What do experienced practitioners discuss when designing Product/Service Systems?

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This paper presents empirical results aimed at increasing the understanding of conceptual activities of Product/Service Systems (PSS) design by experienced designers from industry. Results are derived from a protocol analysis of five PSS design sessions, using the Function–Behavior–Structure coding scheme. Sessions included five pairs of professional designers and the task was to redesign a concept for an existing PSS to improve its resource efficiency. Results show i) the distribution of design issues during PSS design sessions, ii) on average 47% of the overall cognitive design effort spent by the designers is related to behavior, and iii) all the design issues except requirements are constantly focused on during the entirety of the design sessions. Major differences compared to product design are the average occurrence of function for PSS design (23%) for product design (4%) and of structure for PSS design (22%) compared to the product design (35%).

Introduction

Today, a large number of companies increasingly provide a combination of products and services, both in the manufacturing (e.g. [1]) and service industries (e.g. [2]). Such an offering is called a Product/Service System (PSS), which is defined as "tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs" [3]. The services here include consultation, user support, inspection, maintenance, refurbishing, repair, product take-back, and upgrade (see, e.g., [4]). Those companies focus on value [5] to be created, rather than products or services as such. The products and services are a means for the value and are exchangeable with each other in designing a PSS [6]. For instance, a PSS with aircraft engines may provide high engine availability as a value for the user, which can be realized by increased durability of critical components or by arranging maintenance engineers to provide more timely and efficient maintenance services. This industrial phenomenon creates sources of innovation, as it provides possibilities to design new offerings.

However, it is typical that a traditional manufacturer provides services by first carrying out product design and then service design in a sequential manner [7]. This is not an adequate way of designing combined systems, as products and services in a PSS depend on each other [8] and such a sequential design requires multiple iterations, thus decreasing the efficiency of the design. As a consequence PSS design needs to be different from product design (e.g. [9]), service design (e.g. [10]), or a sequential combination of them. What is needed is to design products and services in an integrated manner for the value to be created.

Some prescriptive models and methods for PSS design have been proposed (e.g. [11]). However, scientific understanding of how PSS design is conducted, especially regarding insights based on empirical research, has rarely been documented. For instance, what is discussed during PSS design and what processes occur have yet to be adequately explored. This paper targets this lack of detailed knowledge about PSS design.

Aim

In order to fill the knowledge gap identified above, this paper aims at increasing the understanding of the activities during the conceptual phase of a PSS design. Conceptual design is targeted in this paper because it involves activities characteristic to PSS design such as utilizing exchangeability between products and services [6]. Exchangeability here means being able to exchange efforts for service and product design to improve the overall PSS characteristics of interdependent products and services (ibid). In addition, conceptual design is an early phase of design, and thus more influential on the overall performance of the design. Understanding conceptual design activities is expected to contribute more to the understanding of PSS design than other phases.

Designing a physical product is utilized as a reference to compare characteristics of PSS design with product design. There is already substantial literature showing the characteristics of product design (e.g. [12-16]).

Significance

This paper is based on a limited dataset derived from a small cohort of practicing, professional PSS designers sufficient to answer research questions and to form the basis of hypotheses that can be tested with a statistically significant cohort size. A major contribution of the increased understanding expected from this paper will lie in effective design of further research deriving and testing a set of hypotheses regarding distributions of design issues in the conceptual design of a PSS. This further research will result in more grounded, generalizable knowledge about PSS design.

There is an increasing need in our societies for PSS design. Customers' needs for servitized offerings [8] and fierce competition are often the major motivations for providing a PSS. However, a PSS is also expected to contribute to decreased environmental impacts, for example in resource consumption [17]. The PSS is reported to have the potential to increase product life [18] and to decrease lifecycle environmental impacts [19]. It has indeed been heralded as one of the most effective instruments for enhancing resource efficiency [20]. Therefore, improving PSS design is often demanded by industry and by society at large.

Research questions

This section analyses the PSS literature to derive characteristics of a PSS compared to pure physical products. Based on these derived characteristics, it further reasons about their implications on the conceptual design of a PSS compared to that of products.

Pure physical products are material intensive and most of their added value is derived from the manufacturing processes that transform raw materials into the final product [21]. In contrast to the design of a PSS, when a product is designed its potential service aspects in the use phase of a product lifecycle are less emphasized (ibid). Furthermore, previous research has shown that the structure of the design object recurs frequently in the cognitive activities of designers during product design, and was found to be the dominant design issue [12, 22, 23]. This dominance of structure over other design issues such as behaviour and function could be attributed to the lack of a systems perspective in the product design [23].

On the other hand, a major property of a PSS is its open process systems [24]. This means that a PSS is a system with input and output flows. Output flows are determined by processes in a PSS, which can be used to describe functions and human activities. The human activities [25] are characterized by heterogeneity inherited from generic characteristics of pure service [26]. Pure physical products cannot be considered as open process systems in the same way as a PSS, due to the absence of output flows characterized by human activities and services, which is prevalent in a PSS.

