Computers & Industrial Engineering 104 (2017) 68–79

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

A similarity measurement framework of product-service system design cases based on context-based activity model

Yu Wu [a], Ji-Hyun Lee [b,*], Yong Se Kim [c], Sang Won Lee [d], Sun-Joong Kim [b], Xiaofang Yuan [e]

[a] China-Korea Institute of New Media, Zhongnan University of Economics and Law, Wuhan, People's Republic of China
[b] Graduate School of Culture Technology, KAIST, Daejeon 305-701, Republic of Korea
[c] Creative Design Institute, Sungkyunkwan University, Suwon, Republic of Korea
[d] School of Mechanical Engineering, Sungkyunkwan University, Suwon, Republic of Korea
[e] School of Art and Design, Wuhan University of Technology, Wuhan, People's Republic of China

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 28 October 2016
Accepted 12 December 2016
Available online 18 December 2016

Keywords:
Product-service system
Recommender system
Case representation
Case indexing
Similarity measurement

ABSTRACT

Design experience from previous design cases could help designers solving current design problems. Therefore, a case-based recommender system can recall suitable design cases for designers based on a similarity measurement mechanism. In the context of Product-Service System (PSS) design, the measurement of similarity between different cases becomes more challenging because of the complex nature of the PSS design. In this research, we propose a similarity measurement framework of PSS design cases based on the context-based activity model. In the proposed framework, a PSS design case is indexed and quantified by design activity element, design process, and function requirement. Ways to measure similarity between design indexes and design cases are also specified. A case study along with an empirical validation was conducted to validate the framework.

1. Introduction

Product-Service Systems (PSSs), the combination of products and services, have been increasingly emphasized since the realization that service in combination with products could provide higher profits than products alone. The success of several leading companies such as General Electric Co., IBM Corp., Siemens AG and Hewlett-Packard Co. was illustrative of this (Baines et al., 2007; Sawhney, Balasubramanian, & Krishnan, 2004). The involvement of designers in the development of services brought an extension of the traditional discipline of design, towards a new domain that requires designers with expertise to manage particular characteristics of both products and services (Morelli, 2002). Design experience from previous designs plays a key role in developing design solutions to the problems that confront us (Maher & Zhang, 1993). Thus, the demand for reusing design experience in PSS design is essential to the design problem-solving process. A case-based reasoning (CBR) system can help designers reusing design experience by recalling a suitable design case based on a similarity measurement mechanism and acting as a recommendation system.

One of the important issues in developing a case-based recommender system is to measure the similarity between different cases, as determined by the case representation framework and case recall methods. The development of a case representation framework is more complicated in the context of PSS design because of the complex nature of PSS design and the interdependencies of products and services. The similarity measurement between different PSS design cases becomes challenging. Consequently, there are few comprehensive design knowledge representation frameworks developed for case comparisons. Existing frameworks capture the design knowledge of products and services, not the design knowledge of the design process and other issues. Thus, the design experiences from PSS design cases are incomplete (Lin, Shih, Lu, & Lin, 2010). Most of them lack measurable factors utilized to index PSS design cases. Further, they lack case retrieval strategies that could be developed according to the characteristics of these factors. Accordingly, existing frameworks are suitable for design knowledge reuse, but are not competent for design process comparison (Baxter, Roy, Gao, & Mann, 2009).

Our aim is to develop a similarity measurement framework of PSS design case that could be utilized to build a case-based recommender system (CBR-RS) for accessing design experience more efficiently. A CBR-RS is one application of CBR in the reuse of design knowledge, creating an index of the problem area and applying artificial intelligence techniques to find similar cases (Wood &

* Corresponding author at: Graduate School of Culture Technology, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea.
E-mail address: jihyunlee@kaist.ac.kr (J.-H. Lee).

http://dx.doi.org/10.1016/j.cie.2016.12.015
0360-8352/

Agogino, 1996). Specifically, we focused on the representation and similarity measurement of PSS design cases. To achieve the goal, our methodology is divided into three parts. First, a PSS design case representation framework for capturing design knowledge of products, services, and design processes is proposed. Second, a PSS design case is indexed by PSS design activity elements, PSS design process, and function requirement, and further quantified by using quantitative attributes. Third, similarity measures are developed to calculate the degree of similarity between PSS design cases. The similarity measurement framework of PSS design case, along with methods for case indexing, quantification, and a measure of similarity, is validated through the case study. The similarity measurement framework of PSS design case, along with methods for case indexing, quantification, and a measure of similarity, is validated through the case study, and the similarity results derived from the framework were assessed by a group of experts through the empirical validation survey.

2. Product-service systems and case-based recommender systems

The concept of PSS provides a systemic perspective to view existing environmental problems because it suggests a solution by combining products and services. Product-oriented design strategies have made incremental changes in the economic or environmental performance of the industry; however, PSS fundamentally challenges the current paradigm of the design (Williams, 2006). For consumers, PSS means a shift from buying one physical product to buying system solutions that could reduce environmental impacts. For PSS providers, PSS means a high degree of responsibility for the product's whole life cycle. It consequently means that PSS designers must consider their new role and start to use effective design tools to deal with the complex issue, a typical design process of the PSS. Kim and Lee (2011) introduced a PSS design process including six design stages: (1) requirement identification and value targeting, (2) stakeholder activity design, (3) PSS function modeling, (4) function-activity mapping and PSS concept generation, (5) PSS concept detailing, and (6) PSS concept prototyping. Stakeholder activities are the most important aspect of PSS design. Thus, they also developed *context-based activity modeling* where activities are represented systematically with *actors*, *objects* and *action verbs* as well as *context elements*.

Lorenzi and Ricci (2005) proposed an interpretation framework to model the mechanism of CBR-RSs and explained how generic steps and issues of CBR problem-solving cycles, such as case representation and case retrieval, are specialized in CBR-RS. "Case representation" is vital to produce a set of recommendations for users to retrieve items whose descriptions match the user's query. The knowledge related to a designer's previous activity must be represented for reusing design experience from previous cases; design knowledge can be represented in various formats (e.g., texts, sketches, drawings, behavioral diagrams, or grammatical rules) (Eilouti, 2009). Maher and Zhang (1993) identified three main issues in case representation, the content of design cases, the case memory organization and the presentation of design cases to the user, where identifying the content of the design case determines the design knowledge included. According to Ahmed (2005), the design knowledge concerned could be classified into four types: (1) the design process itself (i.e., description of design tasks in the design stages), (2) The physical product produced, (3) The functions that must be fulfilled and (4) issues that are considered by designers in the design process.

