occurrence of Bs (with an $R^2 = 0.9911$ in Figure 5) and that of Be (with an $R^2 = 0.9832$ in

Table 8) indicates that the behaviour was discussed constantly during the entire process. It should also be noted that other design issues, such as S (14.0%) and F (13.2%), received substantial cognitive design effort as well. It means the designers were not uniquely focused on behaviour but a mixture of behaviour, structure, and function, with behaviour dominating.

The results of the literature analysis (in Section 2.2), Table 1, theoretically shows the relevance of *behaviour* as a design issue in the conceptual design of a PSS: *behaviour* as a system with various types of uncertainty is expected to be analysed 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 analysed due to the PSS's property of being a business model. Therefore, cognitive efforts spent for behaviour in PSS design are rationalized.

The reasoning shown above, based on this case study and an analysis of the literature on PSS, has led the authors to formulate the following hypothesis, Hypothesis 1 (H1).

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

The degree of dominance of behaviour found in this PSS design episode is uncommon in product design. PSS design and product design are compared in Table 10 according to protocol study with the FBS scheme (Jiang et al., 2014), which resulted from 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, Table 10. They are substantially lower than 61.2% in PSS design.

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

Based on the results in Table 10, the following hypothesis, Hypothesis 2 (H2) is formulated.

H2. More effort is spent on behaviour 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 Behaviour: 41.9% for the system level and 48.1% for the component level (Be and Bs in total). This is in accordance 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 Behaviour, and this leads to the following hypothesis, Hypothesis 3 (H3).

H3. In the conceptual design of a PSS, effort is spent on the behaviour 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 Section 4.2.5, 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 8, at four of the ten deciles of the episode, the P-S issue index exceeds 1.

In product design, the P-S issue index is substantially lower than that in PSS design found by this study, according to (Jiang et al., 2014). From Table 10, the P-S index for the two studies of product design is calculated as:

$$(1.1+12.1+15.6) / (19.8+31.2) = 28.8 / 51.0 = 0.56$$

$$(1.8+11.4+13.5) / (28.3+28.0) = 26.7 / 56.3 = 0.47$$

The problem space is expected to be discussed in PSS design due to its business model property (see Table 1): a customer is to be analysed 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 at the customer's own settings, i.e., the customer's purposes and does not necessarily appreciate the hardware as such (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 in common that the problem space becomes more relevant in the conceptual design of a PSS, as compared to that of product.

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 theory of PSS design as compared to product design and is, therefore, considered to be 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.

7.2 Design processes

Distributions of the syntactic processes of the FBS scheme in the case study were shown in Table 9. The distributions of analysis and evaluation from the entire episode were calculated as 25.7% and 45.5%, respectively, i.e., about 70% for both. Examples of analysis and evaluation were 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).

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		6.2	6.1	15.4	15.1	20.6	17.9	2.4	10.5
Product design by mechanical design major		5.9	6.3	15.0	10.5	20.3	27.3	3.4	6.7

In the literature on the processes of PSS design, analysis as a system, performance, and customers are raised as important issues ,**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 et al., 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) state that PSS design involves finding a mapping between activities in a service environment and 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.

8. Conclusion

Product/Service Systems (PSS) have received steadily increasing interest by practitioners, especially among manufacturing companies integrating services with products to combat low-priced product manufacturers. After analysing the literature about PSSs, characteristics and properties of a PSS as compared to physical products were derived, and further, their implications for PSS conceptual design were derived. Design is influenced by its design object, but knowledge for designing PSSs is scarce. Motivated by this lack and the need of insights for PSS design, this article aims to provide a foundations for understanding PSS conceptual design processes. Acknowledging the current lack of evidence-based insights on PSS conceptual design, a case study was conducted and, as a result, five hypotheses were created. The method adopted in the case study was protocol analysis, where the FBS coding scheme was utilized.

The results show that, in this case study, PSS designers put most of their cognitive design effort into behaviour (61% of all the design issues) and analysis and evaluation (71% of all the design processes). The cognitive effort spent on behaviour in this PSS design compared to earlier research with product design, is shown to be much higher. Analysis and evaluation processes are the dominant in this PSS design and compared to product design, are higher. Further, the ratio of effort spent in the problem space over the solution space is 0.88, which is higher than in product design. These results were translated into five hypotheses related to where and how designers expend their cognitive design effort, as shown in Section 7. Further research, driven by these five hypotheses, to analyse more PSS design sessions is needed to generalize insights into PSS design obtained in this study.

The results presented in this article contribute to an increase in our knowledge about the distribution of cognitive design effort in PSS design. The measurement and calculation techniques adopted in this research are shown to effectively produce quantitative results about PSS design, which is also a part of the scientific value of this article, and thus can be used for further research. 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. Combined with previous successful applications of this coding scheme to product design, this article also provides opportunities for comparative studies between PSS design and product design. Outcomes from such research will also provide grounding for the evaluation and development of PSS design methods.

Acknowledgements

The company that provided this research with the PSS case is much appreciated.

Financial support

This research is supported in part by grants from the US National Science Foundation (J.G. grant numbers 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 number DIA 2014/16).

