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Design Entropy Theory: A New Design Methodology for Smart PSS Development

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Abstract. Smart product-service systems (Smart PSS), as an emerging digital servitization paradigm, leverages smart, connected products and their generated services as a solution bundle to meet individual customer needs. Owing to the advanced information and communication technologies, Smart PSS development differs from the existing product and/or service design mainly in three aspects: 1) closed-loop design/redesign iteration; 2) value co-creation in the context; and 3) design with context-awareness. These unique characteristics bring up new design challenges, and to the authors' best knowledge, none of the existing design theories can address them well. Aiming to fill this gap, a novel design methodology for the Smart PSS development is proposed based on the information theory, where both the sysetm and stakeholders can be regarded as the information containers. Hence, the closed-loop design/redesign iteration can be treated as the dynamic change of information and entropy in a balanced ecosystem. Meanwhile, the value co-creation process is considered as the exchange of accumulated information via the container. Lastly, the design context-awareness represents the process of reducing entropy. As a novel prescriptive design theory, it follows Shannon's information theory to determine the best design/redesign solutions by considering the three characteristics integrally. It is hoped that the proposed design entropy theory can largely facilitate today's Smart PSS development with better performance and user satisfaction.

Keywords: Design theory; smart product-service systems; information theory; design entropy; value co-creation; user experience

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Nomenclature

AD	Axiomatic Design
DIKW	Data, Information, Knowledge, Wisdom
FBS	Function-Behavior-Structure
GPS	Global Positioning System
ICT	Information and Communication Technologies
IoT	Internet-of-Things
KE	Kansei Engineering
MC	Mass Customization
OAP	Open Architecture Product
OAPP	Open Architecture Product Platform
PSS	Product-Service Systems
QFD	Quality Function Deployment
SCOAP	Smart, Connected Open Architecture Product
SCP	Smart, Connected Product
STA	Smart Travel Assistant
TRIZ	Teorija Rezhenija Izobretatelskih Zadach
UCD	User-Center Design
WSN	Wireless Sensor Network

1. Introduction

Nowadays, the manufacturing companies are taking ever increasing consideration of digitalization and servitization than ever before, by transforming their business models into a digital servitization one with integrated smart, connected products and services as a solution bundle [1]. In this context, a novel information-driven business paradigm has emerged, i.e. smart product-service systems (Smart PSS), which is defined as "*an IT-driven value co-creation business strategy consisting of various stakeholders as the players, intelligent systems as the infrastructure, smart, connected products (SCPs) as the media and tools, and their generated services as the key values delivered that continuously strives to meet individual customer needs in a sustainable manner*." [2]. By embracing the cutting-edge information and communication technolgoy, such as Internet of Things (IoT), Big Data analytics, and smart, connected products (SCPs), data/information is directly collected from hardware sensors (product-induced data) and social sensors (user-generated data), analyzed concurrently and responded in real-time to meet individual customer needs [3]. Based on our previous work, three unique design characteristics of Smart PSS are described, including 1) *value co-creation in the context*, which maintains that the design plans need to be completed with the participation and cooperation of stakeholders (i.e., users, service providers, and manufacturers/vendors [4]); 2) *closed-loop design/redesign iteration*, which emphasizes that relevant in-context information should be collected and processed throughout the Smart PSS lifecycle, during both the design and usage stage; and 3) *design with context-awareness*, which highlights that Smart PSS should be deeply perceived and adapted to the development context based on the intelligent systems [5].

Ever since PSS first coined in 1999 [6], many research efforts have been reported for its design methods. Fargnoli et al. (2018) presented a methodology based on the analysis of customer requirements by integrating with QFD for PSS [7], and Costa et al. (2018) built a PSS design approach from the human-oriented perspective [8]. Fargnoli et al. (2019) suggested a practical method to fulfil user requirements and expectations [9]. In addition, studies on Smart PSS development have received much attention recently. Chen et al. (2020) prioritized the innovative value propositions to support Smart PSS concept design [10], and Pan et al. (2019) examined the way to design Smart PSS for service-oriented intelligent interoperable logistics [11]. Meanwhile, Liu et al. (2020) developed a framework to analyze system requirements toward customer requirements and co-creative value propositions [12]. Nevertheless, scarcely any works provide a design approach to realize Smart PSS development by satisfying its three unique design characteristics simultaneously. Table 1 categorized nine typical PSS design methodologies from three characteristics. It can be found that none of these methods can consider these characteristics of Smart PSS holistically.

Aiming to fill in the gap, this research work, as the first attempt, proposes an information-driven design entropy theory for the Smart PSS development, which utilized a novel concept of design entropy to take the process of information prediction, summarization, conversion and updating into an overall consideration. The rest of this paper is organized as follows: Section 2 provides a comprehensive review of information design and entropy in information theory. Section 3 defines design entropy theory, discusses the concept of design entropy and conversion ability, explains its design process, and introduces some formulas for the quantitative measurement of design entropy. Section 4 illustrates the concepts with examples. The discussion is highlighted in Section 5. Moreover, the conclusion and future work are summarized in Section 6 at last.

Table 1. Comparison of typical design methodologies for Smart PSS.

	Value co-creation in the context				**Closed-loop design/redesign iteration**				**Design with context-awareness**	
	Users participate subjectively	Designing with user data	Matching user preferences with design	Cooperate with other stakeholders	Requirements analysis	Innovative design	Design evaluation	Iterative design	Perceiving context	Adapting to context
TRIZ		√	√		√	√	√			
QFD	√	√		√	√	√	√			
KE	√	√	√				√			
UCD	√	√		√		√	√	√	√	
AD						√			√	
Service blueprint						√	√			
Adaptable design	√	√	√				√	√	√	
MC	√	√	√	√	√		√	√		
FBS					√	√	√		√	

2. Fundamentals of Design entropy theory

To provide a better view of background knowledge, this section introduces fundamental notions of information, information design and information entropy. Meanwhile, related works of adaptable design are also summarised to support proposing design entropy theory.

2.1. Information design and entropy

Information as an existence independent of material and energy [13] can organize data into valuable content and describe the things' state. Based on the DIKW hierarchy in the concept design domain proposed by Wodehouse and Ion (2010) [14], Figure 1 depicts the relationship hierarchy among data, informationand knowledge in the Smart PSS design domain. Information sits in between the other two levels, denotingthe reflection of individual users' state and requirements, which can be applied in Smart PSS customization process. Hence, information design can be regarded as a subject that treats information as its design object, and its primary concern is the perspicuous and effective presentation of information. For instances, information design has been widely adopted in the suitable visual layout design and the interface design of smartphone applications.