Case indexing is closely related to case retrieval (Jeng & Liang, 1995). There are some guidelines for selecting indexes, such as predictiveness, abstractness, and concreteness. The commonly used indexing methods are checklist-based, relationship-based and explanation-based (Kolodner, 1993). The selection of case indexes depends on the purpose of the CBR system. For example, Lin et al. (2010) proposed a CBR system to provide a strategy for PSS design, in which 12 case indexes related to user behavior, product, and external environment were selected to describe PSS cases. There are two major case retrieval approaches, computational and representational. The computational approach is more widely used in CBR applications where the similarity measures are based on the semantic distance between cases (Liao, Zhang, & Mount, 1998). Similarity measures are more context-dependent and have strong relationships with the type of attributes representing the case: textual, numeric and semantic (Nunez & Sanchez-Marre, 2004). The textual attribute is to describe design requirements and solutions while semantic attributes are used in situations where case indexes have some internal relationship beyond the text. For semantic and textual attributes, taxonomy-based distance is utilized to measure the similarity between concepts in the taxonomy with several approaches such as edge-counting approach, featured-based approach, and information content-based approach.

For the purpose of reusing design experience from previous PSS design cases, the design knowledge related to designers' activity should be represented in the case. According to the context-based activity modeling developed by Kim and Lee (2011), the content of a design case includes the design knowledge of the designer, design tool, design object, and design context. Case index *designer* represents the personal creativity characteristics of a designer. Various tests can be performed to measure creativity characteristics, such as the personal creative test, learning style test, idea generation test, Torrance test of creative thinking, and visual reasoning test. Case index *design tool* includes design methods and software utilized in the PSS design process since they can be organized to build design tool taxonomy. The design methods can be further divided into general design method and PSS design methods, such as CDI PSSD method (Kim & Lee, 2011), MePSS method (Van Halen, Vezzoli, & Wimmer, 2005) and Brissaud method (Maussang, Zwolinski, & Brissaud, 2009)). The design software can be categorized into special software and general software. Case index *design object*, representing the product and service generated in the PSS design process, can be assigned with a unified code as case attribute. Unified codes, such as eCl@ss, UNSPSC, eOTD, and RNTD, provide an open, global multi-sector standard for efficient classification of products and services. The *design context* contains three case indexes: relevant structure, physical context, and psychological context. The relevant structure can be categorized into three sub-categories: PSS design object itself, systemic structure supporting PSS design, and structure of the existing product. Physical context includes time, location and communication. Time can be indexed by two sub-indexes, daily working hours of design activity and the total given time of a design project. Location considers the size of the space determining the collaborative characteristics of the design team, and communication means the physical condition of design communication. The psychological context consists of occupant context, mood context, affect context, social context, cognitive context, and motivation context.

Recent PSS design research emphasizes the importance of reusing past design experiences and cases for achieving creative design outcomes (Ahmed, 2005; Fu et al., 2015; Kim & Kim, 2015; Kim, Lee, & Kim, 2014; Linsey, Markman, & Wood, 2012). In light of this trend, there have been recent studies on the design knowledge management that enable saving and retrieving design cases to design a brand new PSS. Many researchers developed methods, frameworks, and tools for supporting knowledge-based PSS design. Akasaka, Nemoto, Kimita, and Shimomura (2012) represented a

PSS knowledge as a set of both product and service functions, entities, and realization process so that the knowledge can be searched based on the similar functions (Akasaka et al., 2012). A representation framework of PSSs was developed to incorporate various PSS cases (Kim & Kim, 2015). Based on the PSS representation framework, different PSS cases from various dimensions were computationally compared based on the data indexing scheme and algorithms (Kim et al., 2014). However, these proposals for supporting knowledge-based PSS design do not integrate the Product-Service types that include process, result, and context of the designer's practices, thus are limited in scope (Trevisan & Brissaud, 2016). Therefore, a comprehensive design knowledge representation framework that integrates the designer's practices through context-based model is necessary to deal with many issues in designing and implementing PSSs. Moreover, ways to measure the similarity between design indexes and design cases should be addressed so that the similar PSS cases could be utilized in the new design.

3. A similarity measurement framework of product-service systems design case

The similarity measurement framework of PSS design case was developed based on context-based activity modeling of PSS design activity. As shown in Table 1, a PSS design case is indexed by design activity element, design process, and function requirement. To measure the similarity between cases, each case index was quantified and associated with a similarity measure method according to its features. A classification method of products is used to represent the behavior and structure of design object, and the environment of design activity was excluded for the reason that it coincides with the social context that belongs to a psychological context (see Table 2).

3.1. Design activity element

PSS design activity element includes the information related to designer, design object, design tool, and design context. The similarity of design activity element is based on the similarity result of its sub-indexes: *designer*, *design object*, *design tool* and *design context* (Eq. (1)).

$$SIM_{act}(X,Y) = \frac{SIM_{des}(X,Y) + SIM_{tool}(X,Y) + SIM_{obj}(X,Y) + SIM_{con}(X,Y)}{4} \tag{1}$$

3.1.1. Designer

Personal creativity modes represent designers' personal traits in the perception and judgment domains, and Personal Creativity Mode Test (PCMT) identifies personal cognitive preference and creativity mode in the form of the point data in the 2D coordinate system. The Euclidian distance is not suitable for similarity measure because it only shows the distance between two points, and does not cover all the information used for a PCMT result. For this reason, we calculated the cosine similarity using Eq. (2).

$$SIM(X,Y) = \cos(\theta) = \frac{\vec{X}\cdot\vec{Y}}{\|X\|\|Y\|} \tag{2}$$

The results of cosine similarity range from −1 to 1. Further, the similarity results on perception domain and judgment domain can be achieved for two compared designers. The similarity of two designers can be normalized based on their cosine similarity results using Eq. (3), in which SIM_P (D_1, D_2) and SIM_J (D_1, D_2) represent the cosine similarity results of perception and judgment, respectively. The similarity of creativity characteristics between two teams can be calculated from the similarity results between team members.

$$SIM_{Des}(X,Y) = \frac{(SIM_P(D_1,D_2)+1) + (SIM_J(D_1,D_2)+1)}{4} \tag{3}$$

3.1.2. Design tool

In this research, the edge-counting approach proposed by Wu and Palmer (1994) was utilized to measure the similarity between the different design tools (Eq. (4)). One of the improvements of their method is that the number of is-a link (N_1 and N_2) are

Table 1
Similarity measurement framework of PSS design cases.

Case index				Quantification
Design activity element	Designer			PCMT results
	Tool			PSSD method
	Object			UNSPSC
		Relevant structure		UNSPSC
		Physical context	Location	Size of design space
			Time	Working hours per day
				Given days
			Communication	Category of team communication method
		Psychological context	Occupant context	Occupant characteristic
			Mood context	Socio-emotional interaction
			Affective context	Collaborative atmosphere
			Social context	Organization of design team
			Cognitive context	Cognitive level on design problem
			Motivation context	Category of team motivation
Design process	Time spent	Requirement identification and value targeting		
		Stakeholder activity design		
		PSS function modeling		
		Function-activity mapping and PSS concept generation		
		PSS concept detailing		
		PSS concept prototyping		
	Transition behavior	Step transition		Number of step transition
		Stage transition		Number of stage transition
	Stage outcome	Function		Number of function
		Activity		Number of activity
		Affordance		Number of affordance
Function requirement				Function requirement list

Table 2
Measurement framework of design context.