Further, a PSS is characterized by interdependency between product and service [8] and thus interaction between them [27]. This means that the conceptual design of a PSS requires simultaneous and conflicting product and service engineering [8]. It is more complex than the product component or the service component within the PSS. The complexities in conceptual design of a PSS highlight the need for systems thinking [28]. For designing a system, behaviour as a system needs to be analysed. Behaviour of elements is relevant to design in general [29], however the higher level of complexity of a PSS makes the behaviour as a system especially relevant in the conceptual design of a PSS. This may be applied to function as well as behaviour. These lead to the research questions (RQs) below. RQ1 is an elucidatory question that provides the basis for further research. RQ2 focuses on the behavior based on the discussion above. RQ3 refers to product design and is founded on the notion that since there are two disparate subsystems in PSS will there be more discussion about functions that are distributed between them.

- RQ1: What are the distributions of design issues and design processes in the conceptual design of a PSS?
- RQ2: Is behaviour the dominant design issue in the conceptual design of a PSS?
- RQ3: Is function as a design issue more dominant in the conceptual design of a PSS than in the design of a product alone?

Methods

Protocol analysis is adopted in this research to examine the research questions, as it provides empirically-based quantitative evidence as well as 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 also a well-developed, validated method for the acquisition of data on thinking [30, 31]. It has been used extensively in design research, for example in exploratory studies and hypothesis testing, to help the development of the understanding of the cognitive behaviour of designers [32-38].

This research utilizes a method for determining and describing design cognition using a coding scheme based on the Function–Behaviour–Structure (FBS) ontology [39]. 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 [14, 40-43]. It is, therefore, suitable for use in analysing PSS design in comparison with other types of design. The FBS ontology provides a uniform framework for classifying cognitive design issues and cognitive design processes and includes higher level semantics in their representation.

The FBS ontology [39] models designing in terms of three classes of ontological variables, namely function, behaviour, and structure, plus two variables that are expressible in terms of requirements and design description. In this view, the goal of design is to transform a set of functions, driven by the client requirements (R), into a set of design descriptions (D). The *function* (F) of a designed object is defined as its intended purpose, expectations or teleology, while the *behaviour* (B) of that object is either derived (Bs) or expected (Be) from the structure, where *structure* (S) represents the components of an object and their relationships.

The FBS ontology has been referenced extensively as an ontology of design that has been used in various disciplines, and one that transcends individual designers, the design task, the design environment, and whether design is done individually or in teams [14, 44-49].

Materials from the PSS design case

The data for the protocol analysis was derived from design sessions conducted in a laboratory environment with experienced practitioners as participants who were given a PSS redesign task. The aim of this task was to redesign a concept for an existing PSS to improve its resource efficiency in terms of material and energy use. A conceptual design was chosen for this study as it is characteristic of a great deal of PSS design, for example by permitting exchangeability between products and services of the systems which are essential for PSS design [6].

A laboratory environment was chosen over an industrial setting, partly because the prospect of shadowing and monitoring the participants as they carry out design activities in their own industrial setting was ruled out due to confidentiality reasons. In addition, the participants are employees of different manufacturing companies working with different types of PSSs. This would increase the variability of the unit of analysis and characteristics of data, potentially reducing the internal validity of the study. Furthermore, previous research suggests that the design activities of products and services are usually separated in industrial environments and are not integrated at the required level [7]. Hence, all the participants were asked to perform the same design task in a controlled laboratory environment, thus providing the opportunity for unrestricted collaboration between product and service design.

A design brief (see Appendix), which included information necessary to carry out the task, was provided to the participants beforehand. The PSS utilizes a coffee machine used in offices provided by a hypothetical firm that develops, manufactures and delivers the product and related services to its clients. The machine utilized is an actual model available on the real market, but the details of the real provider are not disclosed to the participants. A detailed specification of the machine and the services was provided in the design brief, and the participants were also allowed to visually inspect the physical model. The firm's service portfolio included activities such as installation of the machines, replenishment of the consumables, maintenance, repair and overhaul.

There were 10 participants in total, and they were instructed to perform the task in pairs. In each pair, one participant was instructed to assume the responsibility of a service designer, while the other took the role of a product designer. This instruction was given based on their background and work experience. No information regarding design tools or methods was given to the participants to prevent external influence on the design process. They were provided with a poster-sized sheet of blank paper, post-its and pens in different colors for the design task. The tasks of all the pairs were documented simultaneously using both audio and video recording devices in parallel sessions to obtain richer cognitive information from both verbal and non-verbal actions of the participants [23]. The data collected was later subjected to protocol analysis. The language used during the sessions was Swedish, which was the language spoken daily by all the participants.

The participants are experienced product or service designers with an average experience of 9 years, with a standard deviation of 5.34 years. They work for leading manufacturing industries that provide PSSs in different sectors such as automotive, electronics, composite components, and grinding machines.

The audio and video recordings of the sessions were initially transcribed before being segmented and coded using the FBS ontology by two independent coders. The results of both coders were compared and arbitrated by a third coder, who also made the final decision regarding the codes. The length of the sessions on average was 75 minutes, with a standard deviation of around 10 minutes.