Nowadays, the research on product/service information in engineering design mainly initiates from two aspects, 1) *user-oriented aspect*, where information as the value is mined from user-generated data, and further transferred to users to help them operate product/service [15][16], and 2) *developer-oriented aspect*, of which the information generated by designers is managed to support engineering design process [14][17]. Meanwhile, the main focus of PSS information in engineering design lies in two categories: 1) information module and 2) information system. For the prior one, the traditional product and service modules can be replaced by the novel information modules to facilitate the orchestrating and the builder roles [18]. For the latter one, it is investigated from a lifecycle-oriented design perspective. Aurich et al. [19] proposed an information system of which both input and output information of modules are actively recorded and update to select the solutions more accurately. Although numerous studies has presented potential methods to apply information in the product/service/PSS design, there are few illustrating how to leverage information design in the Smart PSS context.

Information theory was proposed by Shannon in 1948 [20], which systematically discussed the fundamental issues of information communication by using mathematical tools (e.g., probability theory and statistics), including both the quantitative expression of information and the concept of information entropy. In his theory, the fomula of $\mathrm{H} = -\Sigma p_i log p_i$ play a significant role to measure system uncertainty, where p_i is the probability of a system in cell i of its phase space, and H is recognized as the information entropy of the set of probabilities $\mathrm{p}_1, \ldots, \mathrm{p}_\mathrm{n}$. Based on Shannon's information theory, some recent studies have presented the design entropy concept. Slomka (2011) [21] presented design entropy as a measurement for the complexity of a given circuit by resorting to Shannon's information theory, which is mainly used in the digital circuits field rather than the engineering design field. Wu (2016) [22] further defined design entropy as a description of the disorder found in design objects and proposed a design entropy model, which is a measurement of the degree of information chaos in a user interface. Since most design problems in SCPs and e-services of Smart PSS need to be solved by extracting and converting information in real-time, which cannot be solved analytically by the existing design entropy concepts, this paper will propose a novel design entropy concept based on information entropy unlike the existing ones.

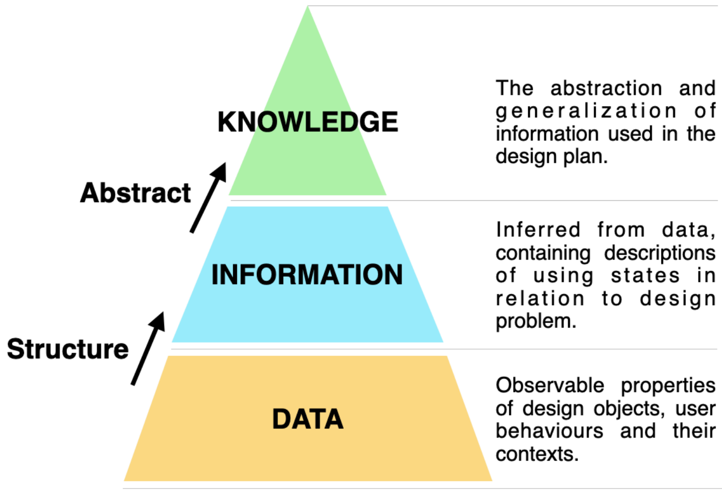

Figure 1. The relationship hierarchy among data, information, and knowledge (derived from Wodehouse and Ion (2010) [14]).

2.2. Adaptable design

Adaptable design was first presented by Gu et al. (2003) to adapt to new requirements [23] by replacing or adding some modules according to the condition changes [24]. Adaptable design can be classified into two aspects, including both design adaptability and product adaptability. The prior one refers to the ability in the design plan of a product so that this design can be changed to create another product. The latter refers to the ability of a product to be adjusted to different usages [23].

Adaptable design is based on modular design principles for readily change and upgrade of existing product family, and has been entensively adopted and improved by utilizing digital or other disciplinary methods (Nagel et al. (2010) [25]). For example, Wu et al. (2006) [26] established a universal design platform for product family development based on convenient knowledge extraction and data representation. Moreover, some researches discussed on how to apply adaptable design in developing OAPs [27][28], which is a class of adaptable product with open interfaces that allows third-party vendors developing and connecting new additive modules [29]. Zhang et al. (2015) [30] introduced a robust adaptable design method for OAP development to improve the quality of design substantially. Zheng et al. (2017) [31] proposed a product configuration system framework and personalized configuration process of OAPP. Zheng et al. (2018) [32] further proposed a new product development paradigm, i.e. smart, connected open architecture product (SCOAP), which follows the adaptable design principles. Wang et al. (2019) [33] elicited user's in-context requirement of the smart, connected bicycle during usage stage for reconfiguration by following the adaptable design principles.

With the above literature, it is deemed that adaptable design can be somewhat leveraged to develop Smart PSS with product/service extendibility and lifecycle consideration, owing to its advantages in delivering adaptable designs or products to satisfy dynamic user requirements. Moreover, the adaptability measure for the product can also be used to calculate the design entropy of Smart PSS, which represents the suitability of adapting a system to varying requirements.

3. Proposed design entropy theory

Motivated by the concept of information entropy and adaptable design, and in order to facilitate the Smart PSS development, this section proposes a new design method, i.e. design entropy theory. Its introduction, definition, design process and tool, are presented in the following sub-sections.

3.1. Introduction of Design entropy theory

Due to the digitization, servitization, and informatization characteristics of Smart PSS, it should take information prediction, summarization, and updating in the system as the research objectives, instead of the physical substances. Smart PSS and stakeholders can be regarded as containers for these information activities, and the design process of Smart PSS can be regarded as the process which collects/extracts useful information from some containers and transmits/materializes them to other physical containers. The information can be inputted by stakeholders directly or extracted from hardware/social sensors collected data.

As depicted in Figure 2, in the Smart PSS lifecycle, information can be stored and transmitted at each stage, and it will not be worn out or aged. Information is different from the physical substance of Smart PSS, which will finally eliminate (or its materials or parts can be reused/remanufactured). Nevertheless, the information carried by the eliminated Smart PSS cannot be deleted, and it can be transmitted to other containers (e.g., the same system with new physical SCPs and other Smart PSS in different types).

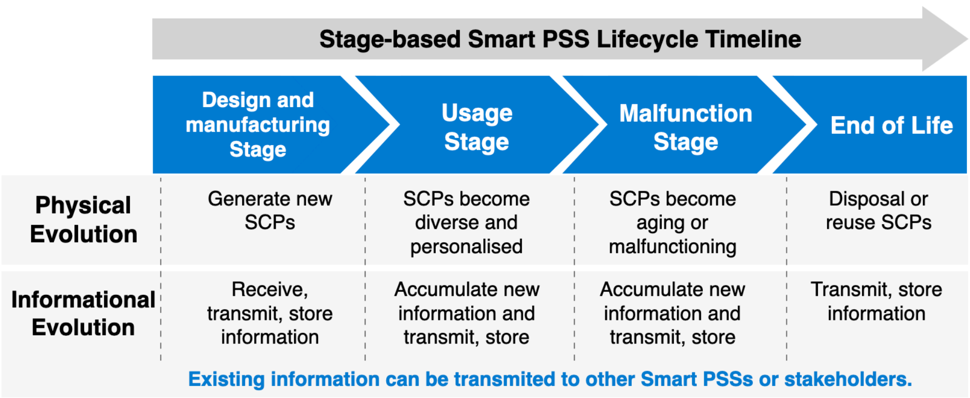

Figure 2. Physical and Informatic evolution in Smart PSS lifecycle.