Case index			Quantification	Similarity measure
Relevant structure		Product elements	Numeric	Euclidian distance
Physical context	Location	Size of design space	One dimension metric	Euclidian distance
	Time	Working hours per day	Numeric	Feature-based
		Given days	Numeric	Feature-based
	Communication	Category of communication	One of a list	Boolean
Psychological context	Occupant context	Occupant characteristic	One dimension metric	Euclidian distance
	Mood context	Socio-emotional interaction	Numeric	Feature-based
	Affective context	Collaborative atmosphere	One of a list	Boolean
	Social context	Organization of team	One of a list	Boolean
	Cognitive context	Cognitive level on problem	One of a list	Boolean
	Motivation context	Category of team motivation	One of a list	Boolean

counted from each term to their Least Common Subsumer (LCS) and also the number of is-a link of the LCS to the root (N_3) of the ontology.

$$SIM_{tool}(X, Y) = \frac{2 \times N_3}{N_1 + N_2 + 2 \times N_3} \quad (4)$$

3.1.3. Design object

Based on the division of segments in UNSPSC, a one-dimensional metric can be proposed, and all products and services can be positioned according to UNSPSC codes into the metrics. The similarity between two products and services can be represented by their Euclidian distance. The specific method is as follows. First, similarity calculation uses Eq. (5), in which DIST (X, Y) means the Euclidian distance of two UNSPSC codes, consisting of four levels such as segment, family, class, and commodity. Thus, the Euclidian distance of two UNSPSC codes can be calculated based on corresponding segments, families, classes, and commodity codes.

$$SIM_{obj}(X, Y) = 1 - DIST(X, Y) = 1 - \sum_{i=1}^{4} w_i \sqrt{dist_i^2(x_i, y_i)} \quad (5)$$

Specifically, the Euclidian distance of these four levels can be calculated using Eq. (6), in which $\max_i$ and $\min_i$ are the maximum and minimum values of the *i*th level in UNSPSC code, respectively. The code is compared hierarchically, from segment to family, from class to the commodity. The compared similarity of low-level components (family is lower than segment component) is much important than high-level results. The different component is assigned with different weight. If the calculated distance is not zero, the calculation will end. The final similarity result comes from the sum of the result of each component, divided by the sum of weights.

$$dist(Xi, Yi) = |x_i - y_i| / |\max_i - \min_i| \quad (6)$$

3.1.4. Design context

There are three different data types of case indexes, *relevant structure, physical context,* and *psychological context,* in the design context, and each case index has several sub-indexes assigned with different types of value. The first is a numeric data type, which is assigned to case indexes such as *relevant structure*, *time,* and *mood context*. For *relevant structure*, the similarity can be calculated using the same method with design object. For *mood context* and *time* comparison, the similarity was calculated using feature-based approaches, where "common" and "different" represent the number of attributes respectively whose values are classified as similar and dissimilar between two cases. α and β are the corresponding weights for "common" and "different" (Eq. (7)).

$$SIM(X, Y) = \frac{\alpha \times common}{\alpha \times common + \beta \times different} \quad (7)$$

The second data type is textual data from a list, which is assigned to *communication, affective context, social context, motivation,* and *cognitive context*. The similarity between these case indexes is based on the Boolean value of the case indexes. If the Boolean value of two design indexes is 1, then the similarity result is 1. *Location* and *occupant context* are assigned to a textual data that form a one-dimensional metric. The similarity of two case indexes is based on the Euclidian distance in the metric. For example, there are five types of location size utilized in our framework, and a one-dimensional metric can be built, and the similarity can be measured using Eq. (8). In Eq. (8), $|\max_i - \min_i|$ means the maximum distance of the metrics and $|x_i - y_i|$ represents the distance difference between compared two cases.

$$SIN_{loc}(X, Y) = 1 - DIST(X, Y) = 1 - |x_i - y_i| / |\max_i - \min_i| \quad (8)$$

3.2. Design process

A design process can be represented by the design activities involved. Even the design process is drawn into the flow-diagram form but returns to the earlier stage frequently in the design process. Therefore, it is very hard to compare design processes by describing the design activities involved. To compare design processes, some measurable factors should be quantified. It has been argued that some design stages have relationships with the outcome of a design process. Cross and Cross (1998) suggested that problem-framing ability is crucial to high-level performance in design. Mullins, Atman, and Shuman (1999) revealed that transitions among steps in the design process have positive effects on students' design quality.

Based on the literature, we developed multiple measurable factors that are suitable for the measurement of PSS design process: time spent on each PSS design stage and step of the stage; the transition behaviors between the design stages and steps happened in the PSS design process; and the amount of the design outcomes generated during the PSS design process. We further categorized the design outcomes into function—the function that the PSS should fulfill; activity—the activity the users may perform in the PSS to satisfy their needs; and affordance—the valid interaction between the function and activity considered by designers in the PSS design process. The case indexes in the design process are assigned to the numeric data type, and the similarity is calculated using the feature-based method. The similarity of the design process is based on the similarity results of time spent, transition behavior and stage outcome (Eq. (9)).

$$SIM_{pro}(X, Y) = \frac{SIM_{tim}(X, Y) + SIM_{tran}(X, Y) + SIM_{out}(X, Y)}{3} \quad (9)$$

3.3. Function requirement

The function of artifacts can be described using the verbs combined with nouns, for example, import gas. The functions and flows have three levels: primary classes, secondary, and tertiary. Functions and flows also have correspondents (synonyms) that map terms not included in the functional basis. Three primary classes, material, signal, and energy, are used to describe flows. Each of the primary classes has secondary flows. For instance, energy can have a secondary class flow of electromagnetic or electricity. Further, some of the secondary flows have tertiary classes. For example, electromagnetic has tertiary classes of optical or solar. A function can be represented using a verb from the function list and nouns from the flow list, for example, collect solid-liquid-gas.

The function requirement is the function list generated in the analysis process and considered in the design solution. In the PSS design process, designers analyze the overall function of the PSS and divide it into sub-functions using a function modeling tool. By utilizing a function dictionary (McAdams, Stone, & Wood, 1999), the function requirements can revert to standardized function requirements. The number of common functions is used to measure the similarity between two design cases. The Van der Weken Method was utilized to calculate the similarity of the function lists of different design cases (Eq. (10)). The number of common functions the two cases shared was described by $|A_1 \cap A_2|$, while $|A_1|$ and $|A_2|$ represented the number of functions each case has.

$$SIM(C1, C2) = \frac{|A_1 \cap A_2|}{|A_1| + |A_2|} \tag{10}$$

4. Case study

A case study was conducted to validate the similarity measurement framework for PSS design cases.