References

Ahmed, S. (2007). An industrial case study: identification of competencies of design engineers. *Journal of Mechanical Design 129(7)*: 709-716.

Alonso-Rasgado, T. and G. Thompson (2006). A rapid design process for Total Care Product creation. *Journal of Engineering Design 17(6)*: 509 - 531.

Alonso-Rasgado, T., G. Thompson and B. Elfstrom (2004). The design of functional (total care) products. *Journal of Engineering Design 15(6)*: 515-540.

Atman, C. J. and K. M. Bursic (1996). Teaching Engineering Design: Can Reading a Textbook Make a Difference? *Research in Engineering Design 8*: 240-250.

Badke-Schaub, P., K. Lauche, A. Neumann and S. Ahmed (2007). Task – team - process: assessment and anlaysis of the development of shared representations in an engineering team. *DTRS 7 Design Meeting Protocols Workshop*, London.

Baines, T. S., A. Z. Bigdeli, O. F. Bustinza and K. Ridgway (2017). Servitization: Revisiting the State-of-the-art and Research Priorities. *International Journal of Operations & Production Management 37(2)*: 256-278.

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

Bertoni, A. (2013). Analyzing Product-Service Systems conceptual design: The effect of colorcoded 3D representation. *Design Studies 34*: 763-793.

Brambila-Macias, S., T. Sakao and C. Kowalkowski (2018). Bridging the Gap between Engineering Design and Marketing: Insights for Research and Practice in Product/Service System Design. *Design Science*.

Breslin, M. and R. Buchanan (2008). On the case study method of research. *Design Issues 24(1)*: 36-40.

Christensen, B. T. and C. D. Schunn (2007). The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory & Cognition 35(1)*: 29-38.

Dinar, M., J. J. Shah, J. Cagan, L. Leifer, J. Linsey, S. M. Smith and N. Vargas Hernandez (2015). Empirical Studies of Designer Thinking: Past, Present, and Future. *Journal of Mechanical Design 137(2)*: 1-13.

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

Eisenbart, B., K. Gericke and L. T. M. Blessing (2017). Taking a look at the utilisation of function models in interdisciplinary design: insights from ten engineering companies. *Research in Engineering Design 28(3)*: 299-331.

Ericsson, K. A. and H. A. Simon (1993). *Protocol Analysis Verbal Reports as Data*. Cambridge, MA, MIT Press.

Erkoyuncu, J. A., C. Durugbo, E. Shehab, R. Roy, R. Parker, A. Gath and D. Howell (2011). Uncertainty driven service cost estimation for decision support at the bidding stage. *International Journal of Production Research 51(19)*: 5771-5788.

Gericke, K., M. Schmidt-Kretschmer and L. Blessing (2007). Dealing with requirements: inferences on idea generation in the early stages of product development. *DTRS 7 Design Meeting Protocols Workshop*, London.

Gero, J. S. (1990). Design Prototypes: A Knowledge Representation Schema for Design. *AI Magazine 11(4)*: 26-36.

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

Gero, J. S. and U. Kannengiesser (2014). The Function-Behaviour-Structure ontology of design. *An Anthology of Theories and Models of Design*. A. Chakrabarti and L. Blessing, Springer**:** 263-283.

Gero, J. S. and T. M. Neill (1998). An approach to the analysis of design protocols. *Design Studies 19*: 21-61.

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

Hubka, V. and W. E. Eder (1987). A scientific approach to engineering design. *Design Studies 8(3)*: 123-137.

INCOSE (2015). *Systems Engineering Handbook, Fourth Edition*. International Council on Systems Engineering, John Wiley.

Jiang, H. (2012). *Understanding Senior Design Students' Product Conceptual Design Activities*. PhD

Thesis, National University of Singapore.

Jiang, H., J. S. Gero and C. C. Yen (2014). Exploring designing styles using Problem-Solution indexes. *Design Computing and Cognition'12*. J. S. Gero, Springer**:** 85-101.

Kan, W. T. and J. S. Gero (2017). *Quantitative Methods for Studying Design Protocols*. Dordrecht, Springer.

Kavakli, M. and J. S. Gero (2002). The structure of concurrent cognitive actions: A case study of novice and expert designers. *Design Studies 23(1)*: 25-40.

Kimita, K., T. Sakao and Y. Shimomura (2017). A failure analysis method for designing highly reliable product-service systems. *Research in Engineering Design*.

Komoto, H. and T. Tomiyama (2008). Integration of a service CAD and a life cycle simulator. *CIRP Annals - Manufacturing Technology 57(1)*: 9-12.

Love, T. (2000). Philosophy of design: a metatheoretical structure for design theory. *Design Studies 21*: 293-313.

Mason, K. and M. Spring (2011). The sites and practices of business models. *Industrial Marketing Management 40*: 1032-1041.

Matschewsky, J., M. L. Kambanou and T. Sakao (2018). Designing and providing integrated productservice systems – challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies. *International Journal of Production Research 56(6)*: 2150-2168.