3.2. Design entropy

Before proposing the new definition of design entropy, the scope of information in Smart PSS needs to be clarified. Information in Smart PSS can be the descriptive and prescriptive one revealing the status of the stakeholders, solution (i.e. SCPs and services), and environment. Following this scope, design entropy can be "*a measure of a deterministic degree of Smart PSS information design*". The absolute value of design entropy is positively related to the systems' uncertainty. If a system's certainty is low, its design entropy should be high, which means that the accuracy of its context-awareness, the quality of real-time iterative designing based on the current context, and the stakeholder's participation and satisfaction degree are low. Consequently, design entropy theory needs to dynamically reduce the design entropy in order to keep the most outstanding deterministic for each context throughout the lifecycle.

To calculate the design entropy, a new measurement called *conversion ability* is introduced, which is denoted by C. Conversion ability represents the ability to convert the information denoted by x_i into the information denoted by x'. As shown in Figure 3, x refers to the information which has no solutions mapping, and x' refers to the information which describes design solutions. The conversion ability of Smart PSS is high, which means that its conversion effect from x to x' is excellent, and the design entropy of this system is low. Let D as the design entropy, and the value of D is calculated by:

$$D = -\log C \qquad (1)$$

, where $0 \leq C \leq 1$, and all $D \geq 0$. Thus if the conversion ability of a system is the highest, the value of C is 1, then $D = 0$. On the contrary, the value of C is 0, then $D = +\infty$. In order to compare the value of design entropy in different contexts and systems, the same logarithmic base 2 is used in each equation of design entropy. Furthermore, the total design entropy of a system is given by

$$D_{total} = D_{innovative} + D_{iterative} \qquad (2)$$

, where $D_{innovative}$ represents innovative design entropy of the system, and $D_{iterative}$ represents iterative design entropy. The former one means the design entropy in the innovative design stage of creating a new Smart PSS. Furthermore, the latter one means the design entropy in the usage and iterative design stage at which the design solutions can be redesigned, modified, or enhanced according to the new information collected from sensors.

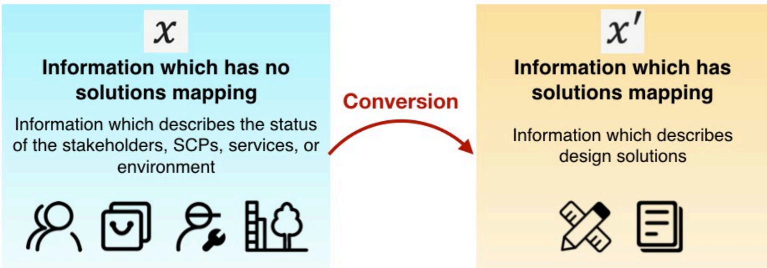

Figure 3. Information conversion in Smart PSS.

3.3. Innovative design entropy

We define the innovative design entropy of a system as $D_{innovative}$ according to the innovative conversion of the system, $C_{innovative}$. That is

$$D_{innovative} = -\log C_{innovative} \qquad (3)$$

This quantity measures how uncertain the system is in its innovative design stage when we know $C_{innovative}$. $C_{innovative}$ refers to the conversion ability of the design plan to effectively convert information in usage stage. We define $C_{innovative}$ by

$$C_{innovative} = A_1 \times Y_1 + A_2 \times Y_2 + \cdots + A_n \times Y_n \qquad (4)$$

, where Y_n is a parameter that represents the ability that a design plan can convert the information in a specific way when the plan is adopted in the future. Different research objects have variable parameters. Since $0 \leq C_{innovative} \leq 1$, let $0 \leq Y_n \leq 1$. Y_n as the normalization processing result of Z_n is given by:

$$Y_n = \frac{2}{1+e^{-Z_n}} - 1 \quad (5)$$

In order to satisfy the three characteristics of Smart PSS, the matching degree with user requirements, adaptability measure, and the number of sensors are utilized as Z_1, Z_2, Z_3 to calculate Y_1, Y_2, Y_3 of Smart PSS. Furthermore, coefficient A_n is a weighting factor to represent the importance of Y_n in the different case. A_n is given by the stakeholders for expressing the importance of Y_n to the system. Thus $0 \leq C_{innovative} \leq 1$ and $0 \leq Y_n \leq 1$, where

$$A_1 + A_2 + \cdots + A_n = 1 \quad (6)$$

3.4. Iterative design entropy

Figure 4 illustrates the process of information conversion in the usage and iterative design stage of Smart PSS. After collecting new information, Smart PSS builds and updates the current usage context according to this novel information. In a specific usage scenario, Smart PSS should firstly determine whether the information is noise, referring to the useless information for the design plan in the current context and delete it thereafter. If it is not noise, this information x needs to be converted into the information x'. After this processing step, only useful information will be updated and stored.

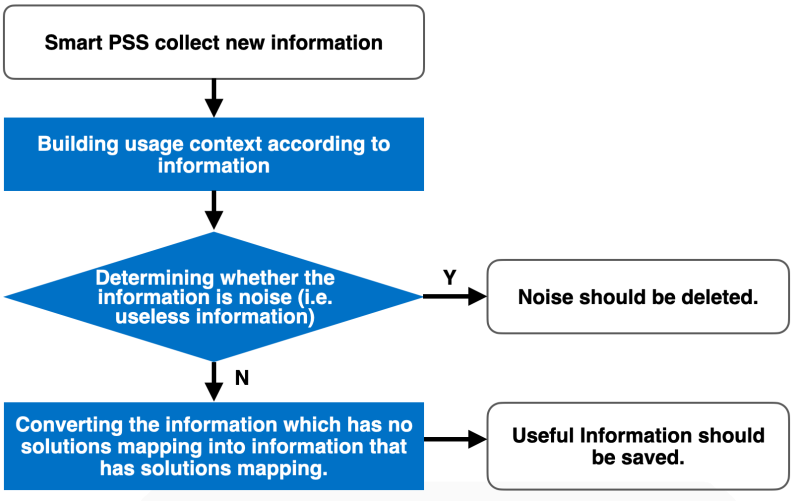

Figure 4. Process of information conversion in in the usage and iterative design stage.