4.1. PSS design experiment

4.1.1. Recruitment of participants

Due to the interdisciplinary nature of PSS design, the design should be conducted by teams whose members come from different domains. We recruited graduate students and researchers with very similar ranges of experience in PSS design, but different backgrounds such as mechanical engineering, industrial design, and service design. Using participants at similar levels of expertise allowed us to make the comparison of the PSS designs in the experiment. According to their personal creativity modes and backgrounds, five design teams were formed for the experiment.

4.1.2. Experimental setup and procedure

The design experiments were conducted indoors. During the design process, the designers' activities and verbal communication were recorded by two camcorders. The cameras were located in front and behind to optimally monitor each designer's actions and communication. To analyze each designer's communication simultaneously, and manipulation of the computer, the screen recording software Camtasia Studio was utilized to record the manipulation process on a computer. Fig. 1 shows the experimental setup for the five design teams. Three teams developed air conditioner related PSS and other two teams designed pay-telephone related PSS.

Before the experiment, participants were engaged in a training session to become familiar with the design process and design tools. In the training session, the participants were presented with a tutorial on PSS design methodology including the core concept and PSS design support tools. They were asked to use the PSS design methodology consisting of six design stages proposed by Kim and Lee (2011): (1) requirement identification and value proposition, (2) stakeholder activity design, (3) PSS functional modeling, (4) function-activity mapping and PSS concept generation, (5) PSS concept detailing, and (6) PSS concept prototyping. In the experiment, participants were given time to read the design brief. They were required to design air conditioner or telephone related services within a certain period. An experimenter instructed them to determine the target product with which they could start their design, stayed behind the camcorder to observe the progress of the experiment, and answered questions from the participants during the design process.

4.2. Data collection and coding method

4.2.1. Protocol collection, segmentation, and coding

Protocol analysis captures designers' verbalizations and the corresponding simultaneous design actions, which allows a more detailed analysis of their reasoning process (Kim & Maher, 2008). The concurrent protocols collected during the task were adopted for this experiment. Thus, all designers' conversation and manipulation during the experiment were recorded and transcribed as protocols. The transcribed protocol data were divided into small segments using an intention-based technique and Interaction Process Analysis (IPA). With the intention-based technique, the protocols were divided into smaller units along the lines of the designer's intentions or changes in actions, while the IPA was utilized to compare interaction and communication behaviors in design teams.

Table 3 shows an excerpt from the protocol segmentation and coding of Team 5. Each segment contains the information related to segment number, the type of designer's action, the start time, end time and the duration of the action. The design actions of all three participants were regarded as one designer, and the verbal protocols and screen recordings were reviewed simultaneously to decide the beginning and end of a segment. There are six stages in the design process, which are further divided into 17 coded design steps (i.e., TAP, LCS, STH, REQ, E3V, SCN, CBAM, SBL, PSSF, FAM, SEM, AFF, PRT, PSSC, BIZM, PSSP, and INFR).

The *mood context* can be measured by analyzing interaction and communication behaviors of design teams. In the IPA coding scheme, there are 12 categories that can be grouped into socio-emotional and task areas. The socio-emotional area is further divided into positives, negatives, and neutral. The positive interactions were coded as SS, STR, and A. The neutral interactions were coded as GS, GOP, GOR, AFOR, AFOP, and AFS. The negative interactions were coded as D, ST, and SA. Table 4 shows an excerpt from the protocol data coding for the participant C of design Team 5.

4.2.2. Collected data

Through protocol analysis and observation, we collected the information related to team interaction, design activity elements, design processes and function requirements as shown in Tables 5–8. For each team, the number of socio-emotional interactions is calculated by the difference between positive and negative interactions, and the mood context is represented by the percentage of socio-emotional interactions in the total interactions.

In this experiment, four teams did not consider a business model in their design process, and only Team 5 spent 0.33 percent of its total time on it. There are no data of "PSS concept prototyping" because it was not asked for in the lab-based setting. We converted the actual time spent on each step to relative time for the effective comparison. For the transition behavior between different design stages and steps, we counted the total number of transition behaviors and then calculated the number per hour.

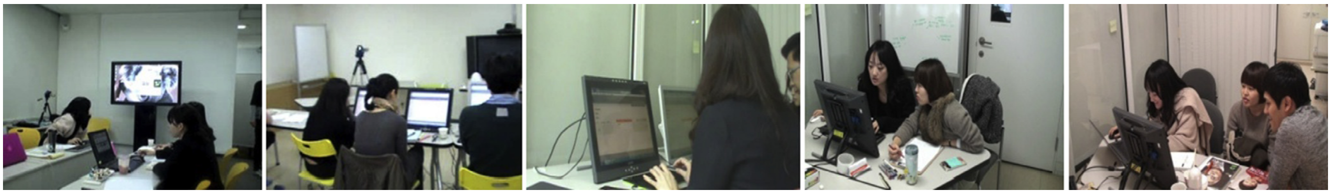

Fig. 1. Experimental setups, Team 1 to 5 are arranged from left to right.

Table 3
Design action protocol data coding for Team 5.

Segment no.	Time	Duration (s)	Action
Segment 49	28:15–28:24	9	STH
Segment 50	26:18–26:23	5	LCS
Segment 51	28:24–30:18	114	REQ
Segment 52	30:18–31:30	12	INFR

Table 4
IPA protocol data coding for participant C in Team 5.

Segment no.	Time	Duration (s)	Interaction
Segment 1	06:56–07:04	8	STR
Segment 2	09:35–09:37	2	STR
Segment 3	09:59–10:00	1	AFOP
Segment 4	09:41–09:42	1	A

We gathered the function requirement information in the function modeling stage of the PSS design process. By utilizing a function dictionary, the function requirements were converted to standardized function requirements (Table 8). Specifically, the results of the five design teams explain several different approaches to PSS design problems. For example, the product function was handled more actively in Teams 1 and 2, while the product was considered in the specific boundary of a service in Teams 3 and 5.

4.3. Analysis of PSS experiment

Using the similarity measurement framework of PSS design case, the collected protocols were analyzed regarding the similarity of five design teams, specifically, design activity elements, design processes, and function requirements.

4.3.1. Design activity element

The similarity results of case index design activity element and its sub-case indexes are shown in Table 9. Regarding designer's creativity characteristic, Teams 1 and 4 are the most similar pair, while the Teams 2 and 4, as well as Teams 2 and 5, are the most dissimilar pairs. The PCMT results show that Team 1 was strong at evaluation in judgment domain but weak in organizing creativity. Similar to Team 1, Team 4 lacked experiential creativity in perception domain and teamwork creativity in judgment domain.