Mc Neill, T., J. S. Gero and J. Warren (1998). Understanding conceptual electronic design using protocol analysis. *Research in Engineering Design 10(3)*: 129-140.

McDonnell, J. and P. Lloyd, Eds. (2009). *About Designing: Analysing Design Meetings*, CRC Press.

Meier, H., R. Roy and G. Seliger (2010). Industrial Product-Service Systems - IPS². *CIRP Annals - Manufacturing Technology 59(2)*: 607-627.

Morelli, N. (2003). Product-service systems, a perspective shift for designers: A case study: the design of a telecentre. *Design Studies 24(1)*: 73-99.

Müller, P., N. Kebir, R. Stark and L. Blessing (2009). PSS Layer Method - Application to Microenergy Systems. *Introduction to Product/Service-System Design*. T. Sakao and M. Lindahl. London, Springer**:** 3-30.

Oliva, R. and R. Kallenberg (2003). Managing the transition from products to services. *International Journal of Service Industry Management 14(2)*: 160-172.

Osterwalder, A., Y. Pigneur and A. Smith (2010). *Business Model Generation*. Hobroken, NJ, John Wiley & Sons, Inc.

Pahl, G. and W. Beitz (1996). *Engineering Design: A Systematic Approach*. London, Springer-Verlag.

Papalambros, P. Y. (2015). Design Science: Why, What and How. *Design Science §1*.

Purcell, T. and J. S. Gero (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(4)*: 389-430.

Regan, W. J. (1963). The Service Revolution. *Journal of Marketing 47(July)*: 57-62.

Robson, C. (2002). *Real World Research - A resource for social scientists and practitioner-researchers*. Malden, MA., Blackwell.

Rolls-Royce (2015). Rolls-Royce Holdings PLC Annual Report 2014. London, Rolls-Royce.

Roy, R. and D. Baxter (2009). Special Issue - Product-Service Systems. *Journal of Engineering Design 20(4)*: 327 – 431.

Sakao, T. and M. Lindahl (2015). A method to improve integrated product service offerings based on life cycle costing. *CIRP Annals - Manufacturing Technology 64(1)*: 33-36.

Sakao, T. and H. Mizuyama (2014). Understanding of a Product/Service System Design: a Holistic Approach to Support Design for Remanufacturing. *Journal of Remanufacturing 4*: 1-24.

Sakao, T., S. Paulsson and H. Mizuyama (2011). Inside a PSS Design Process: Insights through Protocol Analysis. *International Conference on Engineering Design*, Copenhagen.

Sakao, T. and Y. Shimomura (2007). Service Engineering: A Novel Engineering Discipline for Producers to Increase Value Combining Service and Product. *Journal of Cleaner Production 15(6)*: 590-604.

Sakao, T., Y. Shimomura, E. Sundin and M. Comstock (2009). Modeling Design Objects in CAD System for Service/Product Engineering. *Computer-Aided Design 41(3)*: 197-213.

Sakao, T., A. Öhrwall Rönnbäck and G. Ölundh Sandström (2013). Uncovering Benefits and Risks of Integrated Product Service Offerings – Using a Case of Technology Encapsulation. *Journal of Systems Science and Systems Engineering 22(4)*: 421 - 439.

Shimomura, Y., Y. Nemoto and K. Kimita (2015). A method for analysing conceptual design process of product-service systems. *CIRP Annals - Manufacturing Technology*.

Smith, D. J. (2013). Power-by-the-hour: the role of technology in reshaping business strategy at Rolls-Royce. *Technology Analysis & Strategic Management 25(8)*: 987-1007.

Song, T., K. Becker, J. Gero, S. DeBerard, O. Lawanto and E. Reeve (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(2)*: 37-56.

Stempfle, J. and P. Badke-Schaub (2002). Thinking in design teams - an analysis of team communication. *Design Studies 23(5)*: 473-496.

Suwa, M., T. Purcell and J. S. Gero (1998). Macroscopic analysis of design processes based on a scheme for coding designer's actions. *Design Studies 19(4)*: 455-483.

Tang, H.-H. and J. S. Gero (2002). A cognitive method to measure potential creativity in designing. *Workshop 17 - Creative Systems: Approaches to Creativity in AI and Cognitive Science (ECAI-02)*, Lyon.

Teegavarapu, S., J. D. Summers and G. M. Mocko (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., M. Verkuijl and A. Tukker (2002). First Draft PSS Review. Cologne, Econcept.

Tukker, A. (2015). Product services for a resource-efficient and circular economy - a review. *Journal of Cleaner Production 97*: 76–91.

Tukker, A. and U. Tischner, Eds. (2006). *New Business for Old Europe*. Sheffield, Greenleaf Publishing.

van Someren, M. W., Y. F. Bardard and J. A. C. Sandberh (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, R. K. (2006). *Case Study Methods. Handbook of Complementary Methods in Education and Research*. Mahwah, NJ, Erlbaum.

Yu, R., Gu, N., Ostwald, M. and Gero, J. S. (2015). Empirical support for problem-solution co-evolution in a parametric design environment, *AIEDAM* 25(1): 33-44.