Iterative design entropy consists of the sum of the design entropy of all non-noise and unconverted information x, which is collected by the system during the usage stage, which is denoted as:

$$D_{iterative} = \sum_{x \in \mathcal{X}} D(x) \quad (7)$$

, where $\mathcal{X}$ is the set of all non-noisy and unconverted information collected by the system, and information x belongs to the set $\mathcal{X}$. As depicted in Figure 5, the information x_i converted into m pieces of information x'(i.e., $x_1{}'$ to $x_m{}'$), through m items of channels. The design entropy of information x_i is

$$D(x_i) = -\sum_{m \in \mathcal{M}} W(x_i)_m \log C(x_i)_m \quad (8)$$

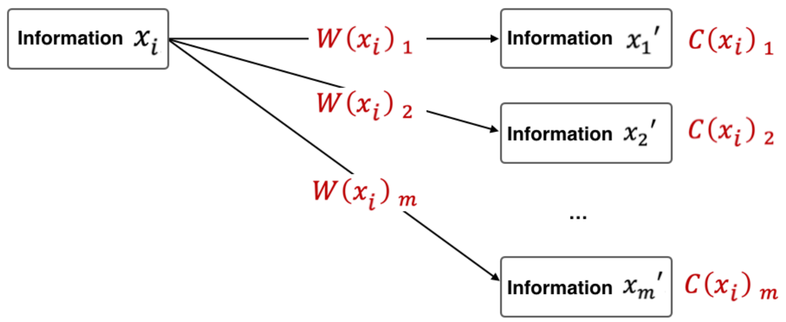

Figure 5. Conversion of information x_i.

, where $\mathcal{M}$ is the set of all channels between information x_i and information after conversion, and channel m belongs to the set $\mathcal{M}$. $W(x_i)_m$ is the weighting factor of channel m, representing the correlation of information x_i and x_m'. $W(x_i)_m$, which will be modified in a diverse context, is given by the stakeholders defined as:

$$W(x_i)_1 + W(x_i)_2 + \cdots + W(x_i)_m = 1 \tag{9}$$

Additionally, $C(x_i)_m$ refers to the conversion ability to convert information x_i into x_m' through channel m, representing the single-channel conversion capability for a single piece of information in the system.

$$C(x_i)_m = A(x_i)_{m_1} \times Y(x_i)_{m_1} + A(x_i)_{m_2} \times Y(x_i)_{m_2} + \cdots + A(x_i)_{m_n} \times Y(x_i)_{m_n} \tag{10}$$

, where $Y(x_i)_{m_n}$ is a parameter that represents the ability that, information x_i can be converted into information x_m' effectively, efficiently and economically. Since $0 \le C_{innovative} \le 1$, we let $0 \le Y(x_i)_{m_n} \le 1$. Each $Y(x_i)_{m_n}$ is determined by $Z(x_i)_{m_n}$, and different information conversion types *n* have different $Z(x_i)_{m_n}$. For Smart PSS development, the user satisfaction degree, time and cost of completing an information conversion are the three core criteria, which are denoted as $Z(x_i)_{m_1}$, $Z(x_i)_{m_2}$, $Z(x_i)_{m_3}$ respectively below.

$Y(x_i)_{m_1}$ refers to the *effective capability* of completing the information conversion from x_i to x_m':

$$Y(x_i)_{m_1} = 0.01 \times Z(x_i)_{m_1} \tag{11}$$

, where $Z(x_i)_{m_1}$ represents the user satisfaction degree (in a 100-point rating scale) for the information conversion from x_i to x_m', and is defined as:

$$Z(x_i)_{m_1} = S(x_i)_{m_1} - S(x_i)_{m_2} \tag{12}$$

, where $S(x_i)_{m_1}$ and $S(x_i)_{m_2}$ respectively represents avarage user satisfaction degree after and before this conversion. The improvement of avarage user satisfaction degree after this conversion is great, means the conversion ability of this channel is high.

$Y(x_i)_{m_2}$ refers to the *efficient capability* of completing the information conversion from x_i to x_m':

$$Y(x_i)_{m_2} = e^{-Z(x_i)_{m_2}} \tag{13}$$

, where $Z(x_i)_{m_2}$ represents the total time of converting information x_i into x_m' and implementing the solution described by x_m', which is defined as

$$Z(x_i)_{m_2} = T(x_i)_{m_1} + T(x_i)_{m_2} \tag{14}$$

, where $T(x_i)_{m_1}$ refers to the converting time of determining the information $x_m{}'$. If designers have already given its conversion way in the innovative design stage, the converting time will be zero here. Otherwise, the developers should intervene and supplement the conversion way, and the time of complementing the plan is the converting time $T(x_i)_{m_1}$. $T(x_i)_{m_2}$ refers to the implementation time of realizing the solution described by x'_{m}. Taking a smart bicycle service system as an example, if some parts of the smart bicycle are broken, a maintenance service will be given to the user. Implementation time means the completion time of executing the solution after determining the information, which describes the maintenance service.

$Y(x_i)_{\mathrm{m}_3}$ refers to the *economical capability* to complete the information conversion from x_i to $x_m{}'$:

$$Y(x_i)_{\mathrm{m}_3} = e^{-Z(x_i)_{m_3}} \tag{15}$$

, where $Z(x_i)_{m_3}$ represents total costs associated with completing this conversion, and it is an indicator of the consumption of any economical resources. If the conversion channel save more costs, its conversion ability should be higher. Therefore, $Z(x_i)_{m_3}$ is inversely proportional to $Y(x_i)_{\mathrm{m}_3}$ and $C(x_i)\ _m$. Additionally, Coefficient $A(x)_{\mathrm{m}_n}$, which refers to the weighting factor of the importance of $Y(x_i)_{\mathrm{m}_n}$, is given by the stakeholders. Thus $0 \le C(x_i)_m \le 1$ and $0 \le Y(x_i)_{\mathrm{m}_n} \le 1$, and

$$A(x)_{m_1} + A(x)_{m_2} + \ldots + A(x)_{m_n} = 1 \tag{16}$$

3.5. Design process of design entropy theory

Design entropy theory gives explicit guidelines toward achieving innovation and iteration for Smart PSS. The phases of the systematic design methodology are as follows:

1) *SCPs and service design plan development phase.* The primary functional requirements (FRs) and the target value of innovative design entropy should be determined. Based on the FRs and target design entropy, the initial design plans of SCPs and service can be presented by using a blueprint or CAD model. The values of the innovation design entropy of these initial design plans should be calculated, and the plan with the lowest value should be selected to develop the final design plan in-depth.

2) *Conversion plan development phase.* According to the final design plan of SCPs and service, the information conversion plan of Smart PSS needs to be outputted. A conversion plan, as a part of the design plan, is used to predict and list information x, which will be collected in future stages, and design its conversion way and converted information x′. Therefore, the design plan of design entropy theory consists of the SCP and service design plan in blueprint or CAD model, and conversion plan in information conversion map to be introduced in Section 3.6.

3) *Conversion plan execution and iteration phase.* Information collected during the usage stage should be converted according to the conversion plan. Meanwhile, the value of system iterative design entropy should be monitored. If the value is higher than the standard value scope, the conversion plan should be checked and iteration. It should be noted that each Smart PSS is used by different users to collect their personal information so that a personal conversion plan will be formed to achieve customization.