Table 5
Team interaction for the five teams.

	Team 1			Team 2			Team 3			Team 4			Team 5		
	1A	1B	1C	2A	2B	2C	3A	3B	3C	4A	4B	4C	5A	5B	5C
Positive	603	39	335	500	352	86	129	312	135	295	95	233	133	144	135
	977			938			576			623			412		
Negative	1	0	0	3	0	0	52	0	0	0	0	0	1	1	1
	1			3			52			0			3		
Neutral	1229	27	410	139	761	144	1076	1038	721	905	360	404	310	234	317
	1666			1044			2835			1669			861		
Total interaction	2644			1985			3463			2292			1276		
Socio-emotional	976			935			524			623			409		
Mood context	0.369			0.471			0.151			0.272			0.321		

Table 6
Design activity elements of the five teams.

			Team 1	Team 2	Team 3	Team 4	Team 5
Designer			10, 0; −5.0 25, 18; 15, −4 0, 35; 10, 28	−20, 25 ;−20, 32 10, −14; 15, −14 35, −25; 20, −18	−25, 28; −35, −28 25, 11; −30, 18 30, −18; 30, 4	10, 0; −5, 0 0, 35; 10, 28 25, 11; −30, 18	25, 18; 15, −4 30, 0; 25, 21 10, −14; 15, −14
Design object			Air conditioner	Air conditioner	Air conditioner	Pay phone	Pay phone
Design tool			PSSD software	PSSD software	PSSD software	PSSD software	PSSD software
Design context	Relevant structure	Product element	Air conditioner	Air conditioner	Air conditioner	Pay phone	Pay phone
	Physical context	Location	Medium size	Large size	Small size	Small size	Small size
		Time	5.3 h 3 days	3.8 h 3 days	3.9 h 3 days	2.5 h 2 days	4.1 h 1 day
		Communication	Offline	Offline	Offline	Offline	Offline
	Psychological context	Occupant context	Medium	Spacious	Crowded	Crowded	Crowded
		Mood context	0.369	0.471	0.151	0.272	0.321
		Affective context	Harmonious, Happy	Silence	Chilly	Familiar, Happy	Tired
		Social context	Team-based	Team-based	Team-based	Team-based	Team-based
		Cognitive context	Hurry	Calm	Excited, active	Exited, active	Hurry
		Motivation context	Forced	Forced	Forced	Forced	Forced

Table 7
Design processes of the five teams.

		Team 1	Team 2	Team 3	Team 4	Team 5
	Total time	59,340	45,120	41,800	18,524	14,652
Requirement identification and value targeting	LCS (Life-Cycle Step)	7.7	1.5	2.7	1.96	4.87
	STH (Stakeholders)	5.1	6.5	9.7	1.90	5.66
	REQ (Requirements)	10.8	18.9	12.6	15.16	6.64
	E3V (E3 Values)	7.9	8.9	4.9	4.24	2.84
Stakeholder activity design	CBAM (Context-based Activity Model)	12.9	2.0	0.5	16.83	6.21
	SCN (Scenarios)	4	1.6	0.05	0	0
	SBL (Service Blueprint)	7.8	8.3	17.5	21.24	32.1
PSS function modeling	PSSF (PSS Function)	5.7	3.7	15.2	9.68	9.89
Function-activity mapping and PSS concept generation	FAM (Function-Activity Mapping)	3.6	2	0	4.86	2.19
	AFF (Affordance)	5.9	7.7	9.6	4.26	8.08
	SEM (Service Elements)	0	3.9	4.3	1.14	0.91
	PRT (Product Elements)	0	1.5	0.1	4.79	4.7
PSS concept detailing	PSSC (PSS Concept)	13.1	2.7	0.05	12.03	0
	BIZM	0	0	0	0	0.33
Transition behavior	Step transitions	33.3	32.2	34.7	30.7	37.1
	Stage transitions	5.3	9.4	10.2	7.0	16.0
Stage outcome	Function	12	22	25	10	8
	Activity	23	20	26	8	13
	Affordance	9	8	9	2	8

Table 8
Function requirements of the five teams (excerpt).

Team 1	Team 2	Team 3	Team 4	Team 5
Collect weather info	Input electricity	Guide search	Import object	Receiver user
Check weather info	Receive user	Import AC info	Import money	Guide user
Calculate weather info	Start air conditioner	Provide AC info	Collect money	Provide telephone type info
Receive user	Eject user	Import user	Display deposit info	Import telephone type info
Start air conditioner	Convey hot air	Import AC info	Store money	Provide payment info
Collect usage info	Decrease temperature	Provide AC info	Calculate deposit	Import deposit
Display usage info	Convey cool air	Guide AC info	Export object	Import rental fee
Collect weather info	Export cool air	Provide AC	Check deposit	Provide one-day phone

Table 9
Similarity results of the *design activity element* and its sub case indexes.

	T1/T2	T1/T3	T1/T4	T1/T5	T2/T3	T2/T4	T2/T5	T3/T4	T3/T5	T4/T5
Designer	0.51	0.58	0.67	0.63	0.50	0.46	0.62	0.61	0.53	0.51
Perception	0.52	0.67	0.82	0.72	0.53	0.53	0.61	0.67	0.64	0.74
Judgment	0.50	0.49	0.53	0.53	0.47	0.38	0.64	0.55	0.41	0.27
Design object	1.00	1.00	0.39	0.39	1.00	0.39	0.39	0.39	0.39	1.00
Design tool	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Design context	0.80	0.66	0.64	0.49	0.70	0.63	0.48	0.61	0.66	0.71
Relevant structure	1.00	1.00	0.39	0.39	1.00	0.39	0.39	0.39	0.39	1.00
Physical context	0.70	0.71	0.50	0.38	0.83	0.61	0.49	0.78	0.66	0.69
Location	0.25	0.25	0.25	0.25	0.50	0.50	0.50	1.00	1.00	1.00
Time	0.86	0.87	0.57	0.55	0.99	0.67	0.63	0.66	0.64	0.56
Working hour	0.72	0.74	0.47	0.77	0.97	0.66	0.93	0.64	0.95	0.61
Deadline	1.00	1.00	0.67	0.33	1.00	0.67	0.33	0.67	0.33	0.50
Communication	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Psychological context	0.51	0.44	0.66	0.69	0.47	0.51	0.53	0.76	0.58	0.64
Occupant context	0.25	0.25	0.25	0.25	0.50	0.50	0.50	1.00	1.00	1.00
Mood context	0.78	0.41	0.74	0.87	0.32	0.58	0.68	0.56	0.47	0.85
Affective context	0	0	1.00	0	0	0	0	0	0	0
Social context	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cognitive context	0	0	0	1.00	0	0	0	1.00	0	0
Motivation context	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Design activity element	0.83	0.81	0.67	0.63	0.80	0.62	0.62	0.65	0.64	0.80

Meanwhile, Team 2 was a good collaborative team, showing capabilities in most of eight creativity modes, which was quite different from those of Team 4. Four pairs (Teams 2 and 3, Teams 4 and 5, Teams 1 and 2, Teams 1 and 3) achieved a similarity result above 0.80 in sub-case indexes.