Results of protocol analysis

Overview

The utterances were segmented and coded, the segments that did not belong to any of the design issues of the FBS ontology were considered as noise and were removed. After the removal of the noise, an average of 958 segments per session, with a standard deviation of around 214 segments, were subjected to further analysis. Table 1 illustrates an excerpt of the segmentation and coding of the transcribed data collected from one of the design sessions, aiming mainly to show examples of utterances for most of the design issues. The two coders carried out their coding independently and then a third person carried out an arbitration. A simple statistical measure of agreement between each coder's codes and the final arbitrated codes is used as the reliability measure since Cohen's kappa was not applicable in this setting. This was done by calculating the ratio of sum of number of agreements between the individual coders coding and the arbitrated codes, over the total number of codes. The two coders had an average of 71% agreement with the final arbitrated codes for all the design sessions.

Table 1 Excerpt of the segmented protocols (translated into English)

Designer	Segment	Code
A	(Writes)	D
A	Service report	S
B	When it is used,	Be
A	And what it is used for I saw that it was	F
B	Which I interpret as each one has his own card	Be
B	And then you go and take coffee	Bs

Design issue distribution

The distribution of occurrence of design issues over the five design sessions is shown in Table 2. The data for R are not reported here as the number of occurrences were too low for this analysis. Design issues Be and Bs have an average percentage of occurrence of 19.56 % and 27.48 %, respectively, over the five design sessions. These two design issues together represent behavior, having an average of 47.04% of the overall design cognitive effort spent by the designers during all five sessions. Almost half of the design issue occurrence is accounted for by behavior in comparison with F (22.92%), S (22.22%) and D (7.48%). The low values of coefficient of variations of all the design issues over different sessions indicates low levels of variance within this limited data set.

Table 2 Design issue distribution [%]

	S1	**S2**	**S3**	**S4**	**S5**	**Mean**	**σ**	**CV**
Function (F)	20.5	26.2	26.2	18.0	23.7	22.92	3.23	0.14
Expected Behavior (Be)	18.2	21.6	15.1	17.5	25.4	19.56	3.58	0.18
Behavior of structure (Bs)	33.3	26.3	24.2	30.8	22.8	27.48	3.97	0.14
Structure (S)	19.4	20.1	28.7	19.6	23.3	22.22	3.53	0.17
Design description (D)	8.4	5.5	5.0	13.8	4.7	7.48	3.42	0.45

Note: "Sn" means "Session n", σ – standard deviation, CV – Coefficient of variation.

The moving averages of the cognitive design effort expended on design issues over the five design sessions are presented in Figures 1, 2, 3, 4 and 5. The figures are generated using LINKODER, a publicly available software application (linkoder.com). Moving average window lengths of 93, 96, 84 and 135 segments were used, which correspond to 1/10th of their respective, complete sessions. This normalizes the data in the figures.

These visualizations qualitatively indicate that the cognitive design effort for the design issues vary significantly over time. These graphical figures provide opportunities for qualitative interpretation of the results, and they visualize the dominance of the design issue behavior (Be and Bs) during the transition over the different segments. All the figures illustrate that the cognitive effort expended on behavior increases during the middle of the sessions.