Furthermore, based on the three design phases mentioned above, the lifecycle of Smart PSS developed with design entropy theory can be described, as shown in Figure 6. In the innovative design phase, the overall design plan of Smart PSS will be completed and output, including SCPs and service design plan and conversion plan. It should be noted that these two plans are interrelated and interactional. When designing a new Smart PSS, SCPs and service design plan should be developed firstly and the conversion plan need to be established based on them. However, the conversion plan should be modified firstly to iterate the design plan, and based on the new conversion plan, the SCPs and service design plan may be renewed if necessary. After manufacturing, Smart PSS will be used by customers. Collecting new information continuously during the usage stage makes iterative design entropy increasing. Therefore, Smart PSS needs to convert the information in real-time to reduce the design entropy. If the information already has a conversion plan, conversion can be directly performed. According to the information x′, parameters/modules can be adjusted for improving the Smart PSS and conveniently using. If there is no conversion plan before or the conversion result is unsatisfactory, it is necessary to supplement or modify the conversion plan, and then re-develop the SCPs/service accrodingly.

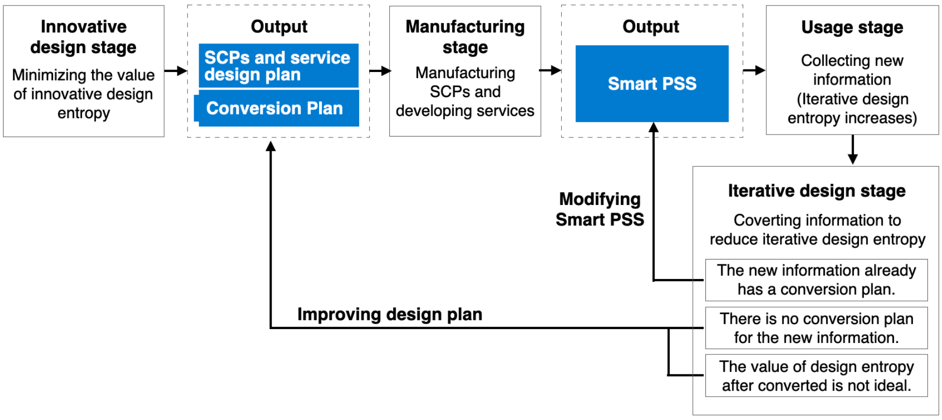

Figure 6. lifecycle of Smart PSS by using design entropy theory.

3.6. Tool of Design entropy theory

Some tools can be presented to build a conversion plan. Information Conversion Map as a novel tool to express a conversion plan is proposed in this paper. This tool can help stakeholders predict and summarize the information which may be collected in the usage stage, and analyze and plan the information conversion. Figure 7 presents the essential elements of the information conversion map. The context where the conversion appeared is marked in the left white box. In the middle, the blue box notes the information x_i before conversion, and the white box records the design entropy $D(x_i)$ of information x_i. The weighting factor $W(x_i)_m$ and the conversion ability $C(x_i)_m$ are marked over and under the conversion line, respectively. The corresponding information $x_m{}'$ after conversion is shown in the right blue box.

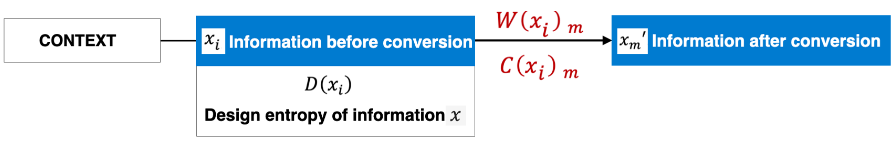

Figure 7. Essential elements of information conversion map.

Figure 8 further depictes the core steps to build and use an information conversion map, which are elaborated below:

Step 1: Predicting and listing the information which will be collected in different usage contexts. According to the design plan, developers should predict and summarize the information to collect in the usage stage by thinking from different usage contexts. Predictions can be made by studing user requirement documents and investigating related product/service usage records.

Step 2: Planning the information after conversion. In this step, the preliminary conversion plan needs to be organized and developed. The developers should analyze information x_i holistically and give the corresponding information after conversion. The developers need to conceive of the conversion plan by combining the design plan and the requirements of stakeholders. It is allowed to have multiple pieces of information after conversion to correspond to one piece of information x_i. Moreover, if there are some repeated information after conversion at this step, it is not necessary to merge them.

Step 3: Marking the weighting factor $W(x_i)_m$ and outputting the information conversion plan. The list of information $x_m{}'$ should be summarized. If there are some duplicate information under the same context, it can be merged. Moreover, the weighting factor $W(x_i)_m$ between information x_i and information $x_m{}'$ needs to be listed above the transformation line. The conversion plan should be completed before SCPs manufacturing and service development. The conversion plan will be continuously adapted and iterated when customers using the system.

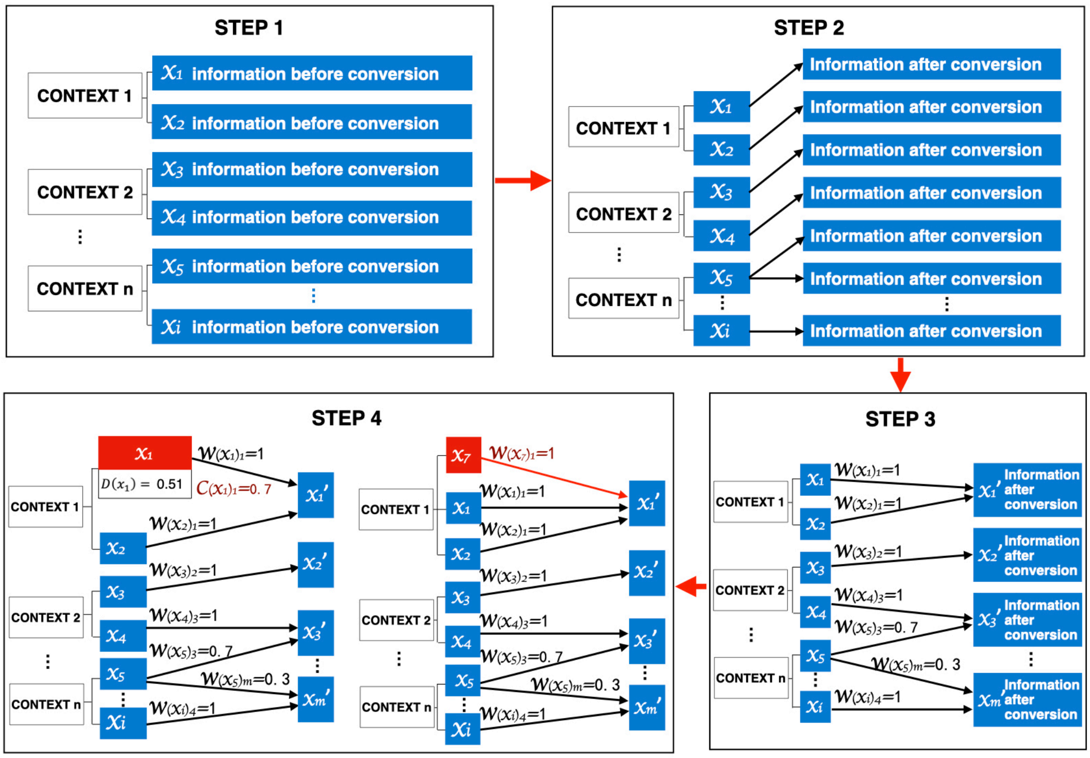

Figure 8. The development process of Information conversion map.