The correlation between *physical context* and its sub-indexes was analyzed (see Table 10). *Physical context* was highly influenced by its sub-case index *time*. Moreover, the sub-case index *communication* was excluded from the analysis because it has a constant value, caused by the same experiment setting.

Among sub-indexes, the *cognitive context* shows the highest influence on psychological context. In this case study, three different types of cognitive context were observed from five teams, and Boolean value was utilized to measure the similarity between case indexes. Only two team pairs got a score of 1.00 while the others got 0. The abnormal distribution of the value of cognitive context influenced the similarity results on *psychological context* (see Table 11).

4.3.2. Design process

The similarity results of case index design process and its sub-case indexes are shown in Table 12. The similarity results of time spent and transition behavior for design cases are in a small range, from 0.46 to 0.76 and 0.92 to 0.61, respectively. The case index time spent was introduced to reveal the time allocation of each design stage and step. Teams 4 and 5 got the highest similarity result (0.76) while Teams 2 and 5 show the lowest score (0.46) on time spent. There is another case index time related to time spent in a design context, reflecting the overall condition of time spent on the five teams. As shown in Table 9, Teams 2 and 3 got the highest score on case index time comparison, while Teams 1 and 5 got the lowest score. Using these both time case indexes, our framework can measure the similarity of time spent by each team comprehensively.

The sub-case index *stage outcome* exhibits the highest influence on the similarity results of the design process as shown in Table 13.

4.3.3. Function requirement

The similarity results of function requirements show relative degrees of handling between each design case and its design problem (Table 14). For example, the high value in Teams 1 and 2 can be understood by active formulation in a problem definition; the product function was framed more actively in the two teams. Additionally, Teams 3 and 5 considered the product effectively in the specific boundary of a service, producing the highest score in the similarity result of function requirements.

Table 10
Correlation matrix of *physical context* and its sub case indexes.

		Physical context
Time	Pearson correlation	0.683[a]
	Sig. (2-tailed)	0.030

[a] Correlation is significant at the 0.05 level (2-tailed).

Table 11
Correlation matrix of *psychological context* and its sub case indexes.

		Psychological context
Cognitive context	Pearson correlation	0.736[a]
	Sig. (2-tailed)	0.015

[a] Correlation is significant at the 0.05 level (2-tailed).

Table 13
Correlation matrix of *design process* and its sub-case indexes.

		Design process
Stage outcome	Pearson corr.	0.747[a]
	Sig. (2-tailed)	0.013

[a] Correlation is significant at the 0.05 level (2-tailed).

4.4. Reflections on PSS design and validation of case indexes

To investigate the relations among case indexes, a correlation analysis was conducted, where case indexes having constant values such as *design tool* and *motivation* were excluded (Table 15). Case index *time spent on requirement identification* and *value targeting* (S1) has a positive relationship with *design object* (DO) (0.859) and *design context* (CO) (0.764). The higher correlations imply that *design object* in PSS development influence designers' activity in the design stage of requirement identification and value targeting. Case index *activity of stage outcome* (ACT) shows a positive correlation with *design object* (DO) (0.808) and *time* (TIM) (0.691) of *design activity element*. It suggests that the design stage outcome is influenced by the time of the design project. Thus, designers may generate more stage outcomes in the longer design process. Also, the type of design object causes the difference of stage outcome.

Case indexes, *function requirement* (FU), and *function* that belongs to *stage outcome* (ACT) are two sub-case indexes that relate to function in the proposed framework. The correlation between these two indexes is not significant, showing little overlap. Two case indexes can represent different aspects related to function. Two case indexes related to time, *time in a physical context* (TIM) and *time spent* (S1 or S2), also show no significant correlation. It suggests that two indexes can represent different aspects of time. Case index *affordance* (AFF) and *activity of stage outcome* (ACT) got 0.743 of correlation. In the design process, affordance is generated by the interaction of activity and function. Thus, the amount of affordance and activity are highly interrelated. However, case index *affordance* (AFF) has different features from those of case index *activity* (ACT). For example, *affordance* shows the positive

Table 12
Similarity results of *design process* and its sub case indexes.

	T1/T2	T1/T3	T1/T4	T1/T5	T2/T3	T2/T4	T2/T5	T3/T4	T3/T5	T4/T5
Time spent	0.57	0.55	0.71	0.50	0.54	0.51	0.46	0.56	0.56	0.76
Stage 1	0.88	0.95	0.74	0.64	0.84	0.65	0.56	0.78	0.67	0.86
Stage 2	0.48	0.73	0.65	0.64	0.66	0.31	0.31	0.47	0.47	0.99
Stage 3	0.65	0.38	0.59	0.58	0.24	0.38	0.37	0.64	0.65	0.98
Stage 4	0.63	0.68	0.63	0.60	0.93	1.00	0.95	0.93	0.88	0.95
Stage 5	0.21	0.00	0.92	0.03	0.02	0.22	0.12	0.00	0.15	0.03
Transition behavior	0.77	0.74	0.84	0.61	0.92	0.85	0.73	0.79	0.79	0.63
Step transition	0.97	0.96	0.92	0.90	0.93	0.95	0.87	0.88	0.94	0.83
Stage transition	0.56	0.52	0.76	0.33	0.92	0.74	0.59	0.69	0.64	0.44
Stage outcome	0.77	0.79	0.47	0.71	0.85	0.37	0.67	0.31	0.57	0.56
Function	0.55	0.48	0.83	0.67	0.88	0.45	0.36	0.40	0.32	0.80
Activity	0.87	0.88	0.35	0.57	0.77	0.40	0.65	0.31	0.50	0.62
Affordance	0.89	1.00	0.22	0.89	0.89	0.25	1.00	0.22	0.89	0.25
Design process	0.70	0.69	0.67	0.61	0.77	0.58	0.62	0.55	0.64	0.65

Stage 1 = Requirement Identification and Value Targeting, Stage 2 = Stakeholder Activity Design, Stage 3 = PSS Function Modeling, Stage 4 = Function-Activity Mapping and PSS Concept Generation, Stage 5 = PSS Concept Detailing.

Table 14
Similarity results of *function requirement*.