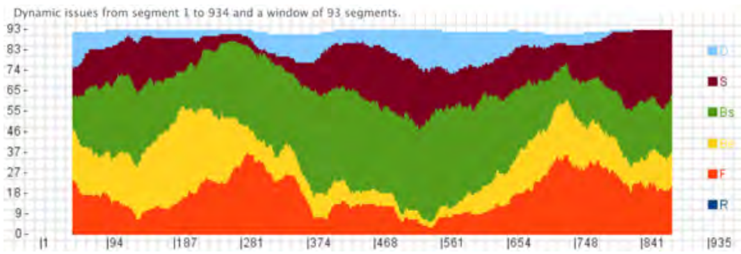

Fig. 1 Moving average of cognitive effort expended on design issues, Session 1

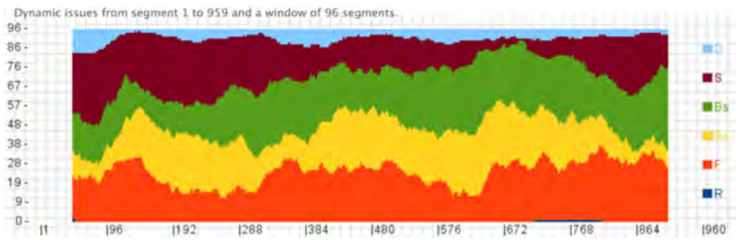

Fig. 2 Moving average of cognitive effort expended on design issues, Session 2

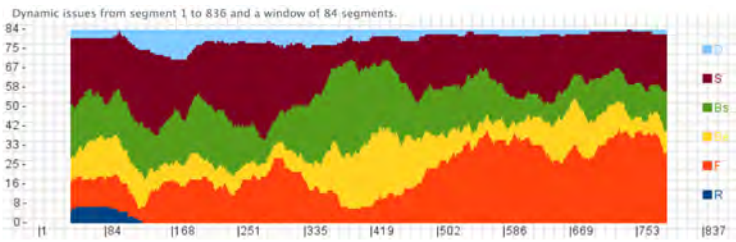

Fig. 3 Moving average of cognitive effort expended on design issues, Session 3

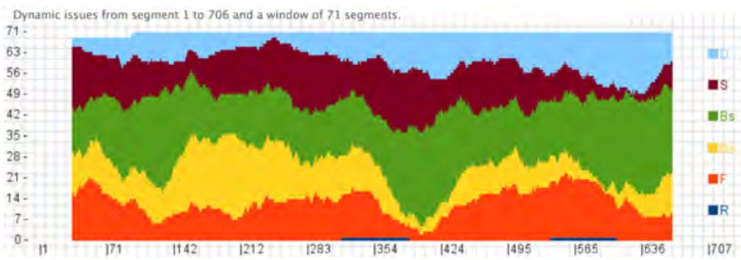

Fig. 4 Moving average of cognitive effort expended on design issues, Session 4

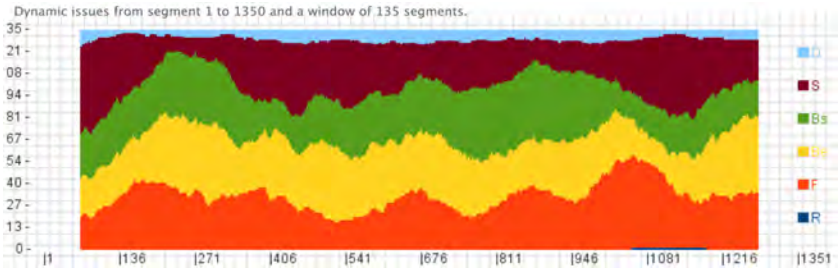

Fig. 5 Moving average of cognitive effort expended on design issues, Session 5

The cumulative occurrences of design issues in the protocol of the first session are presented in Figure 6. An analysis of the data supporting Figure 6 provides quantitative and qualitative insights into the distributions of design issues. It is evident that at the end of the design session the designers had expended the highest cognitive design effort on Bs.

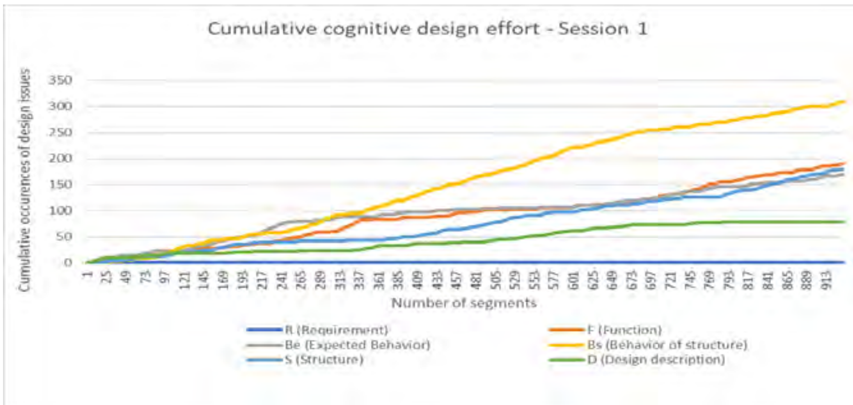

Fig. 6 Cumulative cognitive effort expended on design issues in Session 1

To quantify the shape of each graph, a linear approximation was conducted for each design issue's cumulative occurrence across each session. Figure 7 illustrates such an example of the linear approximation of the cumulative occurrence of the design issue Bs for Session 1.

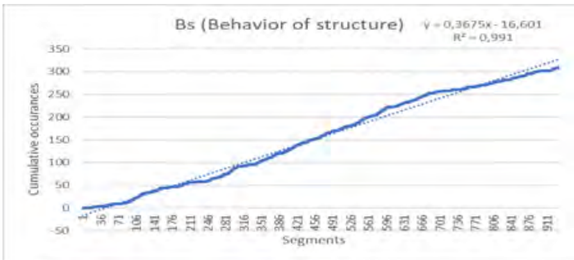

Fig. 7 Linear approximation of the cumulative occurrences of design issue Bs, Session 1

The coefficient of determination for Bs in this session is 0.9910, which indicates a high degree of linearity. The coefficients of determination of the cumulative occurrence of the design issues of all the sessions with the exception of R, since there is insufficient data to carry out the calculation reliably, are shown in Table 3. Design issue Bs has the highest linearity with an average coefficient of determination (R^2) of 0.9918 over the five sessions. It is closely followed by F (0.9833), S (0.9797), Be (0.9758) and D (0.9685), which are higher than the threshold of linearity, and which requires R^2 to be equal to or greater than 0.95. This suggests that all the other design issues are regularly focused on by the designers during the sessions.

Table 3 Coefficients of determination from linear approximation of the transition per design issue

	Session 1	Session 2	Session 3	Session 4	Session 5	Average
F	0.9818	0.9934	0.9573	0.9911	0.9929	0.9833
Be	0.9486	0.9926	0.9853	0.9568	0.9959	0.9758
Bs	0.9910	0.9915	0.9870	0.9944	0.9953	0.9918
S	0.9760	0.9521	0.9907	0.9864	0.9933	0.9797
D	0.9641	0.9889	0.9277	0.9693	0.9925	0.9685

Syntactic design process distribution

The distribution of the syntactic design processes defined by the FBS ontology of all the sessions is shown in Table 4. This distribution is given in terms of percentage of ratio of occurrence of each process over that of all the eight processes. A unidirectional process between the design issues is represented by "→", while a bi-directional process between the design issues is represented by "–".