Step 4: Operating and iterating the conversion plan during customers usage. The value of iterative design entropy needs to be monitored in real-time during the usage stage to enable that the value is as expected. This step summarizes two situations when collecting one piece of new information, which are as follows:

1) If the newly collected information has been predicted in a conversion plan before, the conversion channel of this information can be activated directly, and the system should provide services, adjust parameters, or replace modules according to the corresponding information x_m'. The iterative design entropy of information x_1 can be calculated. If the value is so high that the iterative design entropy of the overall system exceeds the standard, the developers need to intervene and readjust the conversion plan.

2) If the newly collected information has not been predicted before, the design entropy of this information will tend to infinity. The system should modify the conversion plan, e.g. converting the information x_7 to an existing information x_1'. After updating the conversion plan, the system should keep on monitoring the iterative design entropy in real-time.

4. Case Study

Empirical case studies have proved as effective model verification methods [3][15][34][35]. Hereby, this section provides a case study of smart travel assistant (STA) system to verify the effectiveness of the proposed design entropy theory.

4.1. Step 1: SCPs and service plan development.

With the rapid development of wireless sensor networks (WSN), internet-of-things (IoT), and information and communication technologies (ICT), smart assistants (e.g. service robot, navigation APP) have been increasingly introduced in recent years. However, a STA for the elderly in China lacks attention and consequently leaves almost blank in the SCP market. There is an increasing number of elderly people who want to travel to different regions after their retirement.

Elderly users always live in the local retirement homes for traveling conveniently, so that they need a Smart PSS to address their traveling FRs, including 1) helping elderly users to get used to living off-site quickly; 2) sending the health status of elderly to their relatives in real-time; 3) letting retirement homes acquiring the users' habits; 4) assisting elderly users in choosing and visiting the tourism destination by themselves.

In this step, the target innovative design entropy is set as 0.7, which means that the innovative design entropy of initial design plans needs to be equal or below 0.7. Based on the FRs and target design entropy, the initial design plans of STA are presented, as shown in Figure 9. Then, we observe the value of innovative design entropy. After the normalization processing, the matching degree with user requirements, adaptability measure, and the number of sensors are used as Y_1, Y_2, Y_3. According to the importance of Y_1, Y_2, Y_3 for STA, $A_1 = 0.5$, $A_2 = 0.3$, $A_3 = 0.2$ are given by stakeholders. The innovative design entropy of three initial design plans is calculated below:

$$D_{innovative1} = -\log(0.5 \times 0.8 + 0.3 \times 0.7 + 0.2 \times 0.4) = 0.535 \quad (17)$$

$$D_{innovative2} = -log(0.5 \times 0.6 + 0.3 \times 0.6 + 0.2 \times 0.8) = 0.644 \quad (18)$$

$$D_{innovative3} = -log(0.5 \times 0.7 + 0.3 \times 0.5 + 0.2 \times 0.6) = 0.690 \quad (19)$$

After calculating and comparing, plan A with the lowest innovative design entropy should be selected as the design plan for subsequent development.

Figure 9. Initial design plans of STA.

4.2. Step 2: Conversion plan development

According to the design plan A of STA , the information conversion plan is outputted. As shown in Figure 10, the information of the STA is predicted and summarized from three primary contexts of the elderly users' usage. Then, the information after conversion is planned and listed. Figure 11 shows the preliminary conversion plan of the STA. Finally, the weighting factor is marked and the information conversion plan of the STA is output, as depicted in Figure 12.

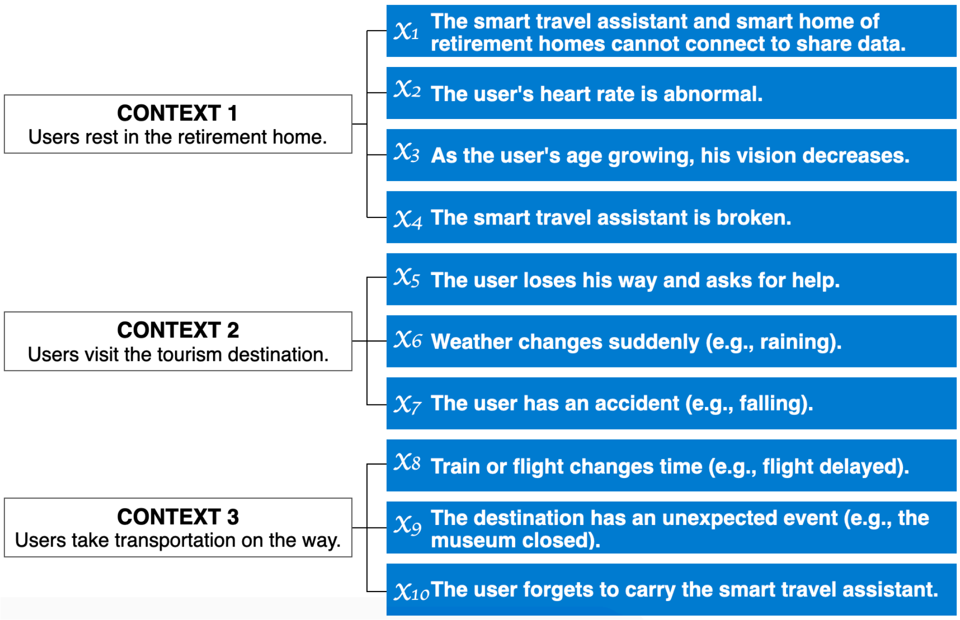

Figure 10. Information prediction list of the STA.