	T1/T2	T1/T3	T1/T4	T1/T5	T2/T3	T2/T4	T2/T5	T3/T4	T3/T5	T4/T5
Function requirement	0.79	0.18	0.68	0.19	0.13	0.50	0.21	0.26	0.83	0.29

Table 15
The correlations among case indexes.

	AC	DP	FU	DO	CO	PH	PSY	TIM	MO	S1	S2	TS1	ACT	AFF
AC	1													
DP		1												
FU			1											
DO				1										
CO					1									
PH						1								
PSY		−0.802					1							
TIM		0.879		0.678			−0.724	1						
MO						−0.634		−0.673	1					
S1	0.911			0.859	0.764					1				
S2			0.680								1			
TS1											0.670	1		
TS2									−0.656		0.634			
ACT	0.765			0.808			−0.722	0.691					1	
AFF													0.743	1
PER							0.639	−0.666						
DEA	0.743			0.695						0.795				
TSP												0.840		
WOR														0.789

Correlation is significant at the 0.05 level (2-tailed). (AC = design activity element, DP = *design process*, FU = *function requirement*, DO = *design process*, CO = *design context*, PH = *physical context*, PSY = *psychological context*, TIM = *time*, MO = *mood*, S1 = *time spent on* requirement identification and value targeting, S2 = *time spent on develop alternatives*, TS1 = *step transition*, TS2 = *stage transition*, ACT = *stage outcome-activity*, AFF = *stage outcome-affordance*, PER = *perception*, DEA = *deadline*, TSP = *time spent*, WOR = *working hour*).

correlation with *working hour* (WOR), which is not observed between *activity* (ACT) and *working hour* (WOR). Case index *transition step* (TS1) has a positive correlation with *time spent on developing alternative* (S2), which suggests that there are more step transitions during the longer design process. Meanwhile, *stage transition* (TS2) does not show correlation with *time spent* (S2).

As mentioned earlier, *psychological context* (PSY) was greatly influenced by *cognitive context* and *affective context*. In the correlation analysis, *psychological context* (PSY) shows obvious negative correlation (−0.802) with *the design process* (DO). Also, *psychological context* (PSY) shows a negative correlations with *time* in *physical context* (TIM) and *activity* in *stage outcome* (ACT). These results imply that the *cognitive context* and *affective context* need more suitable similarity measurement methods. Case index *mood context* (MO) shows a negative correlation with *time* (TIM) and *stage transition* (TS2). *Mood context* (MO) is represented by the relative amount of socio-emotional interactions among team members. Thus, the relative amount of neutral interactions (tasks) should have a positive correlation with *time* (TIM) and *stage transition* (TS2). It means that the *mood context* (MO) represents the number of tasks during the design process, which does not accord with our understanding of mood context. Therefore, the similarity measurement method of *mood context* (MO) should be adjusted to show the influence of mood context on designers' activity and design process.

4.5. Empirical validation

4.5.1. Recruitment of participants

We conducted an empirical validation survey to determine if the similarity results from the proposed framework are acceptable to the experts. Six experts were recruited for this purpose in the validation survey and were asked whether they agree with the similarity results derived from our similarity framework. The group of participants consists of four professors and two PhDs who have more than ten years of their careers in the design field, and they are different members who participated in the case study.

4.5.2. Experimental Setup and procedure

The proposed representation framework consists of four levels (see Table 1). We presented the data of fourth-level (the lowest level) case index and asked participants to assess the similarity of the secondary level case index. For example, the participants were presented with the raw data of time and communication of five teams in *design activity element* and were asked to assess the similarity results of *context*. The reason for this division is that it is too apparent to ask them to assess the third-level case index, and it seems too abstract to ask them to evaluate the first-level (primary) case index. Also, some of the case indexes did not include third-levels as in *design activity element*. Therefore, we concluded that asking the participants to assess the second levels, such as *designer*, *context*, and *time spent* would be appropriate. This would also allow us to validate whether the sublevels, such as *time* and *communication*, appropriately represent the upper concept, *design context*.

There are seven categories in the second-level indexes: *designer, object, context, time spent, transition behavior, stage outcome*, and *function requirement*. We removed "*tool*" index since all the participants in the case study used the same PSS tools. For each section, the participants were asked to assess the similarities between two teams, regarding seven different aspects (i.e. *designer*), and to what extent they agree with the similarity result based on a 7-point scale that provides more granularity and hence better decision making. The text field box was also provided below each question so that the participants could write reasons and explanation for their answers.

The online survey link was distributed through e-mail with two reference materials: the raw data of case study results and the glossary to aid understanding of terms used in the case study. While some of the raw data of case study include some graphical representation, these were intentionally removed. There is a possibility that the graphical data cause bias in the similarity assessment since it is more easily visualized than the data represented with plain text and numbers. Instead, we only presented text data (texts and numbers) during the survey. The glossary included the detailed information of subsections including graph and text descriptions to aid understanding. The survey consists of 70 questions (ten combinations of teams and seven aspects resulted in 70 questions). The survey took about 45 min.

4.5.3. Results

Fig. 2 shows the central tendency of the results from the experts. In this figure, the x-axis indicates the degree of agreement, and the y-axis shows the seven case indexes used in the survey. As the seven-point Likert items are considered as ordinal data, the measure of central tendency was measured by the median value of a set of Likert items. In general, the expert rated that the results derived from the proposed framework were agreeable and acceptable. For the aspects of *design object, context, and transitional behavior*, the central tendency is "Agree (6)." For the aspects of *designer, time spent, stage outcome, and function requirement*, although the central tendency is "Somewhat Agree (5)," there are some strong disagreements for some pairs that we need to discuss.

Fig. 3 shows the average percentage of degree of agreement on ten pairs for each case index. The similarity results for the case indexes of *object, context, time spent,* and *transition behavior* were highly accepted by the experts. While 38.98% of the participants "strongly agreed" and "agreed" with the results of *object*, respectively, 1.69% "somewhat disagreed," and 20.34% "disagreed." Some of the disagreement was caused by the discrepancy of "Air conditioner" and "Payphone," which we assessed the similarity between two products based on UNSPSC code. 8.33%, 46.67%, and 26.67% of the participants "strongly agreed," "agreed," and "somewhat agreed" on the *context*, respectively whereas 6.67% and 1.67% of the participants "somewhat disagreed" and "disagreed" with the results. 20%, 23.33%, and 28.33% of the participants "strongly agreed," "agreed," and "somewhat agreed" on the *time spent*, respectively, and 13.33% and 1.67% "somewhat disagreed," and "disagreed" with the results. 35%, 25%, and 21.67% of the participants "strongly agreed," "agreed," and "somewhat agreed" on the *transition behavior*, respectively. There were only 5% of "somewhat disagreement" and 1.67% "disagreement" on the *transition behavior*.