Table 4 Syntactic design process distributions, expressed as percentages

	S1	S2	S3	S4	S5	Mean	σ	CV
F→Be	14.6	9.8	5.8	11.5	13.8	11.1	3.14	0.28
Be→S	9.9	8.3	6.1	9.9	10.9	9.02	1.68	0.18
S→Bs	17.0	13.2	16.0	18.5	12.9	15.52	2.17	0.13
Be–Bs	20.4	22.8	18.6	21.8	22.0	21.12	1.47	0.06
S→D	6.8	3.4	4.9	5.8	2.9	4.76	1.45	0.30
S→S	18.3	24.6	33.4	16.0	17.7	22.0	6.40	0.29
S→Be	7.7	8.9	7.0	8.2	9.9	8.34	0.99	0.11
S→F	5.3	8.9	8.1	8.2	9.9	8.08	1.53	0.18

Note: "Sn" means "Session n", σ – standard deviation, CV – Coefficient of variation. F→Be: Formulation, Be→S: Synthesis, S→Bs: Analysis, Be – Bs: Evaluation, S→D: Documentation, S→S: Reformulation 1, S→Be: Reformulation 2, S→F: Reformulation 3.

"Reformulation 1" has the highest average percentage of occurrence with 22.0%. This is followed by "Evaluation" with 21.12%, which is a bi-directional syntactic design process between Be and Bs. The low values of coefficient of variations of all the design issues over different sessions indicates low levels of variance within this limited data set.

The moving averages of syntactic design processes of all the sessions are presented in Figures 8 to 12. These figures are also generated using LINKODER. Moving average windows of lengths of 234, 240, 209, 177 and 337 segments are used which correspond to a quarter of their respective complete sessions, to normalize the data in the figures. These figures show that the syntactic design processes change over time and also qualitatively confirm the dominance of Reformulation 1, Evaluation, and Analysis over the five sessions established by the quantitative findings presented in Table 4.