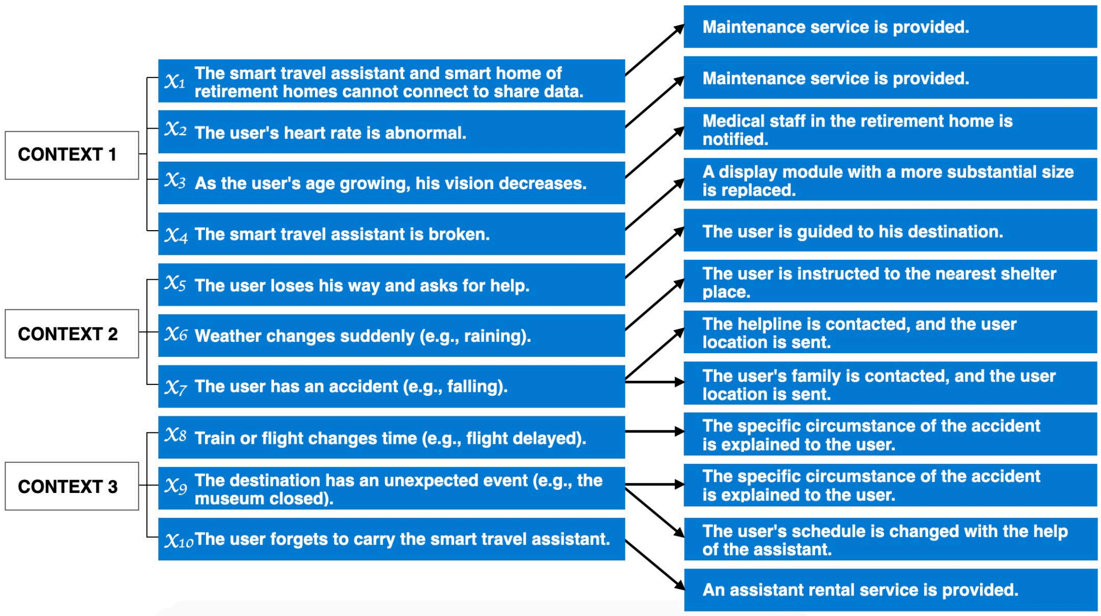

Figure 11. The preliminary conversion plan of the STA.

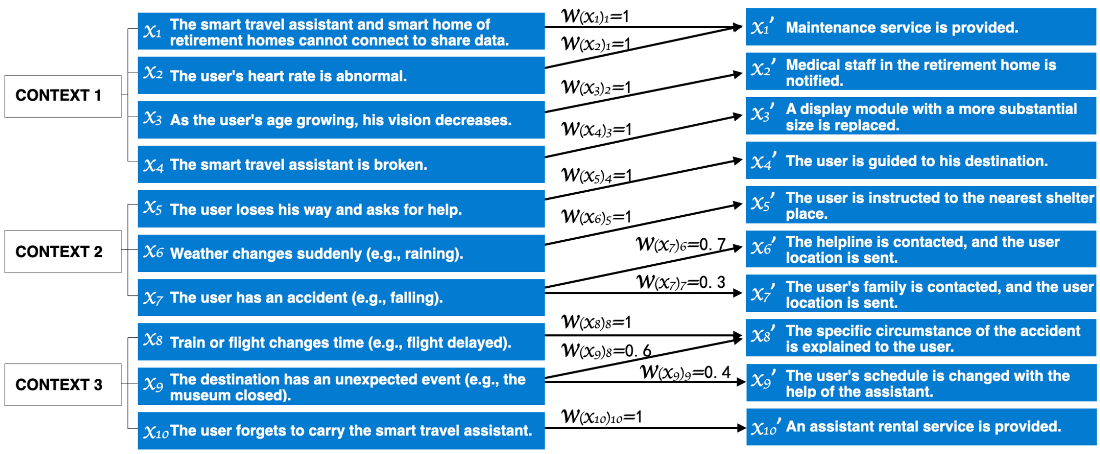

Figure 12. The conversion plan of the STA.

4.3. Step 3: Conversion plan execution and iteration.

During the usage stage, STA collects information x_1, so that the existing information conversion channel is activated. Therefore, the system provides users with maintenance services as described in x_1'. Then, as depicted in Figure 13, the conversion ability is obtained by getting the user satisfaction degree, time, and cost of completing information conversion, and the valve of information x_1 design entropy is calculated and recorded. This value is as expected, so the designers not modify the conversion plan. Moreover, a new information x_{11} without conversion plan is collected, so the conversion plan is modified to convert the information x_{11} to an existing information x_1', as shown in Figure 14. Meanwhile, another new information x_{12} is got, and developers convert it to a new information x_{11}' , as shown in Figure 15.

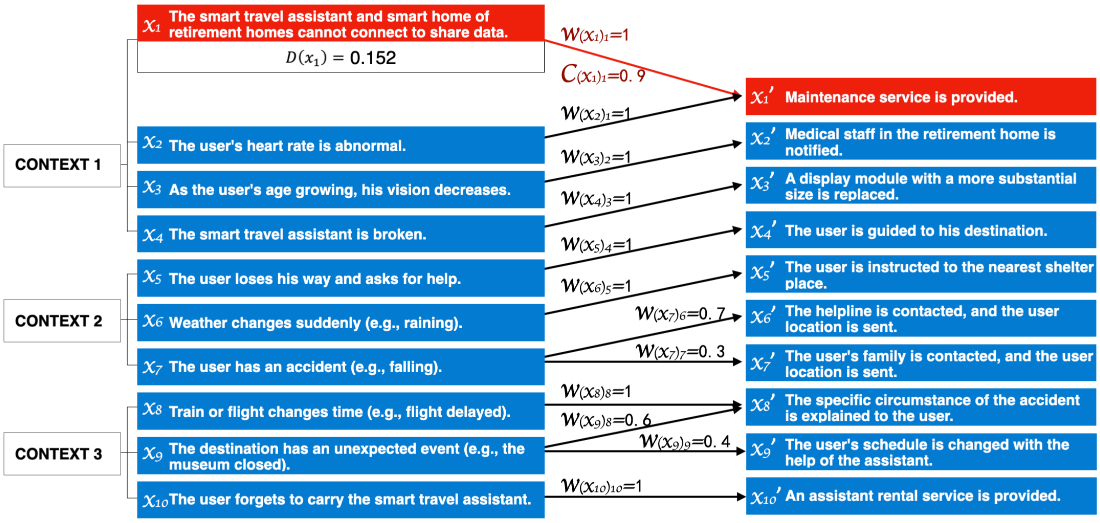

Figure 13. Activating the existing information conversion channel.