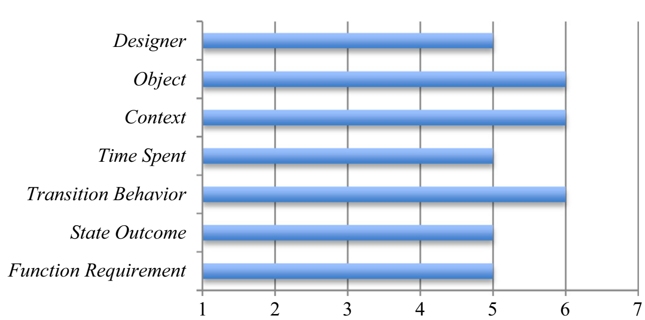

Fig. 2. The median values of evaluation results (1-strongly disagree to 7-strongly agree).

While the central tendencies of the experts' evaluations indicate that the similarity assessments are agreeable to the experts, some disagreements of several aspects have room for further discussion. For *designer*, there was a strong disagreement on the similarity result of 0.50 (min = 0.46; max = 0.67) for Team 2 and Team 3. The possible explanation is that while we utilized the cosine similarity to judge the overall orientation of all three designers combined as a team, the participant could have considered the characteristics of individual designers. For example, the creativity characteristics two designers in Team2 and Team 3 are in the same dimensions: synthesizing and analyzing. Nevertheless, the similarity can be significantly different using the cosine method since we considered the overall orientations of perception and judgment of a team.

For *function requirement*, there were two strong disagreements on the similarity result of 0.13 (min = 0.13; max = 0.83) for Team 2 and Team 3, and one of the participants left the comment saying that the similarity is too low regarding the similarity of "display usage info" of Team 2 and "guide AC info" of Team 3. Also, regarding the similarity result of 0.83 for Team3 and Team5, the participant mentioned "provide one-day phone" and "provide user info" are very different. These disagreements arose since the semantic discrepancy between two phrases was not taken into account.

5. Discussions and conclusion

This research proposed a similarity measurement framework of PSS design case based on context-based activity model. In the proposed framework, a PSS design case was indexed by design activity element, design process, and function requirement, then, the similarity measures of case indexes were developed. A case study was conducted to validate the proposed framework. According to the PSS design knowledge representation framework, the design knowledge was collected by protocol analysis, and the similarity results of each case index were analyzed and discussed quantitatively and qualitatively. The result of the case study along with an empirical validation validates that the proposed framework and similarity measurement methods are applicable for effective PSS design case comparison in practice. The proposed framework performed well for the PSS design case comparison though some points have been noted for improvements.

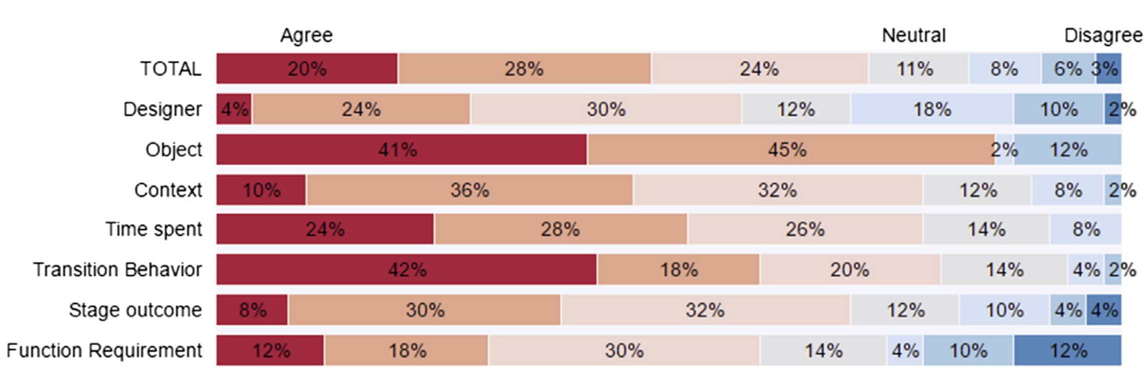

Fig. 3. The evaluation results of seven case indexes.

Specifically, the significant contributions of this study are as follows. First, the comprehensive PSS design knowledge representation framework covers not only the design knowledge of designated products and services but also that of the design process and other factors. The design knowledge that has direct relationships with designers' activity is considered for this research based on the activity theory. The context where the designer's activity occurred, the design process of how the designers' activities proceed, and their decisions and design outcomes at each design stage are focused. Second, this study provides measurable case indexes and case retrieval strategy for PSS design cases comparison. Case indexes related to design activity element, design process, and function requirement were selected to describe PSS design cases in the proposed framework. These case indexes were assigned with textual or numeric data, where a computational case retrieval approach was utilized. According to the characteristics of each case index, Euclidian distance, cosine similarity, and feature-based measure are utilized as case retrieval.

5.1. Limitations and future work

Although this study provides an understanding of the ways to present the PSS design knowledge and explores methods to measure the similarity of PSS design cases, there are some issues that need to be addressed in the further studies. First, a small number of PSS design cases was used in the case study. Thus, more design cases with different experiment setups will be adopted for our future study to ensure the difference in each case index. Further, we will collect PSS design cases from real projects reflecting realistic design conditions. Second, the lack of weight for some case indexes caused the abnormal distribution of similarity results. Thus, some quantitative results were not applicable for the validation. For our future study, different weights will be assigned to case indexes to make the case similarity measurement result more reasonable. The weight of each case index could be determined through theoretical research and case studies. Some researchers have already proposed different contributions of design stages on the quality of the final design in the context of PSS design. Also, the weight of each case index could be assigned by users of the case-based recommender system. Analytic hierarchy process (AHP) may be utilized to help users to decide the weight of each case index.

The empirical validation survey allowed us to devise several directions to improve our similarity framework. For the *function requirement*, we used the standardized functions to measure the number of common functions that two cases were shared. However, for the more accurate result, taking a variety of semantic similarity based on the lexical database into account is necessary and would provide additional insight into relatedness of functions. Also, comparing the characteristics of individual designers of each team, and deriving one representative data is challenging. While this is why we utilized the cosine similarity to compare the two vectors, the common creativity characteristics of individual designers should also be considered along with the overall vector of a team. Therefore, considering the number of common characteristics of each designer would provide additional support along this line of study.

Our future work will provide a more holistic way to represent, index, and compare the PSS design cases, addressing the above issues. Most of all, the similarity measurement methods of case indexes will be further explored. Consequently, our similarity measurement framework of PSS design cases will be elaborated and improved. The understanding of PSS design case similarity measurement is a great source of inspiration for further studies on case-based recommender system for PSS design. The proposed similarity measurement framework of PSS design case could build up an essential mechanism for the development of a case-based PSS design recommender system as a systematical and efficient tool, which can support the retrieval and reuse of prior PSS design knowledge.

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