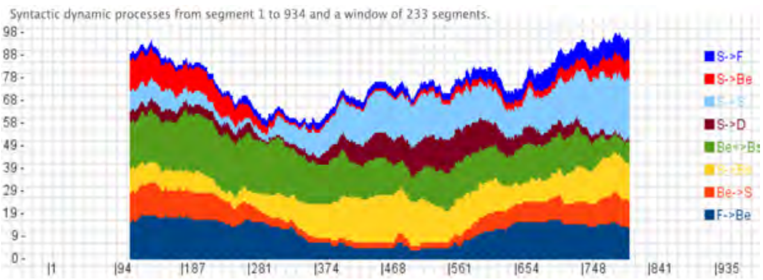

Fig. 8 Moving average of syntactic design processes, Session 1

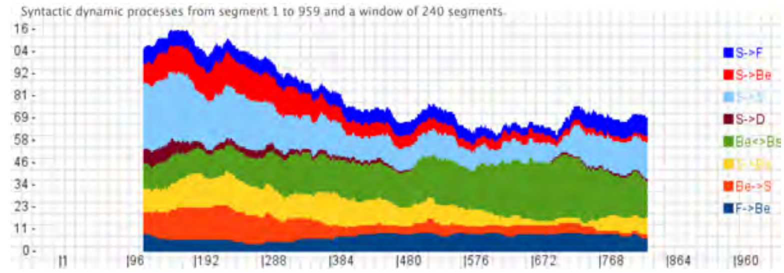

Fig. 9 Moving average of syntactic design processes, Session 2

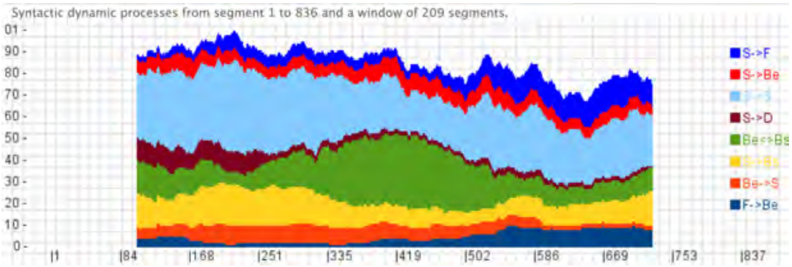

Fig. 10 Moving average of syntactic design processes, Session 3

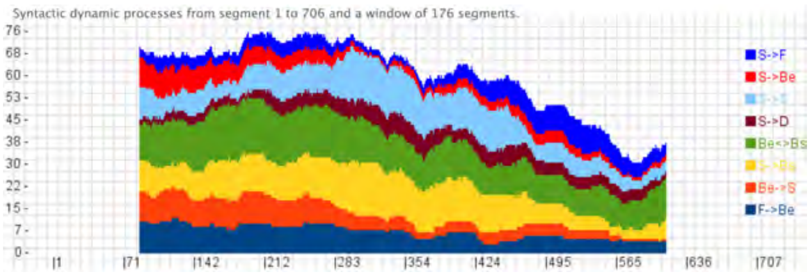

Fig. 11 Moving average of syntactic design processes, Session 4

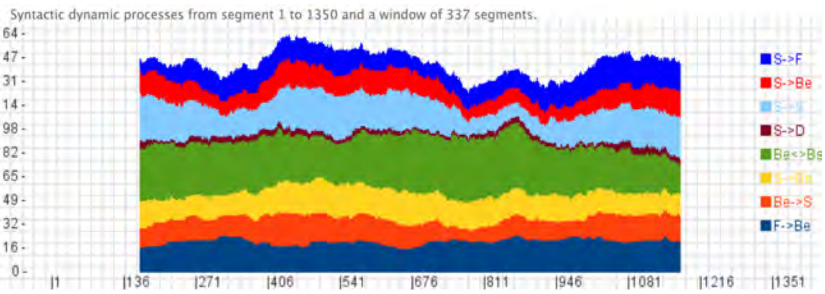

Fig. 12 Moving average of syntactic design processes, Session 5

Comparative analysis of PSS and product design sessions

Multiple empirical studies of product designs have utilized the protocol analysis method with the FBS-based coding scheme [12-15, 23, 43]. As a consequence, the results from all of these and related studies are commensurable with the results of the study of PSS design reported here. Published studies have been selected for comparison [50-52]. The first is from a brainstorming session in industry [50]. The second is from 10 design sessions with undergraduate engineers studying mechanical design [52]. The third is from 10 undergraduate engineers studying engineering mechanics [52]. The fourth is from a software design session in industry [51]. This produces results of a range of designers being studied. From these results it should be possible to observe that product design sessions are similar to each other and that the PSS design session exhibits one or multiple significant differences.

The average percentage distribution of each of the six design issues for these four studies is presented in Table 5.

Table 5 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
This Study	-	0.4	22.9	19.5	27.4	22.2	7.4
Brainstorming	[50]	1.8	4.3	17.3	28.5	37.1	11.0
Engineering Design Major	[52]	2.5	6.2	5.9	30.0	37.2	15.5
Engineering Mechanics Major	[52]	5.2	2.7	8.2	32.0	33.2	18.0
Software	[51]	0.2	0.0	30.1	19.4	30.3	15.9

What can be observed from the results in Table 5 is that for all the product design sessions, the design issue of S is the dominant issue. However, for the PSS design session the dominant design issue is Bs. In all of the four-product design results F sits in the lower half of the distribution of design issues where in the PSS design session it is the second most dominant.

Discussion

The results presented above form the basis for examining the research questions. Concerning RQ1 – What are the distributions of design issues and design processes in the conceptual design of a PSS? - the highest design issue distributions from this study were given to Bs, F, S, and Be (in the descending order as shown in Table 2). These four issues in total received more than 90%, and each of them received a substantially high percentage (more than 18%). In addition, F, Be, Bs, S, and D are consistently focused on by the designers during the sessions. The highest process distributions were for Reformulation 1 (S→S), Evaluation (Be – Bs), and Analysis (S→Bs) (in the descending order as in Table 4). These three processes accounted for around 60% of all process activity. Each of all the eight syntactic processes received more than 5%.

Regarding RQ2 – Is behavior the dominant design issue in the conceptual design of a PSS? – behavior was dominant (47.04% in total of Bs and Be in average as in Table 2). In addition, the processes involving behavior also exhibited high percentage occurrences (Evaluation (Be – Bs) 21.12% and Analysis (S→Bs) 15.52% as shown in Table 4).

For RQ3 – Is function as a design issue more dominant in the conceptual design of a PSS than in the design of a product alone? – the results of the comparative analysis above are used. These comparisons are qualitative at this stage since the experiment group results reported in this paper are based on a small cohort. Function was more dominant in PSS design of this study than in of the product design studies (see Table 5). The average percentage for PSS design was 22.9%, while the percentages for product design were between 0.0% and 6.2

Compared with product design in industry (as shown by "Brainstorming" in Table 5), this study of PSS design in industry shows clear similarities and differences. The percent occurrences for R, Be and Bs are relatively close to each other, while those for F and S show noticeable differences.

Since this study is based on only five sessions, the external validity of the results is limited. Due to the availability of limited data sets, only mean values are considered. However, these issues are countered by documenting the research in a standard and transparent manner, to accommodate the possibility of reproducing the results with larger data sets in the authors' immediate future work. Also, standard deviation and coefficient of variation are used to measure the variability of the results of different sessions, which provides some insights into the statistical reliability of the limited data sets. These results establish the premises for the formulation of the following two hypotheses, which will be addressed in the future work: i) the design issue 'Behavior', is dominant during conceptual design of PSS, ii) 'Analysis' and 'Evaluation' are the dominant processes during conceptual design of PSS. More sessions from the same setting are required to derive statistically reliable results to test these preliminary hypotheses.

Other future works are planned as follows. First, transitions of cognitive efforts over time will be investigated more. For instance, questions such as "which parts of a design session received more efforts on a specific design issue?" maybe addressed, as figures 1 to 5 seem to exhibit differences in efforts on a design issue between parts. Second, differences between product designers and service designers will be examined in terms of design issues and processes. The authors began to make relevant hypotheses for this examination: e.g., presented in their own work [53] was "in PSS design, service designers address the customer more than the provider". Third, quality of different sessions will be analyzed, while this paper with the immediate future work mentioned in the last paragraph focuses on their quantitative aspect. The quality may include that of design solutions obtained from each session. A possible aim is then to extract patterns of design processes that produce solutions with higher quality. Finally, further comparisons are needed between PSS design when the design moves beyond conceptual design with product design to verify the differences seen in the results above.