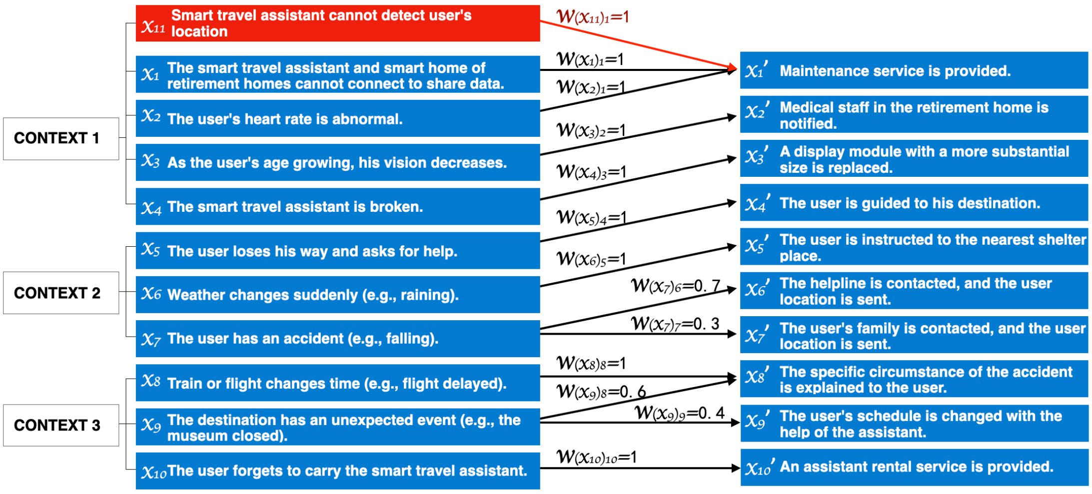

Figure 14. Converting the information x_{11} to an existing information $x_1{}'$.

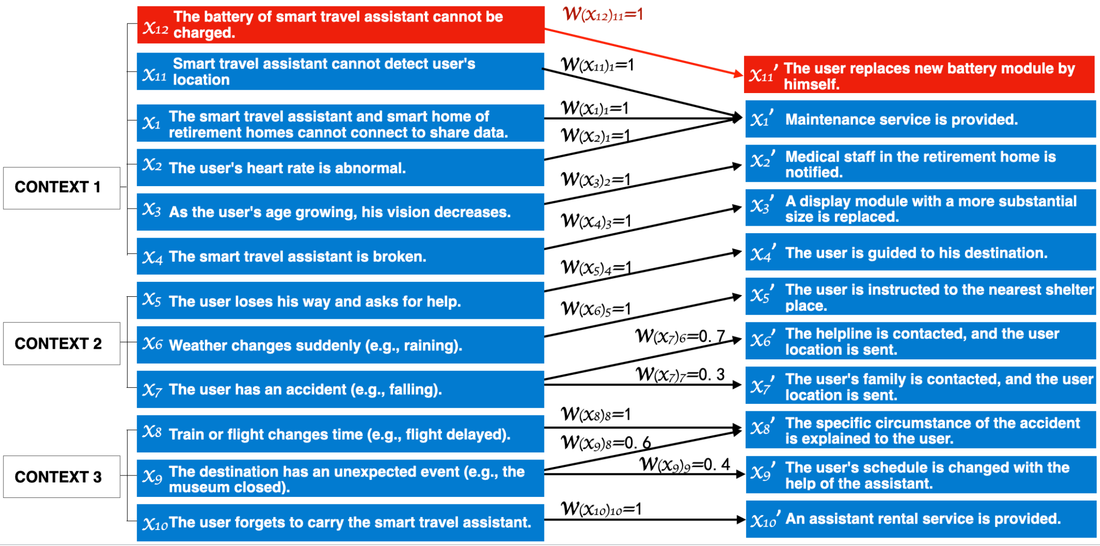

Figure 15. Converting the information x_{12} to a new information $x_{11}{}'$.

5. Discussion

From the above description with the illustrative case study, it appears that design entropy theory can be utilized in Smart PSS development satisfing the three unique design characteristics, which are outlined below:

1) *The value co-creation process* describes the exchange of collecting information through the container (i.e. stakeholders and Smart PSS). Furthermore, design entropy theory presents that stakeholders can set parameters which measure conversion ability together. Meanwhile, the user satisfaction degree of information conversion and the matching degree between design solutions and user requirements have been concerned to ensure users participating.

2) *The closed-loop design/redesign iteration* represents the dynamic change of information and entropy in a balanced system. Design entropy theory focuses on not only innovative design phase but also iterative design phase, which is cirtical to extend the lifecycle in Smart PSS. It observes the status of real-time information conversion by monitoring iterative design entropy.

3) *The design process with context-awareness* denotes the process of reducing design entropy. Design entropy theory suggests that Smart PSS should adjust its design/system to reduce design entropy in an information-driven manner triggered by the specific context. Moreover, it underlines the fact that collected information of Smart PSS from both hardware sensors and social sensors, should be utilized in perceiving and building the usage context.

In addition, the proposed design entropy theory can facilitate Smart PSS development with better performance and user satisfaction. For the former one, design entropy theory improves the performance of Smart PSS through selecting and developing the design plan with the lowest value of innovation design entropy, and ensuring the value of iterative design entropy not exceeding the standard. Meanwhile, the iteration design of existing entities is encouraged to increase the performance of Smart PSS. For the latter one, user satisfaction can be enhanced through realizing the Smart PSS customization with the conversion plan, which can be used for different users by activating different channels of the plan. In addition, the user satisfaction degree of information conversions as core criteria for the value of iterative design entropy will be collected and monitored in the whole usage stage to avoid the situation that users' dissatisfaction for certain information conversion of Smart PSS can not be found promptly.

Despite the advantages of design entropy theory, some limitations still exisit in this work. For instance, due to the limited resources available (e.g. data, users), the illustrative example in Section 4 only describes the conceptual design process without considering the reverse design part. Some real-world engineering applications or examples should be explored in the future to present its practical impact. Nevertheless, it does not affect the core values of the proposed design method in general.

6. Conclusion and future works

Smart PSS, as an emerging IT-driven value co-creation business strategy, has attracted ever-increasing attention among academics and industries recently. Nevertheless, there still lacks a fundamental design methodology for Smart PSS development. To bridge this gap, this paper presents a novel approach that focuses on developing Smart PSS by reducing the design entropy in its closed-loop lifecycle. Design entropy theory is expected to be useful for both the innovative design of a completely new Smart PSS and the iterative redesign of an existing product. As an explorative study, this paper investigated the framework and application of design entropy theory, and mainly contributes to the Smart PSS design field in three aspects. Firstly, the new approach enables Smart PSS to quickly satisfy customer requirements through information from hardware and social sensors. Secondly, a design with the lowest design entropy can be selected before manufacturing to ensure that Smart PSS can easily adapt to the different context in usage. Finally, the new approach can accelerate the design cycle by monitoring the iterative design entropy instead of lengthy testing.

Future research work can be concentrated on the following aspects: 1) Calculate $Y(x)_{\mathrm{m}_n}$ automatically for monitoring iterative design entropy with less human intervention. Such automatic supervision will help designers modify the plan when the design entropy does not meet the standards, rather than keep observing the value of design entropy. 2) Develop a generic platform for conversion plan. The platform can be built to collect conversion plans from different Smart PSS so that when designers develop the conversion plan of information x, information x' with high relevant factors can be recommended to the developers. 3) Propose a standardized measurement model for the design entropy value and add a real-world engineering case to verify it. It is indeed a hard and severe job to ensure design entropy is low enough, where a generally accepted standard for determining the value of design entropy becomes particularly important.

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