Conclusion

This paper aims to increase the understanding of conceptual activities of Product/Service System (PSS) design by professional designers from industry. The exploratory study described in the paper adopted the protocol analysis method using the Function–Behavior–Structure coding scheme and presented empirical results. The results show that almost half of the overall cognitive design effort spent by the designers is related to behavior as a design issue. The design issues discussed most frequently were behavior derived from structure, function, structure, and behavior expected in descending order. In addition, a primary contrast was observed between the focus on function during PSS design sessions and that on structure in product-only design sessions. These results demonstrate that it will be possible to test the preliminary hypotheses by carrying out an experiment that produces statistically reliable results.

This study does not provide generalizable results due to the lack of a statistically reliable cohort size. To obtain additional data from an increased cohort size that enables reliable statistical analysis is an immediate future work by the authors.

Acknowledgements

This research is supported in part by the Mistra REES (Resource Efficient and Effective Solutions) program funded by Mistra (The Swedish Foundation for Strategic Environmental Research) (grant number DIA 2014/16). It is also supported in part by a grant from the US national Science Foundation Grant No. CMMI-1400466 to the third author.

References

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

[2] Sawhney, M., *Putting products into services*. Harvard Business Review, 2016. **94**(9): p. 82-89.

[3] Tischner, U., Verkuijl, M., and Tukker, A., *First Draft PSS Review*, 2002, Econcept: Cologne.

[4] Sakao, T., Napolitano, N., Tronci, M., Sundin, E., and Lindahl, M., *How Are Product-Service Combined Offers Provided in Germany and Italy? – Analysis with Company Sizes and Countries -*. Journal of Systems Science and Systems Engineering, 2008. **17**(3): p. 367–381.

[5] Ulaga, W. and Chacour, S., *Measuring Customer Perceived Value in Business Markets*. Industrial Marketing Management, 2001. **30**: p. 525–540.

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

[7] Matschewsky, J., Kambanou, M.L., and Sakao, T., *Designing and providing integrated productservice systems – challenges, opportunities and solutions resulting from prescriptive approaches in two industrial companies*. International Journal of Production Research, 2017.

[8] Meier, H., Roy, R., and Seliger, G., *Industrial Product-Service Systems - IPS^2*. CIRP Annals - Manufacturing Technology, 2010. **59**(2): p. 607-627.

[9] Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H., Wallace, K., and Blessing, L.T.M., *Engineering Design: A Systematic Approach*. 3rd edition ed2006, London: Springer.

[10] Verma, R., Fitzsimmons, J., Heineke, J., and Davis, M., *New issues and opportunities in service design research*. Journal of Operations Management, 2002. **20**(2): p. 117-120.

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

[12] Kannengiesser, U. and Gero, J.S., *Is Designing Independent of Domain? Comparing Models of Engineering, Software and Service Design*. Research in Engineering Design, 2015. **26**: p. 253-275.

[13] Gero, J.S., Jiang, H., and Vieira, S., *Exploring a multi-meeting engineering design project*, in *4th International Conference on Research into Design (ICoRD'13)*, A. Chakrabarti and R.V. Prakash, Editors. 2013, Springer: Chennai, India. p. 73-84.
[14] Jiang, H., *Understanding Senior Design Students' Product Conceptual Design Activities*, 2012, National University of Singapore: Singapore.
[15] Song, T., *Expert Vs. Novice: Problem Decomposition/Recomposition in Engineering Design*, 2014, Utah State University.
[16] McDonnell, J. and Lloyd, P., eds. *Design Meeting Protocols*. DTRS 72007, University of the Arts: London.
[17] Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J.W., Kara, S., Herrmann, C., and Duflou, J.R., *Toward integrated product and process life cycle planning - An environmental perspective*. CIRP Annals - Manufacturing Technology, 2012. **61**(2): p. 681–702.
[18] Roy, R., *Sustainable product-service systems*. Futures, 2000. **32**: p. 289–299.
[19] Lindahl, M., Sundin, E., and Sakao, T., *Environmental and Economic Benefits of Integrated Product Service Offerings Quantified with Real Business Cases*. Journal of Cleaner Production, 2014. **64**: p. 288-296.
[20] Tukker, A., *Product services for a resource-efficient and circular economy - a review*. Journal of Cleaner Production, 2015. **97**: p. 76–91.
[21] Mont, O.K., *Clarifying the concept of product–service system*. Journal of Cleaner Production, 2002. **10**(3): p. 237-245.
[22] Kan, J. and Gero, J., *Acquiring information from linkography in protocol studies of designers*. Design Studies, 2008. **29**(4): p. 315-337.
[23] Lammi, M. and Becker, K., *Engineering design thinking*. Journal of Technology Education, 2013. **24**(2): p. 55-77.
[24] Durugbo, C., Tiwari, A., and Alcock, J.R., *A review of information flow diagrammatic models for product–service systems*. The International Journal of Advanced Manufacturing Technolgy, 2011. **52**: p. 1193-1208.
[25] Alonso-Rasgado, T. and Thompson, G., *A rapid design process for Total Care Product creation*. Journal of Engineering Design, 2006. **17**(6): p. 509 - 531.
[26] Regan, W.J., *The Service Revolution*. Journal of Marketing, 1963. **47**(July): p. 57-62.
[27] Komoto, H. and Tomiyama, T., *Integration of a service CAD and a life cycle simulator*. CIRP Annals - Manufacturing Technology, 2008. **57**(1): p. 9-12.
[28] Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M., and Wilson, H., *State-of-the-art in product-service systems*. Proceedings of the Institution of Mechanical Engineers - B, 2007. **221**: p. 1543-1552.
[29] Love, T., *Philosophy of design: a metatheoretical structure for design theory*. Design Studies, 2000. **21**: p. 293-313.
[30] Ericsson, K.A. and Simon, H.A., *Protocol Analysis Verbal Reports as Data*. Revised edition ed1993, Cambridge, MA: MIT Press.

[31] van Someren, M.W., Bardard, Y.F., and Sandberh, J.A.C., *The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes*1994, London: Academic Press.
[32] Atman, C.J. and Bursic, K.M., *Teaching Engineering Design: Can Reading a Textbook Make a Difference?* Research in Engineering Design, 1996. **8**: p. 240-250.
[33] Purcell, T. and Gero, J.S., *Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology*. Design Studies, 1998. **19**(4): p. 389-430.
[34] Mc Neill, T., Gero, J.S., and Warren, J., *Understanding conceptual electronic design using protocol analysis*. Research in Engineering Design, 1998. **10**(3): p. 129-140.
[35] Suwa, M., Purcell, T., and Gero, J.S., *Macroscopic analysis of design processes based on a scheme for coding designer's actions*. Design Studies, 1998. **19**(4): p. 455-483.
[36] Tang, H.-H. and Gero, J.S. *A cognitive method to measure potential creativity in designing*. in *Workshop 17 - Creative Systems: Approaches to Creativity in AI and Cognitive Science (ECAI-02)*. 2002. Lyon.
[37] McDonnell, J. and Lloyd, P., eds. *About Designing: Analysing Design Meetings*. 2009, CRC Press.
[38] Hay, L., McTeague, C., Duffy, A.H.B., Pidgeon, L.M., Vuletic, T., and Grealy, M., *A systematic review of protocol studies on conceptual design cognition*, in *7th International Conference on Design Computing and Cognition*, J.S. Gero, Editor 2016, Springer: Chicago. p. 135-153.
[39] Gero, J.S., *Design Prototypes: A Knowledge Representation Schema for Design*. AI Magazine, 1990. **11**(4): p. 26-36.
[40] Gero, J.S. *Generalizing design cognition research*. in *DTRS8: Interpreting Design Thinking, DAB documents*. 2010. Sydney.
[41] Gero, J.S. and Kannengiesser, U., *The Function-Behaviour-Structure ontology of design*, in *An Anthology of Theories and Models of Design*, A. Chakrabarti and L. Blessing, Editors. 2014, Springer. p. 263-283.
[42] Kan, W.T., *Quantitative Methods for Studying Design Protocols*, 2008, The University of Sydney: Sydney.
[43] Kan, W.T. and Gero, J.S., *Quantitative Methods for Studying Design Protocols*, 2017, Springer: Dordrecht.
[44] Branki, C.N., *The acts of cooperative design*. Concurrent Engineering, 1995. **3**(3): p. 237-245.
[45] Kruchten, P., *Casting software design in the function-behavior-structure framework*. IEEE Software, 2005. **22**(2): p. 52-58.
[46] Visser, W., *The Cognitive Artifacts of Designing*2006: CRC Press.
[47] Hofmeister, C., Kruchten, P., Nord, R.L., Obbink, H., Ran, A., and America, P., *A general model of software architecture design derived from five industrial approaches*. Journal of Systems and Software, 2007. **80**: p. 106–126.

[48] Robin, V., Rose, B., and Girard, P., *Modelling collaborative knowledge to support engineering design project manager*. Computers in Industry, 2007. **58**(2): p. 188-198.
[49] Van Wie, M., Bryant, C.R., Bohm, M.R., McAdams, D.A., and Stone, R.B., *A model of function-based representations,*. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 2005. **19**(2): p. 89-111.
[50] Kan, J.W.T. and Gero, J.S., *Using the FBS ontology to capture semantic design information*, in *DTRS7 (Design Thinking Research Symposium)*, J. McDonnell and P. Lloyd, Editors. 2007, University of the Arts: London. p. 155-165.
[51] Kan, J.W.T., Gero, J.S., and Sarkar, S., *Using a generic method to study software design cognition*, in *Workshop on Studying Professional Software Design*, A. van der Hoek, M. Petre, and A. Baker, Editors. 2010. p. kgs1-7.
[52] Williams, C.B., Lee, Y., Paretti, M., and Gero, J.S. *Effects of design education on design cognition: A preliminary comparison of engi-neering students*. in *41st ASEE/IEEE Frontiers in Education*. 2011. ASEE/IEEE.
[53] Widgren, M. and Sakao, T., *Unanswered questions in conceptual design towards Circular Economy*, in *The 14th International Design Conference – (DESIGN 2016)*2016: Dubrovnik. p. 571-578.